The OCaml system release 4.04

Documentation and user's manual

Xavier Leroy,
Damien Doligez, Alain Frisch, Jacques Garrigue, Didier Rémy and Jérôme Vouillon

November 4, 2016

Copyright © 2016 Institut National de Recherche en Informatique et en Automatique

Contents

I An introduction to OCaml **11**

1 The core language **13**
1.1 Basics . . . 13
1.2 Data types . . . 14
1.3 Functions as values . . . 15
1.4 Records and variants . . . 16
1.5 Imperative features . . . 18
1.6 Exceptions . . . 20
1.7 Symbolic processing of expressions . . . 21
1.8 Pretty-printing . . . 22
1.9 Standalone OCaml programs . . . 23

2 The module system **25**
2.1 Structures . . . 25
2.2 Signatures . . . 26
2.3 Functors . . . 27
2.4 Functors and type abstraction . . . 29
2.5 Modules and separate compilation . . . 31

3 Objects in OCaml **33**
3.1 Classes and objects . . . 33
3.2 Immediate objects . . . 36
3.3 Reference to self . . . 37
3.4 Initializers . . . 38
3.5 Virtual methods . . . 38
3.6 Private methods . . . 40
3.7 Class interfaces . . . 42
3.8 Inheritance . . . 43
3.9 Multiple inheritance . . . 44
3.10 Parameterized classes . . . 44
3.11 Polymorphic methods . . . 47
3.12 Using coercions . . . 50
3.13 Functional objects . . . 54
3.14 Cloning objects . . . 55
3.15 Recursive classes . . . 58

3.16 Binary methods . . . 58
3.17 Friends . . . 60

4 Labels and variants **63**
4.1 Labels . . . 63
4.2 Polymorphic variants . . . 69

5 Advanced examples with classes and modules **73**
5.1 Extended example: bank accounts . . . 73
5.2 Simple modules as classes . . . 79
5.3 The subject/observer pattern . . . 84

II The OCaml language **89**

6 The OCaml language **91**
6.1 Lexical conventions . . . 91
6.2 Values . . . 95
6.3 Names . . . 97
6.4 Type expressions . . . 100
6.5 Constants . . . 103
6.6 Patterns . . . 104
6.7 Expressions . . . 108
6.8 Type and exception definitions . . . 121
6.9 Classes . . . 123
6.10 Module types (module specifications) . . . 130
6.11 Module expressions (module implementations) . . . 134
6.12 Compilation units . . . 137

7 Language extensions **139**
7.1 Integer literals for types `int32`, `int64` and `nativeint` . . . 139
7.2 Recursive definitions of values . . . 139
7.3 Lazy patterns . . . 141
7.4 Recursive modules . . . 141
7.5 Private types . . . 142
7.6 Local opens . . . 145
7.7 Record and object notations . . . 146
7.8 Explicit polymorphic type annotations . . . 147
7.9 Locally abstract types . . . 147
7.10 First-class modules . . . 149
7.11 Recovering the type of a module . . . 151
7.12 Substituting inside a signature . . . 151
7.13 Type-level module aliases . . . 152
7.14 Explicit overriding in class definitions . . . 154
7.15 Overriding in open statements . . . 154
7.16 Generalized algebraic datatypes . . . 155

7.17 Syntax for Bigarray access . . . 160
7.18 Attributes . . . 160
7.19 Extension nodes . . . 167
7.20 Quoted strings . . . 169
7.21 Exception cases in pattern matching . . . 169
7.22 Extensible variant types . . . 169
7.23 Generative functors . . . 171
7.24 Extension-only syntax . . . 171
7.25 Inline records . . . 172
7.26 Local exceptions . . . 173
7.27 Documentation comments . . . 173

III The OCaml tools **177**

8 Batch compilation (ocamlc) **179**
8.1 Overview of the compiler . . . 179
8.2 Options . . . 180
8.3 Modules and the file system . . . 191
8.4 Common errors . . . 191
8.5 Warning reference . . . 194

9 The toplevel system (ocaml) **197**
9.1 Options . . . 198
9.2 Toplevel directives . . . 201
9.3 The toplevel and the module system . . . 204
9.4 Common errors . . . 204
9.5 Building custom toplevel systems: `ocamlmktop` . . . 205
9.6 Options . . . 205

10 The runtime system (ocamlrun) **207**
10.1 Overview . . . 207
10.2 Options . . . 208
10.3 Dynamic loading of shared libraries . . . 210
10.4 Common errors . . . 210

11 Native-code compilation (ocamlopt) **213**
11.1 Overview of the compiler . . . 213
11.2 Options . . . 214
11.3 Common errors . . . 225
11.4 Running executables produced by ocamlopt . . . 225
11.5 Compatibility with the bytecode compiler . . . 225

12 Lexer and parser generators (ocamllex, ocamlyacc) 227
12.1 Overview of `ocamllex` . . . 227
12.2 Syntax of lexer definitions . . . 228
12.3 Overview of `ocamlyacc` . . . 233
12.4 Syntax of grammar definitions . . . 233
12.5 Options . . . 236
12.6 A complete example . . . 237
12.7 Common errors . . . 238
12.8 Module `Depend` : Module dependencies. . . . 239

13 The browser/editor (ocamlbrowser) 241

14 The documentation generator (ocamldoc) 243
14.1 Usage . . . 243
14.2 Syntax of documentation comments . . . 250
14.3 Custom generators . . . 260
14.4 Adding command line options . . . 263

15 The debugger (ocamldebug) 265
15.1 Compiling for debugging . . . 265
15.2 Invocation . . . 265
15.3 Commands . . . 266
15.4 Executing a program . . . 267
15.5 Breakpoints . . . 270
15.6 The call stack . . . 270
15.7 Examining variable values . . . 271
15.8 Controlling the debugger . . . 272
15.9 Miscellaneous commands . . . 275
15.10 Running the debugger under Emacs . . . 275

16 Profiling (ocamlprof) 277
16.1 Compiling for profiling . . . 277
16.2 Profiling an execution . . . 278
16.3 Printing profiling information . . . 278
16.4 Time profiling . . . 279

17 The ocamlbuild compilation manager 281

18 Interfacing C with OCaml 283
18.1 Overview and compilation information . . . 283
18.2 The `value` type . . . 290
18.3 Representation of OCaml data types . . . 291
18.4 Operations on values . . . 294
18.5 Living in harmony with the garbage collector . . . 297
18.6 A complete example . . . 301
18.7 Advanced topic: callbacks from C to OCaml . . . 305

18.8 Advanced example with callbacks . . . 309
18.9 Advanced topic: custom blocks . . . 311
18.10 Advanced topic: cheaper C call . . . 315
18.11 Advanced topic: multithreading . . . 317
18.12 Building mixed C/OCaml libraries: `ocamlmklib` . . . 319

19 Optimisation with Flambda **323**
19.1 Overview . . . 323
19.2 Command-line flags . . . 323
19.3 Inlining . . . 326
19.4 Specialisation . . . 331
19.5 Default settings of parameters . . . 334
19.6 Manual control of inlining and specialisation . . . 335
19.7 Simplification . . . 336
19.8 Other code motion transformations . . . 337
19.9 Unboxing transformations . . . 338
19.10 Removal of unused code and values . . . 342
19.11 Other code transformations . . . 342
19.12 Treatment of effects . . . 343
19.13 Compilation of statically-allocated modules . . . 344
19.14 Inhibition of optimisation . . . 344
19.15 Use of unsafe operations . . . 344
19.16 Glossary . . . 345
19.17 Module `Spacetime` : Profiling of a program's space behaviour over time. . . . 346

IV The OCaml library **349**

20 The core library **351**
20.1 Built-in types and predefined exceptions . . . 351
20.2 Module `Pervasives` : The initially opened module. . . . 354

21 The standard library **377**
21.1 Module `Arg` : Parsing of command line arguments. . . . 379
21.2 Module `Array` : Array operations. . . . 382
21.3 Module `Buffer` : Extensible buffers. . . . 386
21.4 Module `Bytes` : Byte sequence operations. . . . 389
21.5 Module `Callback` : Registering OCaml values with the C runtime. . . . 395
21.6 Module `Char` : Character operations. . . . 396
21.7 Module `Complex` : Complex numbers. . . . 397
21.8 Module `Digest` : MD5 message digest. . . . 398
21.9 Module `Ephemeron` : Ephemerons and weak hash table . . . 400
21.10 Module `Filename` : Operations on file names. . . . 408
21.11 Module `Format` : Pretty printing. . . . 410
21.12 Module `Gc` : Memory management control and statistics; finalised values. . . . 425
21.13 Module `Genlex` : A generic lexical analyzer. . . . 431

21.14 Module `Hashtbl` : Hash tables and hash functions. . . . 432
21.15 Module `Int32` : 32-bit integers. . . . 439
21.16 Module `Int64` : 64-bit integers. . . . 442
21.17 Module `Lazy` : Deferred computations. . . . 445
21.18 Module `Lexing` : The run-time library for lexers generated by `ocamllex`. . . . 447
21.19 Module `List` : List operations. . . . 449
21.20 Module `Map` : Association tables over ordered types. . . . 454
21.21 Module `Marshal` : Marshaling of data structures. . . . 459
21.22 Module `MoreLabels` : Extra labeled libraries. . . . 461
21.23 Module `Nativeint` : Processor-native integers. . . . 466
21.24 Module `Oo` : Operations on objects 469
21.25 Module `Parsing` : The run-time library for parsers generated by `ocamlyacc`. . . . 470
21.26 Module `Printexc` : Facilities for printing exceptions and inspecting current call stack. 471
21.27 Module `Printf` : Formatted output functions. . . . 476
21.28 Module `Queue` : First-in first-out queues. . . . 479
21.29 Module `Random` : Pseudo-random number generators (PRNG). . . . 480
21.30 Module `Scanf` : Formatted input functions. . . . 483
21.31 Module `Set` : Sets over ordered types. . . . 492
21.32 Module `Sort` : Sorting and merging lists. . . . 496
21.33 Module `Spacetime` : Profiling of a program's space behaviour over time. . . . 497
21.34 Module `Stack` : Last-in first-out stacks. . . . 499
21.35 Module `StdLabels` : Standard labeled libraries. . . . 500
21.36 Module `Stream` : Streams and parsers. . . . 500
21.37 Module `String` : String operations. . . . 502
21.38 Module `Sys` : System interface. . . . 506
21.39 Module `Uchar` : Unicode characters. . . . 513
21.40 Module `Weak` : Arrays of weak pointers and hash sets of weak pointers. . . . 514

22 The compiler front-end **519**
22.1 Module `Ast_mapper` : The interface of a -ppx rewriter 519
22.2 Module `Asttypes` : Auxiliary AST types used by parsetree and typedtree. . . . 523
22.3 Module `Location` : Source code locations (ranges of positions), used in parsetree. . . 524
22.4 Module `Longident` : Long identifiers, used in parsetree. . . . 526
22.5 Module `Parse` : Entry points in the parser 526
22.6 Module `Parsetree` : Abstract syntax tree produced by parsing 527
22.7 Module `Pprintast` 535

23 The unix library: Unix system calls **537**
23.1 Module `Unix` : Interface to the Unix system. . . . 537
23.2 Module `UnixLabels`: labelized version of the interface 572

24 The num library: arbitrary-precision rational arithmetic **575**
24.1 Module `Num` : Operation on arbitrary-precision numbers. . . . 575
24.2 Module `Big_int` : Operations on arbitrary-precision integers. . . . 579
24.3 Module `Arith_status` : Flags that control rational arithmetic. . . . 583

25 The str library: regular expressions and string processing **585**
25.1 Module `Str` : Regular expressions and high-level string processing 585

26 The threads library **591**
26.1 Module `Thread` : Lightweight threads for Posix `1003.1c` and Win32. 592
26.2 Module `Mutex` : Locks for mutual exclusion. 594
26.3 Module `Condition` : Condition variables to synchronize between threads. 594
26.4 Module `Event` : First-class synchronous communication. 595
26.5 Module `ThreadUnix` : Thread-compatible system calls. 597

27 The graphics library **599**
27.1 Module `Graphics` : Machine-independent graphics primitives. 600

28 The dynlink library: dynamic loading and linking of object files **609**
28.1 Module `Dynlink` : Dynamic loading of object files. 609

29 The bigarray library **613**
29.1 Module `Bigarray` : Large, multi-dimensional, numerical arrays. 614
29.2 Big arrays in the OCaml-C interface 631

V Appendix **635**

Index to the library **637**

Index of keywords **638**

Foreword

This manual documents the release 4.04 of the OCaml system. It is organized as follows.

- Part I, "An introduction to OCaml", gives an overview of the language.
- Part II, "The OCaml language", is the reference description of the language.
- Part III, "The OCaml tools", documents the compilers, toplevel system, and programming utilities.
- Part IV, "The OCaml library", describes the modules provided in the standard library.
- Part V, "Appendix", contains an index of all identifiers defined in the standard library, and an index of keywords.

Conventions

OCaml runs on several operating systems. The parts of this manual that are specific to one operating system are presented as shown below:

Unix:
This is material specific to the Unix family of operating systems, including Linux and MacOS X.

Windows:
This is material specific to Microsoft Windows (2000, XP, Vista, Seven).

License

The OCaml system is copyright © 1996–2016 Institut National de Recherche en Informatique et en Automatique (INRIA). INRIA holds all ownership rights to the OCaml system.

The OCaml system is open source and can be freely redistributed. See the file `LICENSE` in the distribution for licensing information.

The present documentation is copyright © 2016 Institut National de Recherche en Informatique et en Automatique (INRIA). The OCaml documentation and user's manual may be reproduced and distributed in whole or in part, subject to the following conditions:

- The copyright notice above and this permission notice must be preserved complete on all complete or partial copies.

- Any translation or derivative work of the OCaml documentation and user's manual must be approved by the authors in writing before distribution.
- If you distribute the OCaml documentation and user's manual in part, instructions for obtaining the complete version of this manual must be included, and a means for obtaining a complete version provided.
- Small portions may be reproduced as illustrations for reviews or quotes in other works without this permission notice if proper citation is given.

Availability

The complete OCaml distribution can be accessed via the Web site `http://caml.inria.fr/`. This Web site contains a lot of additional information on OCaml.

Part I

An introduction to OCaml

Chapter 1

The core language

This part of the manual is a tutorial introduction to the OCaml language. A good familiarity with programming in a conventional languages (say, Pascal or C) is assumed, but no prior exposure to functional languages is required. The present chapter introduces the core language. Chapter 2 deals with the module system, chapter 3 with the object-oriented features, chapter 4 with extensions to the core language (labeled arguments and polymorphic variants), and chapter 5 gives some advanced examples.

1.1 Basics

For this overview of OCaml, we use the interactive system, which is started by running `ocaml` from the Unix shell, or by launching the `OCamlwin.exe` application under Windows. This tutorial is presented as the transcript of a session with the interactive system: lines starting with `#` represent user input; the system responses are printed below, without a leading `#`.

Under the interactive system, the user types OCaml phrases terminated by `;;` in response to the `#` prompt, and the system compiles them on the fly, executes them, and prints the outcome of evaluation. Phrases are either simple expressions, or `let` definitions of identifiers (either values or functions).

```
# 1+2*3;;
- : int = 7

# let pi = 4.0 *. atan 1.0;;
val pi : float = 3.14159265358979312

# let square x = x *. x;;
val square : float -> float = <fun>

# square (sin pi) +. square (cos pi);;
- : float = 1.
```

The OCaml system computes both the value and the type for each phrase. Even function parameters need no explicit type declaration: the system infers their types from their usage in the function. Notice also that integers and floating-point numbers are distinct types, with distinct operators: `+` and `*` operate on integers, but `+.` and `*.` operate on floats.

```
# 1.0 * 2;;
Error: This expression has type float but an expression was expected of type
         int
```

Recursive functions are defined with the `let rec` binding:

```
# let rec fib n =
#   if n < 2 then n else fib (n-1) + fib (n-2);;
val fib : int -> int = <fun>

# fib 10;;
- : int = 55
```

1.2 Data types

In addition to integers and floating-point numbers, OCaml offers the usual basic data types: booleans, characters, and immutable character strings.

```
# (1 < 2) = false;;
- : bool = false

# 'a';;
- : char = 'a'

# "Hello world";;
- : string = "Hello world"
```

Predefined data structures include tuples, arrays, and lists. General mechanisms for defining your own data structures are also provided. They will be covered in more details later; for now, we concentrate on lists. Lists are either given in extension as a bracketed list of semicolon-separated elements, or built from the empty list `[]` (pronounce "nil") by adding elements in front using the `::` ("cons") operator.

```
# let l = ["is"; "a"; "tale"; "told"; "etc."];;
val l : string list = ["is"; "a"; "tale"; "told"; "etc."]

# "Life" :: l;;
- : string list = ["Life"; "is"; "a"; "tale"; "told"; "etc."]
```

As with all other OCaml data structures, lists do not need to be explicitly allocated and deallocated from memory: all memory management is entirely automatic in OCaml. Similarly, there is no explicit handling of pointers: the OCaml compiler silently introduces pointers where necessary.

As with most OCaml data structures, inspecting and destructuring lists is performed by pattern-matching. List patterns have the exact same shape as list expressions, with identifier representing unspecified parts of the list. As an example, here is insertion sort on a list:

```
# let rec sort lst =
#   match lst with
#     [] -> []
#   | head :: tail -> insert head (sort tail)
```

```
# and insert elt lst =
#   match lst with
#     [] -> [elt]
#   | head :: tail -> if elt <= head then elt :: lst else head :: insert elt tail
# ;;
val sort : 'a list -> 'a list = <fun>
val insert : 'a -> 'a list -> 'a list = <fun>

# sort l;;
- : string list = ["a"; "etc."; "is"; "tale"; "told"]
```

The type inferred for `sort`, `'a list -> 'a list`, means that `sort` can actually apply to lists of any type, and returns a list of the same type. The type `'a` is a *type variable*, and stands for any given type. The reason why `sort` can apply to lists of any type is that the comparisons (`=`, `<=`, etc.) are *polymorphic* in OCaml: they operate between any two values of the same type. This makes `sort` itself polymorphic over all list types.

```
# sort [6;2;5;3];;
- : int list = [2; 3; 5; 6]

# sort [3.14; 2.718];;
- : float list = [2.718; 3.14]
```

The `sort` function above does not modify its input list: it builds and returns a new list containing the same elements as the input list, in ascending order. There is actually no way in OCaml to modify in-place a list once it is built: we say that lists are *immutable* data structures. Most OCaml data structures are immutable, but a few (most notably arrays) are *mutable*, meaning that they can be modified in-place at any time.

1.3 Functions as values

OCaml is a functional language: functions in the full mathematical sense are supported and can be passed around freely just as any other piece of data. For instance, here is a `deriv` function that takes any float function as argument and returns an approximation of its derivative function:

```
# let deriv f dx = function x -> (f (x +. dx) -. f x) /. dx;;
val deriv : (float -> float) -> float -> float -> float = <fun>

# let sin' = deriv sin 1e-6;;
val sin' : float -> float = <fun>

# sin' pi;;
- : float = -1.00000000013961143
```

Even function composition is definable:

```
# let compose f g = function x -> f (g x);;
val compose : ('a -> 'b) -> ('c -> 'a) -> 'c -> 'b = <fun>

# let cos2 = compose square cos;;
val cos2 : float -> float = <fun>
```

Functions that take other functions as arguments are called "functionals", or "higher-order functions". Functionals are especially useful to provide iterators or similar generic operations over a data structure. For instance, the standard OCaml library provides a `List.map` functional that applies a given function to each element of a list, and returns the list of the results:

```
# List.map (function n -> n * 2 + 1) [0;1;2;3;4];;
- : int list = [1; 3; 5; 7; 9]
```

This functional, along with a number of other list and array functionals, is predefined because it is often useful, but there is nothing magic with it: it can easily be defined as follows.

```
# let rec map f l =
#   match l with
#     [] -> []
#   | hd :: tl -> f hd :: map f tl;;
val map : ('a -> 'b) -> 'a list -> 'b list = <fun>
```

1.4 Records and variants

User-defined data structures include records and variants. Both are defined with the `type` declaration. Here, we declare a record type to represent rational numbers.

```
# type ratio = {num: int; denom: int};;
type ratio = { num : int; denom : int; }
```

```
# let add_ratio r1 r2 =
#   {num = r1.num * r2.denom + r2.num * r1.denom;
#    denom = r1.denom * r2.denom};;
val add_ratio : ratio -> ratio -> ratio = <fun>
```

```
# add_ratio {num=1; denom=3} {num=2; denom=5};;
- : ratio = {num = 11; denom = 15}
```

The declaration of a variant type lists all possible shapes for values of that type. Each case is identified by a name, called a constructor, which serves both for constructing values of the variant type and inspecting them by pattern-matching. Constructor names are capitalized to distinguish them from variable names (which must start with a lowercase letter). For instance, here is a variant type for doing mixed arithmetic (integers and floats):

```
# type number = Int of int | Float of float | Error;;
type number = Int of int | Float of float | Error
```

This declaration expresses that a value of type `number` is either an integer, a floating-point number, or the constant `Error` representing the result of an invalid operation (e.g. a division by zero).

Enumerated types are a special case of variant types, where all alternatives are constants:

```
# type sign = Positive | Negative;;
type sign = Positive | Negative
```

```
# let sign_int n = if n >= 0 then Positive else Negative;;
val sign_int : int -> sign = <fun>
```

To define arithmetic operations for the `number` type, we use pattern-matching on the two numbers involved:

```
# let add_num n1 n2 =
#   match (n1, n2) with
#     (Int i1, Int i2) ->
#       (* Check for overflow of integer addition *)
#       if sign_int i1 = sign_int i2 && sign_int (i1 + i2) <> sign_int i1
#       then Float(float i1 +. float i2)
#       else Int(i1 + i2)
#   | (Int i1, Float f2) -> Float(float i1 +. f2)
#   | (Float f1, Int i2) -> Float(f1 +. float i2)
#   | (Float f1, Float f2) -> Float(f1 +. f2)
#   | (Error, _) -> Error
#   | (_, Error) -> Error;;
val add_num : number -> number -> number = <fun>

# add_num (Int 123) (Float 3.14159);;
- : number = Float 126.14159
```

The most common usage of variant types is to describe recursive data structures. Consider for example the type of binary trees:

```
# type 'a btree = Empty | Node of 'a * 'a btree * 'a btree;;
type 'a btree = Empty | Node of 'a * 'a btree * 'a btree
```

This definition reads as follow: a binary tree containing values of type `'a` (an arbitrary type) is either empty, or is a node containing one value of type `'a` and two subtrees containing also values of type `'a`, that is, two `'a btree`.

Operations on binary trees are naturally expressed as recursive functions following the same structure as the type definition itself. For instance, here are functions performing lookup and insertion in ordered binary trees (elements increase from left to right):

```
# let rec member x btree =
#   match btree with
#     Empty -> false
#   | Node(y, left, right) ->
#       if x = y then true else
#       if x < y then member x left else member x right;;
val member : 'a -> 'a btree -> bool = <fun>

# let rec insert x btree =
#   match btree with
#     Empty -> Node(x, Empty, Empty)
#   | Node(y, left, right) ->
#       if x <= y then Node(y, insert x left, right)
#                 else Node(y, left, insert x right);;
val insert : 'a -> 'a btree -> 'a btree = <fun>
```

1.5 Imperative features

Though all examples so far were written in purely applicative style, OCaml is also equipped with full imperative features. This includes the usual `while` and `for` loops, as well as mutable data structures such as arrays. Arrays are either given in extension between `[|` and `|]` brackets, or allocated and initialized with the `Array.make` function, then filled up later by assignments. For instance, the function below sums two vectors (represented as float arrays) componentwise.

```
# let add_vect v1 v2 =
#   let len = min (Array.length v1) (Array.length v2) in
#   let res = Array.make len 0.0 in
#   for i = 0 to len - 1 do
#     res.(i) <- v1.(i) +. v2.(i)
#   done;
#   res;;
val add_vect : float array -> float array -> float array = <fun>

# add_vect [| 1.0; 2.0 |] [| 3.0; 4.0 |];;
- : float array = [|4.; 6.|]
```

Record fields can also be modified by assignment, provided they are declared `mutable` in the definition of the record type:

```
# type mutable_point = { mutable x: float; mutable y: float };;
type mutable_point = { mutable x : float; mutable y : float; }

# let translate p dx dy =
#   p.x <- p.x +. dx; p.y <- p.y +. dy;;
val translate : mutable_point -> float -> float -> unit = <fun>

# let mypoint = { x = 0.0; y = 0.0 };;
val mypoint : mutable_point = {x = 0.; y = 0.}

# translate mypoint 1.0 2.0;;
- : unit = ()

# mypoint;;
- : mutable_point = {x = 1.; y = 2.}
```

OCaml has no built-in notion of variable – identifiers whose current value can be changed by assignment. (The `let` binding is not an assignment, it introduces a new identifier with a new scope.) However, the standard library provides references, which are mutable indirection cells (or one-element arrays), with operators `!` to fetch the current contents of the reference and `:=` to assign the contents. Variables can then be emulated by `let`-binding a reference. For instance, here is an in-place insertion sort over arrays:

```
# let insertion_sort a =
#   for i = 1 to Array.length a - 1 do
#     let val_i = a.(i) in
#     let j = ref i in
#     while !j > 0 && val_i < a.(!j - 1) do
```

```
#       a.(!j) <- a.(!j - 1);
#       j := !j - 1
#     done;
#     a.(!j) <- val_i
#   done;;
val insertion_sort : 'a array -> unit = <fun>
```

References are also useful to write functions that maintain a current state between two calls to the function. For instance, the following pseudo-random number generator keeps the last returned number in a reference:

```
# let current_rand = ref 0;;
val current_rand : int ref = {contents = 0}

# let random () =
#   current_rand := !current_rand * 25713 + 1345;
#   !current_rand;;
val random : unit -> int = <fun>
```

Again, there is nothing magical with references: they are implemented as a single-field mutable record, as follows.

```
# type 'a ref = { mutable contents: 'a };;
type 'a ref = { mutable contents : 'a; }

# let ( ! ) r = r.contents;;
val ( ! ) : 'a ref -> 'a = <fun>

# let ( := ) r newval = r.contents <- newval;;
val ( := ) : 'a ref -> 'a -> unit = <fun>
```

In some special cases, you may need to store a polymorphic function in a data structure, keeping its polymorphism. Without user-provided type annotations, this is not allowed, as polymorphism is only introduced on a global level. However, you can give explicitly polymorphic types to record fields.

```
# type idref = { mutable id: 'a. 'a -> 'a };;
type idref = { mutable id : 'a. 'a -> 'a; }

# let r = {id = fun x -> x};;
val r : idref = {id = <fun>}

# let g s = (s.id 1, s.id true);;
val g : idref -> int * bool = <fun>

# r.id <- (fun x -> print_string "called id\n"; x);;
- : unit = ()

# g r;;
called id
called id
- : int * bool = (1, true)
```

1.6 Exceptions

OCaml provides exceptions for signalling and handling exceptional conditions. Exceptions can also be used as a general-purpose non-local control structure. Exceptions are declared with the `exception` construct, and signalled with the `raise` operator. For instance, the function below for taking the head of a list uses an exception to signal the case where an empty list is given.

```
# exception Empty_list;;
exception Empty_list
```

```
# let head l =
#   match l with
#     [] -> raise Empty_list
#   | hd :: tl -> hd;;
val head : 'a list -> 'a = <fun>
```

```
# head [1;2];;
- : int = 1
```

```
# head [];;
Exception: Empty_list.
```

Exceptions are used throughout the standard library to signal cases where the library functions cannot complete normally. For instance, the `List.assoc` function, which returns the data associated with a given key in a list of (key, data) pairs, raises the predefined exception `Not_found` when the key does not appear in the list:

```
# List.assoc 1 [(0, "zero"); (1, "one")];;
- : string = "one"
```

```
# List.assoc 2 [(0, "zero"); (1, "one")];;
Exception: Not_found.
```

Exceptions can be trapped with the `try`...`with` construct:

```
# let name_of_binary_digit digit =
#   try
#     List.assoc digit [0, "zero"; 1, "one"]
#   with Not_found ->
#     "not a binary digit";;
val name_of_binary_digit : int -> string = <fun>
```

```
# name_of_binary_digit 0;;
- : string = "zero"
```

```
# name_of_binary_digit (-1);;
- : string = "not a binary digit"
```

The `with` part is actually a regular pattern-matching on the exception value. Thus, several exceptions can be caught by one `try`...`with` construct. Also, finalization can be performed by trapping all exceptions, performing the finalization, then raising again the exception:

```
# let temporarily_set_reference ref newval funct =
#   let oldval = !ref in
#   try
#     ref := newval;
#     let res = funct () in
#     ref := oldval;
#     res
#   with x ->
#     ref := oldval;
#     raise x;;
val temporarily_set_reference : 'a ref -> 'a -> (unit -> 'b) -> 'b = <fun>
```

1.7 Symbolic processing of expressions

We finish this introduction with a more complete example representative of the use of OCaml for symbolic processing: formal manipulations of arithmetic expressions containing variables. The following variant type describes the expressions we shall manipulate:

```
# type expression =
#     Const of float
#   | Var of string
#   | Sum of expression * expression    (* e1 + e2 *)
#   | Diff of expression * expression   (* e1 - e2 *)
#   | Prod of expression * expression   (* e1 * e2 *)
#   | Quot of expression * expression   (* e1 / e2 *)
# ;;
type expression =
    Const of float
  | Var of string
  | Sum of expression * expression
  | Diff of expression * expression
  | Prod of expression * expression
  | Quot of expression * expression
```

We first define a function to evaluate an expression given an environment that maps variable names to their values. For simplicity, the environment is represented as an association list.

```
# exception Unbound_variable of string;;
exception Unbound_variable of string
```

```
# let rec eval env exp =
#   match exp with
#     Const c -> c
#   | Var v ->
#       (try List.assoc v env with Not_found -> raise (Unbound_variable v))
#   | Sum(f, g) -> eval env f +. eval env g
#   | Diff(f, g) -> eval env f -. eval env g
```

```
#   | Prod(f, g) -> eval env f *. eval env g
#   | Quot(f, g) -> eval env f /. eval env g;;
val eval : (string * float) list -> expression -> float = <fun>

# eval [("x", 1.0); ("y", 3.14)] (Prod(Sum(Var "x", Const 2.0), Var "y"));;
- : float = 9.42
```

Now for a real symbolic processing, we define the derivative of an expression with respect to a variable `dv`:

```
# let rec deriv exp dv =
#   match exp with
#     Const c -> Const 0.0
#   | Var v -> if v = dv then Const 1.0 else Const 0.0
#   | Sum(f, g) -> Sum(deriv f dv, deriv g dv)
#   | Diff(f, g) -> Diff(deriv f dv, deriv g dv)
#   | Prod(f, g) -> Sum(Prod(f, deriv g dv), Prod(deriv f dv, g))
#   | Quot(f, g) -> Quot(Diff(Prod(deriv f dv, g), Prod(f, deriv g dv)),
#                        Prod(g, g))
# ;;
val deriv : expression -> string -> expression = <fun>

# deriv (Quot(Const 1.0, Var "x")) "x";;
- : expression =
Quot (Diff (Prod (Const 0., Var "x"), Prod (Const 1., Const 1.)),
 Prod (Var "x", Var "x"))
```

1.8 Pretty-printing

As shown in the examples above, the internal representation (also called *abstract syntax*) of expressions quickly becomes hard to read and write as the expressions get larger. We need a printer and a parser to go back and forth between the abstract syntax and the *concrete syntax*, which in the case of expressions is the familiar algebraic notation (e.g. `2*x+1`).

For the printing function, we take into account the usual precedence rules (i.e. `*` binds tighter than `+`) to avoid printing unnecessary parentheses. To this end, we maintain the current operator precedence and print parentheses around an operator only if its precedence is less than the current precedence.

```
# let print_expr exp =
#   (* Local function definitions *)
#   let open_paren prec op_prec =
#     if prec > op_prec then print_string "(" in
#   let close_paren prec op_prec =
#     if prec > op_prec then print_string ")" in
#   let rec print prec exp =     (* prec is the current precedence *)
#     match exp with
#       Const c -> print_float c
```

```
#     | Var v -> print_string v
#     | Sum(f, g) ->
#         open_paren prec 0;
#         print 0 f; print_string " + "; print 0 g;
#         close_paren prec 0
#     | Diff(f, g) ->
#         open_paren prec 0;
#         print 0 f; print_string " - "; print 1 g;
#         close_paren prec 0
#     | Prod(f, g) ->
#         open_paren prec 2;
#         print 2 f; print_string " * "; print 2 g;
#         close_paren prec 2
#     | Quot(f, g) ->
#         open_paren prec 2;
#         print 2 f; print_string " / "; print 3 g;
#         close_paren prec 2
#   in print 0 exp;;
val print_expr : expression -> unit = <fun>

# let e = Sum(Prod(Const 2.0, Var "x"), Const 1.0);;
val e : expression = Sum (Prod (Const 2., Var "x"), Const 1.)

# print_expr e; print_newline ();;
2. * x + 1.
- : unit = ()

# print_expr (deriv e "x"); print_newline ();;
2. * 1. + 0. * x + 0.
- : unit = ()
```

1.9 Standalone OCaml programs

All examples given so far were executed under the interactive system. OCaml code can also be compiled separately and executed non-interactively using the batch compilers `ocamlc` and `ocamlopt`. The source code must be put in a file with extension `.ml`. It consists of a sequence of phrases, which will be evaluated at runtime in their order of appearance in the source file. Unlike in interactive mode, types and values are not printed automatically; the program must call printing functions explicitly to produce some output. Here is a sample standalone program to print Fibonacci numbers:

```
(* File fib.ml *)
let rec fib n =
  if n < 2 then 1 else fib (n-1) + fib (n-2);;
let main () =
  let arg = int_of_string Sys.argv.(1) in
  print_int (fib arg);
  print_newline ();
```

```
  exit 0;;
main ();;
```

`Sys.argv` is an array of strings containing the command-line parameters. `Sys.argv.(1)` is thus the first command-line parameter. The program above is compiled and executed with the following shell commands:

```
$ ocamlc -o fib fib.ml
$ ./fib 10
89
$ ./fib 20
10946
```

More complex standalone OCaml programs are typically composed of multiple source files, and can link with precompiled libraries. Chapters 8 and 11 explain how to use the batch compilers `ocamlc` and `ocamlopt`. Recompilation of multi-file OCaml projects can be automated using third-party build systems, such as the ocamlbuild compilation manager.

Chapter 2

The module system

This chapter introduces the module system of OCaml.

2.1 Structures

A primary motivation for modules is to package together related definitions (such as the definitions of a data type and associated operations over that type) and enforce a consistent naming scheme for these definitions. This avoids running out of names or accidentally confusing names. Such a package is called a *structure* and is introduced by the `struct...end` construct, which contains an arbitrary sequence of definitions. The structure is usually given a name with the `module` binding. Here is for instance a structure packaging together a type of priority queues and their operations:

```
# module PrioQueue =
#   struct
#     type priority = int
#     type 'a queue = Empty | Node of priority * 'a * 'a queue * 'a queue
#     let empty = Empty
#     let rec insert queue prio elt =
#       match queue with
#         Empty -> Node(prio, elt, Empty, Empty)
#       | Node(p, e, left, right) ->
#           if prio <= p
#           then Node(prio, elt, insert right p e, left)
#           else Node(p, e, insert right prio elt, left)
#     exception Queue_is_empty
#     let rec remove_top = function
#         Empty -> raise Queue_is_empty
#       | Node(prio, elt, left, Empty) -> left
#       | Node(prio, elt, Empty, right) -> right
#       | Node(prio, elt, (Node(lprio, lelt, _, _) as left),
#                         (Node(rprio, relt, _, _) as right)) ->
#           if lprio <= rprio
#           then Node(lprio, lelt, remove_top left, right)
```

```
#           else Node(rprio, relt, left, remove_top right)
#     let extract = function
#         Empty -> raise Queue_is_empty
#       | Node(prio, elt, _, _) as queue -> (prio, elt, remove_top queue)
#   end;;
module PrioQueue :
  sig
    type priority = int
    type 'a queue = Empty | Node of priority * 'a * 'a queue * 'a queue
    val empty : 'a queue
    val insert : 'a queue -> priority -> 'a -> 'a queue
    exception Queue_is_empty
    val remove_top : 'a queue -> 'a queue
    val extract : 'a queue -> priority * 'a * 'a queue
  end
```

Outside the structure, its components can be referred to using the "dot notation", that is, identifiers qualified by a structure name. For instance, `PrioQueue.insert` is the function `insert` defined inside the structure `PrioQueue` and `PrioQueue.queue` is the type `queue` defined in `PrioQueue`.

```
# PrioQueue.insert PrioQueue.empty 1 "hello";;
- : string PrioQueue.queue =
PrioQueue.Node (1, "hello", PrioQueue.Empty, PrioQueue.Empty)
```

2.2 Signatures

Signatures are interfaces for structures. A signature specifies which components of a structure are accessible from the outside, and with which type. It can be used to hide some components of a structure (e.g. local function definitions) or export some components with a restricted type. For instance, the signature below specifies the three priority queue operations `empty`, `insert` and `extract`, but not the auxiliary function `remove_top`. Similarly, it makes the `queue` type abstract (by not providing its actual representation as a concrete type).

```
# module type PRIOQUEUE =
#   sig
#     type priority = int         (* still concrete *)
#     type 'a queue               (* now abstract *)
#     val empty : 'a queue
#     val insert : 'a queue -> int -> 'a -> 'a queue
#     val extract : 'a queue -> int * 'a * 'a queue
#     exception Queue_is_empty
#   end;;
module type PRIOQUEUE =
  sig
    type priority = int
    type 'a queue
    val empty : 'a queue
```

```
    val insert : 'a queue -> int -> 'a -> 'a queue
    val extract : 'a queue -> int * 'a * 'a queue
    exception Queue_is_empty
  end
```

Restricting the `PrioQueue` structure by this signature results in another view of the `PrioQueue` structure where the `remove_top` function is not accessible and the actual representation of priority queues is hidden:

```
# module AbstractPrioQueue = (PrioQueue : PRIOQUEUE);;
module AbstractPrioQueue : PRIOQUEUE

# AbstractPrioQueue.remove_top;;
Error: Unbound value AbstractPrioQueue.remove_top

# AbstractPrioQueue.insert AbstractPrioQueue.empty 1 "hello";;
- : string AbstractPrioQueue.queue = <abstr>
```

The restriction can also be performed during the definition of the structure, as in

```
module PrioQueue = (struct ... end : PRIOQUEUE);;
```

An alternate syntax is provided for the above:

```
module PrioQueue : PRIOQUEUE = struct ... end;;
```

2.3 Functors

Functors are "functions" from structures to structures. They are used to express parameterized structures: a structure A parameterized by a structure B is simply a functor F with a formal parameter B (along with the expected signature for B) which returns the actual structure A itself. The functor F can then be applied to one or several implementations $B_1 \ldots B_n$ of B, yielding the corresponding structures $A_1 \ldots A_n$.

For instance, here is a structure implementing sets as sorted lists, parameterized by a structure providing the type of the set elements and an ordering function over this type (used to keep the sets sorted):

```
# type comparison = Less | Equal | Greater;;
type comparison = Less | Equal | Greater

# module type ORDERED_TYPE =
#   sig
#     type t
#     val compare: t -> t -> comparison
#   end;;
module type ORDERED_TYPE = sig type t val compare : t -> t -> comparison end

# module Set =
#   functor (Elt: ORDERED_TYPE) ->
#     struct
#       type element = Elt.t
```

```
#       type set = element list
#       let empty = []
#       let rec add x s =
#         match s with
#           [] -> [x]
#         | hd::tl ->
#            match Elt.compare x hd with
#              Equal   -> s         (* x is already in s *)
#            | Less    -> x :: s    (* x is smaller than all elements of s *)
#            | Greater -> hd :: add x tl
#       let rec member x s =
#         match s with
#           [] -> false
#         | hd::tl ->
#             match Elt.compare x hd with
#               Equal   -> true     (* x belongs to s *)
#             | Less    -> false    (* x is smaller than all elements of s *)
#             | Greater -> member x tl
#     end;;
module Set :
  functor (Elt : ORDERED_TYPE) ->
    sig
      type element = Elt.t
      type set = element list
      val empty : 'a list
      val add : Elt.t -> Elt.t list -> Elt.t list
      val member : Elt.t -> Elt.t list -> bool
    end
```

By applying the `Set` functor to a structure implementing an ordered type, we obtain set operations for this type:

```
# module OrderedString =
#   struct
#     type t = string
#     let compare x y = if x = y then Equal else if x < y then Less else Greater
#   end;;
module OrderedString :
  sig type t = string val compare : 'a -> 'a -> comparison end

# module StringSet = Set(OrderedString);;
module StringSet :
  sig
    type element = OrderedString.t
    type set = element list
    val empty : 'a list
    val add : OrderedString.t -> OrderedString.t list -> OrderedString.t list
    val member : OrderedString.t -> OrderedString.t list -> bool
  end
```

```
# StringSet.member "bar" (StringSet.add "foo" StringSet.empty);;
- : bool = false
```

2.4 Functors and type abstraction

As in the `PrioQueue` example, it would be good style to hide the actual implementation of the type `set`, so that users of the structure will not rely on sets being lists, and we can switch later to another, more efficient representation of sets without breaking their code. This can be achieved by restricting `Set` by a suitable functor signature:

```
# module type SETFUNCTOR =
#   functor (Elt: ORDERED_TYPE) ->
#     sig
#       type element = Elt.t      (* concrete *)
#       type set                  (* abstract *)
#       val empty : set
#       val add : element -> set -> set
#       val member : element -> set -> bool
#     end;;
module type SETFUNCTOR =
  functor (Elt : ORDERED_TYPE) ->
    sig
      type element = Elt.t
      type set
      val empty : set
      val add : element -> set -> set
      val member : element -> set -> bool
    end

# module AbstractSet = (Set : SETFUNCTOR);;
module AbstractSet : SETFUNCTOR

# module AbstractStringSet = AbstractSet(OrderedString);;
module AbstractStringSet :
  sig
    type element = OrderedString.t
    type set = AbstractSet(OrderedString).set
    val empty : set
    val add : element -> set -> set
    val member : element -> set -> bool
  end

# AbstractStringSet.add "gee" AbstractStringSet.empty;;
- : AbstractStringSet.set = <abstr>
```

In an attempt to write the type constraint above more elegantly, one may wish to name the signature of the structure returned by the functor, then use that signature in the constraint:

```
# module type SET =
```

```
#   sig
#     type element
#     type set
#     val empty : set
#     val add : element -> set -> set
#     val member : element -> set -> bool
#   end;;
module type SET =
  sig
    type element
    type set
    val empty : set
    val add : element -> set -> set
    val member : element -> set -> bool
  end

# module WrongSet = (Set : functor(Elt: ORDERED_TYPE) -> SET);;
module WrongSet : functor (Elt : ORDERED_TYPE) -> SET

# module WrongStringSet = WrongSet(OrderedString);;
module WrongStringSet :
  sig
    type element = WrongSet(OrderedString).element
    type set = WrongSet(OrderedString).set
    val empty : set
    val add : element -> set -> set
    val member : element -> set -> bool
  end

# WrongStringSet.add "gee" WrongStringSet.empty;;
Error: This expression has type string but an expression was expected of type
         WrongStringSet.element = WrongSet(OrderedString).element
```

The problem here is that `SET` specifies the type `element` abstractly, so that the type equality between `element` in the result of the functor and `t` in its argument is forgotten. Consequently, `WrongStringSet.element` is not the same type as `string`, and the operations of `WrongStringSet` cannot be applied to strings. As demonstrated above, it is important that the type `element` in the signature `SET` be declared equal to `Elt.t`; unfortunately, this is impossible above since `SET` is defined in a context where `Elt` does not exist. To overcome this difficulty, OCaml provides a `with type` construct over signatures that allows enriching a signature with extra type equalities:

```
# module AbstractSet2 =
#   (Set : functor(Elt: ORDERED_TYPE) -> (SET with type element = Elt.t));;
module AbstractSet2 :
  functor (Elt : ORDERED_TYPE) ->
    sig
      type element = Elt.t
      type set
      val empty : set
      val add : element -> set -> set
      val member : element -> set -> bool
```

```
    end
```

As in the case of simple structures, an alternate syntax is provided for defining functors and restricting their result:

```
module AbstractSet2(Elt: ORDERED_TYPE) : (SET with type element = Elt.t) =
  struct ... end;;
```

Abstracting a type component in a functor result is a powerful technique that provides a high degree of type safety, as we now illustrate. Consider an ordering over character strings that is different from the standard ordering implemented in the `OrderedString` structure. For instance, we compare strings without distinguishing upper and lower case.

```
# module NoCaseString =
#   struct
#     type t = string
#     let compare s1 s2 =
#
OrderedString.compare (String.lowercase_ascii s1) (String.lowercase_ascii s2)
#   end;;
module NoCaseString :
  sig type t = string val compare : string -> string -> comparison end
```

```
# module NoCaseStringSet = AbstractSet(NoCaseString);;
module NoCaseStringSet :
  sig
    type element = NoCaseString.t
    type set = AbstractSet(NoCaseString).set
    val empty : set
    val add : element -> set -> set
    val member : element -> set -> bool
  end
```

```
# NoCaseStringSet.add "FOO" AbstractStringSet.empty;;
Error: This expression has type
         AbstractStringSet.set = AbstractSet(OrderedString).set
       but an expression was expected of type
         NoCaseStringSet.set = AbstractSet(NoCaseString).set
```

Note that the two types `AbstractStringSet.set` and `NoCaseStringSet.set` are not compatible, and values of these two types do not match. This is the correct behavior: even though both set types contain elements of the same type (strings), they are built upon different orderings of that type, and different invariants need to be maintained by the operations (being strictly increasing for the standard ordering and for the case-insensitive ordering). Applying operations from `AbstractStringSet` to values of type `NoCaseStringSet.set` could give incorrect results, or build lists that violate the invariants of `NoCaseStringSet`.

2.5 Modules and separate compilation

All examples of modules so far have been given in the context of the interactive system. However, modules are most useful for large, batch-compiled programs. For these programs, it is a practi-

cal necessity to split the source into several files, called compilation units, that can be compiled separately, thus minimizing recompilation after changes.

In OCaml, compilation units are special cases of structures and signatures, and the relationship between the units can be explained easily in terms of the module system. A compilation unit A comprises two files:

- the implementation file A`.ml`, which contains a sequence of definitions, analogous to the inside of a `struct`...`end` construct;
- the interface file A`.mli`, which contains a sequence of specifications, analogous to the inside of a `sig`...`end` construct.

These two files together define a structure named A as if the following definition was entered at top-level:

```
module A: sig (* contents of file A.mli *) end
        = struct (* contents of file A.ml *) end;;
```

The files that define the compilation units can be compiled separately using the `ocamlc -c` command (the `-c` option means "compile only, do not try to link"); this produces compiled interface files (with extension `.cmi`) and compiled object code files (with extension `.cmo`). When all units have been compiled, their `.cmo` files are linked together using the `ocamlc` command. For instance, the following commands compile and link a program composed of two compilation units `Aux` and `Main`:

```
$ ocamlc -c Aux.mli                     # produces aux.cmi
$ ocamlc -c Aux.ml                      # produces aux.cmo
$ ocamlc -c Main.mli                    # produces main.cmi
$ ocamlc -c Main.ml                     # produces main.cmo
$ ocamlc -o theprogram Aux.cmo Main.cmo
```

The program behaves exactly as if the following phrases were entered at top-level:

```
module Aux: sig (* contents of Aux.mli *) end
          = struct (* contents of Aux.ml *) end;;
module Main: sig (* contents of Main.mli *) end
           = struct (* contents of Main.ml *) end;;
```

In particular, `Main` can refer to `Aux`: the definitions and declarations contained in `Main.ml` and `Main.mli` can refer to definition in `Aux.ml`, using the `Aux.`*ident* notation, provided these definitions are exported in `Aux.mli`.

The order in which the `.cmo` files are given to `ocamlc` during the linking phase determines the order in which the module definitions occur. Hence, in the example above, `Aux` appears first and `Main` can refer to it, but `Aux` cannot refer to `Main`.

Note that only top-level structures can be mapped to separately-compiled files, but neither functors nor module types. However, all module-class objects can appear as components of a structure, so the solution is to put the functor or module type inside a structure, which can then be mapped to a file.

Chapter 3

Objects in OCaml

(Chapter written by Jérôme Vouillon, Didier Rémy and Jacques Garrigue)

This chapter gives an overview of the object-oriented features of OCaml. Note that the relation between object, class and type in OCaml is very different from that in mainstream object-oriented languages like Java or C++, so that you should not assume that similar keywords mean the same thing.

3.1 Classes and objects

The class `point` below defines one instance variable `x` and two methods `get_x` and `move`. The initial value of the instance variable is `0`. The variable `x` is declared mutable, so the method `move` can change its value.

```
# class point =
#   object
#     val mutable x = 0
#     method get_x = x
#     method move d = x <- x + d
#   end;;
class point :
  object val mutable x : int method get_x : int method move : int -> unit end
```

We now create a new point `p`, instance of the `point` class.

```
# let p = new point;;
val p : point = <obj>
```

Note that the type of `p` is `point`. This is an abbreviation automatically defined by the class definition above. It stands for the object type `<get_x : int; move : int -> unit>`, listing the methods of class `point` along with their types.

We now invoke some methods to `p`:

```
# p#get_x;;
- : int = 0
```

```
# p#move 3;;
- : unit = ()

# p#get_x;;
- : int = 3
```

The evaluation of the body of a class only takes place at object creation time. Therefore, in the following example, the instance variable `x` is initialized to different values for two different objects.

```
# let x0 = ref 0;;
val x0 : int ref = {contents = 0}

# class point =
#   object
#     val mutable x = incr x0; !x0
#     method get_x = x
#     method move d = x <- x + d
#   end;;
class point :
  object val mutable x : int method get_x : int method move : int -> unit end

# new point#get_x;;
- : int = 1

# new point#get_x;;
- : int = 2
```

The class `point` can also be abstracted over the initial values of the `x` coordinate.

```
# class point = fun x_init ->
#   object
#     val mutable x = x_init
#     method get_x = x
#     method move d = x <- x + d
#   end;;
class point :
  int ->
  object val mutable x : int method get_x : int method move : int -> unit end
```

Like in function definitions, the definition above can be abbreviated as:

```
# class point x_init =
#   object
#     val mutable x = x_init
#     method get_x = x
#     method move d = x <- x + d
#   end;;
class point :
  int ->
  object val mutable x : int method get_x : int method move : int -> unit end
```

An instance of the class `point` is now a function that expects an initial parameter to create a point object:

```
# new point;;
- : int -> point = <fun>

# let p = new point 7;;
val p : point = <obj>
```

The parameter `x_init` is, of course, visible in the whole body of the definition, including methods. For instance, the method `get_offset` in the class below returns the position of the object relative to its initial position.

```
# class point x_init =
#   object
#     val mutable x = x_init
#     method get_x = x
#     method get_offset = x - x_init
#     method move d = x <- x + d
#   end;;
class point :
  int ->
  object
    val mutable x : int
    method get_offset : int
    method get_x : int
    method move : int -> unit
  end
```

Expressions can be evaluated and bound before defining the object body of the class. This is useful to enforce invariants. For instance, points can be automatically adjusted to the nearest point on a grid, as follows:

```
# class adjusted_point x_init =
#   let origin = (x_init / 10) * 10 in
#   object
#     val mutable x = origin
#     method get_x = x
#     method get_offset = x - origin
#     method move d = x <- x + d
#   end;;
class adjusted_point :
  int ->
  object
    val mutable x : int
    method get_offset : int
    method get_x : int
    method move : int -> unit
  end
```

(One could also raise an exception if the `x_init` coordinate is not on the grid.) In fact, the same effect could here be obtained by calling the definition of class `point` with the value of the `origin`.

```
# class adjusted_point x_init =  point ((x_init / 10) * 10);;
class adjusted_point : int -> point
```

An alternate solution would have been to define the adjustment in a special allocation function:

```
# let new_adjusted_point x_init = new point ((x_init / 10) * 10);;
val new_adjusted_point : int -> point = <fun>
```

However, the former pattern is generally more appropriate, since the code for adjustment is part of the definition of the class and will be inherited.

This ability provides class constructors as can be found in other languages. Several constructors can be defined this way to build objects of the same class but with different initialization patterns; an alternative is to use initializers, as described below in section 3.4.

3.2 Immediate objects

There is another, more direct way to create an object: create it without going through a class.

The syntax is exactly the same as for class expressions, but the result is a single object rather than a class. All the constructs described in the rest of this section also apply to immediate objects.

```
# let p =
#   object
#     val mutable x = 0
#     method get_x = x
#     method move d = x <- x + d
#   end;;
val p : < get_x : int; move : int -> unit > = <obj>

# p#get_x;;
- : int = 0

# p#move 3;;
- : unit = ()

# p#get_x;;
- : int = 3
```

Unlike classes, which cannot be defined inside an expression, immediate objects can appear anywhere, using variables from their environment.

```
# let minmax x y =
#   if x < y then object method min = x method max = y end
#   else object method min = y method max = x end;;
val minmax : 'a -> 'a -> < max : 'a; min : 'a > = <fun>
```

Immediate objects have two weaknesses compared to classes: their types are not abbreviated, and you cannot inherit from them. But these two weaknesses can be advantages in some situations, as we will see in sections 3.3 and 3.10.

3.3 Reference to self

A method or an initializer can send messages to self (that is, the current object). For that, self must be explicitly bound, here to the variable `s` (`s` could be any identifier, even though we will often choose the name `self`.)

```
# class printable_point x_init =
#   object (s)
#     val mutable x = x_init
#     method get_x = x
#     method move d = x <- x + d
#     method print = print_int s#get_x
#   end;;
class printable_point :
  int ->
  object
    val mutable x : int
    method get_x : int
    method move : int -> unit
    method print : unit
  end

# let p = new printable_point 7;;
val p : printable_point = <obj>

# p#print;;
7- : unit = ()
```

Dynamically, the variable `s` is bound at the invocation of a method. In particular, when the class `printable_point` is inherited, the variable `s` will be correctly bound to the object of the subclass.

A common problem with self is that, as its type may be extended in subclasses, you cannot fix it in advance. Here is a simple example.

```
# let ints = ref [];;
val ints : '_a list ref = {contents = []}

# class my_int =
#   object (self)
#     method n = 1
#     method register = ints := self :: !ints
#   end;;
Error: This expression has type < n : int; register : 'a; .. >
       but an expression was expected of type 'b
       Self type cannot escape its class
```

You can ignore the first two lines of the error message. What matters is the last one: putting self into an external reference would make it impossible to extend it through inheritance. We will see in section 3.12 a workaround to this problem. Note however that, since immediate objects are not extensible, the problem does not occur with them.

```
# let my_int =
#   object (self)
#     method n = 1
#     method register = ints := self :: !ints
#   end;;
val my_int : < n : int; register : unit > = <obj>
```

3.4 Initializers

Let-bindings within class definitions are evaluated before the object is constructed. It is also possible to evaluate an expression immediately after the object has been built. Such code is written as an anonymous hidden method called an initializer. Therefore, it can access self and the instance variables.

```
# class printable_point x_init =
#   let origin = (x_init / 10) * 10 in
#   object (self)
#     val mutable x = origin
#     method get_x = x
#     method move d = x <- x + d
#     method print = print_int self#get_x
#     initializer print_string "new point at "; self#print; print_newline ()
#   end;;
class printable_point :
  int ->
  object
    val mutable x : int
    method get_x : int
    method move : int -> unit
    method print : unit
  end

# let p = new printable_point 17;;
new point at 10
val p : printable_point = <obj>
```

Initializers cannot be overridden. On the contrary, all initializers are evaluated sequentially. Initializers are particularly useful to enforce invariants. Another example can be seen in section 5.1.

3.5 Virtual methods

It is possible to declare a method without actually defining it, using the keyword `virtual`. This method will be provided later in subclasses. A class containing virtual methods must be flagged `virtual`, and cannot be instantiated (that is, no object of this class can be created). It still defines type abbreviations (treating virtual methods as other methods.)

```
# class virtual abstract_point x_init =
#   object (self)
#     method virtual get_x : int
#     method get_offset = self#get_x - x_init
#     method virtual move : int -> unit
#   end;;
class virtual abstract_point :
  int ->
  object
    method get_offset : int
    method virtual get_x : int
    method virtual move : int -> unit
  end
# class point x_init =
#   object
#     inherit abstract_point x_init
#     val mutable x = x_init
#     method get_x = x
#     method move d = x <- x + d
#   end;;
class point :
  int ->
  object
    val mutable x : int
    method get_offset : int
    method get_x : int
    method move : int -> unit
  end
```

Instance variables can also be declared as virtual, with the same effect as with methods.

```
# class virtual abstract_point2 =
#   object
#     val mutable virtual x : int
#     method move d = x <- x + d
#   end;;
class virtual abstract_point2 :
  object val mutable virtual x : int method move : int -> unit end
# class point2 x_init =
#   object
#     inherit abstract_point2
#     val mutable x = x_init
#     method get_offset = x - x_init
#   end;;
class point2 :
  int ->
  object
    val mutable x : int
```

```
    method get_offset : int
    method move : int -> unit
  end
```

3.6 Private methods

Private methods are methods that do not appear in object interfaces. They can only be invoked from other methods of the same object.

```
# class restricted_point x_init =
#   object (self)
#     val mutable x = x_init
#     method get_x = x
#     method private move d = x <- x + d
#     method bump = self#move 1
#   end;;
class restricted_point :
  int ->
  object
    val mutable x : int
    method bump : unit
    method get_x : int
    method private move : int -> unit
  end

# let p = new restricted_point 0;;
val p : restricted_point = <obj>

# p#move 10;;
Error: This expression has type restricted_point
       It has no method move

# p#bump;;
- : unit = ()
```

Note that this is not the same thing as private and protected methods in Java or C++, which can be called from other objects of the same class. This is a direct consequence of the independence between types and classes in OCaml: two unrelated classes may produce objects of the same type, and there is no way at the type level to ensure that an object comes from a specific class. However a possible encoding of friend methods is given in section 3.17.

Private methods are inherited (they are by default visible in subclasses), unless they are hidden by signature matching, as described below.

Private methods can be made public in a subclass.

```
# class point_again x =
#   object (self)
#     inherit restricted_point x
#     method virtual move : _
#   end;;
```

```
class point_again :
  int ->
  object
    val mutable x : int
    method bump : unit
    method get_x : int
    method move : int -> unit
  end
```

The annotation `virtual` here is only used to mention a method without providing its definition. Since we didn't add the `private` annotation, this makes the method public, keeping the original definition.

An alternative definition is

```
# class point_again x =
#   object (self : < move : _; ..> )
#     inherit restricted_point x
#   end;;
class point_again :
  int ->
  object
    val mutable x : int
    method bump : unit
    method get_x : int
    method move : int -> unit
  end
```

The constraint on self's type is requiring a public `move` method, and this is sufficient to override `private`.

One could think that a private method should remain private in a subclass. However, since the method is visible in a subclass, it is always possible to pick its code and define a method of the same name that runs that code, so yet another (heavier) solution would be:

```
# class point_again x =
#   object
#     inherit restricted_point x as super
#     method move = super#move
#   end;;
class point_again :
  int ->
  object
    val mutable x : int
    method bump : unit
    method get_x : int
    method move : int -> unit
  end
```

Of course, private methods can also be virtual. Then, the keywords must appear in this order `method private virtual`.

3.7 Class interfaces

Class interfaces are inferred from class definitions. They may also be defined directly and used to restrict the type of a class. Like class declarations, they also define a new type abbreviation.

```
# class type restricted_point_type =
#   object
#     method get_x : int
#     method bump : unit
# end;;
class type restricted_point_type =
  object method bump : unit method get_x : int end

# fun (x : restricted_point_type) -> x;;
- : restricted_point_type -> restricted_point_type = <fun>
```

In addition to program documentation, class interfaces can be used to constrain the type of a class. Both concrete instance variables and concrete private methods can be hidden by a class type constraint. Public methods and virtual members, however, cannot.

```
# class restricted_point' x = (restricted_point x : restricted_point_type);;
class restricted_point' : int -> restricted_point_type
```

Or, equivalently:

```
# class restricted_point' = (restricted_point : int -> restricted_point_type);;
class restricted_point' : int -> restricted_point_type
```

The interface of a class can also be specified in a module signature, and used to restrict the inferred signature of a module.

```
# module type POINT = sig
#   class restricted_point' : int ->
#     object
#       method get_x : int
#       method bump : unit
#     end
# end;;
module type POINT =
  sig
    class restricted_point' :
      int -> object method bump : unit method get_x : int end
  end

# module Point : POINT = struct
#   class restricted_point' = restricted_point
# end;;
module Point : POINT
```

3.8 Inheritance

We illustrate inheritance by defining a class of colored points that inherits from the class of points. This class has all instance variables and all methods of class `point`, plus a new instance variable `c` and a new method `color`.

```
# class colored_point x (c : string) =
#   object
#     inherit point x
#     val c = c
#     method color = c
#   end;;
class colored_point :
  int ->
  string ->
  object
    val c : string
    val mutable x : int
    method color : string
    method get_offset : int
    method get_x : int
    method move : int -> unit
  end

# let p' = new colored_point 5 "red";;
val p' : colored_point = <obj>

# p'#get_x, p'#color;;
- : int * string = (5, "red")
```

A point and a colored point have incompatible types, since a point has no method `color`. However, the function `get_x` below is a generic function applying method `get_x` to any object `p` that has this method (and possibly some others, which are represented by an ellipsis in the type). Thus, it applies to both points and colored points.

```
# let get_succ_x p = p#get_x + 1;;
val get_succ_x : < get_x : int; .. > -> int = <fun>

# get_succ_x p + get_succ_x p';;
- : int = 8
```

Methods need not be declared previously, as shown by the example:

```
# let set_x p = p#set_x;;
val set_x : < set_x : 'a; .. > -> 'a = <fun>

# let incr p = set_x p (get_succ_x p);;
val incr : < get_x : int; set_x : int -> 'a; .. > -> 'a = <fun>
```

3.9 Multiple inheritance

Multiple inheritance is allowed. Only the last definition of a method is kept: the redefinition in a subclass of a method that was visible in the parent class overrides the definition in the parent class. Previous definitions of a method can be reused by binding the related ancestor. Below, `super` is bound to the ancestor `printable_point`. The name `super` is a pseudo value identifier that can only be used to invoke a super-class method, as in `super#print`.

```
# class printable_colored_point y c =
#   object (self)
#     val c = c
#     method color = c
#     inherit printable_point y as super
#     method print =
#       print_string "(";
#       super#print;
#       print_string ", ";
#       print_string (self#color);
#       print_string ")"
#   end;;
class printable_colored_point :
  int ->
  string ->
  object
    val c : string
    val mutable x : int
    method color : string
    method get_x : int
    method move : int -> unit
    method print : unit
  end

# let p' = new printable_colored_point 17 "red";;
new point at (10, red)
val p' : printable_colored_point = <obj>

# p'#print;;
(10, red)- : unit = ()
```

A private method that has been hidden in the parent class is no longer visible, and is thus not overridden. Since initializers are treated as private methods, all initializers along the class hierarchy are evaluated, in the order they are introduced.

3.10 Parameterized classes

Reference cells can be implemented as objects. The naive definition fails to typecheck:

```
# class oref x_init =
#   object
```

```
#     val mutable x = x_init
#     method get = x
#     method set y = x <- y
#   end;;
Error: Some type variables are unbound in this type:
         class oref :
           'a ->
           object
             val mutable x : 'a
             method get : 'a
             method set : 'a -> unit
           end
       The method get has type 'a where 'a is unbound
```

The reason is that at least one of the methods has a polymorphic type (here, the type of the value stored in the reference cell), thus either the class should be parametric, or the method type should be constrained to a monomorphic type. A monomorphic instance of the class could be defined by:

```
# class oref (x_init:int) =
#   object
#     val mutable x = x_init
#     method get = x
#     method set y = x <- y
#   end;;
class oref :
  int ->
  object val mutable x : int method get : int method set : int -> unit end
```

Note that since immediate objects do not define a class type, they have no such restriction.

```
# let new_oref x_init =
#   object
#     val mutable x = x_init
#     method get = x
#     method set y = x <- y
#   end;;
val new_oref : 'a -> < get : 'a; set : 'a -> unit > = <fun>
```

On the other hand, a class for polymorphic references must explicitly list the type parameters in its declaration. Class type parameters are listed between `[` and `]`. The type parameters must also be bound somewhere in the class body by a type constraint.

```
# class ['a] oref x_init =
#   object
#     val mutable x = (x_init : 'a)
#     method get = x
#     method set y = x <- y
#   end;;
class ['a] oref :
```

```
  'a -> object val mutable x : 'a method get : 'a method set : 'a -> unit end
# let r = new oref 1 in r#set 2; (r#get);;
- : int = 2
```

The type parameter in the declaration may actually be constrained in the body of the class definition. In the class type, the actual value of the type parameter is displayed in the `constraint` clause.

```
# class ['a] oref_succ (x_init:'a) =
#   object
#     val mutable x = x_init + 1
#     method get = x
#     method set y = x <- y
#   end;;
class ['a] oref_succ :
  'a ->
  object
    constraint 'a = int
    val mutable x : int
    method get : int
    method set : int -> unit
  end
```

Let us consider a more complex example: define a circle, whose center may be any kind of point. We put an additional type constraint in method `move`, since no free variables must remain unaccounted for by the class type parameters.

```
# class ['a] circle (c : 'a) =
#   object
#     val mutable center = c
#     method center = center
#     method set_center c = center <- c
#     method move = (center#move : int -> unit)
#   end;;
class ['a] circle :
  'a ->
  object
    constraint 'a = < move : int -> unit; .. >
    val mutable center : 'a
    method center : 'a
    method move : int -> unit
    method set_center : 'a -> unit
  end
```

An alternate definition of `circle`, using a `constraint` clause in the class definition, is shown below. The type `#point` used below in the `constraint` clause is an abbreviation produced by the definition of class `point`. This abbreviation unifies with the type of any object belonging to a subclass of class `point`. It actually expands to `< get_x : int; move : int -> unit; .. >`. This leads to the following alternate definition of `circle`, which has slightly stronger constraints on its argument, as we now expect `center` to have a method `get_x`.

```
# class ['a] circle (c : 'a) =
#   object
#     constraint 'a = #point
#     val mutable center = c
#     method center = center
#     method set_center c = center <- c
#     method move = center#move
#   end;;
class ['a] circle :
  'a ->
  object
    constraint 'a = #point
    val mutable center : 'a
    method center : 'a
    method move : int -> unit
    method set_center : 'a -> unit
  end
```

The class `colored_circle` is a specialized version of class `circle` that requires the type of the center to unify with `#colored_point`, and adds a method `color`. Note that when specializing a parameterized class, the instance of type parameter must always be explicitly given. It is again written between `[` and `]`.

```
# class ['a] colored_circle c =
#   object
#     constraint 'a = #colored_point
#     inherit ['a] circle c
#     method color = center#color
#   end;;
class ['a] colored_circle :
  'a ->
  object
    constraint 'a = #colored_point
    val mutable center : 'a
    method center : 'a
    method color : string
    method move : int -> unit
    method set_center : 'a -> unit
  end
```

3.11 Polymorphic methods

While parameterized classes may be polymorphic in their contents, they are not enough to allow polymorphism of method use.

A classical example is defining an iterator.

```
# List.fold_left;;
- : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a = <fun>
```

```
# class ['a] intlist (l : int list) =
#   object
#     method empty = (l = [])
#     method fold f (accu : 'a) = List.fold_left f accu l
#   end;;
class ['a] intlist :
  int list ->
  object method empty : bool method fold : ('a -> int -> 'a) -> 'a -> 'a end
```

At first look, we seem to have a polymorphic iterator, however this does not work in practice.

```
# let l = new intlist [1; 2; 3];;
val l : '_a intlist = <obj>

# l#fold (fun x y -> x+y) 0;;
- : int = 6

# l;;
- : int intlist = <obj>

# l#fold (fun s x -> s ^ string_of_int x ^ " ") "";;
Error: This expression has type int but an expression was expected of type
         string
```

Our iterator works, as shows its first use for summation. However, since objects themselves are not polymorphic (only their constructors are), using the `fold` method fixes its type for this individual object. Our next attempt to use it as a string iterator fails.

The problem here is that quantification was wrongly located: it is not the class we want to be polymorphic, but the `fold` method. This can be achieved by giving an explicitly polymorphic type in the method definition.

```
# class intlist (l : int list) =
#   object
#     method empty = (l = [])
#     method fold : 'a. ('a -> int -> 'a) -> 'a -> 'a =
#       fun f accu -> List.fold_left f accu l
#   end;;
class intlist :
  int list ->
  object method empty : bool method fold : ('a -> int -> 'a) -> 'a -> 'a end

# let l = new intlist [1; 2; 3];;
val l : intlist = <obj>

# l#fold (fun x y -> x+y) 0;;
- : int = 6

# l#fold (fun s x -> s ^ string_of_int x ^ " ") "";;
- : string = "1 2 3 "
```

As you can see in the class type shown by the compiler, while polymorphic method types must be fully explicit in class definitions (appearing immediately after the method name), quantified type

variables can be left implicit in class descriptions. Why require types to be explicit? The problem is that `(int -> int -> int) -> int -> int` would also be a valid type for `fold`, and it happens to be incompatible with the polymorphic type we gave (automatic instantiation only works for toplevel types variables, not for inner quantifiers, where it becomes an undecidable problem.) So the compiler cannot choose between those two types, and must be helped.

However, the type can be completely omitted in the class definition if it is already known, through inheritance or type constraints on self. Here is an example of method overriding.

```
# class intlist_rev l =
#   object
#     inherit intlist l
#     method fold f accu = List.fold_left f accu (List.rev l)
#   end;;
```

The following idiom separates description and definition.

```
# class type ['a] iterator =
#   object method fold : ('b -> 'a -> 'b) -> 'b -> 'b end;;

# class intlist l =
#   object (self : int #iterator)
#     method empty = (l = [])
#     method fold f accu = List.fold_left f accu l
#   end;;
```

Note here the `(self : int #iterator)` idiom, which ensures that this object implements the interface `iterator`.

Polymorphic methods are called in exactly the same way as normal methods, but you should be aware of some limitations of type inference. Namely, a polymorphic method can only be called if its type is known at the call site. Otherwise, the method will be assumed to be monomorphic, and given an incompatible type.

```
# let sum lst = lst#fold (fun x y -> x+y) 0;;
val sum : < fold : (int -> int -> int) -> int -> 'a; .. > -> 'a = <fun>

# sum l;;
Error: This expression has type intlist
       but an expression was expected of type
         < fold : (int -> int -> int) -> int -> 'a; .. >
       Types for method fold are incompatible
```

The workaround is easy: you should put a type constraint on the parameter.

```
# let sum (lst : _ #iterator) = lst#fold (fun x y -> x+y) 0;;
val sum : int #iterator -> int = <fun>
```

Of course the constraint may also be an explicit method type. Only occurences of quantified variables are required.

```
# let sum lst =
#   (lst : < fold : 'a. ('a -> _ -> 'a) -> 'a -> 'a; .. >)#fold (+) 0;;
val sum : < fold : 'a. ('a -> int -> 'a) -> 'a -> 'a; .. > -> int = <fun>
```

Another use of polymorphic methods is to allow some form of implicit subtyping in method arguments. We have already seen in section 3.8 how some functions may be polymorphic in the class of their argument. This can be extended to methods.

```
# class type point0 = object method get_x : int end;;
class type point0 = object method get_x : int end
```

```
# class distance_point x =
#   object
#     inherit point x
#     method distance : 'a. (#point0 as 'a) -> int =
#       fun other -> abs (other#get_x - x)
#   end;;
class distance_point :
  int ->
  object
    val mutable x : int
    method distance : #point0 -> int
    method get_offset : int
    method get_x : int
    method move : int -> unit
  end
```

```
# let p = new distance_point 3 in
# (p#distance (new point 8), p#distance (new colored_point 1 "blue"));;
- : int * int = (5, 2)
```

Note here the special syntax `(#point0 as 'a)` we have to use to quantify the extensible part of `#point0`. As for the variable binder, it can be omitted in class specifications. If you want polymorphism inside object field it must be quantified independently.

```
# class multi_poly =
#   object
#     method m1 : 'a. (< n1 : 'b. 'b -> 'b; .. > as 'a) -> _ =
#       fun o -> o#n1 true, o#n1 "hello"
#     method m2 : 'a 'b. (< n2 : 'b -> bool; .. > as 'a) -> 'b -> _ =
#       fun o x -> o#n2 x
#   end;;
class multi_poly :
  object
    method m1 : < n1 : 'b. 'b -> 'b; .. > -> bool * string
    method m2 : < n2 : 'b -> bool; .. > -> 'b -> bool
  end
```

In method `m1`, `o` must be an object with at least a method `n1`, itself polymorphic. In method `m2`, the argument of `n2` and `x` must have the same type, which is quantified at the same level as `'a`.

3.12 Using coercions

Subtyping is never implicit. There are, however, two ways to perform subtyping. The most general construction is fully explicit: both the domain and the codomain of the type coercion must be

given.

We have seen that points and colored points have incompatible types. For instance, they cannot be mixed in the same list. However, a colored point can be coerced to a point, hiding its `color` method:

```
# let colored_point_to_point cp = (cp : colored_point :> point);;
val colored_point_to_point : colored_point -> point = <fun>

# let p = new point 3 and q = new colored_point 4 "blue";;
val p : point = <obj>
val q : colored_point = <obj>

# let l = [p; (colored_point_to_point q)];;
val l : point list = [<obj>; <obj>]
```

An object of type `t` can be seen as an object of type `t'` only if `t` is a subtype of `t'`. For instance, a point cannot be seen as a colored point.

```
# (p : point :> colored_point);;
Error: Type point = < get_offset : int; get_x : int; move : int -> unit >
       is not a subtype of
         colored_point =
           < color : string; get_offset : int; get_x : int;
             move : int -> unit >
```

Indeed, narrowing coercions without runtime checks would be unsafe. Runtime type checks might raise exceptions, and they would require the presence of type information at runtime, which is not the case in the OCaml system. For these reasons, there is no such operation available in the language.

Be aware that subtyping and inheritance are not related. Inheritance is a syntactic relation between classes while subtyping is a semantic relation between types. For instance, the class of colored points could have been defined directly, without inheriting from the class of points; the type of colored points would remain unchanged and thus still be a subtype of points.

The domain of a coercion can often be omitted. For instance, one can define:

```
# let to_point cp = (cp :> point);;
val to_point : #point -> point = <fun>
```

In this case, the function `colored_point_to_point` is an instance of the function `to_point`. This is not always true, however. The fully explicit coercion is more precise and is sometimes unavoidable. Consider, for example, the following class:

```
# class c0 = object method m = {< >} method n = 0 end;;
class c0 : object ('a) method m : 'a method n : int end
```

The object type `c0` is an abbreviation for `<m : 'a; n : int> as 'a`. Consider now the type declaration:

```
# class type c1 =  object method m : c1 end;;
class type c1 = object method m : c1 end
```

The object type c1 is an abbreviation for the type <m : 'a> as 'a. The coercion from an object of type c0 to an object of type c1 is correct:

```
# fun (x:c0) -> (x : c0 :> c1);;
- : c0 -> c1 = <fun>
```

However, the domain of the coercion cannot always be omitted. In that case, the solution is to use the explicit form. Sometimes, a change in the class-type definition can also solve the problem

```
# class type c2 = object ('a) method m : 'a end;;
class type c2 = object ('a) method m : 'a end
```

```
# fun (x:c0) -> (x :> c2);;
- : c0 -> c2 = <fun>
```

While class types c1 and c2 are different, both object types c1 and c2 expand to the same object type (same method names and types). Yet, when the domain of a coercion is left implicit and its co-domain is an abbreviation of a known class type, then the class type, rather than the object type, is used to derive the coercion function. This allows leaving the domain implicit in most cases when coercing form a subclass to its superclass. The type of a coercion can always be seen as below:

```
# let to_c1 x = (x :> c1);;
val to_c1 : < m : #c1; .. > -> c1 = <fun>
```

```
# let to_c2 x = (x :> c2);;
val to_c2 : #c2 -> c2 = <fun>
```

Note the difference between these two coercions: in the case of to_c2, the type #c2 = < m : 'a; .. > as 'a is polymorphically recursive (according to the explicit recursion in the class type of c2); hence the success of applying this coercion to an object of class c0. On the other hand, in the first case, c1 was only expanded and unrolled twice to obtain < m : < m : c1; .. >; .. > (remember #c1 = < m : c1; .. >), without introducing recursion. You may also note that the type of to_c2 is #c2 -> c2 while the type of to_c1 is more general than #c1 -> c1. This is not always true, since there are class types for which some instances of #c are not subtypes of c, as explained in section 3.16. Yet, for parameterless classes the coercion (_ :> c) is always more general than (_ : #c :> c).

A common problem may occur when one tries to define a coercion to a class c while defining class c. The problem is due to the type abbreviation not being completely defined yet, and so its subtypes are not clearly known. Then, a coercion (_ :> c) or (_ : #c :> c) is taken to be the identity function, as in

```
# function x -> (x :> 'a);;
- : 'a -> 'a = <fun>
```

As a consequence, if the coercion is applied to self, as in the following example, the type of self is unified with the closed type c (a closed object type is an object type without ellipsis). This would constrain the type of self be closed and is thus rejected. Indeed, the type of self cannot be closed: this would prevent any further extension of the class. Therefore, a type error is generated when the unification of this type with another type would result in a closed object type.

```
# class c = object method m = 1 end
# and d = object (self)
#   inherit c
#   method n = 2
#   method as_c = (self :> c)
# end;;
Error: This expression cannot be coerced to type c = < m : int >; it has type
         < as_c : c; m : int; n : int; .. >
       but is here used with type c
       Self type cannot escape its class
```

However, the most common instance of this problem, coercing self to its current class, is detected as a special case by the type checker, and properly typed.

```
# class c = object (self) method m = (self :> c) end;;
class c : object method m : c end
```

This allows the following idiom, keeping a list of all objects belonging to a class or its subclasses:

```
# let all_c = ref [];;
val all_c : '_a list ref = {contents = []}

# class c (m : int) =
#   object (self)
#     method m = m
#     initializer all_c := (self :> c) :: !all_c
#   end;;
class c : int -> object method m : int end
```

This idiom can in turn be used to retrieve an object whose type has been weakened:

```
# let rec lookup_obj obj = function [] -> raise Not_found
#   | obj' :: l ->
#       if (obj :> < >) = (obj' :> < >) then obj' else lookup_obj obj l ;;
val lookup_obj : < .. > -> (< .. > as 'a) list -> 'a = <fun>

# let lookup_c obj = lookup_obj obj !all_c;;
val lookup_c : < .. > -> < m : int > = <fun>
```

The type `< m : int >` we see here is just the expansion of `c`, due to the use of a reference; we have succeeded in getting back an object of type `c`.

The previous coercion problem can often be avoided by first defining the abbreviation, using a class type:

```
# class type c' = object method m : int end;;
class type c' = object method m : int end

# class c : c' = object method m = 1 end
# and d = object (self)
#   inherit c
#   method n = 2
```

```
#   method as_c = (self :> c')
# end;;
class c : c'
and d : object method as_c : c' method m : int method n : int end
```

It is also possible to use a virtual class. Inheriting from this class simultaneously forces all methods of `c` to have the same type as the methods of `c'`.

```
# class virtual c' = object method virtual m : int end;;
class virtual c' : object method virtual m : int end
```

```
# class c = object (self) inherit c' method m = 1 end;;
class c : object method m : int end
```

One could think of defining the type abbreviation directly:

```
# type c' = <m : int>;;
```

However, the abbreviation `#c'` cannot be defined directly in a similar way. It can only be defined by a class or a class-type definition. This is because a `#`-abbreviation carries an implicit anonymous variable `..` that cannot be explicitly named. The closer you get to it is:

```
# type 'a c'_class = 'a constraint 'a = < m : int; .. >;;
```

with an extra type variable capturing the open object type.

3.13 Functional objects

It is possible to write a version of class `point` without assignments on the instance variables. The override construct `{< ... >}` returns a copy of "self" (that is, the current object), possibly changing the value of some instance variables.

```
# class functional_point y =
#   object
#     val x = y
#     method get_x = x
#     method move d = {< x = x + d >}
#   end;;
class functional_point :
  int ->
  object ('a) val x : int method get_x : int method move : int -> 'a end
```

```
# let p = new functional_point 7;;
val p : functional_point = <obj>
```

```
# p#get_x;;
- : int = 7
```

```
# (p#move 3)#get_x;;
- : int = 10
```

```
# p#get_x;;
- : int = 7
```

Note that the type abbreviation `functional_point` is recursive, which can be seen in the class type of `functional_point`: the type of self is `'a` and `'a` appears inside the type of the method `move`.

The above definition of `functional_point` is not equivalent to the following:

```
# class bad_functional_point y =
#   object
#     val x = y
#     method get_x = x
#     method move d = new bad_functional_point (x+d)
#   end;;
class bad_functional_point :
  int ->
  object
    val x : int
    method get_x : int
    method move : int -> bad_functional_point
  end
```

While objects of either class will behave the same, objects of their subclasses will be different. In a subclass of `bad_functional_point`, the method `move` will keep returning an object of the parent class. On the contrary, in a subclass of `functional_point`, the method `move` will return an object of the subclass.

Functional update is often used in conjunction with binary methods as illustrated in section 5.2.1.

3.14 Cloning objects

Objects can also be cloned, whether they are functional or imperative. The library function `Oo.copy` makes a shallow copy of an object. That is, it returns a new object that has the same methods and instance variables as its argument. The instance variables are copied but their contents are shared. Assigning a new value to an instance variable of the copy (using a method call) will not affect instance variables of the original, and conversely. A deeper assignment (for example if the instance variable is a reference cell) will of course affect both the original and the copy.

The type of `Oo.copy` is the following:

```
# Oo.copy;;
- : (< .. > as 'a) -> 'a = <fun>
```

The keyword `as` in that type binds the type variable `'a` to the object type `< .. >`. Therefore, `Oo.copy` takes an object with any methods (represented by the ellipsis), and returns an object of the same type. The type of `Oo.copy` is different from type `< .. > -> < .. >` as each ellipsis represents a different set of methods. Ellipsis actually behaves as a type variable.

```
# let p = new point 5;;
val p : point = <obj>

# let q = Oo.copy p;;
```

```
val q : point = <obj>
```

```
# q#move 7; (p#get_x, q#get_x);;
- : int * int = (5, 12)
```

In fact, `Oo.copy p` will behave as `p#copy` assuming that a public method `copy` with body `{< >}` has been defined in the class of `p`.

Objects can be compared using the generic comparison functions `=` and `<>`. Two objects are equal if and only if they are physically equal. In particular, an object and its copy are not equal.

```
# let q = Oo.copy p;;
val q : point = <obj>
```

```
# p = q, p = p;;
- : bool * bool = (false, true)
```

Other generic comparisons such as (`<`, `<=`, ...) can also be used on objects. The relation `<` defines an unspecified but strict ordering on objects. The ordering relationship between two objects is fixed once for all after the two objects have been created and it is not affected by mutation of fields.

Cloning and override have a non empty intersection. They are interchangeable when used within an object and without overriding any field:

```
# class copy =
#   object
#     method copy = {< >}
#   end;;
class copy : object ('a) method copy : 'a end
```

```
# class copy =
#   object (self)
#     method copy = Oo.copy self
#   end;;
class copy : object ('a) method copy : 'a end
```

Only the override can be used to actually override fields, and only the `Oo.copy` primitive can be used externally.

Cloning can also be used to provide facilities for saving and restoring the state of objects.

```
# class backup =
#   object (self : 'mytype)
#     val mutable copy = None
#     method save = copy <- Some {< copy = None >}
#     method restore = match copy with Some x -> x | None -> self
#   end;;
class backup :
  object ('a)
    val mutable copy : 'a option
    method restore : 'a
    method save : unit
  end
```

The above definition will only backup one level. The backup facility can be added to any class by using multiple inheritance.

```
# class ['a] backup_ref x = object inherit ['a] oref x inherit backup end;;
class ['a] backup_ref :
  'a ->
  object ('b)
    val mutable copy : 'b option
    val mutable x : 'a
    method get : 'a
    method restore : 'b
    method save : unit
    method set : 'a -> unit
  end
```

```
# let rec get p n = if n = 0 then p # get else get (p # restore) (n-1);;
val get : (< get : 'b; restore : 'a; .. > as 'a) -> int -> 'b = <fun>
```

```
# let p = new backup_ref 0  in
# p # save; p # set 1; p # save; p # set 2;
# [get p 0; get p 1; get p 2; get p 3; get p 4];;
- : int list = [2; 1; 1; 1; 1]
```

We can define a variant of backup that retains all copies. (We also add a method `clear` to manually erase all copies.)

```
# class backup =
#   object (self : 'mytype)
#     val mutable copy = None
#     method save = copy <- Some {< >}
#     method restore = match copy with Some x -> x | None -> self
#     method clear = copy <- None
#   end;;
class backup :
  object ('a)
    val mutable copy : 'a option
    method clear : unit
    method restore : 'a
    method save : unit
  end


# class ['a] backup_ref x = object inherit ['a] oref x inherit backup end;;
class ['a] backup_ref :
  'a ->
  object ('b)
    val mutable copy : 'b option
    val mutable x : 'a
    method clear : unit
    method get : 'a
    method restore : 'b
```

```
    method save : unit
    method set : 'a -> unit
  end
# let p = new backup_ref 0  in
# p # save; p # set 1; p # save; p # set 2;
# [get p 0; get p 1; get p 2; get p 3; get p 4];;
- : int list = [2; 1; 0; 0; 0]
```

3.15 Recursive classes

Recursive classes can be used to define objects whose types are mutually recursive.

```
# class window =
#   object
#     val mutable top_widget = (None : widget option)
#     method top_widget = top_widget
#   end
# and widget (w : window) =
#   object
#     val window = w
#     method window = window
#   end;;
class window :
  object
    val mutable top_widget : widget option
    method top_widget : widget option
  end
and widget : window -> object val window : window method window : window end
```

Although their types are mutually recursive, the classes `widget` and `window` are themselves independent.

3.16 Binary methods

A binary method is a method which takes an argument of the same type as self. The class `comparable` below is a template for classes with a binary method `leq` of type `'a -> bool` where the type variable `'a` is bound to the type of self. Therefore, `#comparable` expands to `< leq : 'a -> bool; .. > as 'a`. We see here that the binder `as` also allows writing recursive types.

```
# class virtual comparable =
#   object (_ : 'a)
#     method virtual leq : 'a -> bool
#   end;;
class virtual comparable : object ('a) method virtual leq : 'a -> bool end
```

We then define a subclass `money` of `comparable`. The class `money` simply wraps floats as comparable objects. We will extend it below with more operations. We have to use a type constraint on the class parameter `x` because the primitive `<=` is a polymorphic function in OCaml. The `inherit` clause ensures that the type of objects of this class is an instance of `#comparable`.

```
# class money (x : float) =
#   object
#     inherit comparable
#     val repr = x
#     method value = repr
#     method leq p = repr <= p#value
#   end;;
class money :
  float ->
  object ('a)
    val repr : float
    method leq : 'a -> bool
    method value : float
  end
```

Note that the type `money` is not a subtype of type `comparable`, as the self type appears in contravariant position in the type of method `leq`. Indeed, an object `m` of class `money` has a method `leq` that expects an argument of type `money` since it accesses its `value` method. Considering `m` of type `comparable` would allow a call to method `leq` on `m` with an argument that does not have a method `value`, which would be an error.

Similarly, the type `money2` below is not a subtype of type `money`.

```
# class money2 x =
#   object
#     inherit money x
#     method times k = {< repr = k *. repr >}
#   end;;
class money2 :
  float ->
  object ('a)
    val repr : float
    method leq : 'a -> bool
    method times : float -> 'a
    method value : float
  end
```

It is however possible to define functions that manipulate objects of type either `money` or `money2`: the function `min` will return the minimum of any two objects whose type unifies with `#comparable`. The type of `min` is not the same as `#comparable -> #comparable -> #comparable`, as the abbreviation `#comparable` hides a type variable (an ellipsis). Each occurrence of this abbreviation generates a new variable.

```
# let min (x : #comparable) y =
#   if x#leq y then x else y;;
val min : (#comparable as 'a) -> 'a -> 'a = <fun>
```

This function can be applied to objects of type `money` or `money2`.

```
# (min (new money  1.3) (new money 3.1))#value;;
- : float = 1.3
# (min (new money2 5.0) (new money2 3.14))#value;;
- : float = 3.14
```

More examples of binary methods can be found in sections 5.2.1 and 5.2.3.

Note the use of override for method `times`. Writing `new money2 (k *. repr)` instead of `{< repr = k *. repr >}` would not behave well with inheritance: in a subclass `money3` of `money2` the `times` method would return an object of class `money2` but not of class `money3` as would be expected.

The class `money` could naturally carry another binary method. Here is a direct definition:

```
# class money x =
#   object (self : 'a)
#     val repr = x
#     method value = repr
#     method print = print_float repr
#     method times k = {< repr = k *. x >}
#     method leq (p : 'a) = repr <= p#value
#     method plus (p : 'a) = {< repr = x +. p#value >}
#   end;;
class money :
  float ->
  object ('a)
    val repr : float
    method leq : 'a -> bool
    method plus : 'a -> 'a
    method print : unit
    method times : float -> 'a
    method value : float
  end
```

3.17 Friends

The above class `money` reveals a problem that often occurs with binary methods. In order to interact with other objects of the same class, the representation of `money` objects must be revealed, using a method such as `value`. If we remove all binary methods (here `plus` and `leq`), the representation can easily be hidden inside objects by removing the method `value` as well. However, this is not possible as soon as some binary method requires access to the representation of objects of the same class (other than self).

```
# class safe_money x =
#   object (self : 'a)
#     val repr = x
#     method print = print_float repr
```

```
#     method times k = {< repr = k *. x >}
#   end;;
class safe_money :
  float ->
  object ('a)
    val repr : float
    method print : unit
    method times : float -> 'a
  end
```

Here, the representation of the object is known only to a particular object. To make it available to other objects of the same class, we are forced to make it available to the whole world. However we can easily restrict the visibility of the representation using the module system.

```
# module type MONEY =
#   sig
#     type t
#     class c : float ->
#       object ('a)
#         val repr : t
#         method value : t
#         method print : unit
#         method times : float -> 'a
#         method leq : 'a -> bool
#         method plus : 'a -> 'a
#       end
#   end;;
# module Euro : MONEY =
#   struct
#     type t = float
#     class c x =
#       object (self : 'a)
#         val repr = x
#         method value = repr
#         method print = print_float repr
#         method times k = {< repr = k *. x >}
#         method leq (p : 'a) = repr <= p#value
#         method plus (p : 'a) = {< repr = x +. p#value >}
#       end
#   end;;
```

Another example of friend functions may be found in section 5.2.3. These examples occur when a group of objects (here objects of the same class) and functions should see each others internal representation, while their representation should be hidden from the outside. The solution is always to define all friends in the same module, give access to the representation and use a signature constraint to make the representation abstract outside the module.

Chapter 4

Labels and variants

(Chapter written by Jacques Garrigue)

This chapter gives an overview of the new features in OCaml 3: labels, and polymorphic variants.

4.1 Labels

If you have a look at modules ending in `Labels` in the standard library, you will see that function types have annotations you did not have in the functions you defined yourself.

```
# ListLabels.map;;
- : f:('a -> 'b) -> 'a list -> 'b list = <fun>

# StringLabels.sub;;
- : string -> pos:int -> len:int -> string = <fun>
```

Such annotations of the form `name:` are called *labels*. They are meant to document the code, allow more checking, and give more flexibility to function application. You can give such names to arguments in your programs, by prefixing them with a tilde `~`.

```
# let f ~x ~y = x - y;;
val f : x:int -> y:int -> int = <fun>

# let x = 3 and y = 2 in f ~x ~y;;
- : int = 1
```

When you want to use distinct names for the variable and the label appearing in the type, you can use a naming label of the form `~name:`. This also applies when the argument is not a variable.

```
# let f ~x:x1 ~y:y1 = x1 - y1;;
val f : x:int -> y:int -> int = <fun>

# f ~x:3 ~y:2;;
- : int = 1
```

Labels obey the same rules as other identifiers in OCaml, that is you cannot use a reserved keyword (like `in` or `to`) as label.

Formal parameters and arguments are matched according to their respective labels[1], the absence of label being interpreted as the empty label. This allows commuting arguments in applications. One can also partially apply a function on any argument, creating a new function of the remaining parameters.

```
# let f ~x ~y = x - y;;
val f : x:int -> y:int -> int = <fun>

# f ~y:2 ~x:3;;
- : int = 1

# ListLabels.fold_left;;
- : f:('a -> 'b -> 'a) -> init:'a -> 'b list -> 'a = <fun>

# ListLabels.fold_left [1;2;3] ~init:0 ~f:( + );;
- : int = 6

# ListLabels.fold_left ~init:0;;
- : f:(int -> 'a -> int) -> 'a list -> int = <fun>
```

If several arguments of a function bear the same label (or no label), they will not commute among themselves, and order matters. But they can still commute with other arguments.

```
# let hline ~x:x1 ~x:x2 ~y = (x1, x2, y);;
val hline : x:'a -> x:'b -> y:'c -> 'a * 'b * 'c = <fun>

# hline ~x:3 ~y:2 ~x:5;;
- : int * int * int = (3, 5, 2)
```

As an exception to the above parameter matching rules, if an application is total (omitting all optional arguments), labels may be omitted. In practice, many applications are total, so that labels can often be omitted.

```
# f 3 2;;
- : int = 1

# ListLabels.map succ [1;2;3];;
- : int list = [2; 3; 4]
```

But beware that functions like `ListLabels.fold_left` whose result type is a type variable will never be considered as totally applied.

```
# ListLabels.fold_left ( + ) 0 [1;2;3];;
Error: This expression has type int -> int -> int
       but an expression was expected of type 'a list
```

When a function is passed as an argument to a higher-order function, labels must match in both types. Neither adding nor removing labels are allowed.

[1] This correspond to the commuting label mode of Objective Caml 3.00 through 3.02, with some additional flexibility on total applications. The so-called classic mode (`-nolabels` options) is now deprecated for normal use.

```
# let h g = g ~x:3 ~y:2;;
val h : (x:int -> y:int -> 'a) -> 'a = <fun>

# h f;;
- : int = 1

# h ( + );;
Error: This expression has type int -> int -> int
       but an expression was expected of type x:int -> y:int -> 'a
```

Note that when you don't need an argument, you can still use a wildcard pattern, but you must prefix it with the label.

```
# h (fun ~x:_ ~y -> y+1);;
- : int = 3
```

4.1.1 Optional arguments

An interesting feature of labeled arguments is that they can be made optional. For optional parameters, the question mark `?` replaces the tilde `~` of non-optional ones, and the label is also prefixed by `?` in the function type. Default values may be given for such optional parameters.

```
# let bump ?(step = 1) x = x + step;;
val bump : ?step:int -> int -> int = <fun>

# bump 2;;
- : int = 3

# bump ~step:3 2;;
- : int = 5
```

A function taking some optional arguments must also take at least one non-optional argument. The criterion for deciding whether an optional argument has been omitted is the non-labeled application of an argument appearing after this optional argument in the function type. Note that if that argument is labeled, you will only be able to eliminate optional arguments through the special case for total applications.

```
# let test ?(x = 0) ?(y = 0) () ?(z = 0) () = (x, y, z);;
val test : ?x:int -> ?y:int -> unit -> ?z:int -> unit -> int * int * int =
  <fun>

# test ();;
- : ?z:int -> unit -> int * int * int = <fun>

# test ~x:2 () ~z:3 ();;
- : int * int * int = (2, 0, 3)
```

Optional parameters may also commute with non-optional or unlabeled ones, as long as they are applied simultaneously. By nature, optional arguments do not commute with unlabeled arguments applied independently.

```
# test ~y:2 ~x:3 () ();;
- : int * int * int = (3, 2, 0)

# test () () ~z:1 ~y:2 ~x:3;;
- : int * int * int = (3, 2, 1)

# (test () ()) ~z:1;;
Error: This expression has type int * int * int
       This is not a function; it cannot be applied.
```

Here `(test () ())` is already `(0,0,0)` and cannot be further applied.

Optional arguments are actually implemented as option types. If you do not give a default value, you have access to their internal representation, `type 'a option = None | Some of 'a`. You can then provide different behaviors when an argument is present or not.

```
# let bump ?step x =
#   match step with
#   | None -> x * 2
#   | Some y -> x + y
# ;;
val bump : ?step:int -> int -> int = <fun>
```

It may also be useful to relay an optional argument from a function call to another. This can be done by prefixing the applied argument with `?`. This question mark disables the wrapping of optional argument in an option type.

```
# let test2 ?x ?y () = test ?x ?y () ();;
val test2 : ?x:int -> ?y:int -> unit -> int * int * int = <fun>

# test2 ?x:None;;
- : ?y:int -> unit -> int * int * int = <fun>
```

4.1.2 Labels and type inference

While they provide an increased comfort for writing function applications, labels and optional arguments have the pitfall that they cannot be inferred as completely as the rest of the language.

You can see it in the following two examples.

```
# let h' g = g ~y:2 ~x:3;;
val h' : (y:int -> x:int -> 'a) -> 'a = <fun>

# h' f;;
Error: This expression has type x:int -> y:int -> int
       but an expression was expected of type y:int -> x:int -> 'a

# let bump_it bump x =
#   bump ~step:2 x;;
val bump_it : (step:int -> 'a -> 'b) -> 'a -> 'b = <fun>

# bump_it bump 1;;
Error: This expression has type ?step:int -> int -> int
       but an expression was expected of type step:int -> 'a -> 'b
```

The first case is simple: `g` is passed `~y` and then `~x`, but `f` expects `~x` and then `~y`. This is correctly handled if we know the type of `g` to be `x:int -> y:int -> int` in advance, but otherwise this causes the above type clash. The simplest workaround is to apply formal parameters in a standard order.

The second example is more subtle: while we intended the argument `bump` to be of type `?step:int -> int -> int`, it is inferred as `step:int -> int -> 'a`. These two types being incompatible (internally normal and optional arguments are different), a type error occurs when applying `bump_it` to the real `bump`.

We will not try here to explain in detail how type inference works. One must just understand that there is not enough information in the above program to deduce the correct type of `g` or `bump`. That is, there is no way to know whether an argument is optional or not, or which is the correct order, by looking only at how a function is applied. The strategy used by the compiler is to assume that there are no optional arguments, and that applications are done in the right order.

The right way to solve this problem for optional parameters is to add a type annotation to the argument `bump`.

```
# let bump_it (bump : ?step:int -> int -> int) x =
#   bump ~step:2 x;;
val bump_it : (?step:int -> int -> int) -> int -> int = <fun>

# bump_it bump 1;;
- : int = 3
```

In practice, such problems appear mostly when using objects whose methods have optional arguments, so that writing the type of object arguments is often a good idea.

Normally the compiler generates a type error if you attempt to pass to a function a parameter whose type is different from the expected one. However, in the specific case where the expected type is a non-labeled function type, and the argument is a function expecting optional parameters, the compiler will attempt to transform the argument to have it match the expected type, by passing `None` for all optional parameters.

```
# let twice f (x : int) = f(f x);;
val twice : (int -> int) -> int -> int = <fun>

# twice bump 2;;
- : int = 8
```

This transformation is coherent with the intended semantics, including side-effects. That is, if the application of optional parameters shall produce side-effects, these are delayed until the received function is really applied to an argument.

4.1.3 Suggestions for labeling

Like for names, choosing labels for functions is not an easy task. A good labeling is a labeling which

- makes programs more readable,
- is easy to remember,

- when possible, allows useful partial applications.

We explain here the rules we applied when labeling OCaml libraries.

To speak in an "object-oriented" way, one can consider that each function has a main argument, its *object*, and other arguments related with its action, the *parameters*. To permit the combination of functions through functionals in commuting label mode, the object will not be labeled. Its role is clear from the function itself. The parameters are labeled with names reminding of their nature or their role. The best labels combine nature and role. When this is not possible the role is to be preferred, since the nature will often be given by the type itself. Obscure abbreviations should be avoided.

```
ListLabels.map : f:('a -> 'b) -> 'a list -> 'b list
UnixLabels.write : file_descr -> buf:bytes -> pos:int -> len:int -> unit
```

When there are several objects of same nature and role, they are all left unlabeled.

```
ListLabels.iter2 : f:('a -> 'b -> 'c) -> 'a list -> 'b list -> unit
```

When there is no preferable object, all arguments are labeled.

```
BytesLabels.blit :
  src:bytes -> src_pos:int -> dst:bytes -> dst_pos:int -> len:int -> unit
```

However, when there is only one argument, it is often left unlabeled.

```
BytesLabels.create : int -> bytes
```

This principle also applies to functions of several arguments whose return type is a type variable, as long as the role of each argument is not ambiguous. Labeling such functions may lead to awkward error messages when one attempts to omit labels in an application, as we have seen with `ListLabels.fold_left`.

Here are some of the label names you will find throughout the libraries.

Label	Meaning
`f:`	a function to be applied
`pos:`	a position in a string, array or byte sequence
`len:`	a length
`buf:`	a byte sequence or string used as buffer
`src:`	the source of an operation
`dst:`	the destination of an operation
`init:`	the initial value for an iterator
`cmp:`	a comparison function, *e.g.* `Pervasives.compare`
`mode:`	an operation mode or a flag list

All these are only suggestions, but keep in mind that the choice of labels is essential for readability. Bizarre choices will make the program harder to maintain.

In the ideal, the right function name with right labels should be enough to understand the function's meaning. Since one can get this information with OCamlBrowser or the `ocaml` toplevel, the documentation is only used when a more detailed specification is needed.

4.2 Polymorphic variants

Variants as presented in section 1.4 are a powerful tool to build data structures and algorithms. However they sometimes lack flexibility when used in modular programming. This is due to the fact that every constructor is assigned to an unique type when defined and used. Even if the same name appears in the definition of multiple types, the constructor itself belongs to only one type. Therefore, one cannot decide that a given constructor belongs to multiple types, or consider a value of some type to belong to some other type with more constructors.

With polymorphic variants, this original assumption is removed. That is, a variant tag does not belong to any type in particular, the type system will just check that it is an admissible value according to its use. You need not define a type before using a variant tag. A variant type will be inferred independently for each of its uses.

Basic use

In programs, polymorphic variants work like usual ones. You just have to prefix their names with a backquote character `.

```
# [`On; `Off];;
- : [> `Off | `On ] list = [`On; `Off]

# `Number 1;;
- : [> `Number of int ] = `Number 1

# let f = function `On -> 1 | `Off -> 0 | `Number n -> n;;
val f : [< `Number of int | `Off | `On ] -> int = <fun>

# List.map f [`On; `Off];;
- : int list = [1; 0]
```

`[>`Off|`On] list` means that to match this list, you should at least be able to match `` `Off `` and `` `On ``, without argument. `[<`On|`Off|`Number of int]` means that `f` may be applied to `` `Off ``, `` `On `` (both without argument), or `` `Number `` n where n is an integer. The `>` and `<` inside the variant types show that they may still be refined, either by defining more tags or by allowing less. As such, they contain an implicit type variable. Because each of the variant types appears only once in the whole type, their implicit type variables are not shown.

The above variant types were polymorphic, allowing further refinement. When writing type annotations, one will most often describe fixed variant types, that is types that cannot be refined. This is also the case for type abbreviations. Such types do not contain `<` or `>`, but just an enumeration of the tags and their associated types, just like in a normal datatype definition.

```
# type 'a vlist = [`Nil | `Cons of 'a * 'a vlist];;
type 'a vlist = [ `Cons of 'a * 'a vlist | `Nil ]

# let rec map f : 'a vlist -> 'b vlist = function
#   | `Nil -> `Nil
#   | `Cons(a, l) -> `Cons(f a, map f l)
# ;;
val map : ('a -> 'b) -> 'a vlist -> 'b vlist = <fun>
```

Advanced use

Type-checking polymorphic variants is a subtle thing, and some expressions may result in more complex type information.

```
# let f = function `A -> `C | `B -> `D | x -> x;;
val f : ([> `A | `B | `C | `D ] as 'a) -> 'a = <fun>

# f `E;;
- : [> `A | `B | `C | `D | `E ] = `E
```

Here we are seeing two phenomena. First, since this matching is open (the last case catches any tag), we obtain the type `[> `A | `B]` rather than `[< `A | `B]` in a closed matching. Then, since `x` is returned as is, input and return types are identical. The notation `as 'a` denotes such type sharing. If we apply `f` to yet another tag `` `E ``, it gets added to the list.

```
# let f1 = function `A x -> x = 1 | `B -> true | `C -> false
# let f2 = function `A x -> x = "a" | `B -> true ;;
val f1 : [< `A of int | `B | `C ] -> bool = <fun>
val f2 : [< `A of string | `B ] -> bool = <fun>

# let f x = f1 x && f2 x;;
val f : [< `A of string & int | `B ] -> bool = <fun>
```

Here `f1` and `f2` both accept the variant tags `` `A `` and `` `B ``, but the argument of `` `A `` is `int` for `f1` and `string` for `f2`. In `f`'s type `` `C ``, only accepted by `f1`, disappears, but both argument types appear for `` `A `` as `int & string`. This means that if we pass the variant tag `` `A `` to `f`, its argument should be *both* `int` and `string`. Since there is no such value, `f` cannot be applied to `` `A ``, and `` `B `` is the only accepted input.

Even if a value has a fixed variant type, one can still give it a larger type through coercions. Coercions are normally written with both the source type and the destination type, but in simple cases the source type may be omitted.

```
# type 'a wlist = [`Nil | `Cons of 'a * 'a wlist | `Snoc of 'a wlist * 'a];;
type 'a wlist = [ `Cons of 'a * 'a wlist | `Nil | `Snoc of 'a wlist * 'a ]

# let wlist_of_vlist  l = (l : 'a vlist :> 'a wlist);;
val wlist_of_vlist : 'a vlist -> 'a wlist = <fun>

# let open_vlist l = (l : 'a vlist :> [> 'a vlist]);;
val open_vlist : 'a vlist -> [> 'a vlist ] = <fun>

# fun x -> (x :> [`A|`B|`C]);;
- : [< `A | `B | `C ] -> [ `A | `B | `C ] = <fun>
```

You may also selectively coerce values through pattern matching.

```
# let split_cases = function
#   | `Nil | `Cons _ as x -> `A x
#   | `Snoc _ as x -> `B x
# ;;
val split_cases :
  [< `Cons of 'a | `Nil | `Snoc of 'b ] ->
  [> `A of [> `Cons of 'a | `Nil ] | `B of [> `Snoc of 'b ] ] = <fun>
```

When an or-pattern composed of variant tags is wrapped inside an alias-pattern, the alias is given a type containing only the tags enumerated in the or-pattern. This allows for many useful idioms, like incremental definition of functions.

```
# let num x = `Num x
# let eval1 eval (`Num x) = x
# let rec eval x = eval1 eval x ;;
val num : 'a -> [> `Num of 'a ] = <fun>
val eval1 : 'a -> [< `Num of 'b ] -> 'b = <fun>
val eval : [< `Num of 'a ] -> 'a = <fun>

# let plus x y = `Plus(x,y)
# let eval2 eval = function
#   | `Plus(x,y) -> eval x + eval y
#   | `Num _ as x -> eval1 eval x
# let rec eval x = eval2 eval x ;;
val plus : 'a -> 'b -> [> `Plus of 'a * 'b ] = <fun>
val eval2 : ('a -> int) -> [< `Num of int | `Plus of 'a * 'a ] -> int = <fun>
val eval : ([< `Num of int | `Plus of 'a * 'a ] as 'a) -> int = <fun>
```

To make this even more comfortable, you may use type definitions as abbreviations for or-patterns. That is, if you have defined `type myvariant = [`Tag1 of int | `Tag2 of bool]`, then the pattern `#myvariant` is equivalent to writing `(`Tag1(_ : int) | `Tag2(_ : bool))`.

Such abbreviations may be used alone,

```
# let f = function
#   | #myvariant -> "myvariant"
#   | `Tag3 -> "Tag3";;
val f : [< `Tag1 of int | `Tag2 of bool | `Tag3 ] -> string = <fun>
```

or combined with with aliases.

```
# let g1 = function `Tag1 _ -> "Tag1" | `Tag2 _ -> "Tag2";;
val g1 : [< `Tag1 of 'a | `Tag2 of 'b ] -> string = <fun>

# let g = function
#   | #myvariant as x -> g1 x
#   | `Tag3 -> "Tag3";;
val g : [< `Tag1 of int | `Tag2 of bool | `Tag3 ] -> string = <fun>
```

4.2.1 Weaknesses of polymorphic variants

After seeing the power of polymorphic variants, one may wonder why they were added to core language variants, rather than replacing them.

The answer is twofold. One first aspect is that while being pretty efficient, the lack of static type information allows for less optimizations, and makes polymorphic variants slightly heavier than core language ones. However noticeable differences would only appear on huge data structures.

More important is the fact that polymorphic variants, while being type-safe, result in a weaker type discipline. That is, core language variants do actually much more than ensuring type-safety,

they also check that you use only declared constructors, that all constructors present in a data-structure are compatible, and they enforce typing constraints to their parameters.

For this reason, you must be more careful about making types explicit when you use polymorphic variants. When you write a library, this is easy since you can describe exact types in interfaces, but for simple programs you are probably better off with core language variants.

Beware also that some idioms make trivial errors very hard to find. For instance, the following code is probably wrong but the compiler has no way to see it.

```
# type abc = [`A | `B | `C] ;;
type abc = [ `A | `B | `C ]

# let f = function
#   | `As -> "A"
#   | #abc -> "other" ;;
val f : [< `A | `As | `B | `C ] -> string = <fun>

# let f : abc -> string = f ;;
val f : abc -> string = <fun>
```

You can avoid such risks by annotating the definition itself.

```
# let f : abc -> string = function
#   | `As -> "A"
#   | #abc -> "other" ;;
Error: This pattern matches values of type [? `As ]
       but a pattern was expected which matches values of type abc
       The second variant type does not allow tag(s) `As
```

Chapter 5

Advanced examples with classes and modules

(Chapter written by Didier Rémy)

In this chapter, we show some larger examples using objects, classes and modules. We review many of the object features simultaneously on the example of a bank account. We show how modules taken from the standard library can be expressed as classes. Lastly, we describe a programming pattern know of as *virtual types* through the example of window managers.

5.1 Extended example: bank accounts

In this section, we illustrate most aspects of Object and inheritance by refining, debugging, and specializing the following initial naive definition of a simple bank account. (We reuse the module `Euro` defined at the end of chapter 3.)

```
# let euro = new Euro.c;;
val euro : float -> Euro.c = <fun>

# let zero = euro 0.;;
val zero : Euro.c = <obj>

# let neg x = x#times (-1.);;
val neg : < times : float -> 'a; .. > -> 'a = <fun>

# class account =
#   object
#     val mutable balance = zero
#     method balance = balance
#     method deposit x = balance <- balance # plus x
#     method withdraw x =
#       if x#leq balance then (balance <- balance # plus (neg x); x) else zero
#   end;;
class account :
  object
```

```
    val mutable balance : Euro.c
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method withdraw : Euro.c -> Euro.c
  end
# let c = new account in c # deposit (euro 100.); c # withdraw (euro 50.);;
- : Euro.c = <obj>
```

We now refine this definition with a method to compute interest.

```
# class account_with_interests =
#   object (self)
#     inherit account
#     method private interest = self # deposit (self # balance # times 0.03)
#   end;;
class account_with_interests :
  object
    val mutable balance : Euro.c
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method private interest : unit
    method withdraw : Euro.c -> Euro.c
  end
```

We make the method `interest` private, since clearly it should not be called freely from the outside. Here, it is only made accessible to subclasses that will manage monthly or yearly updates of the account.

We should soon fix a bug in the current definition: the deposit method can be used for withdrawing money by depositing negative amounts. We can fix this directly:

```
# class safe_account =
#   object
#     inherit account
#     method deposit x = if zero#leq x then balance <- balance#plus x
#   end;;
class safe_account :
  object
    val mutable balance : Euro.c
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method withdraw : Euro.c -> Euro.c
  end
```

However, the bug might be fixed more safely by the following definition:

```
# class safe_account =
#   object
#     inherit account as unsafe
#     method deposit x =
```

```
#       if zero#leq x then unsafe # deposit x
#       else raise (Invalid_argument "deposit")
#   end;;
class safe_account :
  object
    val mutable balance : Euro.c
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method withdraw : Euro.c -> Euro.c
  end
```

In particular, this does not require the knowledge of the implementation of the method `deposit`.

To keep track of operations, we extend the class with a mutable field `history` and a private method `trace` to add an operation in the log. Then each method to be traced is redefined.

```
# type 'a operation = Deposit of 'a | Retrieval of 'a;;
type 'a operation = Deposit of 'a | Retrieval of 'a
```

```
# class account_with_history =
#   object (self)
#     inherit safe_account as super
#     val mutable history = []
#     method private trace x = history <- x :: history
#     method deposit x = self#trace (Deposit x);  super#deposit x
#     method withdraw x = self#trace (Retrieval x); super#withdraw x
#     method history = List.rev history
#   end;;
class account_with_history :
  object
    val mutable balance : Euro.c
    val mutable history : Euro.c operation list
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method history : Euro.c operation list
    method private trace : Euro.c operation -> unit
    method withdraw : Euro.c -> Euro.c
  end
```

One may wish to open an account and simultaneously deposit some initial amount. Although the initial implementation did not address this requirement, it can be achieved by using an initializer.

```
# class account_with_deposit x =
#   object
#     inherit account_with_history
#     initializer balance <- x
#   end;;
class account_with_deposit :
  Euro.c ->
  object
    val mutable balance : Euro.c
```

```
    val mutable history : Euro.c operation list
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method history : Euro.c operation list
    method private trace : Euro.c operation -> unit
    method withdraw : Euro.c -> Euro.c
  end
```

A better alternative is:

```
# class account_with_deposit x =
#   object (self)
#     inherit account_with_history
#     initializer self#deposit x
#   end;;
class account_with_deposit :
  Euro.c ->
  object
    val mutable balance : Euro.c
    val mutable history : Euro.c operation list
    method balance : Euro.c
    method deposit : Euro.c -> unit
    method history : Euro.c operation list
    method private trace : Euro.c operation -> unit
    method withdraw : Euro.c -> Euro.c
  end
```

Indeed, the latter is safer since the call to `deposit` will automatically benefit from safety checks and from the trace. Let's test it:

```
# let ccp = new account_with_deposit (euro 100.) in
# let _balance = ccp#withdraw (euro 50.) in
# ccp#history;;
- : Euro.c operation list = [Deposit <obj>; Retrieval <obj>]
```

Closing an account can be done with the following polymorphic function:

```
# let close c = c#withdraw c#balance;;
val close : < balance : 'a; withdraw : 'a -> 'b; .. > -> 'b = <fun>
```

Of course, this applies to all sorts of accounts.

Finally, we gather several versions of the account into a module `Account` abstracted over some currency.

```
# let today () = (01,01,2000) (* an approximation *)
# module Account (M:MONEY) =
#   struct
#     type m = M.c
#     let m = new M.c
#     let zero = m 0.
```

```
#     class bank =
#       object (self)
#         val mutable balance = zero
#         method balance = balance
#         val mutable history = []
#         method private trace x = history <- x::history
#         method deposit x =
#           self#trace (Deposit x);
#           if zero#leq x then balance <- balance # plus x
#           else raise (Invalid_argument "deposit")
#         method withdraw x =
#           if x#leq balance then
#             (balance <- balance # plus (neg x); self#trace (Retrieval x); x)
#           else zero
#         method history = List.rev history
#       end
#     class type client_view =
#       object
#         method deposit : m -> unit
#         method history : m operation list
#         method withdraw : m -> m
#         method balance : m
#       end
#     class virtual check_client x =
#       let y = if (m 100.)#leq x then x
#       else raise (Failure "Insufficient initial deposit") in
#       object (self) initializer self#deposit y end
#     module Client (B : sig class bank : client_view end) =
#       struct
#         class account x : client_view =
#           object
#             inherit B.bank
#             inherit check_client x
#           end
#         let discount x =
#           let c = new account x in
#           if today() < (1998,10,30) then c # deposit (m 100.); c
#       end
#   end;;
```

This shows the use of modules to group several class definitions that can in fact be thought of as a single unit. This unit would be provided by a bank for both internal and external uses. This is implemented as a functor that abstracts over the currency so that the same code can be used to provide accounts in different currencies.

The class `bank` is the *real* implementation of the bank account (it could have been inlined). This is the one that will be used for further extensions, refinements, etc. Conversely, the client will

only be given the client view.

```
# module Euro_account = Account(Euro);;

# module Client = Euro_account.Client (Euro_account);;

# new Client.account (new Euro.c 100.);;
```

Hence, the clients do not have direct access to the `balance`, nor the `history` of their own accounts. Their only way to change their balance is to deposit or withdraw money. It is important to give the clients a class and not just the ability to create accounts (such as the promotional `discount` account), so that they can personalize their account. For instance, a client may refine the `deposit` and `withdraw` methods so as to do his own financial bookkeeping, automatically. On the other hand, the function `discount` is given as such, with no possibility for further personalization.

It is important to provide the client's view as a functor `Client` so that client accounts can still be built after a possible specialization of the `bank`. The functor `Client` may remain unchanged and be passed the new definition to initialize a client's view of the extended account.

```
# module Investment_account (M : MONEY) =
#   struct
#     type m = M.c
#     module A = Account(M)
#     class bank =
#       object
#         inherit A.bank as super
#         method deposit x =
#           if (new M.c 1000.)#leq x then
#             print_string "Would you like to invest?";
#           super#deposit x
#       end
#     module Client = A.Client
#   end;;
```

The functor `Client` may also be redefined when some new features of the account can be given to the client.

```
# module Internet_account (M : MONEY) =
#   struct
#     type m = M.c
#     module A = Account(M)
#     class bank =
#       object
#         inherit A.bank
#         method mail s = print_string s
#       end
#     class type client_view =
#       object
#         method deposit : m -> unit
```

```
#         method history : m operation list
#         method withdraw : m -> m
#         method balance : m
#         method mail : string -> unit
#       end
#     module Client (B : sig class bank : client_view end) =
#       struct
#         class account x : client_view =
#           object
#             inherit B.bank
#             inherit A.check_client x
#           end
#       end
#   end;;
```

5.2 Simple modules as classes

One may wonder whether it is possible to treat primitive types such as integers and strings as objects. Although this is usually uninteresting for integers or strings, there may be some situations where this is desirable. The class `money` above is such an example. We show here how to do it for strings.

5.2.1 Strings

A naive definition of strings as objects could be:

```
# class ostring s =
#   object
#      method get n = String.get s n
#      method print = print_string s
#      method escaped = new ostring (String.escaped s)
#   end;;
class ostring :
  string ->
  object
    method escaped : ostring
    method get : int -> char
    method print : unit
  end
```

However, the method `escaped` returns an object of the class `ostring`, and not an object of the current class. Hence, if the class is further extended, the method `escaped` will only return an object of the parent class.

```
# class sub_string s =
#   object
```

```
#      inherit ostring s
#      method sub start len = new sub_string (String.sub s  start len)
#   end;;
class sub_string :
  string ->
  object
    method escaped : ostring
    method get : int -> char
    method print : unit
    method sub : int -> int -> sub_string
  end
```

As seen in section 3.16, the solution is to use functional update instead. We need to create an instance variable containing the representation `s` of the string.

```
# class better_string s =
#   object
#      val repr = s
#      method get n = String.get repr n
#      method print = print_string repr
#      method escaped = {< repr = String.escaped repr >}
#      method sub start len = {< repr = String.sub s start len >}
#   end;;
class better_string :
  string ->
  object ('a)
    val repr : string
    method escaped : 'a
    method get : int -> char
    method print : unit
    method sub : int -> int -> 'a
  end
```

As shown in the inferred type, the methods `escaped` and `sub` now return objects of the same type as the one of the class.

Another difficulty is the implementation of the method `concat`. In order to concatenate a string with another string of the same class, one must be able to access the instance variable externally. Thus, a method `repr` returning s must be defined. Here is the correct definition of strings:

```
# class ostring s =
#   object (self : 'mytype)
#      val repr = s
#      method repr = repr
#      method get n = String.get repr n
#      method print = print_string repr
#      method escaped = {< repr = String.escaped repr >}
#      method sub start len = {< repr = String.sub s start len >}
#      method concat (t : 'mytype) = {< repr = repr ^ t#repr >}
#   end;;
```

```
class ostring :
  string ->
  object ('a)
    val repr : string
    method concat : 'a -> 'a
    method escaped : 'a
    method get : int -> char
    method print : unit
    method repr : string
    method sub : int -> int -> 'a
  end
```

Another constructor of the class string can be defined to return a new string of a given length:

```
# class cstring n = ostring (String.make n ' ');;
class cstring : int -> ostring
```

Here, exposing the representation of strings is probably harmless. We do could also hide the representation of strings as we hid the currency in the class `money` of section 3.17.

Stacks

There is sometimes an alternative between using modules or classes for parametric data types. Indeed, there are situations when the two approaches are quite similar. For instance, a stack can be straightforwardly implemented as a class:

```
# exception Empty;;
exception Empty
```

```
# class ['a] stack =
#   object
#     val mutable l = ([] : 'a list)
#     method push x = l <- x::l
#     method pop = match l with [] -> raise Empty | a::l' -> l <- l'; a
#     method clear = l <- []
#     method length = List.length l
#   end;;
class ['a] stack :
  object
    val mutable l : 'a list
    method clear : unit
    method length : int
    method pop : 'a
    method push : 'a -> unit
  end
```

However, writing a method for iterating over a stack is more problematic. A method `fold` would have type `('b -> 'a -> 'b) -> 'b -> 'b`. Here `'a` is the parameter of the stack. The parameter `'b` is not related to the class `'a stack` but to the argument that will be passed to the method `fold`. A naive approach is to make `'b` an extra parameter of class `stack`:

```
# class ['a, 'b] stack2 =
#   object
#     inherit ['a] stack
#     method fold f (x : 'b) = List.fold_left f x l
#   end;;
class ['a, 'b] stack2 :
  object
    val mutable l : 'a list
    method clear : unit
    method fold : ('b -> 'a -> 'b) -> 'b -> 'b
    method length : int
    method pop : 'a
    method push : 'a -> unit
  end
```

However, the method `fold` of a given object can only be applied to functions that all have the same type:

```
# let s = new stack2;;
val s : ('_a, '_b) stack2 = <obj>

# s#fold ( + ) 0;;
- : int = 0

# s;;
- : (int, int) stack2 = <obj>
```

A better solution is to use polymorphic methods, which were introduced in OCaml version 3.05. Polymorphic methods makes it possible to treat the type variable `'b` in the type of `fold` as universally quantified, giving `fold` the polymorphic type `Forall 'b. ('b -> 'a -> 'b) -> 'b -> 'b`. An explicit type declaration on the method `fold` is required, since the type checker cannot infer the polymorphic type by itself.

```
# class ['a] stack3 =
#   object
#     inherit ['a] stack
#     method fold : 'b. ('b -> 'a -> 'b) -> 'b -> 'b
#                 = fun f x -> List.fold_left f x l
#   end;;
class ['a] stack3 :
  object
    val mutable l : 'a list
    method clear : unit
    method fold : ('b -> 'a -> 'b) -> 'b -> 'b
    method length : int
    method pop : 'a
    method push : 'a -> unit
  end
```

5.2.2 Hashtbl

A simplified version of object-oriented hash tables should have the following class type.

```
# class type ['a, 'b] hash_table =
#   object
#     method find : 'a -> 'b
#     method add : 'a -> 'b -> unit
#   end;;
class type ['a, 'b] hash_table =
  object method add : 'a -> 'b -> unit method find : 'a -> 'b end
```

A simple implementation, which is quite reasonable for small hash tables is to use an association list:

```
# class ['a, 'b] small_hashtbl : ['a, 'b] hash_table =
#   object
#     val mutable table = []
#     method find key = List.assoc key table
#     method add key valeur = table <- (key, valeur) :: table
#   end;;
class ['a, 'b] small_hashtbl : ['a, 'b] hash_table
```

A better implementation, and one that scales up better, is to use a true hash table... whose elements are small hash tables!

```
# class ['a, 'b] hashtbl size : ['a, 'b] hash_table =
#   object (self)
#     val table = Array.init size (fun i -> new small_hashtbl)
#     method private hash key =
#       (Hashtbl.hash key) mod (Array.length table)
#     method find key = table.(self#hash key) # find key
#     method add key = table.(self#hash key) # add key
#   end;;
class ['a, 'b] hashtbl : int -> ['a, 'b] hash_table
```

5.2.3 Sets

Implementing sets leads to another difficulty. Indeed, the method `union` needs to be able to access the internal representation of another object of the same class.

This is another instance of friend functions as seen in section 3.17. Indeed, this is the same mechanism used in the module `Set` in the absence of objects.

In the object-oriented version of sets, we only need to add an additional method `tag` to return the representation of a set. Since sets are parametric in the type of elements, the method `tag` has a parametric type `'a tag`, concrete within the module definition but abstract in its signature. From outside, it will then be guaranteed that two objects with a method `tag` of the same type will share the same representation.

```
# module type SET =
#   sig
#     type 'a tag
#     class ['a] c :
#       object ('b)
#         method is_empty : bool
#         method mem : 'a -> bool
#         method add : 'a -> 'b
#         method union : 'b -> 'b
#         method iter : ('a -> unit) -> unit
#         method tag : 'a tag
#       end
#   end;;
# module Set : SET =
#   struct
#     let rec merge l1 l2 =
#       match l1 with
#         [] -> l2
#       | h1 :: t1 ->
#           match l2 with
#             [] -> l1
#           | h2 :: t2 ->
#               if h1 < h2 then h1 :: merge t1 l2
#               else if h1 > h2 then h2 :: merge l1 t2
#               else merge t1 l2
#     type 'a tag = 'a list
#     class ['a] c =
#       object (_ : 'b)
#         val repr = ([] : 'a list)
#         method is_empty = (repr = [])
#         method mem x = List.exists (( = ) x) repr
#         method add x = {< repr = merge [x] repr >}
#         method union (s : 'b) = {< repr = merge repr s#tag >}
#         method iter (f : 'a -> unit) = List.iter f repr
#         method tag = repr
#       end
#   end;;
```

5.3 The subject/observer pattern

The following example, known as the subject/observer pattern, is often presented in the literature as a difficult inheritance problem with inter-connected classes. The general pattern amounts to the definition a pair of two classes that recursively interact with one another.

The class `observer` has a distinguished method `notify` that requires two arguments, a subject and an event to execute an action.

```
# class virtual ['subject, 'event] observer =
#   object
#     method virtual notify : 'subject ->  'event -> unit
#   end;;
class virtual ['subject, 'event] observer :
  object method virtual notify : 'subject -> 'event -> unit end
```

The class `subject` remembers a list of observers in an instance variable, and has a distinguished method `notify_observers` to broadcast the message `notify` to all observers with a particular event `e`.

```
# class ['observer, 'event] subject =
#   object (self)
#     val mutable observers = ([]:'observer list)
#     method add_observer obs = observers <- (obs :: observers)
#     method notify_observers (e : 'event) =
#         List.iter (fun x -> x#notify self e) observers
#   end;;
class ['a, 'event] subject :
  object ('b)
    constraint 'a = < notify : 'b -> 'event -> unit; .. >
    val mutable observers : 'a list
    method add_observer : 'a -> unit
    method notify_observers : 'event -> unit
  end
```

The difficulty usually lies in defining instances of the pattern above by inheritance. This can be done in a natural and obvious manner in OCaml, as shown on the following example manipulating windows.

```
# type event = Raise | Resize | Move;;
type event = Raise | Resize | Move

# let string_of_event = function
#     Raise -> "Raise" | Resize -> "Resize" | Move -> "Move";;
val string_of_event : event -> string = <fun>

# let count = ref 0;;
val count : int ref = {contents = 0}

# class ['observer] window_subject =
#   let id = count := succ !count; !count in
#   object (self)
#     inherit ['observer, event] subject
#     val mutable position = 0
#     method identity = id
#     method move x = position <- position + x; self#notify_observers Move
```

```
#     method draw = Printf.printf "{Position = %d}\n"  position;
#   end;;
class ['a] window_subject :
  object ('b)
    constraint 'a = < notify : 'b -> event -> unit; .. >
    val mutable observers : 'a list
    val mutable position : int
    method add_observer : 'a -> unit
    method draw : unit
    method identity : int
    method move : int -> unit
    method notify_observers : event -> unit
  end
# class ['subject] window_observer =
#   object
#     inherit ['subject, event] observer
#     method notify s e = s#draw
#   end;;
class ['a] window_observer :
  object
    constraint 'a = < draw : unit; .. >
    method notify : 'a -> event -> unit
  end
```

As can be expected, the type of `window` is recursive.

```
# let window = new window_subject;;
val window : < notify : 'a -> event -> unit; _.. > window_subject as 'a =
  <obj>
```

However, the two classes of `window_subject` and `window_observer` are not mutually recursive.

```
# let window_observer = new window_observer;;
val window_observer : < draw : unit; _.. > window_observer = <obj>
# window#add_observer window_observer;;
- : unit = ()
# window#move 1;;
{Position = 1}
- : unit = ()
```

Classes `window_observer` and `window_subject` can still be extended by inheritance. For instance, one may enrich the `subject` with new behaviors and refine the behavior of the observer.

```
# class ['observer] richer_window_subject =
#   object (self)
#     inherit ['observer] window_subject
#     val mutable size = 1
#     method resize x = size <- size + x; self#notify_observers Resize
#     val mutable top = false
```

```
#     method raise = top <- true; self#notify_observers Raise
#     method draw = Printf.printf "{Position = %d; Size = %d}\n"  position size;
#   end;;
class ['a] richer_window_subject :
  object ('b)
    constraint 'a = < notify : 'b -> event -> unit; .. >
    val mutable observers : 'a list
    val mutable position : int
    val mutable size : int
    val mutable top : bool
    method add_observer : 'a -> unit
    method draw : unit
    method identity : int
    method move : int -> unit
    method notify_observers : event -> unit
    method raise : unit
    method resize : int -> unit
  end
# class ['subject] richer_window_observer =
#   object
#     inherit ['subject] window_observer as super
#     method notify s e = if e <> Raise then s#raise; super#notify s e
#   end;;
class ['a] richer_window_observer :
  object
    constraint 'a = < draw : unit; raise : unit; .. >
    method notify : 'a -> event -> unit
  end
```

We can also create a different kind of observer:

```
# class ['subject] trace_observer =
#   object
#     inherit ['subject, event] observer
#     method notify s e =
#       Printf.printf
#         "<Window %d <== %s>\n" s#identity (string_of_event e)
#   end;;
class ['a] trace_observer :
  object
    constraint 'a = < identity : int; .. >
    method notify : 'a -> event -> unit
  end
```

and attach several observers to the same object:

```
# let window = new richer_window_subject;;
val window :
  < notify : 'a -> event -> unit; _.. > richer_window_subject as 'a = <obj>
```

```
# window#add_observer (new richer_window_observer);;
- : unit = ()

# window#add_observer (new trace_observer);;
- : unit = ()

# window#move 1; window#resize 2;;
<Window 1 <== Move>
<Window 1 <== Raise>
{Position = 1; Size = 1}
{Position = 1; Size = 1}
<Window 1 <== Resize>
<Window 1 <== Raise>
{Position = 1; Size = 3}
{Position = 1; Size = 3}
- : unit = ()
```

Part II

The OCaml language

Chapter 6

The OCaml language

Foreword

This document is intended as a reference manual for the OCaml language. It lists the language constructs, and gives their precise syntax and informal semantics. It is by no means a tutorial introduction to the language: there is not a single example. A good working knowledge of OCaml is assumed.

No attempt has been made at mathematical rigor: words are employed with their intuitive meaning, without further definition. As a consequence, the typing rules have been left out, by lack of the mathematical framework required to express them, while they are definitely part of a full formal definition of the language.

Notations

The syntax of the language is given in BNF-like notation. Terminal symbols are set in typewriter font (`like this`). Non-terminal symbols are set in italic font (*like that*). Square brackets $[\ldots]$ denote optional components. Curly brackets $\{\ldots\}$ denotes zero, one or several repetitions of the enclosed components. Curly brackets with a trailing plus sign $\{\ldots\}^+$ denote one or several repetitions of the enclosed components. Parentheses $(\ldots)$ denote grouping.

6.1 Lexical conventions

Blanks

The following characters are considered as blanks: space, horizontal tabulation, carriage return, line feed and form feed. Blanks are ignored, but they separate adjacent identifiers, literals and keywords that would otherwise be confused as one single identifier, literal or keyword.

Comments

Comments are introduced by the two characters `(*`, with no intervening blanks, and terminated by the characters `*)`, with no intervening blanks. Comments are treated as blank characters. Comments do not occur inside string or character literals. Nested comments are handled correctly.

Identifiers

ident ::= (*letter* | _) {*letter* | 0...9 | _ | '}
capitalized-ident ::= (A...Z) {*letter* | 0...9 | _ | '}
lowercase-ident ::= (a...z | _) {*letter* | 0...9 | _ | '}
letter ::= A...Z | a...z

Identifiers are sequences of letters, digits, _ (the underscore character), and ' (the single quote), starting with a letter or an underscore. Letters contain at least the 52 lowercase and uppercase letters from the ASCII set. The current implementation also recognizes as letters some characters from the ISO 8859-1 set (characters 192–214 and 216–222 as uppercase letters; characters 223–246 and 248–255 as lowercase letters). This feature is deprecated and should be avoided for future compatibility.

All characters in an identifier are meaningful. The current implementation accepts identifiers up to 16000000 characters in length.

In many places, OCaml makes a distinction between capitalized identifiers and identifiers that begin with a lowercase letter. The underscore character is considered a lowercase letter for this purpose.

Integer literals

integer-literal ::= [-] (0...9) {0...9 | _}
| [-] (0x | 0X) (0...9 | A...F | a...f) {0...9 | A...F | a...f | _}
| [-] (0o | 0O) (0...7) {0...7 | _}
| [-] (0b | 0B) (0...1) {0...1 | _}

An integer literal is a sequence of one or more digits, optionally preceded by a minus sign. By default, integer literals are in decimal (radix 10). The following prefixes select a different radix:

Prefix	Radix
0x, 0X	hexadecimal (radix 16)
0o, 0O	octal (radix 8)
0b, 0B	binary (radix 2)

(The initial 0 is the digit zero; the O for octal is the letter O.) The interpretation of integer literals that fall outside the range of representable integer values is undefined.

For convenience and readability, underscore characters (_) are accepted (and ignored) within integer literals.

Floating-point literals

float-literal ::= [-] (0...9) {0...9 | _} [. {0...9 | _}] [(e | E) [+ | -] (0...9) {0...9 | _}]
| [-] (0x | 0X) (0...9 | A...F | a...f) {0...9 | A...F | a...f | _}
[. {0...9 | A...F | a...f | _}] [(p | P) [+ | -] (0...9) {0...9 | _}]

Floating-point decimal literals consist in an integer part, a fractional part and an exponent part. The integer part is a sequence of one or more digits, optionally preceded by a minus sign.

The fractional part is a decimal point followed by zero, one or more digits. The exponent part is the character `e` or `E` followed by an optional `+` or `-` sign, followed by one or more digits. It is interpreted as a power of 10. The fractional part or the exponent part can be omitted but not both, to avoid ambiguity with integer literals. The interpretation of floating-point literals that fall outside the range of representable floating-point values is undefined.

Floating-point hexadecimal literals are denoted with the `0x` or `0X` prefix. The syntax is similar to that of floating-point decimal literals, with the following differences. The integer part and the fractional part use hexadecimal digits. The exponent part starts with the character `p` or `P`. It is written in decimal and interpreted as a power of 2.

For convenience and readability, underscore characters (`_`) are accepted (and ignored) within floating-point literals.

Character literals

char-literal ::= `'` *regular-char* `'`
| `'` *escape-sequence* `'`

escape-sequence ::= `\` (`\` | `"` | `'` | `n` | `t` | `b` | `r` | *space*)
| `\` (`0`...`9`) (`0`...`9`) (`0`...`9`)
| `\x` (`0`...`9` | `A`...`F` | `a`...`f`) (`0`...`9` | `A`...`F` | `a`...`f`)
| `\o` (`0`...`3`) (`0`...`7`) (`0`...`7`)

Character literals are delimited by `'` (single quote) characters. The two single quotes enclose either one character different from `'` and `\`, or one of the escape sequences below:

Sequence	Character denoted
`\\`	backslash (\)
`\"`	double quote (")
`\'`	single quote (')
`\n`	linefeed (LF)
`\r`	carriage return (CR)
`\t`	horizontal tabulation (TAB)
`\b`	backspace (BS)
`\`*space*	space (SPC)
`\`*ddd*	the character with ASCII code *ddd* in decimal
`\x`*hh*	the character with ASCII code *hh* in hexadecimal
`\o`*ooo*	the character with ASCII code *ooo* in octal

String literals

string-literal ::= `"` {*string-character*} `"`

string-character ::= *regular-string-char*
| *escape-sequence*
| `\` *newline* {*space* | *tab*}

String literals are delimited by " (double quote) characters. The two double quotes enclose a sequence of either characters different from " and \, or escape sequences from the table given above for character literals.

To allow splitting long string literals across lines, the sequence *newline spaces-or-tabs* (a backslash at the end of a line followed by any number of spaces and horizontal tabulations at the beginning of the next line) is ignored inside string literals.

The current implementation places practically no restrictions on the length of string literals.

Naming labels

To avoid ambiguities, naming labels in expressions cannot just be defined syntactically as the sequence of the three tokens `~`, *ident* and `:`, and have to be defined at the lexical level.

label-name ::= *lowercase-ident*

label ::= `~` *label-name* `:`

optlabel ::= `?` *label-name* `:`

Naming labels come in two flavours: *label* for normal arguments and *optlabel* for optional ones. They are simply distinguished by their first character, either `~` or `?`.

Despite *label* and *optlabel* being lexical entities in expressions, their expansions `~` *label-name* `:` and `?` *label-name* `:` will be used in grammars, for the sake of readability. Note also that inside type expressions, this expansion can be taken literally, *i.e.* there are really 3 tokens, with optional blanks between them.

Prefix and infix symbols

infix-symbol ::= (`=` | `<` | `>` | `@` | `^` | `|` | `&` | `+` | `-` | `*` | `/` | `$` | `%`) {*operator-char*}
| `#` {*operator-char*}$^+$

prefix-symbol ::= `!` {*operator-char*}
| (`?` | `~`) {*operator-char*}$^+$

operator-char ::= `!` | `$` | `%` | `&` | `*` | `+` | `-` | `.` | `/` | `:` | `<` | `=` | `>` | `?` | `@` | `^` | `|` | `~`

Sequences of "operator characters", such as `<=>` or `!!`, are read as a single token from the *infix-symbol* or *prefix-symbol* class. These symbols are parsed as prefix and infix operators inside expressions, but otherwise behave like normal identifiers.

Keywords

The identifiers below are reserved as keywords, and cannot be employed otherwise:

```
and         as          assert      asr         begin       class
constraint  do          done        downto      else        end
exception   external    false       for         fun         function
functor     if          in          include     inherit     initializer
land        lazy        let         lor         lsl         lsr
```

```
lxor        match       method      mod         module      mutable
new         nonrec      object      of          open        or
private     rec         sig         struct      then        to
true        try         type        val         virtual     when
while       with
```

The following character sequences are also keywords:

```
!=    #     &     &&    '     (     )     *     +     ,     -
-.    ->    .     ..    :     ::    :=    :>    ;     ;;    <
<-    =     >     >]    >}    ?     [     [<    [>    [|    ]
_     `     {     {<    |     |]    ||    }     ~
```

Note that the following identifiers are keywords of the Camlp4 extensions and should be avoided for compatibility reasons.

```
parser    value    $     $$    $:    <:    <<    >>    ??
```

Ambiguities

Lexical ambiguities are resolved according to the "longest match" rule: when a character sequence can be decomposed into two tokens in several different ways, the decomposition retained is the one with the longest first token.

Line number directives

linenum-directive ::= `#` {`0`...`9`}$^+$
| `#` {`0`...`9`}$^+$ `"` {*string-character*} `"`

Preprocessors that generate OCaml source code can insert line number directives in their output so that error messages produced by the compiler contain line numbers and file names referring to the source file before preprocessing, instead of after preprocessing. A line number directive is composed of a `#` (sharp sign), followed by a positive integer (the source line number), optionally followed by a character string (the source file name). Line number directives are treated as blanks during lexical analysis.

6.2 Values

This section describes the kinds of values that are manipulated by OCaml programs.

6.2.1 Base values

Integer numbers

Integer values are integer numbers from -2^{30} to $2^{30}-1$, that is -1073741824 to 1073741823. The implementation may support a wider range of integer values: on 64-bit platforms, the current implementation supports integers ranging from -2^{62} to $2^{62}-1$.

Floating-point numbers

Floating-point values are numbers in floating-point representation. The current implementation uses double-precision floating-point numbers conforming to the IEEE 754 standard, with 53 bits of mantissa and an exponent ranging from −1022 to 1023.

Characters

Character values are represented as 8-bit integers between 0 and 255. Character codes between 0 and 127 are interpreted following the ASCII standard. The current implementation interprets character codes between 128 and 255 following the ISO 8859-1 standard.

Character strings

String values are finite sequences of characters. The current implementation supports strings containing up to $2^{24} - 5$ characters (16777211 characters); on 64-bit platforms, the limit is $2^{57} - 9$.

6.2.2 Tuples

Tuples of values are written `(`v_1 `,` ... `,`v_n `)`, standing for the n-tuple of values v_1 to v_n. The current implementation supports tuple of up to $2^{22} - 1$ elements (4194303 elements).

6.2.3 Records

Record values are labeled tuples of values. The record value written `{` *field*$_1$ `=`v_1 `;` ... `;` *field*$_n$ `=`v_n `}` associates the value v_i to the record field *field*$_i$, for $i = 1 \ldots n$. The current implementation supports records with up to $2^{22} - 1$ fields (4194303 fields).

6.2.4 Arrays

Arrays are finite, variable-sized sequences of values of the same type. The current implementation supports arrays containing up to $2^{22} - 1$ elements (4194303 elements) unless the elements are floating-point numbers (2097151 elements in this case); on 64-bit platforms, the limit is $2^{54} - 1$ for all arrays.

6.2.5 Variant values

Variant values are either a constant constructor, or a non-constant constructor applied to a number of values. The former case is written *constr*; the latter case is written *constr* `(`v_1 `,`... `,`v_n `)`, where the v_i are said to be the arguments of the non-constant constructor *constr*. The parentheses may be omitted if there is only one argument.

The following constants are treated like built-in constant constructors:

Constant	Constructor
`false`	the boolean false
`true`	the boolean true
`()`	the "unit" value
`[]`	the empty list

The current implementation limits each variant type to have at most 246 non-constant constructors and $2^{30} - 1$ constant constructors.

6.2.6 Polymorphic variants

Polymorphic variants are an alternate form of variant values, not belonging explicitly to a predefined variant type, and following specific typing rules. They can be either constant, written ` *tag-name*, or non-constant, written ` *tag-name* `(`*v*`)`.

6.2.7 Functions

Functional values are mappings from values to values.

6.2.8 Objects

Objects are composed of a hidden internal state which is a record of instance variables, and a set of methods for accessing and modifying these variables. The structure of an object is described by the toplevel class that created it.

6.3 Names

Identifiers are used to give names to several classes of language objects and refer to these objects by name later:

- value names (syntactic class *value-name*),
- value constructors and exception constructors (class *constr-name*),
- labels (*label-name*, defined in section 6.1),
- polymorphic variant tags (*tag-name*),
- type constructors (*typeconstr-name*),
- record fields (*field-name*),
- class names (*class-name*),
- method names (*method-name*),
- instance variable names (*inst-var-name*),
- module names (*module-name*),
- module type names (*modtype-name*).

These eleven name spaces are distinguished both by the context and by the capitalization of the identifier: whether the first letter of the identifier is in lowercase (written *lowercase-ident* below) or in uppercase (written *capitalized-ident*). Underscore is considered a lowercase letter for this purpose.

Naming objects

value-name ::= *lowercase-ident*
| `(` *operator-name* `)`

operator-name ::= *prefix-symbol* | *infix-op*

infix-op ::= *infix-symbol*
| `*` | `+` | `-` | `-.` | `=` | `!=` | `<` | `>` | `or` | `||` | `&` | `&&` | `:=`
| `mod` | `land` | `lor` | `lxor` | `lsl` | `lsr` | `asr`

constr-name ::= *capitalized-ident*

tag-name ::= *capitalized-ident*

typeconstr-name ::= *lowercase-ident*

field-name ::= *lowercase-ident*

module-name ::= *capitalized-ident*

modtype-name ::= *ident*

class-name ::= *lowercase-ident*

inst-var-name ::= *lowercase-ident*

method-name ::= *lowercase-ident*

As shown above, prefix and infix symbols as well as some keywords can be used as value names, provided they are written between parentheses. The capitalization rules are summarized in the table below.

Name space	Case of first letter
Values	lowercase
Constructors	uppercase
Labels	lowercase
Polymorphic variant tags	uppercase
Exceptions	uppercase
Type constructors	lowercase
Record fields	lowercase
Classes	lowercase
Instance variables	lowercase
Methods	lowercase
Modules	uppercase
Module types	any

Note on polymorphic variant tags: the current implementation accepts lowercase variant tags in addition to capitalized variant tags, but we suggest you avoid lowercase variant tags for portability and compatibility with future OCaml versions.

Referring to named objects

value-path	::=	[*module-path* .] *value-name*
constr	::=	[*module-path* .] *constr-name*
typeconstr	::=	[*extended-module-path* .] *typeconstr-name*
field	::=	[*module-path* .] *field-name*
modtype-path	::=	[*extended-module-path* .] *modtype-name*
class-path	::=	[*module-path* .] *class-name*
classtype-path	::=	[*extended-module-path* .] *class-name*
module-path	::=	*module-name* {. *module-name*}
extended-module-path	::=	*extended-module-name* {. *extended-module-name*}
extended-module-name	::=	*module-name* {(*extended-module-path*)}

A named object can be referred to either by its name (following the usual static scoping rules for names) or by an access path *prefix* . *name*, where *prefix* designates a module and *name* is the name of an object defined in that module. The first component of the path, *prefix*, is either a simple module name or an access path $name_1$. $name_2 \ldots$, in case the defining module is itself nested inside other modules. For referring to type constructors, module types, or class types, the *prefix* can also contain simple functor applications (as in the syntactic class *extended-module-path* above) in case the defining module is the result of a functor application.

Label names, tag names, method names and instance variable names need not be qualified: the former three are global labels, while the latter are local to a class.

6.4 Type expressions

typexpr ::= `'` *ident*
| `_`
| `(` *typexpr* `)`
| [[`?`] *label-name* `:`] *typexpr* `->` *typexpr*
| *typexpr* {`*` *typexpr*}$^+$
| *typeconstr*
| *typexpr typeconstr*
| `(` *typexpr* {`,` *typexpr*} `)` *typeconstr*
| *typexpr* `as` `'` *ident*
| *polymorphic-variant-type*
| `<` [`..`] `>`
| `<` *method-type* {`;` *method-type*} [`;` | `;` `..`] `>`
| `#` *class-path*
| *typexpr* `#` *class-path*
| `(` *typexpr* {`,` *typexpr*} `)` `#` *class-path*

poly-typexpr ::= *typexpr*
| {`'` *ident*}$^+$ `.` *typexpr*

method-type ::= *method-name* `:` *poly-typexpr*

The table below shows the relative precedences and associativity of operators and non-closed type constructions. The constructions with higher precedences come first.

Operator	Associativity
Type constructor application	–
`#`	–
`*`	–
`->`	right
`as`	–

Type expressions denote types in definitions of data types as well as in type constraints over patterns and expressions.

Type variables

The type expression `'` *ident* stands for the type variable named *ident*. The type expression `_` stands for either an anonymous type variable or anonymous type parameters. In data type definitions, type variables are names for the data type parameters. In type constraints, they represent unspecified types that can be instantiated by any type to satisfy the type constraint. In general the scope of a named type variable is the whole top-level phrase where it appears, and it can only be generalized when leaving this scope. Anonymous variables have no such restriction. In the following cases, the scope of named type variables is restricted to the type expression where they appear: 1) for universal (explicitly polymorphic) type variables; 2) for type variables that only appear in public method specifications (as those variables will be made universal, as described in section 6.9.1); 3)

for variables used as aliases, when the type they are aliased to would be invalid in the scope of the enclosing definition (*i.e.* when it contains free universal type variables, or locally defined types.)

Parenthesized types

The type expression `(` *typexpr* `)` denotes the same type as *typexpr*.

Function types

The type expression $typexpr_1$ `->` $typexpr_2$ denotes the type of functions mapping arguments of type $typexpr_1$ to results of type $typexpr_2$.

label-name `:` $typexpr_1$ `->` $typexpr_2$ denotes the same function type, but the argument is labeled *label*.

`?` *label-name* `:` $typexpr_1$ `->` $typexpr_2$ denotes the type of functions mapping an optional labeled argument of type $typexpr_1$ to results of type $typexpr_2$. That is, the physical type of the function will be $typexpr_1$ `option ->` $typexpr_2$.

Tuple types

The type expression $typexpr_1$ `*` ... `*` $typexpr_n$ denotes the type of tuples whose elements belong to types $typexpr_1, \ldots typexpr_n$ respectively.

Constructed types

Type constructors with no parameter, as in *typeconstr*, are type expressions.

The type expression *typexpr typeconstr*, where *typeconstr* is a type constructor with one parameter, denotes the application of the unary type constructor *typeconstr* to the type *typexpr*.

The type expression $(typexpr_1, \ldots, typexpr_n)$ *typeconstr*, where *typeconstr* is a type constructor with n parameters, denotes the application of the n-ary type constructor *typeconstr* to the types $typexpr_1$ through $typexpr_n$.

In the type expression `_` *typeconstr*, the anonymous type expression `_` stands in for anonymous type parameters and is equivalent to $(_, \ldots, _)$ with as many repetitions of `_` as the arity of *typeconstr*.

Aliased and recursive types

The type expression *typexpr* `as '` *ident* denotes the same type as *typexpr*, and also binds the type variable *ident* to type *typexpr* both in *typexpr* and in other types. In general the scope of an alias is the same as for a named type variable, and covers the whole enclosing definition. If the type variable *ident* actually occurs in *typexpr*, a recursive type is created. Recursive types for which there exists a recursive path that does not contain an object or polymorphic variant type constructor are rejected, except when the `-rectypes` mode is selected.

If `'` *ident* denotes an explicit polymorphic variable, and *typexpr* denotes either an object or polymorphic variant type, the row variable of *typexpr* is captured by `'` *ident*, and quantified upon.

Polymorphic variant types

polymorphic-variant-type ::= `[` *tag-spec-first* {`|` *tag-spec*} `]`
| `[>` [*tag-spec*] {`|` *tag-spec*} `]`
| `[<` [`|`] *tag-spec-full* {`|` *tag-spec-full*} [`>` {`` ` `` *tag-name*}$^+$] `]`

tag-spec-first ::= `` ` `` *tag-name* [`of` *typexpr*]
| [*typexpr*] `&` *tag-spec*

tag-spec ::= `` ` `` *tag-name* [`of` *typexpr*]
| *typexpr*

tag-spec-full ::= `` ` `` *tag-name* [`of` [`&`] *typexpr* {`&` *typexpr*}]
| *typexpr*

Polymorphic variant types describe the values a polymorphic variant may take.

The first case is an exact variant type: all possible tags are known, with their associated types, and they can all be present. Its structure is fully known.

The second case is an open variant type, describing a polymorphic variant value: it gives the list of all tags the value could take, with their associated types. This type is still compatible with a variant type containing more tags. A special case is the unknown type, which does not define any tag, and is compatible with any variant type.

The third case is a closed variant type. It gives information about all the possible tags and their associated types, and which tags are known to potentially appear in values. The exact variant type (first case) is just an abbreviation for a closed variant type where all possible tags are also potentially present.

In all three cases, tags may be either specified directly in the `` ` `` *tag-name* [`of` *typexpr*] form, or indirectly through a type expression, which must expand to an exact variant type, whose tag specifications are inserted in its place.

Full specifications of variant tags are only used for non-exact closed types. They can be understood as a conjunctive type for the argument: it is intended to have all the types enumerated in the specification.

Such conjunctive constraints may be unsatisfiable. In such a case the corresponding tag may not be used in a value of this type. This does not mean that the whole type is not valid: one can still use other available tags. Conjunctive constraints are mainly intended as output from the type checker. When they are used in source programs, unsolvable constraints may cause early failures.

Object types

An object type `<` [*method-type* {`;` *method-type*}] `>` is a record of method types.

Each method may have an explicit polymorphic type: {`'` *ident*}$^+$ `.` *typexpr*. Explicit polymorphic variables have a local scope, and an explicit polymorphic type can only be unified to an equivalent one, where only the order and names of polymorphic variables may change.

The type `<` {*method-type* `;`} `..` `>` is the type of an object whose method names and types are described by $\mathit{method\text{-}type}_1, \ldots, \mathit{method\text{-}type}_n$, and possibly some other methods represented by the ellipsis. This ellipsis actually is a special kind of type variable (called *row variable* in the literature) that stands for any number of extra method types.

#-types

The type `#` *class-path* is a special kind of abbreviation. This abbreviation unifies with the type of any object belonging to a subclass of class *class-path*. It is handled in a special way as it usually hides a type variable (an ellipsis, representing the methods that may be added in a subclass). In particular, it vanishes when the ellipsis gets instantiated. Each type expression `#` *class-path* defines a new type variable, so type `#` *class-path* `->` `#` *class-path* is usually not the same as type (`#` *class-path* `as '` *ident*) `->` `'` *ident*.

Use of #-types to abbreviate polymorphic variant types is deprecated. If t is an exact variant type then `#`t translates to `[<`t `]`, and `#`t `[>` `` ` `` $tag_1 \ldots$ `` ` `` tag_k `]` translates to `[<`t `>` `` ` `` $tag_1 \ldots$ `` ` `` tag_k `]`

Variant and record types

There are no type expressions describing (defined) variant types nor record types, since those are always named, i.e. defined before use and referred to by name. Type definitions are described in section 6.8.1.

6.5 Constants

constant	::=	*integer-literal*
	|	*float-literal*
	|	*char-literal*
	|	*string-literal*
	|	*constr*
	|	`false`
	|	`true`
	|	`( )`
	|	`begin end`
	|	`[ ]`
	|	`[| |]`
	|	`` ` `` *tag-name*

The syntactic class of constants comprises literals from the four base types (integers, floating-point numbers, characters, character strings), and constant constructors from both normal and polymorphic variants, as well as the special constants `false`, `true`, `( )`, `[ ]`, and `[| |]`, which behave like constant constructors, and `begin end`, which is equivalent to `( )`.

6.6 Patterns

pattern ::= *value-name*
| `_`
| *constant*
| *pattern* `as` *value-name*
| `(` *pattern* `)`
| `(` *pattern* `:` *typexpr* `)`
| *pattern* `|` *pattern*
| *constr pattern*
| `` ` `` *tag-name pattern*
| `#` *typeconstr*
| *pattern* {`,` *pattern*}$^{+}$
| `{` *field* [`:` *typexpr*] `=` *pattern* {`;` *field* [`:` *typexpr*] `=` *pattern*} [`;`] `}`
| `[` *pattern* {`;` *pattern*} [`;`] `]`
| *pattern* `::` *pattern*
| `[|` *pattern* {`;` *pattern*} [`;`] `|]`
| *char-literal* `..` *char-literal*

The table below shows the relative precedences and associativity of operators and non-closed pattern constructions. The constructions with higher precedences come first.

Operator	Associativity
`..`	–
`lazy` (see section 7.3)	–
Constructor application, Tag application	right
`::`	right
`,`	–
`|`	left
`as`	–

Patterns are templates that allow selecting data structures of a given shape, and binding identifiers to components of the data structure. This selection operation is called pattern matching; its outcome is either "this value does not match this pattern", or "this value matches this pattern, resulting in the following bindings of names to values".

Variable patterns

A pattern that consists in a value name matches any value, binding the name to the value. The pattern `_` also matches any value, but does not bind any name.

Patterns are *linear*: a variable cannot be bound several times by a given pattern. In particular, there is no way to test for equality between two parts of a data structure using only a pattern (but `when` guards can be used for this purpose).

Constant patterns

A pattern consisting in a constant matches the values that are equal to this constant.

Alias patterns

The pattern *pattern*$_1$ `as` *value-name* matches the same values as *pattern*$_1$. If the matching against *pattern*$_1$ is successful, the name *value-name* is bound to the matched value, in addition to the bindings performed by the matching against *pattern*$_1$.

Parenthesized patterns

The pattern `(` *pattern*$_1$ `)` matches the same values as *pattern*$_1$. A type constraint can appear in a parenthesized pattern, as in `(` *pattern*$_1$ `:` *typexpr* `)`. This constraint forces the type of *pattern*$_1$ to be compatible with *typexpr*.

"Or" patterns

The pattern *pattern*$_1$ `|` *pattern*$_2$ represents the logical "or" of the two patterns *pattern*$_1$ and *pattern*$_2$. A value matches *pattern*$_1$ `|` *pattern*$_2$ if it matches *pattern*$_1$ or *pattern*$_2$. The two sub-patterns *pattern*$_1$ and *pattern*$_2$ must bind exactly the same identifiers to values having the same types. Matching is performed from left to right. More precisely, in case some value v matches *pattern*$_1$ `|` *pattern*$_2$, the bindings performed are those of *pattern*$_1$ when v matches *pattern*$_1$. Otherwise, value v matches *pattern*$_2$ whose bindings are performed.

Variant patterns

The pattern *constr* `(` *pattern*$_1$ `,` ... `,` *pattern*$_n$ `)` matches all variants whose constructor is equal to *constr*, and whose arguments match *pattern*$_1$ ... *pattern*$_n$. It is a type error if n is not the number of arguments expected by the constructor.

The pattern *constr* `_` matches all variants whose constructor is *constr*.

The pattern *pattern*$_1$ `::` *pattern*$_2$ matches non-empty lists whose heads match *pattern*$_1$, and whose tails match *pattern*$_2$.

The pattern `[` *pattern*$_1$ `;` ... `;` *pattern*$_n$ `]` matches lists of length n whose elements match *pattern*$_1$ ... *pattern*$_n$, respectively. This pattern behaves like *pattern*$_1$ `::` ... `::` *pattern*$_n$ `::` `[]`.

Polymorphic variant patterns

The pattern `` ` `` *tag-name* *pattern*$_1$ matches all polymorphic variants whose tag is equal to *tag-name*, and whose argument matches *pattern*$_1$.

Polymorphic variant abbreviation patterns

If the type `[('a,'b,...)]` *typeconstr* `=` `[` `` ` `` *tag-name*$_1$ *typexpr*$_1$ `|` ... `|` `` ` `` *tag-name*$_n$ *typexpr*$_n$ `]` is defined, then the pattern `#` *typeconstr* is a shorthand for the following or-pattern: `(` `` ` `` *tag-name*$_1$ `(_ :` *typexpr*$_1$ `)` `|` ... `|` `` ` `` *tag-name*$_n$ `(_ :` *typexpr*$_n$ `))`. It matches all values of type `[<` *typeconstr* `]`.

Tuple patterns

The pattern $pattern_1$ `,` ... `,` $pattern_n$ matches n-tuples whose components match the patterns $pattern_1$ through $pattern_n$. That is, the pattern matches the tuple values $(v_1, \ldots, v_n)$ such that $pattern_i$ matches v_i for $i = 1, \ldots, n$.

Record patterns

The pattern `{` $field_1$ `=` $pattern_1$ `;` ... `;` $field_n$ `=` $pattern_n$ `}` matches records that define at least the fields $field_1$ through $field_n$, and such that the value associated to $field_i$ matches the pattern $pattern_i$, for $i = 1, \ldots, n$. The record value can define more fields than $field_1$ ... $field_n$; the values associated to these extra fields are not taken into account for matching. Optional type constraints can be added field by field with `{` $field_1$ `:` $typexpr_1$ `=` $pattern_1$ `;` ... `;` $field_n$ `:` $typexpr_n$ `=` $pattern_n$ `}` to force the type of $field_k$ to be compatible with $typexpr_k$.

Array patterns

The pattern `[|` $pattern_1$ `;` ... `;` $pattern_n$ `|]` matches arrays of length n such that the i-th array element matches the pattern $pattern_i$, for $i = 1, \ldots, n$.

Range patterns

The pattern `'`c `' .. '`d `'` is a shorthand for the pattern

`'`c `' | '`c_1 `' | '`c_2 `' |` ... `|  '`c_n `' | '`d `'`

where c_1, c_2, ..., c_n are the characters that occur between c and d in the ASCII character set. For instance, the pattern `'0'..'9'` matches all characters that are digits.

6.7 Expressions

expr ::= *value-path*
| *constant*
| `(` *expr* `)`
| `begin` *expr* `end`
| `(` *expr* `:` *typexpr* `)`
| *expr* {`,` *expr*}$^+$
| *constr expr*
| `` ` `` *tag-name expr*
| *expr* `::` *expr*
| `[` *expr* {`;` *expr*} [`;`] `]`
| `[|` *expr* {`;` *expr*} [`;`] `|]`
| `{` *field* [`:` *typexpr*] `=` *expr* {`;` *field* [`:` *typexpr*] `=` *expr*} [`;`] `}`
| `{` *expr* `with` *field* [`:` *typexpr*] `=` *expr* {`;` *field* [`:` *typexpr*] `=` *expr*} [`;`] `}`
| *expr* {*argument*}$^+$
| *prefix-symbol expr*
| `-` *expr*
| `-.` *expr*
| *expr infix-op expr*
| *expr* `.` *field*
| *expr* `.` *field* `<-` *expr*
| *expr* `.(` *expr* `)`
| *expr* `.(` *expr* `)` `<-` *expr*
| *expr* `.[` *expr* `]`
| *expr* `.[` *expr* `]` `<-` *expr*
| `if` *expr* `then` *expr* [`else` *expr*]
| `while` *expr* `do` *expr* `done`
| `for` *value-name* `=` *expr* (`to` | `downto`) *expr* `do` *expr* `done`
| *expr* `;` *expr*
| `match` *expr* `with` *pattern-matching*
| `function` *pattern-matching*
| `fun` {*parameter*}$^+$ [`:` *typexpr*] `->` *expr*
| `try` *expr* `with` *pattern-matching*
| `let` [`rec`] *let-binding* {`and` *let-binding*} `in` *expr*
| `new` *class-path*
| `object` *class-body* `end`
| *expr* `#` *method-name*
| *inst-var-name*
| *inst-var-name* `<-` *expr*
| `(` *expr* `:>` *typexpr* `)`
| `(` *expr* `:` *typexpr* `:>` *typexpr* `)`
| `{<` [*inst-var-name* `=` *expr* {`;` *inst-var-name* `=` *expr*} [`;`]] `>}`
| `assert` *expr*
| `lazy` *expr*
| `let module` *module-name* {`(` *module-name* `:` *module-type* `)`} [`:` *module-type*]
`=` *module-expr* `in` *expr*

argument ::= *expr*
| `~` *label-name*
| `~` *label-name* `:` *expr*
| `?` *label-name*
| `?` *label-name* `:` *expr*

pattern-matching ::= [`|`] *pattern* [`when` *expr*] `->` *expr* {`|` *pattern* [`when` *expr*] `->` *expr*}

let-binding ::= *pattern* `=` *expr*
| *value-name* {*parameter*} [`:` *typexpr*] [`:>` *typexpr*] `=` *expr*

parameter ::= *pattern*
| `~` *label-name*
| `~` `(` *label-name* [`:` *typexpr*] `)`
| `~` *label-name* `:` *pattern*
| `?` *label-name*
| `?` `(` *label-name* [`:` *typexpr*] [`=` *expr*] `)`
| `?` *label-name* `:` *pattern*
| `?` *label-name* `:` `(` *pattern* [`:` *typexpr*] [`=` *expr*] `)`

The table below shows the relative precedences and associativity of operators and non-closed constructions. The constructions with higher precedence come first. For infix and prefix symbols, we write "`*`..." to mean "any symbol starting with `*`".

Construction or operator	Associativity
prefix-symbol	–
`.` `.(` `.[` `.{` (see section 7.17)	–
`#`...	–
function application, constructor application, tag application, `assert`, `lazy`	left
`-` `-.` (prefix)	–
`**`... `lsl` `lsr` `asr`	right
`*`... `/`... `%`... `mod` `land` `lor` `lxor`	left
`+`... `-`...	left
`::`	right
`@`... `^`...	right
`=`... `<`... `>`... `|`... `&`... `$`... `!=`	left
`&` `&&`	right
`or` `||`	right
`,`	–
`<-` `:=`	right
`if`	–
`;`	right
`let` `match` `fun` `function` `try`	–

6.7.1 Basic expressions

Constants

An expression consisting in a constant evaluates to this constant.

Value paths

An expression consisting in an access path evaluates to the value bound to this path in the current evaluation environment. The path can be either a value name or an access path to a value component of a module.

Parenthesized expressions

The expressions `(` *expr* `)` and `begin` *expr* `end` have the same value as *expr*. The two constructs are semantically equivalent, but it is good style to use `begin`...`end` inside control structures:

```
if ... then begin ... ; ... end else begin ... ; ... end
```

and `(`...`)` for the other grouping situations.

Parenthesized expressions can contain a type constraint, as in `(` *expr* `:` *typexpr* `)`. This constraint forces the type of *expr* to be compatible with *typexpr*.

Parenthesized expressions can also contain coercions `(` *expr* [`:` *typexpr*] `:>` *typexpr* `)` (see subsection 6.7.6 below).

Function application

Function application is denoted by juxtaposition of (possibly labeled) expressions. The expression *expr* $argument_1 \ldots argument_n$ evaluates the expression *expr* and those appearing in $argument_1$ to $argument_n$. The expression *expr* must evaluate to a functional value f, which is then applied to the values of $argument_1, \ldots, argument_n$.

The order in which the expressions *expr*, $argument_1, \ldots, argument_n$ are evaluated is not specified.

Arguments and parameters are matched according to their respective labels. Argument order is irrelevant, except among arguments with the same label, or no label.

If a parameter is specified as optional (label prefixed by `?`) in the type of *expr*, the corresponding argument will be automatically wrapped with the constructor `Some`, except if the argument itself is also prefixed by `?`, in which case it is passed as is. If a non-labeled argument is passed, and its corresponding parameter is preceded by one or several optional parameters, then these parameters are *defaulted*, *i.e.* the value `None` will be passed for them. All other missing parameters (without corresponding argument), both optional and non-optional, will be kept, and the result of the function will still be a function of these missing parameters to the body of f.

As a special case, if the function has a known arity, all the arguments are unlabeled, and their number matches the number of non-optional parameters, then labels are ignored and non-optional parameters are matched in their definition order. Optional arguments are defaulted.

In all cases but exact match of order and labels, without optional parameters, the function type should be known at the application point. This can be ensured by adding a type constraint. Principality of the derivation can be checked in the `-principal` mode.

Function definition

Two syntactic forms are provided to define functions. The first form is introduced by the keyword `function`:

$$\begin{array}{lll} \texttt{function} & \mathit{pattern}_1 & \texttt{->}\ \mathit{expr}_1 \\ \texttt{|} & \ldots & \\ \texttt{|} & \mathit{pattern}_n & \texttt{->}\ \mathit{expr}_n \end{array}$$

This expression evaluates to a functional value with one argument. When this function is applied to a value v, this value is matched against each pattern $pattern_1$ to $pattern_n$. If one of these matchings succeeds, that is, if the value v matches the pattern $pattern_i$ for some i, then the expression $expr_i$ associated to the selected pattern is evaluated, and its value becomes the value of the function application. The evaluation of $expr_i$ takes place in an environment enriched by the bindings performed during the matching.

If several patterns match the argument v, the one that occurs first in the function definition is selected. If none of the patterns matches the argument, the exception `Match_failure` is raised.

The other form of function definition is introduced by the keyword `fun`:

$$\texttt{fun}\ \mathit{parameter}_1 \ldots \mathit{parameter}_n\ \texttt{->}\ \mathit{expr}$$

This expression is equivalent to:

$$\texttt{fun}\ \mathit{parameter}_1\ \texttt{->} \ldots \texttt{fun}\ \mathit{parameter}_n\ \texttt{->}\ \mathit{expr}$$

An optional type constraint *typexpr* can be added before `->` to enforce the type of the result to be compatible with the constraint *typexpr*:

$$\texttt{fun}\ \mathit{parameter}_1 \ldots \mathit{parameter}_n\ \texttt{:}\ \mathit{typexpr}\ \texttt{->}\ \mathit{expr}$$

is equivalent to

$$\texttt{fun}\ \mathit{parameter}_1\ \texttt{->} \ldots \texttt{fun}\ \mathit{parameter}_n\ \texttt{->}\ (\mathit{expr}\ \texttt{:}\ \mathit{typexpr})$$

Beware of the small syntactic difference between a type constraint on the last parameter

$$\texttt{fun}\ \mathit{parameter}_1 \ldots (\mathit{parameter}_n\ \texttt{:}\ \mathit{typexpr})\ \texttt{->}\ \mathit{expr}$$

and one on the result

$$\texttt{fun}\ \mathit{parameter}_1 \ldots \mathit{parameter}_n\ \texttt{:}\ \mathit{typexpr}\ \texttt{->}\ \mathit{expr}$$

The parameter patterns `~` *lab* and `~(` *lab* [`:` *typ*] `)` are shorthands for respectively `~` *lab* `:` *lab* and `~` *lab* `:(` *lab* [`:` *typ*] `)`, and similarly for their optional counterparts.

A function of the form `fun ?` *lab* `:(` *pattern* `=` $expr_0$ `)` `->` *expr* is equivalent to

$$\texttt{fun ?}\ \mathit{lab}\ \texttt{:}\ \mathit{ident}\ \texttt{->}\ \texttt{let}\ \mathit{pattern}\ \texttt{=}\ \texttt{match}\ \mathit{ident}\ \texttt{with Some}\ \mathit{ident}\ \texttt{->}\ \mathit{ident}\ \texttt{|}\ \texttt{None ->}\ \mathit{expr}_0\ \texttt{in}\ \mathit{expr}$$

where *ident* is a fresh variable, except that it is unspecified when $expr_0$ is evaluated.

After these two transformations, expressions are of the form

$$\texttt{fun}\ [\mathit{label}_1]\ \mathit{pattern}_1\ \texttt{->} \ldots \texttt{fun}\ [\mathit{label}_n]\ \mathit{pattern}_n\ \texttt{->}\ \mathit{expr}$$

If we ignore labels, which will only be meaningful at function application, this is equivalent to

`function` *pattern*$_1$ `->` ... `function` *pattern*$_n$ `->` *expr*

That is, the `fun` expression above evaluates to a curried function with n arguments: after applying this function n times to the values $v_1 \ldots v_n$, the values will be matched in parallel against the patterns *pattern*$_1 \ldots$ *pattern*$_n$. If the matching succeeds, the function returns the value of *expr* in an environment enriched by the bindings performed during the matchings. If the matching fails, the exception `Match_failure` is raised.

Guards in pattern-matchings

The cases of a pattern matching (in the `function`, `match` and `try` constructs) can include guard expressions, which are arbitrary boolean expressions that must evaluate to `true` for the match case to be selected. Guards occur just before the `->` token and are introduced by the `when` keyword:

`function`	*pattern*$_1$ [`when` *cond*$_1$]	`->`	*expr*$_1$
`|`	...		
`|`	*pattern*$_n$ [`when` *cond*$_n$]	`->`	*expr*$_n$

Matching proceeds as described before, except that if the value matches some pattern *pattern*$_i$ which has a guard *cond*$_i$, then the expression *cond*$_i$ is evaluated (in an environment enriched by the bindings performed during matching). If *cond*$_i$ evaluates to `true`, then *expr*$_i$ is evaluated and its value returned as the result of the matching, as usual. But if *cond*$_i$ evaluates to `false`, the matching is resumed against the patterns following *pattern*$_i$.

Local definitions

The `let` and `let rec` constructs bind value names locally. The construct

`let` *pattern*$_1$ `=` *expr*$_1$ `and` ... `and` *pattern*$_n$ `=` *expr*$_n$ `in` *expr*

evaluates *expr*$_1 \ldots$ *expr*$_n$ in some unspecified order and matches their values against the patterns *pattern*$_1 \ldots$ *pattern*$_n$. If the matchings succeed, *expr* is evaluated in the environment enriched by the bindings performed during matching, and the value of *expr* is returned as the value of the whole `let` expression. If one of the matchings fails, the exception `Match_failure` is raised.

An alternate syntax is provided to bind variables to functional values: instead of writing

`let` *ident* `=` `fun` *parameter*$_1 \ldots$ *parameter*$_m$ `->` *expr*

in a `let` expression, one may instead write

`let` *ident parameter*$_1 \ldots$ *parameter*$_m$ `=` *expr*

Recursive definitions of names are introduced by `let rec`:

`let rec` *pattern*$_1$ `=` *expr*$_1$ `and` ... `and` *pattern*$_n$ `=` *expr*$_n$ `in` *expr*

The only difference with the `let` construct described above is that the bindings of names to values performed by the pattern-matching are considered already performed when the expressions $expr_1$ to $expr_n$ are evaluated. That is, the expressions $expr_1$ to $expr_n$ can reference identifiers that are bound by one of the patterns $pattern_1, \ldots, pattern_n$, and expect them to have the same value as in *expr*, the body of the `let rec` construct.

The recursive definition is guaranteed to behave as described above if the expressions $expr_1$ to $expr_n$ are function definitions (`fun`... or `function`...), and the patterns $pattern_1 \ldots pattern_n$ are just value names, as in:

`let rec` $name_1$ `=` `fun` ... `and` ... `and` $name_n$ `=` `fun` ... `in` *expr*

This defines $name_1 \ldots name_n$ as mutually recursive functions local to *expr*.

The behavior of other forms of `let rec` definitions is implementation-dependent. The current implementation also supports a certain class of recursive definitions of non-functional values, as explained in section 7.2.

6.7.2 Control structures

Sequence

The expression $expr_1$ `;` $expr_2$ evaluates $expr_1$ first, then $expr_2$, and returns the value of $expr_2$.

Conditional

The expression `if` $expr_1$ `then` $expr_2$ `else` $expr_3$ evaluates to the value of $expr_2$ if $expr_1$ evaluates to the boolean `true`, and to the value of $expr_3$ if $expr_1$ evaluates to the boolean `false`.

The `else` $expr_3$ part can be omitted, in which case it defaults to `else ()`.

Case expression

The expression

```
match  expr
 with  pattern1  ->  expr1
    |  ...
    |  patternn  ->  exprn
```

matches the value of *expr* against the patterns $pattern_1$ to $pattern_n$. If the matching against $pattern_i$ succeeds, the associated expression $expr_i$ is evaluated, and its value becomes the value of the whole `match` expression. The evaluation of $expr_i$ takes place in an environment enriched by the bindings performed during matching. If several patterns match the value of *expr*, the one that occurs first in the `match` expression is selected. If none of the patterns match the value of *expr*, the exception `Match_failure` is raised.

Boolean operators

The expression $expr_1$ `&&` $expr_2$ evaluates to `true` if both $expr_1$ and $expr_2$ evaluate to `true`; otherwise, it evaluates to `false`. The first component, $expr_1$, is evaluated first. The second component, $expr_2$, is not evaluated if the first component evaluates to `false`. Hence, the expression $expr_1$ `&&` $expr_2$ behaves exactly as

`if` *expr*$_1$ `then` *expr*$_2$ `else false`.

The expression *expr*$_1$ `||` *expr*$_2$ evaluates to `true` if one of the expressions *expr*$_1$ and *expr*$_2$ evaluates to `true`; otherwise, it evaluates to `false`. The first component, *expr*$_1$, is evaluated first. The second component, *expr*$_2$, is not evaluated if the first component evaluates to `true`. Hence, the expression *expr*$_1$ `||` *expr*$_2$ behaves exactly as

`if` *expr*$_1$ `then true else` *expr*$_2$.

The boolean operators `&` and `or` are deprecated synonyms for (respectively) `&&` and `||`.

Loops

The expression `while` *expr*$_1$ `do` *expr*$_2$ `done` repeatedly evaluates *expr*$_2$ while *expr*$_1$ evaluates to `true`. The loop condition *expr*$_1$ is evaluated and tested at the beginning of each iteration. The whole `while`...`done` expression evaluates to the unit value `()`.

The expression `for` *name* `=` *expr*$_1$ `to` *expr*$_2$ `do` *expr*$_3$ `done` first evaluates the expressions *expr*$_1$ and *expr*$_2$ (the boundaries) into integer values n and p. Then, the loop body *expr*$_3$ is repeatedly evaluated in an environment where *name* is successively bound to the values n, $n+1$, ..., $p-1$, p. The loop body is never evaluated if $n > p$.

The expression `for` *name* `=` *expr*$_1$ `downto` *expr*$_2$ `do` *expr*$_3$ `done` evaluates similarly, except that *name* is successively bound to the values n, $n-1$, ..., $p+1$, p. The loop body is never evaluated if $n < p$.

In both cases, the whole `for` expression evaluates to the unit value `()`.

Exception handling

The expression

```
try   expr
with  pattern1  ->  expr1
   |  ...
   |  patternn  ->  exprn
```

evaluates the expression *expr* and returns its value if the evaluation of *expr* does not raise any exception. If the evaluation of *expr* raises an exception, the exception value is matched against the patterns *pattern*$_1$ to *pattern*$_n$. If the matching against *pattern*$_i$ succeeds, the associated expression *expr*$_i$ is evaluated, and its value becomes the value of the whole `try` expression. The evaluation of *expr*$_i$ takes place in an environment enriched by the bindings performed during matching. If several patterns match the value of *expr*, the one that occurs first in the `try` expression is selected. If none of the patterns matches the value of *expr*, the exception value is raised again, thereby transparently "passing through" the `try` construct.

6.7.3 Operations on data structures

Products

The expression *expr*$_1$ `,` ... `,` *expr*$_n$ evaluates to the n-tuple of the values of expressions *expr*$_1$ to *expr*$_n$. The evaluation order of the subexpressions is not specified.

Variants

The expression *constr expr* evaluates to the unary variant value whose constructor is *constr*, and whose argument is the value of *expr*. Similarly, the expression *constr* `(` $expr_1$ `,` ... `,` $expr_n$ `)` evaluates to the n-ary variant value whose constructor is *constr* and whose arguments are the values of $expr_1, \ldots, expr_n$.

The expression *constr* `(` $expr_1, \ldots, expr_n$ `)` evaluates to the variant value whose constructor is *constr*, and whose arguments are the values of $expr_1 \ldots expr_n$.

For lists, some syntactic sugar is provided. The expression $expr_1$ `::` $expr_2$ stands for the constructor `(::)` applied to the arguments `(` $expr_1$ `,` $expr_2$ `)`, and therefore evaluates to the list whose head is the value of $expr_1$ and whose tail is the value of $expr_2$. The expression `[` $expr_1$ `;` ... `;` $expr_n$ `]` is equivalent to $expr_1$ `::` ... `::` $expr_n$ `::` `[]`, and therefore evaluates to the list whose elements are the values of $expr_1$ to $expr_n$.

Polymorphic variants

The expression `` ` `` *tag-name expr* evaluates to the polymorphic variant value whose tag is *tag-name*, and whose argument is the value of *expr*.

Records

The expression `{` $field_1$ `=` $expr_1$ `;` ... `;` $field_n$ `=` $expr_n$ `}` evaluates to the record value $\{field_1 = v_1; \ldots; field_n = v_n\}$ where v_i is the value of $expr_i$ for $i = 1, \ldots, n$. The fields $field_1$ to $field_n$ must all belong to the same record type; each field of this record type must appear exactly once in the record expression, though they can appear in any order. The order in which $expr_1$ to $expr_n$ are evaluated is not specified. Optional type constraints can be added after each field `{` $field_1$ `:` $typexpr_1$ `=` $expr_1$ `;` ... `;` $field_n$ `:` $typexpr_n$ `=` $expr_n$ `}` to force the type of $field_k$ to be compatible with $typexpr_k$.

The expression `{` *expr* `with` $field_1$ `=` $expr_1$ `;` ... `;` $field_n$ `=` $expr_n$ `}` builds a fresh record with fields $field_1 \ldots field_n$ equal to $expr_1 \ldots expr_n$, and all other fields having the same value as in the record *expr*. In other terms, it returns a shallow copy of the record *expr*, except for the fields $field_1 \ldots field_n$, which are initialized to $expr_1 \ldots expr_n$. As previously, it is possible to add an optional type constraint on each field being updated with `{` *expr* `with` $field_1$ `:` $typexpr_1$ `=` $expr_1$ `;` ... `;` $field_n$ `:` $typexpr_n$ `=` $expr_n$ `}`.

The expression $expr_1$ `.` *field* evaluates $expr_1$ to a record value, and returns the value associated to *field* in this record value.

The expression $expr_1$ `.` *field* `<-` $expr_2$ evaluates $expr_1$ to a record value, which is then modified in-place by replacing the value associated to *field* in this record by the value of $expr_2$. This operation is permitted only if *field* has been declared `mutable` in the definition of the record type. The whole expression $expr_1$ `.` *field* `<-` $expr_2$ evaluates to the unit value `()`.

Arrays

The expression `[|` $expr_1$ `;` ... `;` $expr_n$ `|]` evaluates to a n-element array, whose elements are initialized with the values of $expr_1$ to $expr_n$ respectively. The order in which these expressions are evaluated is unspecified.

The expression $expr_1$ `.(` $expr_2$ `)` returns the value of element number $expr_2$ in the array denoted by $expr_1$. The first element has number 0; the last element has number $n-1$, where n is the size of the array. The exception `Invalid_argument` is raised if the access is out of bounds.

The expression $expr_1$ `.(` $expr_2$ `)` `<-` $expr_3$ modifies in-place the array denoted by $expr_1$, replacing element number $expr_2$ by the value of $expr_3$. The exception `Invalid_argument` is raised if the access is out of bounds. The value of the whole expression is `()`.

Strings

The expression $expr_1$ `.[` $expr_2$ `]` returns the value of character number $expr_2$ in the string denoted by $expr_1$. The first character has number 0; the last character has number $n-1$, where n is the length of the string. The exception `Invalid_argument` is raised if the access is out of bounds.

The expression $expr_1$ `.[` $expr_2$ `]` `<-` $expr_3$ modifies in-place the string denoted by $expr_1$, replacing character number $expr_2$ by the value of $expr_3$. The exception `Invalid_argument` is raised if the access is out of bounds. The value of the whole expression is `()`.

Note: this possibility is offered only for backward compatibility with older versions of OCaml and will be removed in a future version. New code should use byte sequences and the `Bytes.set` function.

6.7.4 Operators

Symbols from the class *infix-symbol*, as well as the keywords `*`, `+`, `-`, `-.`, `=`, `!=`, `<`, `>`, `or`, `||`, `&`, `&&`, `:=`, `mod`, `land`, `lor`, `lxor`, `lsl`, `lsr`, and `asr` can appear in infix position (between two expressions). Symbols from the class *prefix-symbol*, as well as the keywords `-` and `-.` can appear in prefix position (in front of an expression).

Infix and prefix symbols do not have a fixed meaning: they are simply interpreted as applications of functions bound to the names corresponding to the symbols. The expression *prefix-symbol expr* is interpreted as the application `(` *prefix-symbol* `)` *expr*. Similarly, the expression $expr_1$ *infix-symbol* $expr_2$ is interpreted as the application `(` *infix-symbol* `)` $expr_1$ $expr_2$.

The table below lists the symbols defined in the initial environment and their initial meaning. (See the description of the core library module `Pervasives` in chapter 20 for more details). Their meaning may be changed at any time using `let (` *infix-op* `)` $name_1$ $name_2$ `=`...

Note: the operators `&&`, `||`, and `~-` are handled specially and it is not advisable to change their meaning.

The keywords `-` and `-.` can appear both as infix and prefix operators. When they appear as prefix operators, they are interpreted respectively as the functions `(~-)` and `(~-.)`.

Operator	Initial meaning
`+`	Integer addition.
`-` (infix)	Integer subtraction.
`~-` `-` (prefix)	Integer negation.
`*`	Integer multiplication.
`/`	Integer division. Raise `Division_by_zero` if second argument is zero.
`mod`	Integer modulus. Raise `Division_by_zero` if second argument is zero.
`land`	Bitwise logical "and" on integers.
`lor`	Bitwise logical "or" on integers.
`lxor`	Bitwise logical "exclusive or" on integers.
`lsl`	Bitwise logical shift left on integers.
`lsr`	Bitwise logical shift right on integers.
`asr`	Bitwise arithmetic shift right on integers.
`+.`	Floating-point addition.
`-.` (infix)	Floating-point subtraction.
`~-.` `-.` (prefix)	Floating-point negation.
`*.`	Floating-point multiplication.
`/.`	Floating-point division.
`**`	Floating-point exponentiation.
`@`	List concatenation.
`^`	String concatenation.
`!`	Dereferencing (return the current contents of a reference).
`:=`	Reference assignment (update the reference given as first argument with the value of the second argument).
`=`	Structural equality test.
`<>`	Structural inequality test.
`==`	Physical equality test.
`!=`	Physical inequality test.
`<`	Test "less than".
`<=`	Test "less than or equal".
`>`	Test "greater than".
`>=`	Test "greater than or equal".
`&&` `&`	Boolean conjunction.
`||` `or`	Boolean disjunction.

6.7.5 Objects

Object creation

When *class-path* evaluates to a class body, `new` *class-path* evaluates to a new object containing the instance variables and methods of this class.

When *class-path* evaluates to a class function, `new` *class-path* evaluates to a function expecting the same number of arguments and returning a new object of this class.

Immediate object creation

Creating directly an object through the `object` *class-body* `end` construct is operationally equivalent to defining locally a `class` *class-name* `=` `object` *class-body* `end` —see sections 6.9.2 and following for the syntax of *class-body*— and immediately creating a single object from it by `new` *class-name*.

The typing of immediate objects is slightly different from explicitly defining a class in two respects. First, the inferred object type may contain free type variables. Second, since the class body of an immediate object will never be extended, its self type can be unified with a closed object type.

Method invocation

The expression *expr* `#` *method-name* invokes the method *method-name* of the object denoted by *expr*.

If *method-name* is a polymorphic method, its type should be known at the invocation site. This is true for instance if *expr* is the name of a fresh object (`let` *ident* `=` `new` *class-path* ...) or if there is a type constraint. Principality of the derivation can be checked in the `-principal` mode.

Accessing and modifying instance variables

The instance variables of a class are visible only in the body of the methods defined in the same class or a class that inherits from the class defining the instance variables. The expression *inst-var-name* evaluates to the value of the given instance variable. The expression *inst-var-name* `<-` *expr* assigns the value of *expr* to the instance variable *inst-var-name*, which must be mutable. The whole expression *inst-var-name* `<-` *expr* evaluates to `()`.

Object duplication

An object can be duplicated using the library function `Oo.copy` (see section 21.24). Inside a method, the expression `{<` *inst-var-name* `=` *expr* { `;` *inst-var-name* `=` *expr*} `>}` returns a copy of self with the given instance variables replaced by the values of the associated expressions; other instance variables have the same value in the returned object as in self.

6.7.6 Coercions

Expressions whose type contains object or polymorphic variant types can be explicitly coerced (weakened) to a supertype. The expression `(` *expr* `:>` *typexpr* `)` coerces the expression *expr* to type *typexpr*. The expression `(` *expr* `:` $typexpr_1$ `:>` $typexpr_2$ `)` coerces the expression *expr* from type $typexpr_1$ to type $typexpr_2$.

The former operator will sometimes fail to coerce an expression *expr* from a type typ_1 to a type typ_2 even if type typ_1 is a subtype of type typ_2: in the current implementation it only expands two levels of type abbreviations containing objects and/or polymorphic variants, keeping only recursion when it is explicit in the class type (for objects). As an exception to the above algorithm, if both the inferred type of *expr* and *typ* are ground (*i.e.* do not contain type variables), the former operator behaves as the latter one, taking the inferred type of *expr* as typ_1. In case of failure with the former operator, the latter one should be used.

It is only possible to coerce an expression *expr* from type typ_1 to type typ_2, if the type of *expr* is an instance of typ_1 (like for a type annotation), and typ_1 is a subtype of typ_2. The type of the coerced expression is an instance of typ_2. If the types contain variables, they may be instantiated by the subtyping algorithm, but this is only done after determining whether typ_1 is a potential subtype of typ_2. This means that typing may fail during this latter unification step, even if some instance of typ_1 is a subtype of some instance of typ_2. In the following paragraphs we describe the subtyping relation used.

Object types

A fixed object type admits as subtype any object type that includes all its methods. The types of the methods shall be subtypes of those in the supertype. Namely,

$$\texttt{<}\ met_1\ \texttt{:}\ typ_1\ \texttt{;}\ \ldots\ \texttt{;}\ met_n\ \texttt{:}\ typ_n\ \texttt{>}$$

is a supertype of

$$\texttt{<}\ met_1\ \texttt{:}\ typ'_1\texttt{;}\ \ldots\ \texttt{;}\ met_n\ \texttt{:}\ typ'_n\texttt{;}\ met_{n+1}\texttt{:}\ typ'_{n+1}\texttt{;}\ \ldots\ \texttt{;}\ met_{n+m}\texttt{:}\ typ'_{n+m}\ [\texttt{;}\ \texttt{..}]\ \texttt{>}$$

which may contain an ellipsis `..` if every typ_i is a supertype of the corresponding typ'_i.

A monomorphic method type can be a supertype of a polymorphic method type. Namely, if *typ* is an instance of typ', then $\texttt{'}a_1 \ldots \texttt{'}a_n$ `.` typ' is a subtype of *typ*.

Inside a class definition, newly defined types are not available for subtyping, as the type abbreviations are not yet completely defined. There is an exception for coercing *self* to the (exact) type of its class: this is allowed if the type of *self* does not appear in a contravariant position in the class type, *i.e.* if there are no binary methods.

Polymorphic variant types

A polymorphic variant type *typ* is a subtype of another polymorphic variant type typ' if the upper bound of *typ* (*i.e.* the maximum set of constructors that may appear in an instance of *typ*) is included in the lower bound of typ', and the types of arguments for the constructors of *typ* are subtypes of those in typ'. Namely,

$$\texttt{[}\ [\texttt{<}]\ \texttt{`}\ C_1\ \texttt{of}\ typ_1\ \texttt{|}\ \ldots\ \texttt{|}\ \texttt{`}\ C_n\ \texttt{of}\ typ_n\ \texttt{]}$$

which may be a shrinkable type, is a subtype of

$$\texttt{[}\ [\texttt{>}]\ \texttt{`}\ C_1\ \texttt{of}\ typ'_1\texttt{|}\ \ldots\ \texttt{|}\ \texttt{`}\ C_n\ \texttt{of}\ typ'_n\texttt{|}\ \texttt{`}\ C_{n+1}\texttt{of}\ typ'_{n+1}\texttt{|}\ \ldots\ \texttt{|}\ \texttt{`}\ C_{n+m}\texttt{of}\ typ'_{n+m}\texttt{]}$$

which may be an extensible type, if every typ_i is a subtype of typ'_i.

Variance

Other types do not introduce new subtyping, but they may propagate the subtyping of their arguments. For instance, typ_1 `*` typ_2 is a subtype of typ'_1`*` typ'_2 when typ_1 and typ_2 are respectively subtypes of typ'_1 and typ'_2. For function types, the relation is more subtle: typ_1 `->` typ_2 is a subtype of typ'_1 `->` typ'_2 if typ_1 is a supertype of typ'_1 and typ_2 is a subtype of typ'_2. For this reason, function types are covariant in their second argument (like tuples), but contravariant in their first argument.

Mutable types, like `array` or `ref` are neither covariant nor contravariant, they are nonvariant, that is they do not propagate subtyping.

For user-defined types, the variance is automatically inferred: a parameter is covariant if it has only covariant occurrences, contravariant if it has only contravariant occurrences, variance-free if it has no occurrences, and nonvariant otherwise. A variance-free parameter may change freely through subtyping, it does not have to be a subtype or a supertype. For abstract and private types, the variance must be given explicitly (see section 6.8.1), otherwise the default is nonvariant. This is also the case for constrained arguments in type definitions.

6.7.7 Other

Assertion checking

OCaml supports the `assert` construct to check debugging assertions. The expression `assert` *expr* evaluates the expression *expr* and returns `()` if *expr* evaluates to `true`. If it evaluates to `false` the exception `Assert_failure` is raised with the source file name and the location of *expr* as arguments. Assertion checking can be turned off with the `-noassert` compiler option. In this case, *expr* is not evaluated at all.

As a special case, `assert␣false` is reduced to `raise (Assert_failure ...)`, which gives it a polymorphic type. This means that it can be used in place of any expression (for example as a branch of any pattern-matching). It also means that the `assert␣false` "assertions" cannot be turned off by the `-noassert` option.

Lazy expressions

The expression `lazy` *expr* returns a value v of type `Lazy.t` that encapsulates the computation of *expr*. The argument *expr* is not evaluated at this point in the program. Instead, its evaluation will be performed the first time the function `Lazy.force` is applied to the value v, returning the actual value of *expr*. Subsequent applications of `Lazy.force` to v do not evaluate *expr* again. Applications of `Lazy.force` may be implicit through pattern matching (see 7.3).

Local modules

The expression `let module` *module-name* `=` *module-expr* `in` *expr* locally binds the module expression *module-expr* to the identifier *module-name* during the evaluation of the expression *expr*. It then returns the value of *expr*. For example:

```
let remove_duplicates comparison_fun string_list =
  let module StringSet =
    Set.Make(struct type t = string
                    let compare = comparison_fun end) in
  StringSet.elements
    (List.fold_right StringSet.add string_list StringSet.empty)
```

6.8 Type and exception definitions

6.8.1 Type definitions

Type definitions bind type constructors to data types: either variant types, record types, type abbreviations, or abstract data types. They also bind the value constructors and record fields associated with the definition.

type-definition	::=	`type` [`nonrec`] *typedef* {`and` *typedef*}
typedef	::=	[*type-params*] *typeconstr-name type-information*
type-information	::=	[*type-equation*] [*type-representation*] {*type-constraint*}
type-equation	::=	`=` *typexpr*
type-representation	::=	`=` [`|`] *constr-decl* {`|` *constr-decl*}
	|	`=` *record-decl*
type-params	::=	*type-param*
	|	`(` *type-param* {`,` *type-param*} `)`
type-param	::=	[*variance*] `'` *ident*
variance	::=	`+`
	|	`-`
record-decl	::=	`{` *field-decl* {`;` *field-decl*} [`;`] `}`
constr-decl	::=	(*constr-name* | `[]` | `(::)`) [`of` *constr-args*]
constr-args	::=	*typexpr* {`*` *typexpr*}
field-decl	::=	[`mutable`] *field-name* `:` *poly-typexpr*
type-constraint	::=	`constraint` `'` *ident* `=` *typexpr*

Type definitions are introduced by the `type` keyword, and consist in one or several simple definitions, possibly mutually recursive, separated by the `and` keyword. Each simple definition defines one type constructor.

A simple definition consists in a lowercase identifier, possibly preceded by one or several type parameters, and followed by an optional type equation, then an optional type representation, and then a constraint clause. The identifier is the name of the type constructor being defined.

In the right-hand side of type definitions, references to one of the type constructor name being defined are considered as recursive, unless `type` is followed by `nonrec`. The `nonrec` keyword was introduced in OCaml 4.02.2.

The optional type parameters are either one type variable `'` *ident*, for type constructors with one parameter, or a list of type variables `('` $ident_1, \ldots,$ `'` $ident_n$ `)`, for type constructors with several parameters. Each type parameter may be prefixed by a variance constraint `+` (resp. `-`) indicating that the parameter is covariant (resp. contravariant). These type parameters can appear in the type expressions of the right-hand side of the definition, optionally restricted by a variance constraint ; *i.e.* a covariant parameter may only appear on the right side of a functional arrow (more precisely,

follow the left branch of an even number of arrows), and a contravariant parameter only the left side (left branch of an odd number of arrows). If the type has a representation or an equation, and the parameter is free (*i.e.* not bound via a type constraint to a constructed type), its variance constraint is checked but subtyping *etc.* will use the inferred variance of the parameter, which may be less restrictive; otherwise (*i.e.* for abstract types or non-free parameters), the variance must be given explicitly, and the parameter is invariant if no variance is given.

The optional type equation `=` *typexpr* makes the defined type equivalent to the type expression *typexpr*: one can be substituted for the other during typing. If no type equation is given, a new type is generated: the defined type is incompatible with any other type.

The optional type representation describes the data structure representing the defined type, by giving the list of associated constructors (if it is a variant type) or associated fields (if it is a record type). If no type representation is given, nothing is assumed on the structure of the type besides what is stated in the optional type equation.

The type representation `=` [`|`] *constr-decl* {`|` *constr-decl*} describes a variant type. The constructor declarations $\mathit{constr\text{-}decl}_1, \ldots, \mathit{constr\text{-}decl}_n$ describe the constructors associated to this variant type. The constructor declaration *constr-name* `of` $\mathit{typexpr}_1$ `*...*` $\mathit{typexpr}_n$ declares the name *constr-name* as a non-constant constructor, whose arguments have types $\mathit{typexpr}_1 \ldots \mathit{typexpr}_n$. The constructor declaration *constr-name* declares the name *constr-name* as a constant constructor. Constructor names must be capitalized.

The type representation `=` `{` *field-decl* {`;` *field-decl*} [`;`] `}` describes a record type. The field declarations $\mathit{field\text{-}decl}_1, \ldots, \mathit{field\text{-}decl}_n$ describe the fields associated to this record type. The field declaration *field-name* `:` *poly-typexpr* declares *field-name* as a field whose argument has type *poly-typexpr*. The field declaration `mutable` *field-name* `:` *poly-typexpr* behaves similarly; in addition, it allows physical modification of this field. Immutable fields are covariant, mutable fields are non-variant. Both mutable and immutable fields may have a explicitly polymorphic types. The polymorphism of the contents is statically checked whenever a record value is created or modified. Extracted values may have their types instantiated.

The two components of a type definition, the optional equation and the optional representation, can be combined independently, giving rise to four typical situations:

Abstract type: no equation, no representation.
When appearing in a module signature, this definition specifies nothing on the type constructor, besides its number of parameters: its representation is hidden and it is assumed incompatible with any other type.

Type abbreviation: an equation, no representation.
This defines the type constructor as an abbreviation for the type expression on the right of the `=` sign.

New variant type or record type: no equation, a representation.
This generates a new type constructor and defines associated constructors or fields, through which values of that type can be directly built or inspected.

Re-exported variant type or record type: an equation, a representation.
In this case, the type constructor is defined as an abbreviation for the type expression given in the equation, but in addition the constructors or fields given in the representation remain

attached to the defined type constructor. The type expression in the equation part must agree with the representation: it must be of the same kind (record or variant) and have exactly the same constructors or fields, in the same order, with the same arguments.

The type variables appearing as type parameters can optionally be prefixed by `+` or `-` to indicate that the type constructor is covariant or contravariant with respect to this parameter. This variance information is used to decide subtyping relations when checking the validity of `:>` coercions (see section 6.7.6).

For instance, `type +'a t` declares `t` as an abstract type that is covariant in its parameter; this means that if the type τ is a subtype of the type σ, then τ `t` is a subtype of σ `t`. Similarly, `type -'a t` declares that the abstract type `t` is contravariant in its parameter: if τ is a subtype of σ, then σ `t` is a subtype of τ `t`. If no `+` or `-` variance annotation is given, the type constructor is assumed non-variant in the corresponding parameter. For instance, the abstract type declaration `type 'a t` means that τ `t` is neither a subtype nor a supertype of σ `t` if τ is subtype of σ.

The variance indicated by the `+` and `-` annotations on parameters is enforced only for abstract and private types, or when there are type constraints. Otherwise, for abbreviations, variant and record types without type constraints, the variance properties of the type constructor are inferred from its definition, and the variance annotations are only checked for conformance with the definition.

The construct `constraint '` *ident* `=` *typexpr* allows the specification of type parameters. Any actual type argument corresponding to the type parameter *ident* has to be an instance of *typexpr* (more precisely, *ident* and *typexpr* are unified). Type variables of *typexpr* can appear in the type equation and the type declaration.

6.8.2 Exception definitions

exception-definition ::= `exception` *constr-decl*
| `exception` *constr-name* `=` *constr*

Exception definitions add new constructors to the built-in variant type `exn` of exception values. The constructors are declared as for a definition of a variant type.

The form `exception` *constr-decl* generates a new exception, distinct from all other exceptions in the system. The form `exception` *constr-name* `=` *constr* gives an alternate name to an existing exception.

6.9 Classes

Classes are defined using a small language, similar to the module language.

6.9.1 Class types

Class types are the class-level equivalent of type expressions: they specify the general shape and type properties of classes.

class-type ::= [[`?`] *label-name* `:`] *typexpr* `->` *class-type*
| *class-body-type*

class-body-type ::= `object` [`(` *typexpr* `)`] {*class-field-spec*} `end`
| [`[` *typexpr* {`,` *typexpr*} `]`] *classtype-path*

class-field-spec ::= `inherit` *class-body-type*
| `val` [`mutable`] [`virtual`] *inst-var-name* `:` *typexpr*
| `val virtual mutable` *inst-var-name* `:` *typexpr*
| `method` [`private`] [`virtual`] *method-name* `:` *poly-typexpr*
| `method virtual private` *method-name* `:` *poly-typexpr*
| `constraint` *typexpr* `=` *typexpr*

Simple class expressions

The expression *classtype-path* is equivalent to the class type bound to the name *classtype-path*. Similarly, the expression `[` $typexpr_1$ `,` ... $typexpr_n$ `]` *classtype-path* is equivalent to the parametric class type bound to the name *classtype-path*, in which type parameters have been instantiated to respectively $typexpr_1$, ... $typexpr_n$.

Class function type

The class type expression *typexpr* `->` *class-type* is the type of class functions (functions from values to classes) that take as argument a value of type *typexpr* and return as result a class of type *class-type*.

Class body type

The class type expression `object` [`(` *typexpr* `)`] {*class-field-spec*} `end` is the type of a class body. It specifies its instance variables and methods. In this type, *typexpr* is matched against the self type, therefore providing a name for the self type.

A class body will match a class body type if it provides definitions for all the components specified in the class body type, and these definitions meet the type requirements given in the class body type. Furthermore, all methods either virtual or public present in the class body must also be present in the class body type (on the other hand, some instance variables and concrete private methods may be omitted). A virtual method will match a concrete method, which makes it possible to forget its implementation. An immutable instance variable will match a mutable instance variable.

Inheritance

The inheritance construct `inherit` *class-body-type* provides for inclusion of methods and instance variables from other class types. The instance variable and method types from *class-body-type* are added into the current class type.

Instance variable specification

A specification of an instance variable is written `val` [`mutable`] [`virtual`] *inst-var-name* `:` *typexpr*, where *inst-var-name* is the name of the instance variable and *typexpr* its expected type. The flag `mutable` indicates whether this instance variable can be physically modified. The flag `virtual` indicates that this instance variable is not initialized. It can be initialized later through inheritance.

An instance variable specification will hide any previous specification of an instance variable of the same name.

Method specification

The specification of a method is written `method` [`private`] *method-name* `:` *poly-typexpr*, where *method-name* is the name of the method and *poly-typexpr* its expected type, possibly polymorphic. The flag `private` indicates that the method cannot be accessed from outside the object.

The polymorphism may be left implicit in public method specifications: any type variable which is not bound to a class parameter and does not appear elsewhere inside the class specification will be assumed to be universal, and made polymorphic in the resulting method type. Writing an explicit polymorphic type will disable this behaviour.

If several specifications are present for the same method, they must have compatible types. Any non-private specification of a method forces it to be public.

Virtual method specification

A virtual method specification is written `method` [`private`] `virtual` *method-name* `:` *poly-typexpr*, where *method-name* is the name of the method and *poly-typexpr* its expected type.

Constraints on type parameters

The construct `constraint` $typexpr_1$ `=` $typexpr_2$ forces the two type expressions to be equal. This is typically used to specify type parameters: in this way, they can be bound to specific type expressions.

6.9.2 Class expressions

Class expressions are the class-level equivalent of value expressions: they evaluate to classes, thus providing implementations for the specifications expressed in class types.

class-expr ::=
- *class-path*
- `[` *typexpr* {`,` *typexpr*} `]` *class-path*
- `(` *class-expr* `)`
- `(` *class-expr* `:` *class-type* `)`
- *class-expr* {*argument*}$^+$
- `fun` {*parameter*}$^+$ `->` *class-expr*
- `let` [`rec`] *let-binding* {`and` *let-binding*} `in` *class-expr*
- `object` *class-body* `end`

class-field ::= `inherit` *class-expr* [`as` *lowercase-ident*]
| `val` [`mutable`] *inst-var-name* [`:` *typexpr*] `=` *expr*
| `val` [`mutable`] `virtual` *inst-var-name* `:` *typexpr*
| `val virtual mutable` *inst-var-name* `:` *typexpr*
| `method` [`private`] *method-name* {*parameter*} [`:` *typexpr*] `=` *expr*
| `method` [`private`] *method-name* `:` *poly-typexpr* `=` *expr*
| `method` [`private`] `virtual` *method-name* `:` *poly-typexpr*
| `method virtual private` *method-name* `:` *poly-typexpr*
| `constraint` *typexpr* `=` *typexpr*
| `initializer` *expr*

Simple class expressions

The expression *class-path* evaluates to the class bound to the name *class-path*. Similarly, the expression `[` $typexpr_1$ `,` ... $typexpr_n$ `]` *class-path* evaluates to the parametric class bound to the name *class-path*, in which type parameters have been instantiated respectively to $typexpr_1$, ... $typexpr_n$.

The expression `(` *class-expr* `)` evaluates to the same module as *class-expr*.

The expression `(` *class-expr* `:` *class-type* `)` checks that *class-type* matches the type of *class-expr* (that is, that the implementation *class-expr* meets the type specification *class-type*). The whole expression evaluates to the same class as *class-expr*, except that all components not specified in *class-type* are hidden and can no longer be accessed.

Class application

Class application is denoted by juxtaposition of (possibly labeled) expressions. It denotes the class whose constructor is the first expression applied to the given arguments. The arguments are evaluated as for expression application, but the constructor itself will only be evaluated when objects are created. In particular, side-effects caused by the application of the constructor will only occur at object creation time.

Class function

The expression `fun` [[`?`] *label-name* `:`] *pattern* `->` *class-expr* evaluates to a function from values to classes. When this function is applied to a value v, this value is matched against the pattern *pattern* and the result is the result of the evaluation of *class-expr* in the extended environment.

Conversion from functions with default values to functions with patterns only works identically for class functions as for normal functions.

The expression

`fun` $parameter_1 \ldots parameter_n$ `->` *class-expr*

is a short form for

`fun` $parameter_1$ `->` ... `fun` $parameter_n$ `->` *expr*

Local definitions

The `let` and `let rec` constructs bind value names locally, as for the core language expressions.

If a local definition occurs at the very beginning of a class definition, it will be evaluated when the class is created (just as if the definition was outside of the class). Otherwise, it will be evaluated when the object constructor is called.

Class body

class-body ::= [`(` *pattern* [`:` *typexpr*] `)`] {*class-field*}

The expression `object` *class-body* `end` denotes a class body. This is the prototype for an object : it lists the instance variables and methods of an objet of this class.

A class body is a class value: it is not evaluated at once. Rather, its components are evaluated each time an object is created.

In a class body, the pattern `(` *pattern* [`:` *typexpr*] `)` is matched against self, therefore providing a binding for self and self type. Self can only be used in method and initializers.

Self type cannot be a closed object type, so that the class remains extensible.

Since OCaml 4.01, it is an error if the same method or instance variable name is defined several times in the same class body.

Inheritance

The inheritance construct `inherit` *class-expr* allows reusing methods and instance variables from other classes. The class expression *class-expr* must evaluate to a class body. The instance variables, methods and initializers from this class body are added into the current class. The addition of a method will override any previously defined method of the same name.

An ancestor can be bound by appending `as` *lowercase-ident* to the inheritance construct. *lowercase-ident* is not a true variable and can only be used to select a method, i.e. in an expression *lowercase-ident* `#` *method-name*. This gives access to the method *method-name* as it was defined in the parent class even if it is redefined in the current class. The scope of this ancestor binding is limited to the current class. The ancestor method may be called from a subclass but only indirectly.

Instance variable definition

The definition `val` [`mutable`] *inst-var-name* `=` *expr* adds an instance variable *inst-var-name* whose initial value is the value of expression *expr*. The flag `mutable` allows physical modification of this variable by methods.

An instance variable can only be used in the methods and initializers that follow its definition.

Since version 3.10, redefinitions of a visible instance variable with the same name do not create a new variable, but are merged, using the last value for initialization. They must have identical types and mutability. However, if an instance variable is hidden by omitting it from an interface, it will be kept distinct from other instance variables with the same name.

Virtual instance variable definition

A variable specification is written `val` [`mutable`] `virtual` *inst-var-name* `:` *typexpr*. It specifies whether the variable is modifiable, and gives its type.

Virtual instance variables were added in version 3.10.

Method definition

A method definition is written `method` *method-name* `=` *expr*. The definition of a method overrides any previous definition of this method. The method will be public (that is, not private) if any of the definition states so.

A private method, `method private` *method-name* `=` *expr*, is a method that can only be invoked on self (from other methods of the same object, defined in this class or one of its subclasses). This invocation is performed using the expression *value-name* `#` *method-name*, where *value-name* is directly bound to self at the beginning of the class definition. Private methods do not appear in object types. A method may have both public and private definitions, but as soon as there is a public one, all subsequent definitions will be made public.

Methods may have an explicitly polymorphic type, allowing them to be used polymorphically in programs (even for the same object). The explicit declaration may be done in one of three ways: (1) by giving an explicit polymorphic type in the method definition, immediately after the method name, *i.e.* `method` [`private`] *method-name* `:` {`'` *ident*}$^+$ `.` *typexpr* `=` *expr*; (2) by a forward declaration of the explicit polymorphic type through a virtual method definition; (3) by importing such a declaration through inheritance and/or constraining the type of *self*.

Some special expressions are available in method bodies for manipulating instance variables and duplicating self:

expr	::=	...
	|	*inst-var-name* `<-` *expr*
	|	`{<` [*inst-var-name* `=` *expr* {`;` *inst-var-name* `=` *expr*} [`;`]] `>}`

The expression *inst-var-name* `<-` *expr* modifies in-place the current object by replacing the value associated to *inst-var-name* by the value of *expr*. Of course, this instance variable must have been declared mutable.

The expression `{<` *inst-var-name*$_1$ `=` *expr*$_1$ `;` ... `;` *inst-var-name*$_n$ `=` *expr*$_n$ `>}` evaluates to a copy of the current object in which the values of instance variables *inst-var-name*$_1, \ldots,$ *inst-var-name*$_n$ have been replaced by the values of the corresponding expressions *expr*$_1, \ldots,$ *expr*$_n$.

Virtual method definition

A method specification is written `method` [`private`] `virtual` *method-name* `:` *poly-typexpr*. It specifies whether the method is public or private, and gives its type. If the method is intended to be polymorphic, the type must be explicitly polymorphic.

Constraints on type parameters

The construct `constraint` *typexpr*$_1$ `=` *typexpr*$_2$ forces the two type expressions to be equals. This is typically used to specify type parameters: in that way they can be bound to specific type expressions.

Initializers

A class initializer `initializer` *expr* specifies an expression that will be evaluated whenever an object is created from the class, once all its instance variables have been initialized.

6.9.3 Class definitions

class-definition ::= `class` *class-binding* {`and` *class-binding*}

class-binding ::= [`virtual`] [`[` *type-parameters* `]`] *class-name* {*parameter*} [`:` *class-type*] `=` *class-expr*

type-parameters ::= `'` *ident* {`,` `'` *ident*}

A class definition `class` *class-binding* {`and` *class-binding*} is recursive. Each *class-binding* defines a *class-name* that can be used in the whole expression except for inheritance. It can also be used for inheritance, but only in the definitions that follow its own.

A class binding binds the class name *class-name* to the value of expression *class-expr*. It also binds the class type *class-name* to the type of the class, and defines two type abbreviations : *class-name* and `#` *class-name*. The first one is the type of objects of this class, while the second is more general as it unifies with the type of any object belonging to a subclass (see section 6.4).

Virtual class

A class must be flagged virtual if one of its methods is virtual (that is, appears in the class type, but is not actually defined). Objects cannot be created from a virtual class.

Type parameters

The class type parameters correspond to the ones of the class type and of the two type abbreviations defined by the class binding. They must be bound to actual types in the class definition using type constraints. So that the abbreviations are well-formed, type variables of the inferred type of the class must either be type parameters or be bound in the constraint clause.

6.9.4 Class specifications

class-specification ::= `class` *class-spec* {`and` *class-spec*}

class-spec ::= [`virtual`] [`[` *type-parameters* `]`] *class-name* `:` *class-type*

This is the counterpart in signatures of class definitions. A class specification matches a class definition if they have the same type parameters and their types match.

6.9.5 Class type definitions

classtype-definition ::= `class type` *classtype-def* {`and` *classtype-def*}

classtype-def ::= [`virtual`] [`[` *type-parameters* `]`] *class-name* `=` *class-body-type*

A class type definition `class` *class-name* `=` *class-body-type* defines an abbreviation *class-name* for the class body type *class-body-type*. As for class definitions, two type abbreviations *class-name* and `#` *class-name* are also defined. The definition can be parameterized by some type parameters. If any method in the class type body is virtual, the definition must be flagged `virtual`.

Two class type definitions match if they have the same type parameters and they expand to matching types.

6.10 Module types (module specifications)

Module types are the module-level equivalent of type expressions: they specify the general shape and type properties of modules.

module-type ::= *modtype-path*
| `sig` {*specification* [`;;`]} `end`
| `functor` `(` *module-name* `:` *module-type* `)` `->` *module-type*
| *module-type* `->` *module-type*
| *module-type* `with` *mod-constraint* {`and` *mod-constraint*}
| `(` *module-type* `)`

mod-constraint ::= `type` [*type-params*] *typeconstr* *type-equation* {*type-constraint*}
| `module` *module-path* `=` *extended-module-path*

specification ::= `val` *value-name* `:` *typexpr*
| `external` *value-name* `:` *typexpr* `=` *external-declaration*
| *type-definition*
| `exception` *constr-decl*
| *class-specification*
| *classtype-definition*
| `module` *module-name* `:` *module-type*
| `module` *module-name* {`(` *module-name* `:` *module-type* `)`} `:` *module-type*
| `module type` *modtype-name*
| `module type` *modtype-name* `=` *module-type*
| `open` *module-path*
| `include` *module-type*

6.10.1 Simple module types

The expression *modtype-path* is equivalent to the module type bound to the name *modtype-path*. The expression `(` *module-type* `)` denotes the same type as *module-type*.

6.10.2 Signatures

Signatures are type specifications for structures. Signatures `sig`...`end` are collections of type specifications for value names, type names, exceptions, module names and module type names.

A structure will match a signature if the structure provides definitions (implementations) for all the names specified in the signature (and possibly more), and these definitions meet the type requirements given in the signature.

An optional `;;` is allowed after each specification in a signature. It serves as a syntactic separator with no semantic meaning.

Value specifications

A specification of a value component in a signature is written `val` *value-name* `:` *typexpr*, where *value-name* is the name of the value and *typexpr* its expected type.

The form `external` *value-name* `:` *typexpr* `=` *external-declaration* is similar, except that it requires in addition the name to be implemented as the external function specified in *external-declaration* (see chapter 18).

Type specifications

A specification of one or several type components in a signature is written `type` *typedef* {`and` *typedef*} and consists of a sequence of mutually recursive definitions of type names.

Each type definition in the signature specifies an optional type equation `=` *typexpr* and an optional type representation `=` *constr-decl* ... or `= {` *field-decl* ... `}`. The implementation of the type name in a matching structure must be compatible with the type expression specified in the equation (if given), and have the specified representation (if given). Conversely, users of that signature will be able to rely on the type equation or type representation, if given. More precisely, we have the following four situations:

Abstract type: no equation, no representation.
: Names that are defined as abstract types in a signature can be implemented in a matching structure by any kind of type definition (provided it has the same number of type parameters). The exact implementation of the type will be hidden to the users of the structure. In particular, if the type is implemented as a variant type or record type, the associated constructors and fields will not be accessible to the users; if the type is implemented as an abbreviation, the type equality between the type name and the right-hand side of the abbreviation will be hidden from the users of the structure. Users of the structure consider that type as incompatible with any other type: a fresh type has been generated.

Type abbreviation: an equation `=` *typexpr*, no representation.
: The type name must be implemented by a type compatible with *typexpr*. All users of the structure know that the type name is compatible with *typexpr*.

New variant type or record type: no equation, a representation.
: The type name must be implemented by a variant type or record type with exactly the constructors or fields specified. All users of the structure have access to the constructors or fields, and can use them to create or inspect values of that type. However, users of the structure consider that type as incompatible with any other type: a fresh type has been generated.

Re-exported variant type or record type: an equation, a representation.
This case combines the previous two: the representation of the type is made visible to all users, and no fresh type is generated.

Exception specification

The specification `exception` *constr-decl* in a signature requires the matching structure to provide an exception with the name and arguments specified in the definition, and makes the exception available to all users of the structure.

Class specifications

A specification of one or several classes in a signature is written `class` *class-spec* {`and` *class-spec*} and consists of a sequence of mutually recursive definitions of class names.

Class specifications are described more precisely in section 6.9.4.

Class type specifications

A specification of one or several classe types in a signature is written `class type` *classtype-def* {`and` *classtype-def*} and consists of a sequence of mutually recursive definitions of class type names. Class type specifications are described more precisely in section 6.9.5.

Module specifications

A specification of a module component in a signature is written `module` *module-name* `:` *module-type*, where *module-name* is the name of the module component and *module-type* its expected type. Modules can be nested arbitrarily; in particular, functors can appear as components of structures and functor types as components of signatures.

For specifying a module component that is a functor, one may write

`module` *module-name* `(` $name_1$ `:` $module\text{-}type_1$ `)` ... `(` $name_n$ `:` $module\text{-}type_n$ `)` `:` *module-type*

instead of

`module` *module-name* `:` `functor` `(` $name_1$ `:` $module\text{-}type_1$ `)` `->` ... `->` *module-type*

Module type specifications

A module type component of a signature can be specified either as a manifest module type or as an abstract module type.

An abstract module type specification `module type` *modtype-name* allows the name *modtype-name* to be implemented by any module type in a matching signature, but hides the implementation of the module type to all users of the signature.

A manifest module type specification `module type` *modtype-name* `=` *module-type* requires the name *modtype-name* to be implemented by the module type *module-type* in a matching signature, but makes the equality between *modtype-name* and *module-type* apparent to all users of the signature.

Opening a module path

The expression `open` *module-path* in a signature does not specify any components. It simply affects the parsing of the following items of the signature, allowing components of the module denoted by *module-path* to be referred to by their simple names *name* instead of path accesses *module-path* `.` *name*. The scope of the `open` stops at the end of the signature expression.

Including a signature

The expression `include` *module-type* in a signature performs textual inclusion of the components of the signature denoted by *module-type*. It behaves as if the components of the included signature were copied at the location of the `include`. The *module-type* argument must refer to a module type that is a signature, not a functor type.

6.10.3 Functor types

The module type expression `functor (` *module-name* `:` *module-type*$_1$ `) ->` *module-type*$_2$ is the type of functors (functions from modules to modules) that take as argument a module of type *module-type*$_1$ and return as result a module of type *module-type*$_2$. The module type *module-type*$_2$ can use the name *module-name* to refer to type components of the actual argument of the functor. If the type *module-type*$_2$ does not depend on type components of *module-name*, the module type expression can be simplified with the alternative short syntax *module-type*$_1$ `->` *module-type*$_2$. No restrictions are placed on the type of the functor argument; in particular, a functor may take another functor as argument ("higher-order" functor).

6.10.4 The `with` operator

Assuming *module-type* denotes a signature, the expression *module-type* `with` *mod-constraint* {`and` *mod-constraint*} denotes the same signature where type equations have been added to some of the type specifications, as described by the constraints following the `with` keyword. The constraint `type` [*type-parameters*] *typeconstr* `=` *typexpr* adds the type equation `=` *typexpr* to the specification of the type component named *typeconstr* of the constrained signature. The constraint `module` *module-path* `=` *extended-module-path* adds type equations to all type components of the sub-structure denoted by *module-path*, making them equivalent to the corresponding type components of the structure denoted by *extended-module-path*.

For instance, if the module type name `S` is bound to the signature

```
sig type t module M: (sig type u end) end
```

then `S with type t=int` denotes the signature

```
sig type t=int module M: (sig type u end) end
```

and `S with module M = N` denotes the signature

```
sig type t module M: (sig type u=N.u end) end
```

A functor taking two arguments of type `S` that share their `t` component is written

```
functor (A: S) (B: S with type t = A.t) ...
```

Constraints are added left to right. After each constraint has been applied, the resulting signature must be a subtype of the signature before the constraint was applied. Thus, the `with` operator can only add information on the type components of a signature, but never remove information.

6.11 Module expressions (module implementations)

Module expressions are the module-level equivalent of value expressions: they evaluate to modules, thus providing implementations for the specifications expressed in module types.

module-expr ::= *module-path*
| `struct` [*module-items*] `end`
| `functor` `(` *module-name* `:` *module-type* `)` `->` *module-expr*
| *module-expr* `(` *module-expr* `)`
| `(` *module-expr* `)`
| `(` *module-expr* `:` *module-type* `)`

module-items ::= {`;;`} (*definition* | *expr*) {{`;;`} (*definition* | `;;` *expr*)} {`;;`}

definition ::= `let` [`rec`] *let-binding* {`and` *let-binding*}
| `external` *value-name* `:` *typexpr* `=` *external-declaration*
| *type-definition*
| *exception-definition*
| *class-definition*
| *classtype-definition*
| `module` *module-name* {`(` *module-name* `:` *module-type* `)`} [`:` *module-type*] `=` *module-expr*
| `module type` *modtype-name* `=` *module-type*
| `open` *module-path*
| `include` *module-expr*

6.11.1 Simple module expressions

The expression *module-path* evaluates to the module bound to the name *module-path*.

The expression `(` *module-expr* `)` evaluates to the same module as *module-expr*.

The expression `(` *module-expr* `:` *module-type* `)` checks that the type of *module-expr* is a subtype of *module-type*, that is, that all components specified in *module-type* are implemented in *module-expr*, and their implementation meets the requirements given in *module-type*. In other terms, it checks that the implementation *module-expr* meets the type specification *module-type*. The whole expression evaluates to the same module as *module-expr*, except that all components not specified in *module-type* are hidden and can no longer be accessed.

6.11.2 Structures

Structures `struct`...`end` are collections of definitions for value names, type names, exceptions, module names and module type names. The definitions are evaluated in the order in which they appear in the structure. The scopes of the bindings performed by the definitions extend to the end of the structure. As a consequence, a definition may refer to names bound by earlier definitions in the same structure.

For compatibility with toplevel phrases (chapter 9), optional `;;` are allowed after and before each definition in a structure. These `;;` have no semantic meanings. Similarly, an *expr* preceded by `;;` is allowed as a component of a structure. It is equivalent to `let _ =` *expr*, i.e. *expr* is evaluated for its side-effects but is not bound to any identifier. If *expr* is the first component of a structure, the preceding `;;` can be omitted.

Value definitions

A value definition `let` [`rec`] *let-binding* {`and` *let-binding*} bind value names in the same way as a `let`...`in`... expression (see section 6.7.1). The value names appearing in the left-hand sides of the bindings are bound to the corresponding values in the right-hand sides.

A value definition `external` *value-name* `:` *typexpr* `=` *external-declaration* implements *value-name* as the external function specified in *external-declaration* (see chapter 18).

Type definitions

A definition of one or several type components is written `type` *typedef* {`and` *typedef*} and consists of a sequence of mutually recursive definitions of type names.

Exception definitions

Exceptions are defined with the syntax `exception` *constr-decl* or `exception` *constr-name* `=` *constr*.

Class definitions

A definition of one or several classes is written `class` *class-binding* {`and` *class-binding*} and consists of a sequence of mutually recursive definitions of class names. Class definitions are described more precisely in section 6.9.3.

Class type definitions

A definition of one or several classes is written `class type` *classtype-def* {`and` *classtype-def*} and consists of a sequence of mutually recursive definitions of class type names. Class type definitions are described more precisely in section 6.9.5.

Module definitions

The basic form for defining a module component is `module` *module-name* `=` *module-expr*, which evaluates *module-expr* and binds the result to the name *module-name*.

One can write

`module` *module-name* `:` *module-type* `=` *module-expr*

instead of

`module` *module-name* `=` `(` *module-expr* `:` *module-type* `).`

Another derived form is

`module` *module-name* `(` $name_1$ `:` $module\text{-}type_1$ `)` ... `(` $name_n$ `:` $module\text{-}type_n$ `)` `=` *module-expr*

which is equivalent to

`module` *module-name* `=` `functor` `(` $name_1$ `:` $module\text{-}type_1$ `)` `->` ... `->` *module-expr*

Module type definitions

A definition for a module type is written `module type` *modtype-name* `=` *module-type*. It binds the name *modtype-name* to the module type denoted by the expression *module-type*.

Opening a module path

The expression `open` *module-path* in a structure does not define any components nor perform any bindings. It simply affects the parsing of the following items of the structure, allowing components of the module denoted by *module-path* to be referred to by their simple names *name* instead of path accesses *module-path* `.` *name*. The scope of the `open` stops at the end of the structure expression.

Including the components of another structure

The expression `include` *module-expr* in a structure re-exports in the current structure all definitions of the structure denoted by *module-expr*. For instance, if the identifier `S` is bound to the module

```
struct type t = int  let x = 2 end
```

the module expression

```
struct include S  let y = (x + 1 : t) end
```

is equivalent to the module expression

```
struct type t = S.t  let x = S.x  let y = (x + 1 : t) end
```

The difference between `open` and `include` is that `open` simply provides short names for the components of the opened structure, without defining any components of the current structure, while `include` also adds definitions for the components of the included structure.

6.11.3 Functors

Functor definition

The expression `functor` `(` *module-name* `:` *module-type* `)` `->` *module-expr* evaluates to a functor that takes as argument modules of the type $module\text{-}type_1$, binds *module-name* to these modules, evaluates *module-expr* in the extended environment, and returns the resulting modules as results. No restrictions are placed on the type of the functor argument; in particular, a functor may take another functor as argument ("higher-order" functor).

Functor application

The expression *module-expr*$_1$ `(` *module-expr*$_2$ `)` evaluates *module-expr*$_1$ to a functor and *module-expr*$_2$ to a module, and applies the former to the latter. The type of *module-expr*$_2$ must match the type expected for the arguments of the functor *module-expr*$_1$.

6.12 Compilation units

unit-interface ::= {*specification* [`;;`]}

unit-implementation ::= [*module-items*]

Compilation units bridge the module system and the separate compilation system. A compilation unit is composed of two parts: an interface and an implementation. The interface contains a sequence of specifications, just as the inside of a `sig` ... `end` signature expression. The implementation contains a sequence of definitions and expressions, just as the inside of a `struct` ... `end` module expression. A compilation unit also has a name *unit-name*, derived from the names of the files containing the interface and the implementation (see chapter 8 for more details). A compilation unit behaves roughly as the module definition

`module` *unit-name* `: sig` *unit-interface* `end = struct` *unit-implementation* `end`

A compilation unit can refer to other compilation units by their names, as if they were regular modules. For instance, if `U` is a compilation unit that defines a type `t`, other compilation units can refer to that type under the name `U.t`; they can also refer to `U` as a whole structure. Except for names of other compilation units, a unit interface or unit implementation must not have any other free variables. In other terms, the type-checking and compilation of an interface or implementation proceeds in the initial environment

name$_1$ `: sig` *specification*$_1$ `end` ... *name*$_n$ `: sig` *specification*$_n$ `end`

where *name*$_1$ ... *name*$_n$ are the names of the other compilation units available in the search path (see chapter 8 for more details) and *specification*$_1$ ... *specification*$_n$ are their respective interfaces.

Chapter 7

Language extensions

This chapter describes language extensions and convenience features that are implemented in OCaml, but not described in the OCaml reference manual.

7.1 Integer literals for types `int32`, `int64` and `nativeint`

(Introduced in Objective Caml 3.07)

constant	::=	...
	|	*int32-literal*
	|	*int64-literal*
	|	*nativeint-literal*
int32-literal	::=	*integer-literal* `l`
int64-literal	::=	*integer-literal* `L`
nativeint-literal	::=	*integer-literal* `n`

An integer literal can be followed by one of the letters `l`, `L` or `n` to indicate that this integer has type `int32`, `int64` or `nativeint` respectively, instead of the default type `int` for integer literals. The library modules `Int32`[21.15], `Int64`[21.16] and `Nativeint`[21.23] provide operations on these integer types.

7.2 Recursive definitions of values

(Introduced in Objective Caml 1.00)

As mentioned in section 6.7.1, the `let rec` binding construct, in addition to the definition of recursive functions, also supports a certain class of recursive definitions of non-functional values, such as

`let rec` $name_1$ `=` `1 ::` $name_2$ `and` $name_2$ `=` `2 ::` $name_1$ `in` *expr*

which binds $name_1$ to the cyclic list `1::2::1::2::...`, and $name_2$ to the cyclic list `2::1::2::1::...` Informally, the class of accepted definitions consists of those definitions where the defined names occur only inside function bodies or as argument to a data constructor.

More precisely, consider the expression:

`let rec` *name*$_1$ `=` *expr*$_1$ `and` ... `and` *name*$_n$ `=` *expr*$_n$ `in` *expr*

It will be accepted if each one of *expr*$_1$ ... *expr*$_n$ is statically constructive with respect to *name*$_1$ ... *name*$_n$, is not immediately linked to any of *name*$_1$ ... *name*$_n$, and is not an array constructor whose arguments have abstract type.

An expression *e* is said to be *statically constructive with respect to* the variables *name*$_1$ ... *name*$_n$ if at least one of the following conditions is true:

- *e* has no free occurrence of any of *name*$_1$ ... *name*$_n$
- *e* is a variable
- *e* has the form `fun` ... `->` ...
- *e* has the form `function` ... `->` ...
- *e* has the form `lazy (` ... `)`
- *e* has one of the following forms, where each one of *expr*$_1$ ... *expr*$_m$ is statically constructive with respect to *name*$_1$ ... *name*$_n$, and *expr*$_0$ is statically constructive with respect to *name*$_1$ ... *name*$_n$, *xname*$_1$ ... *xname*$_m$:
  - `let` [`rec`] *xname*$_1$ `=` *expr*$_1$ `and` ... `and` *xname*$_m$ `=` *expr*$_m$ `in` *expr*$_0$
  - `let module` ... `in` *expr*$_1$
  - *constr* `(` *expr*$_1$ `,` ... `,` *expr*$_m$ `)`
  - `` ` `` *tag-name* `(` *expr*$_1$ `,` ... `,` *expr*$_m$ `)`
  - `[|` *expr*$_1$ `;` ... `;` *expr*$_m$ `|]`
  - `{` *field*$_1$ `=` *expr*$_1$ `;` ... `;` *field*$_m$ `=` *expr*$_m$ `}`
  - `{` *expr*$_1$ `with` *field*$_2$ `=` *expr*$_2$ `;` ... `;` *field*$_m$ `=` *expr*$_m$ `}` where *expr*$_1$ is not immediately linked to *name*$_1$ ... *name*$_n$
  - `(` *expr*$_1$ `,` ... `,` *expr*$_m$ `)`
  - *expr*$_1$ `;` ... `;` *expr*$_m$

An expression *e* is said to be *immediately linked to* the variable *name* in the following cases:

- *e* is *name*
- *e* has the form *expr*$_1$ `;` ... `;` *expr*$_m$ where *expr*$_m$ is immediately linked to *name*
- *e* has the form `let` [`rec`] *xname*$_1$ `=` *expr*$_1$ `and` ... `and` *xname*$_m$ `=` *expr*$_m$ `in` *expr*$_0$ where *expr*$_0$ is immediately linked to *name* or to one of the *xname*$_i$ such that *expr*$_i$ is immediately linked to *name*.

7.3 Lazy patterns

(Introduced in Objective Caml 3.11)

pattern ::= ...
| `lazy` *pattern*

The pattern `lazy` *pattern* matches a value v of type `Lazy.t`, provided *pattern* matches the result of forcing v with `Lazy.force`. A successful match of a pattern containing `lazy` sub-patterns forces the corresponding parts of the value being matched, even those that imply no test such as `lazy` *value-name* or `lazy _`. Matching a value with a *pattern-matching* where some patterns contain `lazy` sub-patterns may imply forcing parts of the value, even when the pattern selected in the end has no `lazy` sub-pattern.

For more information, see the description of module `Lazy` in the standard library (section 21.17).

7.4 Recursive modules

(Introduced in Objective Caml 3.07)

definition ::= ...
| `module rec` *module-name* `:` *module-type* `=` *module-expr*
{`and` *module-name* `:` *module-type* `=` *module-expr*}

specification ::= ...
| `module rec` *module-name* `:` *module-type* {`and` *module-name* `:` *module-type*}

Recursive module definitions, introduced by the `module␣rec ... and ...` construction, generalize regular module definitions `module` *module-name* `=` *module-expr* and module specifications `module` *module-name* `:` *module-type* by allowing the defining *module-expr* and the *module-type* to refer recursively to the module identifiers being defined. A typical example of a recursive module definition is:

```
module rec A : sig
                 type t = Leaf of string | Node of ASet.t
                 val compare: t -> t -> int
               end
             = struct
                 type t = Leaf of string | Node of ASet.t
                 let compare t1 t2 =
                   match (t1, t2) with
                     (Leaf s1, Leaf s2) -> Pervasives.compare s1 s2
                   | (Leaf _, Node _) -> 1
                   | (Node _, Leaf _) -> -1
                   | (Node n1, Node n2) -> ASet.compare n1 n2
               end
```

```
    and ASet : Set.S with type elt = A.t
             = Set.Make(A)
```

It can be given the following specification:

```
module rec A : sig
                 type t = Leaf of string | Node of ASet.t
                 val compare: t -> t -> int
               end
    and ASet : Set.S with type elt = A.t
```

This is an experimental extension of OCaml: the class of recursive definitions accepted, as well as its dynamic semantics are not final and subject to change in future releases.

Currently, the compiler requires that all dependency cycles between the recursively-defined module identifiers go through at least one "safe" module. A module is "safe" if all value definitions that it contains have function types $typexpr_1$ `->` $typexpr_2$. Evaluation of a recursive module definition proceeds by building initial values for the safe modules involved, binding all (functional) values to `fun _ -> raiseUndefined_recursive_module`. The defining module expressions are then evaluated, and the initial values for the safe modules are replaced by the values thus computed. If a function component of a safe module is applied during this computation (which corresponds to an ill-founded recursive definition), the `Undefined_recursive_module` exception is raised.

Note that, in the *specification* case, the *module-type*s must be parenthesized if they use the `with` *mod-constraint* construct.

7.5 Private types

Private type declarations in module signatures, of the form `type t = private ...`, enable libraries to reveal some, but not all aspects of the implementation of a type to clients of the library. In this respect, they strike a middle ground between abstract type declarations, where no information is revealed on the type implementation, and data type definitions and type abbreviations, where all aspects of the type implementation are publicized. Private type declarations come in three flavors: for variant and record types (section 7.5.1), for type abbreviations (section 7.5.2), and for row types (section 7.5.3).

7.5.1 Private variant and record types

(Introduced in Objective Caml 3.07)

type-representation	::=	...
	|	`=` `private` [`|`] *constr-decl* {`|` *constr-decl*}
	|	`=` `private` *record-decl*

Values of a variant or record type declared `private` can be de-structured normally in pattern-matching or via the *expr* `.` *field* notation for record accesses. However, values of these types cannot be constructed directly by constructor application or record construction. Moreover, assignment on a mutable field of a private record type is not allowed.

The typical use of private types is in the export signature of a module, to ensure that construction of values of the private type always go through the functions provided by the module, while still allowing pattern-matching outside the defining module. For example:

```
module M : sig
             type t = private A | B of int
             val a : t
             val b : int -> t
           end
         = struct
             type t = A | B of int
             let a = A
             let b n = assert (n > 0); B n
           end
```

Here, the `private` declaration ensures that in any value of type `M.t`, the argument to the `B` constructor is always a positive integer.

With respect to the variance of their parameters, private types are handled like abstract types. That is, if a private type has parameters, their variance is the one explicitly given by prefixing the parameter by a '`+`' or a '`-`', it is invariant otherwise.

7.5.2 Private type abbreviations

(Introduced in Objective Caml 3.11)

type-equation ::= ...
| `= private` *typexpr*

Unlike a regular type abbreviation, a private type abbreviation declares a type that is distinct from its implementation type *typexpr*. However, coercions from the type to *typexpr* are permitted. Moreover, the compiler "knows" the implementation type and can take advantage of this knowledge to perform type-directed optimizations. For ambiguity reasons, *typexpr* cannot be an object or polymorphic variant type, but a similar behaviour can be obtained through private row types.

The following example uses a private type abbreviation to define a module of nonnegative integers:

```
module N : sig
             type t = private int
             val of_int: int -> t
             val to_int: t -> int
           end
         = struct
             type t = int
             let of_int n = assert (n >= 0); n
             let to_int n = n
           end
```

The type `N.t` is incompatible with `int`, ensuring that nonnegative integers and regular integers are not confused. However, if `x` has type `N.t`, the coercion `(x :> int)` is legal and returns the underlying integer, just like `N.to_int x`. Deep coercions are also supported: if `l` has type `N.t list`, the coercion `(l :> int list)` returns the list of underlying integers, like `List.map N.to_int l` but without copying the list `l`.

Note that the coercion `(` *expr* `:>` *typexpr* `)` is actually an abbreviated form, and will only work in presence of private abbreviations if neither the type of *expr* nor *typexpr* contain any type variables. If they do, you must use the full form `(` *expr* `:` $typexpr_1$ `:>` $typexpr_2$ `)` where $typexpr_1$ is the expected type of *expr*. Concretely, this would be `(x : N.t :> int)` and `(l : N.t list :> int list)` for the above examples.

7.5.3 Private row types

(Introduced in Objective Caml 3.09)

type-equation ::= ...
| `=` `private` *typexpr*

Private row types are type abbreviations where part of the structure of the type is left abstract. Concretely *typexpr* in the above should denote either an object type or a polymorphic variant type, with some possibility of refinement left. If the private declaration is used in an interface, the corresponding implementation may either provide a ground instance, or a refined private type.

```
module M : sig type c = private < x : int; .. > val o : c end =
  struct
    class c = object method x = 3 method y = 2 end
    let o = new c
  end
```

This declaration does more than hiding the `y` method, it also makes the type `c` incompatible with any other closed object type, meaning that only `o` will be of type `c`. In that respect it behaves similarly to private record types. But private row types are more flexible with respect to incremental refinement. This feature can be used in combination with functors.

```
module F(X : sig type c = private < x : int; .. > end) =
  struct
    let get_x (o : X.c) = o#x
  end
module G(X : sig type c = private < x : int; y : int; .. > end) =
  struct
    include F(X)
    let get_y (o : X.c) = o#y
  end
```

A polymorphic variant type [t], for example

```
type t = [ `A of int | `B of bool ]
```

can be refined in two ways. A definition [u] may add new field to [t], and the declaration

```
type u = private [> t]
```

will keep those new fields abstract. Construction of values of type [u] is possible using the known variants of [t], but any pattern-matching will require a default case to handle the potential extra fields. Dually, a declaration [u] may restrict the fields of [t] through abstraction: the declaration

```
type v = private [< t > `A]
```

corresponds to private variant types. One cannot create a value of the private type [v], except using the constructors that are explicitly listed as present, `(`A n)` in this example; yet, when patter-matching on a [v], one should assume that any of the constructors of [t] could be present.

Similarly to abstract types, the variance of type parameters is not inferred, and must be given explicitly.

7.6 Local opens

(Introduced in OCaml 3.12, extended to patterns in 4.03)

expr	::=	...
	|	`let open` *module-path* `in` *expr*
	|	*module-path* `.(` *expr* `)`
pattern	::=	...
	|	*module-path* `.(` *pattern* `)`

The expressions `let open` *module-path* `in` *expr* and *module-path* `.(` *expr* `)` are strictly equivalent. On the pattern side, only the pattern *module-path* `.(` *pattern* `)` is available. These constructions locally open the module referred to by the module path *module-path* in the respective scope of the expression *expr* or pattern *pattern*.

Restricting opening to the scope of a single expression or pattern instead of a whole structure allows one to benefit from shorter syntax to refer to components of the opened module, without polluting the global scope. Also, this can make the code easier to read (the open statement is closer to where it is used) and to refactor (because the code fragment is more self-contained).

Local opens for delimited expressions or patterns (Introduced in OCaml 4.02)

expr	::=	...
	|	*module-path* `.[` *expr* `]`
	|	*module-path* `.[|` *expr* `|]`
	|	*module-path* `.{` *expr* `}`
	|	*module-path* `.{<` *expr* `>}`
pattern	::=	...
	|	*module-path* `.[` *pattern* `]`
	|	*module-path* `.[|` *pattern* `|]`
	|	*module-path* `.{` *pattern* `}`

When the body of a local open expression or pattern is delimited by `[ ]`, `[| |]`, or `{ }`, the parentheses can be omitted. For expression, parentheses can also be omitted for `{< >}`. For example, *module-path* `.[` *expr* `]` is equivalent to *module-path* `.([` *expr* `])`, and *module-path* `.[|` *pattern* `|]` is equivalent to *module-path* `.([|` *pattern* `|])`.

7.7 Record and object notations

(Introduced in OCaml 3.12, object copy notation added in Ocaml 4.03)

pattern ::= ...
| `{` *field* [`=` *pattern*] {`;` *field* [`=` *pattern*]} [`;` `_`] [`;`] `}`

expr ::= ...
| `{` *field* [`=` *expr*] {`;` *field* [`=` *expr*]} [`;`] `}`
| `{` *expr* `with` *field* [`=` *expr*] {`;` *field* [`=` *expr*]} [`;`] `}`
| `{ <` *expr* `with` *field* [`=` *expr*] {`;` *field* [`=` *expr*]} [`;`] `> }`

In a record pattern, a record construction expression or an object copy expression, a single identifier *id* stands for *id* = *id*, and a qualified identifier *module-path* `.` *id* stands for *module-path* `.` *id* = *id*. For example, assuming the record type

```
type point = { x: float; y: float }
```

has been declared, the following expressions are equivalent:

```
let x = 1. and y = 2. in { x = x; y = y },
let x = 1. and y = 2. in { x; y },
let x = 1. and y = 2. in { x = x; y }
```

On the object side, all following methods are equivalent:

```
object
  val x=0. val y=0. val z=0.
  method f_0 x y = {< x; y >}
  method f_1 x y = {< x = x; y >}
  method f_2 x y = {< x=x ; y = y >}
end
```

Likewise, the following functions are equivalent:

```
fun {x = x; y = y} -> x +. y
fun {x; y} -> x +. y
```

Optionally, a record pattern can be terminated by `; _` to convey the fact that not all fields of the record type are listed in the record pattern and that it is intentional. By default, the compiler ignores the `; _` annotation. If warning 9 is turned on, the compiler will warn when a record pattern fails to list all fields of the corresponding record type and is not terminated by `; _`. Continuing the `point` example above,

```
fun {x} -> x +. 1.
```

will warn if warning 9 is on, while

```
fun {x; _} -> x +. 1.
```

will not warn. This warning can help spot program points where record patterns may need to be modified after new fields are added to a record type.

7.8 Explicit polymorphic type annotations

(Introduced in OCaml 3.12)

let-binding ::= ...
| *value-name* `:` *poly-typexpr* `=` *expr*

Polymorphic type annotations in `let`-definitions behave in a way similar to polymorphic methods: they explicitly require the defined value to be polymorphic, and allow one to use this polymorphism in recursive occurrences (when using `let rec`). Note however that this is a normal polymorphic type, unifiable with any instance of itself.

There are two possible applications of this feature. One is polymorphic recursion:

```
type 'a t = Leaf of 'a | Node of ('a * 'a) t
let rec depth : 'a. 'a t -> 'b = function
    Leaf _ -> 1
  | Node x -> 1 + depth x
```

Note that `'b` is not explicitly polymorphic here, and it will actually be unified with `int`.

The other application is to ensure that some definition is sufficiently polymorphic.

```
# let id : 'a. 'a -> 'a = fun x -> x+1 ;;
Error: This definition has type int -> int which is less general than
         'a. 'a -> 'a
```

7.9 Locally abstract types

(Introduced in OCaml 3.12, short syntax added in 4.03)

parameter ::= ...
| `(` `type` {*typeconstr-name*}$^+$ `)`

The expression `fun (` `type` *typeconstr-name* `) ->` *expr* introduces a type constructor named *typeconstr-name* which is considered abstract in the scope of the sub-expression, but then replaced by a fresh type variable. Note that contrary to what the syntax could suggest, the expression `fun (` `type` *typeconstr-name* `) ->` *expr* itself does not suspend the evaluation of *expr* as a regular abstraction would. The syntax has been chosen to fit nicely in the context of function declarations, where it is generally used. It is possible to freely mix regular function parameters with pseudo type parameters, as in:

```
let f = fun (type t) (foo : t list) -> ...
```

and even use the alternative syntax for declaring functions:

```
let f (type t) (foo : t list) = ...
```

If several locally abstract types need to be introduced, it is possible to use the syntax `fun ( type` *typeconstr-name*$_1$ ... *typeconstr-name*$_n$ `) ->` *expr* as syntactic sugar for `fun ( type` *typeconstr-name*$_1$ `) ->` ... `-> fun ( type` *typeconstr-name*$_n$ `) ->` *expr*. For instance,

```
let f = fun (type t u v) -> fun (foo : (t * u * v) list) -> ...
let f' (type t u v) (foo : (t * u * v) list) = ...
```

This construction is useful because the type constructors it introduces can be used in places where a type variable is not allowed. For instance, one can use it to define an exception in a local module within a polymorphic function.

```
let f (type t) () =
  let module M = struct exception E of t end in
  (fun x -> M.E x), (function M.E x -> Some x | _ -> None)
```

Here is another example:

```
let sort_uniq (type s) (cmp : s -> s -> int) =
  let module S = Set.Make(struct type t = s let compare = cmp end) in
  fun l ->
    S.elements (List.fold_right S.add l S.empty)
```

It is also extremely useful for first-class modules (see section 7.10) and generalized algebraic datatypes (GADTs: see section 7.16).

Polymorphic syntax (Introduced in OCaml 4.00)

let-binding ::= ...
| *value-name* `:` `type` {*typeconstr-name*}$^+$ `.` *typexpr* `=` *expr*

class-field ::= ...
| `method` [`private`] *method-name* `:` `type` {*typeconstr-name*}$^+$ `.` *typexpr* `=` *expr*
| `method!` [`private`] *method-name* `:` `type` {*typeconstr-name*}$^+$ `.` *typexpr* `=` *expr*

The `(type` *typeconstr-name* `)` syntax construction by itself does not make polymorphic the type variable it introduces, but it can be combined with explicit polymorphic annotations where needed. The above rule is provided as syntactic sugar to make this easier:

```
let rec f : type t1 t2. t1 * t2 list -> t1 = ...
```

is automatically expanded into

```
let rec f : 't1 't2. 't1 * 't2 list -> 't1 =
  fun (type t1) (type t2) -> (... : t1 * t2 list -> t1)
```

This syntax can be very useful when defining recursive functions involving GADTs, see the section 7.16 for a more detailed explanation.

The same feature is provided for method definitions. The `method!` form combines this extension with the "explicit overriding" extension described in section 7.14.

7.10 First-class modules

(Introduced in OCaml 3.12; pattern syntax and package type inference introduced in 4.00; structural comparison of package types introduced in 4.02.)

typexpr	::=	...
	|	`(` `module` *package-type* `)`
module-expr	::=	...
	|	`(` `val` *expr* [`:` *package-type*] `)`
expr	::=	...
	|	`(` `module` *module-expr* [`:` *package-type*] `)`
pattern	::=	...
	|	`(` `module` *module-name* [`:` *package-type*] `)`
package-type	::=	*modtype-path*
	|	*modtype-path* `with` *package-constraint* {`and` *package-constraint*}
package-constraint	::=	`type` *typeconstr* `=` *typexpr*

Modules are typically thought of as static components. This extension makes it possible to pack a module as a first-class value, which can later be dynamically unpacked into a module.

The expression `(` `module` *module-expr* `:` *package-type* `)` converts the module (structure or functor) denoted by module expression *module-expr* to a value of the core language that encapsulates this module. The type of this core language value is `(` `module` *package-type* `)`. The *package-type* annotation can be omitted if it can be inferred from the context.

Conversely, the module expression `(` `val` *expr* `:` *package-type* `)` evaluates the core language expression *expr* to a value, which must have type `module` *package-type*, and extracts the module that was encapsulated in this value. Again *package-type* can be omitted if the type of *expr* is known.

The pattern `(` `module` *module-name* `:` *package-type* `)` matches a package with type *package-type* and binds it to *module-name*. It is not allowed in toplevel let bindings. Again *package-type* can be omitted if it can be inferred from the enclosing pattern.

The *package-type* syntactic class appearing in the `(` `module` *package-type* `)` type expression and in the annotated forms represents a subset of module types. This subset consists of named module types with optional constraints of a limited form: only non-parametrized types can be specified.

For type-checking purposes (and starting from OCaml 4.02), package types are compared using the structural comparison of module types.

In general, the module expression `(` `val` *expr* `:` *package-type* `)` cannot be used in the body of a functor, because this could cause unsoundness in conjunction with applicative functors. Since OCaml 4.02, this is relaxed in two ways: if *package-type* does not contain nominal type declarations (*i.e.* types that are created with a proper identity), then this expression can be used anywhere, and even if it contains such types it can be used inside the body of a generative functor, described in section 7.23. It can also be used anywhere in the context of a local module binding `let module` *module-name* `=` `(` `val` $expr_1$ `:` *package-type* `)` `in` $expr_2$.

Basic example A typical use of first-class modules is to select at run-time among several implementations of a signature. Each implementation is a structure that we can encapsulate as a first-class module, then store in a data structure such as a hash table:

```
module type DEVICE = sig ... end
let devices : (string, (module DEVICE)) Hashtbl.t = Hashtbl.create 17

module SVG = struct ... end
let _ = Hashtbl.add devices "SVG" (module SVG : DEVICE)

module PDF = struct ... end
let _ = Hashtbl.add devices "PDF" (module PDF: DEVICE)
```

We can then select one implementation based on command-line arguments, for instance:

```
module Device =
  (val (try Hashtbl.find devices (parse_cmdline())
        with Not_found -> eprintf "Unknown device %s\n"; exit 2)
   : DEVICE)
```

Alternatively, the selection can be performed within a function:

```
let draw_using_device device_name picture =
  let module Device =
    (val (Hashtbl.find_devices device_name) : DEVICE)
  in
    Device.draw picture
```

Advanced examples With first-class modules, it is possible to parametrize some code over the implementation of a module without using a functor.

```
let sort (type s) (module Set : Set.S with type elt = s) l =
  Set.elements (List.fold_right Set.add l Set.empty)
val sort : (module Set.S with type elt = 'a) -> 'a list -> 'a list
```

To use this function, one can wrap the `Set.Make` functor:

```
let make_set (type s) cmp =
  let module S = Set.Make(struct
    type t = s
    let compare = cmp
  end) in
  (module S : Set.S with type elt = s)
val make_set : ('a -> 'a -> int) -> (module Set.S with type elt = 'a)
```

7.11 Recovering the type of a module

(Introduced in OCaml 3.12)

module-type ::= ...
| `module type of` *module-expr*

The construction `module type of` *module-expr* expands to the module type (signature or functor type) inferred for the module expression *module-expr*. To make this module type reusable in many situations, it is intentionally not strengthened: abstract types and datatypes are not explicitly related with the types of the original module. For the same reason, module aliases in the inferred type are expanded.

A typical use, in conjunction with the signature-level `include` construct, is to extend the signature of an existing structure. In that case, one wants to keep the types equal to types in the original module. This can done using the following idiom.

```
module type MYHASH = sig
  include module type of struct include Hashtbl end
  val replace: ('a, 'b) t -> 'a -> 'b -> unit
end
```

The signature `MYHASH` then contains all the fields of the signature of the module `Hashtbl` (with strengthened type definitions), plus the new field `replace`. An implementation of this signature can be obtained easily by using the `include` construct again, but this time at the structure level:

```
module MyHash : MYHASH = struct
  include Hashtbl
  let replace t k v = remove t k; add t k v
end
```

Another application where the absence of strengthening comes handy, is to provide an alternative implementation for an existing module.

```
module MySet : module type of Set = struct
  ...
end
```

This idiom guarantees that `Myset` is compatible with Set, but allows it to represent sets internally in a different way.

7.12 Substituting inside a signature

(Introduced in OCaml 3.12)

mod-constraint ::= ...
| `type` [*type-params*] *typeconstr-name* `:=` *typexpr*
| `module` *module-name* `:=` *extended-module-path*

"Destructive" substitution (`with... :=...`) behaves essentially like normal signature constraints (`with... =...`), but it additionally removes the redefined type or module from the signature. There are a number of restrictions: one can only remove types and modules at the outermost level (not inside submodules), and in the case of `with␣type` the definition must be another type constructor with the same type parameters.

A natural application of destructive substitution is merging two signatures sharing a type name.

```
module type Printable = sig
  type t
  val print : Format.formatter -> t -> unit
end
module type Comparable = sig
  type t
  val compare : t -> t -> int
end
module type PrintableComparable = sig
  include Printable
  include Comparable with type t := t
end
```

One can also use this to completely remove a field:

```
# module type S = Comparable with type t := int;;
module type S = sig val compare : int -> int -> int end
```

or to rename one:

```
# module type S = sig
#   type u
#   include Comparable with type t := u
# end;;
module type S = sig type u val compare : u -> u -> int end
```

Note that you can also remove manifest types, by substituting with the same type.

```
# module type ComparableInt = Comparable with type t = int ;;
module type ComparableInt = sig type t = int val compare : t -> t -> int end
# module type CompareInt = ComparableInt with type t := int ;;
module type CompareInt = sig val compare : int -> int -> int end
```

7.13 Type-level module aliases

(Introduced in OCaml 4.02)

specification ::= ...
| `module` *module-name* `=` *module-path*

The above specification, inside a signature, only matches a module definition equal to *module-path*. Conversely, a type-level module alias can be matched by itself, or by any supertype of the type of the module it references.

There are several restrictions on *module-path*:

1. it should be of the form $M_0.M_1...M_n$ (*i.e.* without functor applications);
2. inside the body of a functor, M_0 should not be one of the functor parameters;
3. inside a recursive module definition, M_0 should not be one of the recursively defined modules.

Such specifications are also inferred. Namely, when P is a path satisfying the above constraints,

```
# module N = P
```

has type

```
module N = P
```

Type-level module aliases are used when checking module path equalities. That is, in a context where module name N is known to be an alias for P, not only these two module paths check as equal, but $F\ (N)$ and $F\ (P)$ are also recognized as equal. In the default compilation mode, this is the only difference with the previous approach of module aliases having just the same module type as the module they reference.

When the compiler flag `-no-alias-deps` is enabled, type-level module aliases are also exploited to avoid introducing dependencies between compilation units. Namely, a module alias referring to a module inside another compilation unit does not introduce a link-time dependency on that compilation unit, as long as it is not dereferenced; it still introduces a compile-time dependency if the interface needs to be read, *i.e.* if the module is a submodule of the compilation unit, or if some type components are referred to. Additionally, accessing a module alias introduces a link-time dependency on the compilation unit containing the module referenced by the alias, rather than the compilation unit containing the alias. Note that these differences in link-time behavior may be incompatible with the previous behavior, as some compilation units might not be extracted from libraries, and their side-effects ignored.

These weakened dependencies make possible to use module aliases in place of the `-pack` mechanism. Suppose that you have a library `Mylib` composed of modules `A` and `B`. Using `-pack`, one would issue the command line

```
ocamlc -pack a.cmo b.cmo -o mylib.cmo
```

and as a result obtain a `Mylib` compilation unit, containing physically `A` and `B` as submodules, and with no dependencies on their respective compilation units. Here is a concrete example of a possible alternative approach:

1. Rename the files containing `A` and `B` to `Mylib_A` and `Mylib_B`.
2. Create a packing interface `Mylib.ml`, containing the following lines.

```
module A = Mylib_A
module B = Mylib_B
```

3. Compile `Mylib.ml` using `-no-alias-deps`, and the other files using `-no-alias-deps` and `-open Mylib` (the last one is equivalent to adding the line `open! Mylib` at the top of each file).

```
ocamlc -c -no-alias-deps Mylib.ml
ocamlc -c -no-alias-deps -open Mylib Mylib_*.mli Mylib_*.ml
```

4. Finally, create a library containing all the compilation units, and export all the compiled interfaces.

```
ocamlc -a Mylib*.cmo -o Mylib.cma
```

This approach lets you access `A` and `B` directly inside the library, and as `Mylib.A` and `Mylib.B` from outside. It also has the advantage that `Mylib` is no longer monolithic: if you use `Mylib.A`, only `Mylib_A` will be linked in, not `Mylib_B`.

7.14 Explicit overriding in class definitions

(Introduced in OCaml 3.12)

class-field ::= ...
| `inherit!` *class-expr* [`as` *lowercase-ident*]
| `val!` [`mutable`] *inst-var-name* [`:` *typexpr*] `=` *expr*
| `method!` [`private`] *method-name* {*parameter*} [`:` *typexpr*] `=` *expr*
| `method!` [`private`] *method-name* `:` *poly-typexpr* `=` *expr*

The keywords `inherit!`, `val!` and `method!` have the same semantics as `inherit`, `val` and `method`, but they additionally require the definition they introduce to be an overriding. Namely, `method!` requires *method-name* to be already defined in this class, `val!` requires *inst-var-name* to be already defined in this class, and `inherit!` requires *class-expr* to override some definitions. If no such overriding occurs, an error is signaled.

As a side-effect, these 3 keywords avoid the warnings 7 (method override) and 13 (instance variable override). Note that warning 7 is disabled by default.

7.15 Overriding in open statements

(Introduced in OCaml 4.01)

definition ::= ...
| `open!` *module-path*

specification ::= ...
| `open!` *module-path*

expr ::= ...
| `let open!` *module-path* `in` *expr*

Since OCaml 4.01, `open` statements shadowing an existing identifier (which is later used) trigger the warning 44. Adding a `!` character after the `open` keyword indicates that such a shadowing is intentional and should not trigger the warning.

7.16 Generalized algebraic datatypes

(Introduced in OCaml 4.00)

constr-decl ::= ...
| *constr-name* `:` [*constr-args* `->`] *typexpr*

type-param ::= ...
| [*variance*] `_`

Generalized algebraic datatypes, or GADTs, extend usual sum types in two ways: constraints on type parameters may change depending on the value constructor, and some type variables may be existentially quantified. Adding constraints is done by giving an explicit return type (the rightmost *typexpr* in the above syntax), where type parameters are instantiated. This return type must use the same type constructor as the type being defined, and have the same number of parameters. Variables are made existential when they appear inside a constructor's argument, but not in its return type.

Since the use of a return type often eliminates the need to name type parameters in the left-hand side of a type definition, one can replace them with anonymous types `_` in that case.

The constraints associated to each constructor can be recovered through pattern-matching. Namely, if the type of the scrutinee of a pattern-matching contains a locally abstract type, this type can be refined according to the constructor used. These extra constraints are only valid inside the corresponding branch of the pattern-matching. If a constructor has some existential variables, fresh locally abstract types are generated, and they must not escape the scope of this branch.

Recursive functions

Here is a concrete example:

```
type _ term =
  | Int : int -> int term
  | Add : (int -> int -> int) term
  | App : ('b -> 'a) term * 'b term -> 'a term

let rec eval : type a. a term -> a = function
  | Int n    -> n                 (* a = int *)
  | Add      -> (fun x y -> x+y)  (* a = int -> int -> int *)
  | App(f,x) -> (eval f) (eval x)
          (* eval called at types (b->a) and b for fresh b *)

let two = eval (App (App (Add, Int 1), Int 1))
val two : int = 2
```

It is important to remark that the function `eval` is using the polymorphic syntax for locally abstract types. When defining a recursive function that manipulates a GADT, explicit polymorphic recursion should generally be used. For instance, the following definition fails with a type error:

```
        let rec eval (type a) : a term -> a = function
          | Int n    -> n
          | Add      -> (fun x y -> x+y)
          | App(f,x) -> (eval f) (eval x)
(*                             ^
   Error: This expression has type ($App_'b -> a) term but an expression was
   expected of type 'a
   The type constructor $App_'b would escape its scope
*)
```

In absence of an explicit polymorphic annotation, a monomorphic type is inferred for the recursive function. If a recursive call occurs inside the function definition at a type that involves an existential GADT type variable, this variable flows to the type of the recursive function, and thus escapes its scope. In the above example, this happens in the branch `App(f,x)` when `eval` is called with `f` as an argument. In this branch, the type of `f` is `($App_ 'b-> a)`. The prefix `$` in `$App_ 'b` denotes an existential type named by the compiler (see 7.16). Since the type of `eval` is `'a term -> 'a`, the call `eval f` makes the existential type `$App_'b` flow to the type variable `'a` and escape its scope. This triggers the above error.

Type inference

Type inference for GADTs is notoriously hard. This is due to the fact some types may become ambiguous when escaping from a branch. For instance, in the `Int` case above, `n` could have either type `int` or `a`, and they are not equivalent outside of that branch. As a first approximation, type inference will always work if a pattern-matching is annotated with types containing no free type variables (both on the scrutinee and the return type). This is the case in the above example, thanks to the type annotation containing only locally abstract types.

In practice, type inference is a bit more clever than that: type annotations do not need to be immediately on the pattern-matching, and the types do not have to be always closed. As a result, it is usually enough to only annotate functions, as in the example above. Type annotations are propagated in two ways: for the scrutinee, they follow the flow of type inference, in a way similar to polymorphic methods; for the return type, they follow the structure of the program, they are split on functions, propagated to all branches of a pattern matching, and go through tuples, records, and sum types. Moreover, the notion of ambiguity used is stronger: a type is only seen as ambiguous if it was mixed with incompatible types (equated by constraints), without type annotations between them. For instance, the following program types correctly.

```
        let rec sum : type a. a term -> _ = fun x ->
          let y =
            match x with
            | Int n -> n
            | Add   -> 0
            | App(f,x) -> sum f + sum x
```

```
  in y + 1
val sum : 'a term -> int = <fun>
```

Here the return type `int` is never mixed with `a`, so it is seen as non-ambiguous, and can be inferred. When using such partial type annotations we strongly suggest specifying the `-principal` mode, to check that inference is principal.

The exhaustiveness check is aware of GADT constraints, and can automatically infer that some cases cannot happen. For instance, the following pattern matching is correctly seen as exhaustive (the `Add` case cannot happen).

```
let get_int : int term -> int = function
  | Int n    -> n
  | App(_,_) -> 0
```

Refutation cases and redundancy (Introduced in OCaml 4.03)

Usually, the exhaustiveness check only tries to check whether the cases omitted from the pattern matching are typable or not. However, you can force it to try harder by adding *refutation cases*:

matching-case ::= *pattern* [`when` *expr*] `->` *expr*
| *pattern* `->` `.`

In presence of a refutation case, the exhaustiveness check will first compute the intersection of the pattern with the complement of the cases preceding it. It then checks whether the resulting patterns can really match any concrete values by trying to type-check them. Wild cards in the generated patterns are handled in a special way: if their type is a variant type with only GADT constructors, then the pattern is split into the different constructors, in order to check whether any of them is possible (this splitting is not done for arguments of these constructors, to avoid non-termination.) We also split tuples and variant types with only one case, since they may contain GADTs inside. For instance, the following code is deemed exhaustive:

```
type _ t =
  | Int : int t
  | Bool : bool t

let deep : (char t * int) option -> char = function
  | None -> 'c'
  | _ -> .
```

Namely, the inferred remaining case is `Some _`, which is split into `Some (Int, _)` and `Some (Bool, _)`, which are both untypable. Note that the refutation case could be omitted here, because it is automatically added when there is only one case in the pattern matching.

Another addition is that the redundancy check is now aware of GADTs: a case will be detected as redundant if it could be replaced by a refutation case using the same pattern.

Advanced examples The `term` type we have defined above is an *indexed* type, where a type parameter reflects a property of the value contents. Another use of GADTs is *singleton* types, where a GADT value represents exactly one type. This value can be used as runtime representation for this type, and a function receiving it can have a polytypic behavior.

Here is an example of a polymorphic function that takes the runtime representation of some type `t` and a value of the same type, then pretty-prints the value as a string:

```
type _ typ =
  | Int : int typ
  | String : string typ
  | Pair : 'a typ * 'b typ -> ('a * 'b) typ

let rec to_string: type t. t typ -> t -> string =
  fun t x ->
  match t with
  | Int -> string_of_int x
  | String -> Printf.sprintf "%S" x
  | Pair(t1,t2) ->
      let (x1, x2) = x in
      Printf.sprintf "(%s,%s)" (to_string t1 x1) (to_string t2 x2)
```

Another frequent application of GADTs is equality witnesses.

```
type (_,_) eq = Eq : ('a,'a) eq

let cast : type a b. (a,b) eq -> a -> b = fun Eq x -> x
```

Here type `eq` has only one constructor, and by matching on it one adds a local constraint allowing the conversion between `a` and `b`. By building such equality witnesses, one can make equal types which are syntactically different.

Here is an example using both singleton types and equality witnesses to implement dynamic types.

```
let rec eq_type : type a b. a typ -> b typ -> (a,b) eq option =
  fun a b ->
  match a, b with
  | Int, Int -> Some Eq
  | String, String -> Some Eq
  | Pair(a1,a2), Pair(b1,b2) ->
      begin match eq_type a1 b1, eq_type a2 b2 with
      | Some Eq, Some Eq -> Some Eq
      | _ -> None
      end
  | _ -> None

type dyn = Dyn : 'a typ * 'a -> dyn
```

```
let get_dyn : type a. a typ -> dyn -> a option =
  fun a (Dyn(b,x)) ->
  match eq_type a b with
  | None -> None
  | Some Eq -> Some x
```

Existential type names in error messages (Updated in OCaml 4.03.0)

The typing of pattern matching in presence of GADT can generate many existential types. When necessary, error messages refer to these existential types using compiler-generated names. Currently, the compiler generates these names according to the following nomenclature:

- First, types whose name starts with a `$` are existentials.
- `$Constr_'a` denotes an existential type introduced for the type variable `'a` of the GADT constructor `Constr`:

```
#    type any = Any : 'name -> any
#    let escape (Any x) = x;;
 Error: This expression has type $Any_'name
        but an expression was expected of type 'a
        The type constructor $Any_'name would escape its scope
```

- `$Constr` denotes an existential type introduced for an anonymous type variable in the GADT constructor `Constr`:

```
#  type any = Any : _ -> any
#  let escape (Any x) = x;;
 Error: This expression has type $Any but an expression was expected of type
        'a
        The type constructor $Any would escape its scope
```

- `$'a` if the existential variable was unified with the type variable `'a` during typing:

```
#  type ('arg,'result,'aux) fn =
#   | Fun: ('a ->'b) -> ('a,'b,unit) fn
#   | Mem1: ('a ->'b) * 'a * 'b -> ('a, 'b, 'a * 'b) fn
#  let apply: ('arg,'result, _ ) fn -> 'arg -> 'result = fun f x ->
#   match f with
#   | Fun f -> f x
#   | Mem1 (f,y,fy) -> if x = y then fy else f x;;
 Error: This pattern matches values of type
         ($'arg, $'result, $'arg * $'result) fn
        but a pattern was expected which matches values of type
         ($'arg, $'result, unit) fn
        Type $'arg * $'result is not compatible with type unit
```

- `$n` (n a number) is an internally generated existential which could not be named using one of the previous schemes.

As shown by the last item, the current behavior is imperfect and may be improved in future versions.

Equations on non-local abstract types (Introduced in OCaml 4.04)

GADT pattern-matching may also add type equations to non-local abstract types. The behaviour is the same as with local abstract types. Reusing the above `eq` type, one can write:

```
module M : sig type t val x : t val e : (x,int) eq end = struct
  type t = int
  let x = 33
  let e = Eq
end

let x : int = let Eq = M.e in M.x
```

Of course, not all abstract types can be refined, as this would contradict the exhaustiveness check. Namely, builtin types (those defined by the compiler itself, such as `int` or `array`), and abstract types defined by the local module, are non-instantiable, and as such cause a type error rather than introduce an equation.

7.17 Syntax for Bigarray access

(Introduced in Objective Caml 3.00)

$$
\begin{array}{rcl}
expr & ::= & \ldots \\
& | & expr\ \texttt{.\{}\ expr\ \{\texttt{,}\ expr\}\ \texttt{\}} \\
& | & expr\ \texttt{.\{}\ expr\ \{\texttt{,}\ expr\}\ \texttt{\}}\ \texttt{<-}\ expr
\end{array}
$$

This extension provides syntactic sugar for getting and setting elements in the arrays provided by the `Bigarray`[29.1] library.

The short expressions are translated into calls to functions of the `Bigarray` module as described in the following table.

expression	translation
$expr_0$ `.{` $expr_1$ `}`	`Bigarray.Array1.get` $expr_0$ $expr_1$
$expr_0$ `.{` $expr_1$ `}` `<-` $expr$	`Bigarray.Array1.set` $expr_0$ $expr_1$ $expr$
$expr_0$ `.{` $expr_1$ `,` $expr_2$ `}`	`Bigarray.Array2.get` $expr_0$ $expr_1$ $expr_2$
$expr_0$ `.{` $expr_1$ `,` $expr_2$ `}` `<-` $expr$	`Bigarray.Array2.set` $expr_0$ $expr_1$ $expr_2$ $expr$
$expr_0$ `.{` $expr_1$ `,` $expr_2$ `,` $expr_3$ `}`	`Bigarray.Array3.get` $expr_0$ $expr_1$ $expr_2$ $expr_3$
$expr_0$ `.{` $expr_1$ `,` $expr_2$ `,` $expr_3$ `}` `<-` $expr$	`Bigarray.Array3.set` $expr_0$ $expr_1$ $expr_2$ $expr_3$ $expr$
$expr_0$ `.{` $expr_1$ `,` ... `,` $expr_n$ `}`	`Bigarray.Genarray.get` $expr_0$ `[|` $expr_1$ `,` ... `,` $expr_n$ `|]`
$expr_0$ `.{` $expr_1$ `,` ... `,` $expr_n$ `}` `<-` $expr$	`Bigarray.Genarray.set` $expr_0$ `[|` $expr_1$ `,` ... `,` $expr_n$ `|]` $expr$

The last two entries are valid for any $n > 3$.

7.18 Attributes

(Introduced in OCaml 4.02, infix notations for constructs other than expressions added in 4.03)

Attributes are "decorations" of the syntax tree which are mostly ignored by the type-checker but can be used by external tools. An attribute is made of an identifier and a payload, which can be a structure, a type expression (prefixed with `:`), a signature (prefixed with `:`) or a pattern (prefixed with `?`) optionally followed by a `when` clause:

attr-id	::=	*lowercase-ident*
	|	*capitalized-ident*
	|	*attr-id* `.` *attr-id*
attr-payload	::=	[*module-items*]
	|	`:` *typexpr*
	|	`:` [*specification*]
	|	`?` *pattern* [`when` *expr*]

The first form of attributes is attached with a postfix notation on "algebraic" categories:

attribute	::=	`[@` *attr-id attr-payload* `]`
expr	::=	...
	|	*expr attribute*
typexpr	::=	...
	|	*typexpr attribute*
pattern	::=	...
	|	*pattern attribute*
module-expr	::=	...
	|	*module-expr attribute*
module-type	::=	...
	|	*module-type attribute*
class-expr	::=	...
	|	*class-expr attribute*
class-type	::=	...
	|	*class-type attribute*

This form of attributes can also be inserted after the `` ` `` *tag-name* in polymorphic variant type expressions (*tag-spec-first*, *tag-spec*, *tag-spec-full*) or after the *method-name* in *method-type*.

The same syntactic form is also used to attach attributes to labels and constructors in type declarations:

field-decl	::=	[`mutable`] *field-name* `:` *poly-typexpr* {*attribute*}
constr-decl	::=	(*constr-name* | `()`) [`of` *constr-args*] {*attribute*}

Note: when a label declaration is followed by a semi-colon, attributes can also be put after the semi-colon (in which case they are merged to those specified before).

The second form of attributes are attached to "blocks" such as type declarations, class fields, etc:

item-attribute ::= `[@@` *attr-id attr-payload* `]`

typedef ::= ...
| *typedef item-attribute*

exception-definition ::= `exception` *constr-decl*
| `exception` *constr-name* `=` *constr*

module-items ::= [`;;`] (*definition* | *expr* {*item-attribute*}) {[`;;`] *definition* | `;;` *expr* {*item-attribute*}} [`;`

class-binding ::= ...
| *class-binding item-attribute*

class-spec ::= ...
| *class-spec item-attribute*

classtype-def ::= ...
| *classtype-def item-attribute*

definition ::= `let` [`rec`] *let-binding* {`and` *let-binding*}
| `external` *value-name* `:` *typexpr* `=` *external-declaration* {*item-attribute*}
| *type-definition*
| *exception-definition* {*item-attribute*}
| *class-definition*
| *classtype-definition*
| `module` *module-name* {`(` *module-name* `:` *module-type* `)`} [`:` *module-type*]
`=` *module-expr* {*item-attribute*}
| `module type` *modtype-name* `=` *module-type* {*item-attribute*}
| `open` *module-path* {*item-attribute*}
| `include` *module-expr* {*item-attribute*}
| `module rec` *module-name* `:` *module-type* `=`
module-expr {*item-attribute*}
{`and` *module-name* `:` *module-type* `=` *module-expr*
{*item-attribute*}}

specification ::= `val` *value-name* `:` *typexpr* {*item-attribute*}
| `external` *value-name* `:` *typexpr* `=` *external-declaration* {*item-attribute*}
| *type-definition*
| `exception` *constr-decl* {*item-attribute*}
| *class-specification*
| *classtype-definition*
| `module` *module-name* `:` *module-type* {*item-attribute*}
| `module` *module-name* {`(` *module-name* `:` *module-type* `)`} `:` *module-type* {*item-attribu*
| `module type` *modtype-name* {*item-attribute*}
| `module type` *modtype-name* `=` *module-type* {*item-attribute*}
| `open` *module-path* {*item-attribute*}
| `include` *module-type* {*item-attribute*}

class-field-spec ::= ...
| *class-field-spec item-attribute*

class-field ::= ...
| *class-field item-attribute*

A third form of attributes appears as stand-alone structure or signature items in the module or class sub-languages. They are not attached to any specific node in the syntax tree:

floating-attribute	::=	`[@@@` *attr-id attr-payload* `]`
definition	::=	...
	|	*floating-attribute*
specification	::=	...
	|	*floating-attribute*
class-field-spec	::=	...
	|	*floating-attribute*
class-field	::=	...
	|	*floating-attribute*

(Note: contrary to what the grammar above describes, *item-attributes* cannot be attached to these floating attributes in *class-field-spec* and *class-field*.)

It is also possible to specify attributes using an infix syntax. For instance:

```
let[@foo] x = 2 in x + 1          === (let x = 2 [@@foo] in x + 1)
begin[@foo][@bar x] ... end       === (begin ... end)[@foo][@@bar x]
module[@foo] M = ...              === module M = ... [@@foo]
type[@foo] t = T                  === type t = T [@@foo]
method[@foo] m = ...              === method m = ... [@@foo]
```

For `let`, the attributes are applied to each bindings:

```
let[@foo] x = 2 and y = 3 in x + y === (let x = 2 [@@foo] and y = 3 in x + y)
let[@foo] x = 2
and[@bar] y = 3 in x + y           === (let x = 2 [@@foo] and y = 3 [@bar] in x + y)
```

7.18.1 Built-in attributes

Some attributes are understood by the type-checker:

- "ocaml.warning" or "warning", with a string literal payload. This can be used as floating attributes in a signature/structure/object/object type. The string is parsed and has the same effect as the `-w` command-line option, in the scope between the attribute and the end of the current signature/structure/object/object type. The attribute can also be used on an expression, in which case its scope is limited to that expression. Note that it is not well-defined which scope is used for a specific warning. This is implementation dependant and can change between versions. For instance, warnings triggered by the "ppwarning" attribute (see below) are issued using the global warning configuration.
- "ocaml.warnerror" or "warnerror", with a string literal payload. Same as "ocaml.warning", for the `-warn-error` command-line option.

- "ocaml.deprecated" or "deprecated". Can be applied to most kind of items in signatures or structures. When the element is later referenced, a warning (3) is triggered. If the payload of the attribute is a string literal, the warning message includes this text. It is also possible to use this "ocaml.deprecated" as a floating attribute on top of an ".mli" file (i.e. before any other non-attribute item) or on top of an ".ml" file without a corresponding interface; this marks the unit itself as being deprecated.

- "ocaml.deprecated_mutable" or "deprecated_mutable". Can be applied to a mutable record label. If the label is later used to modify the field (with "expr.l ¡- expr"), a warning (3) will be triggered. If the payload of the attribute is a string literal, the warning message includes this text.

- "ocaml.ppwarning" or "ppwarning", in any context, with a string literal payload. The text is reported as warning (22) by the compiler (currently, the warning location is the location of the string payload). This is mostly useful for preprocessors which need to communicate warnings to the user. This could also be used to mark explicitly some code location for further inspection.

- "ocaml.warn_on_literal_pattern" or "warn_on_literal_pattern" annotate constructors in type definition. A warning (52) is then emitted when this constructor is pattern matched with a constant literal as argument. This attribute denotes constructors whose argument is purely informative and may change in the future. Therefore, pattern matching on this argument with a constant literal is unreliable. For instance, all built-in exception constructors are marked as "warn_on_literal_pattern". Note that, due to an implementation limitation, this warning (52) is only triggered for single argument constructor.

- "ocaml.tailcall" or "tailcall" can be applied to function application in order to check that the call is tailcall optimized. If it it not the case, a warning (51) is emitted.

- "ocaml.inline" or "inline" take either "never", "always" or nothing as payload on a function or functor definition. If no payload is provided, the default value is "always". This payload controls when applications of the annotated functions should be inlined.

- "ocaml.inlined" or "inlined" can be applied to any function or functor application to check that the call is inlined by the compiler. If the call is not inlined, a warning (55) is emitted.

- "ocaml.noalloc", "ocaml.unboxed"and "ocaml.untagged" or "noalloc", "unboxed" and "untagged" can be used on external definitions to obtain finer control over the C-to-OCaml interface. See 18.10 for more details.

- "ocaml.immediate" or "immediate" applied on an abstract type mark the type as having a non-pointer implementation (e.g. "int", "bool", "char" or enumerated types). Mutation of these immediate types does not activate the garbage collector's write barrier, which can significantly boost performance in programs relying heavily on mutable state.

- `ocaml.unboxed` or `unboxed` can be used on a type definition if the type is a single-field record or a concrete type with a single constructor that has a single argument. It tells the compiler to optimize the representation of the type by removing the block that represents the record

or the constructor (i.e. a value of this type is physically equal to its argument). In the case of GADTs, an additional restriction applies: the argument must not be an existential variable, represented by an existential type variable, or an abstract type constructor applied to an existential type variable.

- `ocaml.boxed` or `boxed` can be used on type definitions to mean the opposite of `ocaml.unboxed`: keep the unoptimized representation of the type. When there is no annotation, the default is currently `boxed` but it may change in the future.

```
module X = struct
  [@@@warning "+9"]  (* locally enable warning 9 in this structure *)
  ...
end
  [@@deprecated "Please use module 'Y' instead."]

let x = begin[@warning "+9"] ... end in ....

type t = A | B
  [@@deprecated "Please use type 's' instead."]

let f x =
  assert (x >= 0) [@ppwarning "TODO: remove this later"];

let rec no_op = function
  | [] -> ()
  | _ :: q -> (no_op[@tailcall]) q;;

let f x = x [@@inline]

let () = (f[@inlined]) ()

type fragile =
  | Int of int [@warn_on_literal_pattern]
  | String of string [@warn_on_literal_pattern]

let f = function
| Int 0 | String "constant" -> () (* trigger warning 52 *)
| _ -> ()

module Immediate: sig
  type t [@@immediate]
  val x: t ref
end = struct
  type t = A | B
  let x = ref 0
end
```

. . . .

7.19 Extension nodes

(Introduced in OCaml 4.02, infix notations for constructs other than expressions added in 4.03)

Extension nodes are generic placeholders in the syntax tree. They are rejected by the typechecker and are intended to be "expanded" by external tools such as `-ppx` rewriters.

Extension nodes share the same notion of identifier and payload as attributes 7.18.

The first form of extension node is used for "algebraic" categories:

extension	::=	`[%` *attr-id attr-payload* `]`
expr	::=	...
	|	*extension*
typexpr	::=	...
	|	*extension*
pattern	::=	...
	|	*extension*
module-expr	::=	...
	|	*extension*
module-type	::=	...
	|	*extension*
class-expr	::=	...
	|	*extension*
class-type	::=	...
	|	*extension*

A second form of extension node can be used in structures and signatures, both in the module and object languages:

item-extension ::= `[%%` *attr-id attr-payload* `]`

definition ::= ...
| *item-extension*

specification ::= ...
| *item-extension*

class-field-spec ::= ...
| *item-extension*

class-field ::=
| *item-extension*

An infix form is available for extension nodes when the payload is of the same kind (expression with expression, pattern with pattern ...).

Examples:

```
let%foo x = 2 in x + 1     === [%foo let x = 2 in x + 1]
begin%foo ... end          === [%foo begin ... end]
module%foo M = ..          === [%%foo module M = ... ]
val%foo x : t              === [%%foo: val x : t]
```

When this form is used together with the infix syntax for attributes, the attributes are considered to apply to the payload:

```
fun%foo[@bar] x -> x + 1 === [%foo (fun x -> x + 1)[@foo ] ];
```

7.19.1 Built-in extension nodes

(Introduced in OCaml 4.03)

Some extension nodes are understood by the compiler itself:

- "ocaml.extension_constructor" or "extension_constructor" take as payload a constructor from an extensible variant type (see 7.22) and return its extension constructor slot.

```
type t = ..
type t += X of int | Y of string
let x = [%extension_constructor X]
let y = [%extension_constructor Y]

#  x <> y;;
- : bool = true
```

7.20 Quoted strings

(Introduced in OCaml 4.02)

Quoted strings provide a different lexical syntax to write string literals in OCaml code. This can be used to embed pieces of foreign syntax fragments in OCaml code, to be interpret by a `-ppx` filter or just a library.

string-literal	::=	...
	|	`{` *quoted-string-id* `|.....|` *quoted-string-id* `}`
quoted-string-id	::=	{`a`... `z` | `_`}

The opening delimiter has the form `{id|` where `id` is a (possibly empty) sequence of lowercase letters and underscores. The corresponding closing delimiter is `|id}` (with the same identifier). Unlike regular OCaml string literals, quoted strings do not interpret any character in a special way.

Example:

```
String.length {|\"|}          (* returns 2 *)
String.length {foo|\"|foo}    (* returns 2 *)
```

7.21 Exception cases in pattern matching

(Introduced in OCaml 4.02)

A new form of exception patterns is allowed, only as a toplevel pattern under a `match`...`with` pattern-matching (other occurrences are rejected by the type-checker).

pattern	::=	...
	|	`exception` *pattern*

Cases with such a toplevel pattern are called "exception cases", as opposed to regular "value cases". Exception cases are applied when the evaluation of the matched expression raises an exception. The exception value is then matched against all the exception cases and re-raised if none of them accept the exception (as for a `try`...`with` block). Since the bodies of all exception and value cases is outside the scope of the exception handler, they are all considered to be in tail-position: if the `match`...`with` block itself is in tail position in the current function, any function call in tail position in one of the case bodies results in an actual tail call.

It is an error if all cases are exception cases in a given pattern matching.

7.22 Extensible variant types

(Introduced in OCaml 4.02)

type-representation ::= ...
| `= ..`

specification ::= ...
| `type` [*type-params*] *typeconstr type-extension-spec*

definition ::= ...
| `type` [*type-params*] *typeconstr type-extension-def*

type-extension-spec ::= `+=` [`private`] [`|`] *constr-decl* {`|` *constr-decl*}

type-extension-def ::= `+=` [`private`] [`|`] *constr-def* {`|` *constr-def*}

constr-def ::= *constr-decl*
| *constr-name* `=` *constr*

Extensible variant types are variant types which can be extended with new variant constructors. Extensible variant types are defined using `..`. New variant constructors are added using `+=`.

```
type attr = ..

type attr += Str of string

type attr +=
  | Int of int
  | Float of float
```

Pattern matching on an extensible variant type requires a default case to handle unknown variant constructors:

```
let to_string = function
  | Str s -> s
  | Int i -> string_of_int i
  | Float f -> string_of_float f
  | _ -> "?"
```

A preexisting example of an extensible variant type is the built-in `exn` type used for exceptions. Indeed, exception constructors can be declared using the type extension syntax:

```
type exn += Exc of int
```

Extensible variant constructors can be rebound to a different name. This allows exporting variants from another module.

```
type Expr.attr += Str = Expr.Str
```

Extensible variant constructors can be declared `private`. As with regular variants, this prevents them from being constructed directly by constructor application while still allowing them to be destructured in pattern-matching.

7.23 Generative functors

(Introduced in OCaml 4.02)

module-expr ::= ...
| `functor () ->` *module-expr*
| *module-expr* `()`

definition ::= ...
| `module` *module-name* {`(` *module-name* `:` *module-type* `)` | `()`} [`:` *module-type*] `=` *module-expr*

module-type ::= ...
| `functor () ->` *module-type*

specification ::= ...
| `module` *module-name* {`(` *module-name* `:` *module-type* `)` | `()`} `:` *module-type*

A generative functor takes a unit `()` argument. In order to use it, one must necessarily apply it to this unit argument, ensuring that all type components in the result of the functor behave in a generative way, *i.e.* they are different from types obtained by other applications of the same functor. This is equivalent to taking an argument of signature `sig end`, and always applying to `struct end`, but not to some defined module (in the latter case, applying twice to the same module would return identical types).

As a side-effect of this generativity, one is allowed to unpack first-class modules in the body of generative functors.

7.24 Extension-only syntax

(Introduced in OCaml 4.02.2, extended in 4.03)

Some syntactic constructions are accepted during parsing and rejected during type checking. These syntactic constructions can therefore not be used directly in vanilla OCaml. However, `-ppx` rewriters and other external tools can exploit this parser leniency to extend the language with these new syntactic constructions by rewriting them to vanilla constructions.

7.24.1 Extension operators

(Introduced in OCaml 4.02.2)

infix-symbol ::= ...
| `#` {*operator-chars*} `#` {*operator-char* | `#`}

Operator names starting with a `#` character and containing more than one `#` character are reserved for extensions.

7.24.2 Extension literals

(Introduced in OCaml 4.03)

float-literal ::= ...
| [-] (0...9) {0...9 | _} [. {0...9 | _}] [(e | E) [+ | -] (0...9) {0...9 | _}] [g...z | G...Z]
| [-] (0x | 0X) (0...9 | A...F | a...f) {0...9 | A...F | a...f | _}
[. {0...9 | A...F | a...f | _}] [(p | P) [+ | -] (0...9) {0...9 | _}] [g...z | G...Z]

int-literal ::= ...
| [-] (0...9) {0...9 | _} [g...z | G...Z]
| [-] (0x | 0X) (0...9 | A...F | a...f) {0...9 | A...F | a...f | _} [g...z | G...Z]
| [-] (0o | 0O) (0...7) {0...7 | _} [g...z | G...Z]
| [-] (0b | 0B) (0...1) {0...1 | _} [g...z | G...Z]

Int and float literals followed by an one-letter identifier in the range [g.. z | G.. Z] are extension-only literals.

7.25 Inline records

(Introduced in OCaml 4.03)

constr-args ::= ...
| *record-decl*

The arguments of a sum-type constructors can now be defined using the same syntax as records. Mutable and polymorphic fields are allowed. GADT syntax is supported. Attributes can be specified on individual fields.

Syntactically, building or matching constructors with such an inline record argument is similar to working with a unary constructor whose unique argument is a declared record type. A pattern can bind the inline record as a pseudo-value, but the record cannot escape the scope of the binding and can only be used with the dot-notation to extract or modify fields or to build new constructor values.

```
type t =
  | Point of {width: int; mutable x: float; mutable y: float}
  | ...

let v = Point {width = 10; x = 0.; y = 0.}

let scale l = function
  | Point p -> Point {p with x = l * p.x; y = l * p.y}
  | ....

let print = function
```

```
  | Point {x; y; _} -> Printf.printf "%f/%f" x y
  | ....

let reset = function
  | Point p -> p.x <- 0.; p.y <- 0.
  | ...

let invalid = function
  | Point p -> p  (* INVALID *)
  | ...
```

7.26 Local exceptions

(Introduced in OCaml 4.04)

It is possible to define local exceptions in expressions:

expr ::= ...
| `let exception` *constr-decl* `in` *expr*

The syntactic scope of the exception constructor is the inner expression, but nothing prevents exception values created with this constructor from escaping this scope. Two executions of the definition above result in two incompatible exception constructors (as for any exception definition).

7.27 Documentation comments

(Introduced in OCaml 4.03)

Comments which start with `**` are treated specially by the compiler. They are automatically converted during parsing into attributes (see 7.18) to allow tools to process them as documentation.

Such comments can take three forms: *floating comments*, *item comments* and *label comments*. Any comment starting with `**` which does not match one of these forms will cause the compiler to emit warning 50.

Comments which start with `**` are also used by the ocamldoc documentation generator (see 14). The three comment forms recognised by the compiler are a subset of the forms accepted by ocamldoc (see 14.2).

7.27.1 Floating comments

Comments surrounded by blank lines that appear within structures, signatures, classes or class types are converted into *floating-attribute*s. For example:

```
type t = T

(** Now some definitions for [t] *)

let mkT = T
```

will be converted to:

```
type t = T

[@@@ocaml.text " Now some definitions for [t] "]

let mkT = T
```

7.27.2 Item comments

Comments which appear *immediately before* or *immediately after* a structure item, signature item, class item or class type item are converted into *item-attribute*s. Immediately before or immediately after means that there must be no blank lines, `;;`, or other documentation comments between them. For example:

```
type t = T
(** A description of [t] *)
```

or

```
(** A description of [t] *)
type t = T
```

will be converted to:

```
type t = T
[@@ocaml.doc " A description of [t] "]
```

Note that, if a comment appears immediately next to multiple items, as in:

```
type t = T
(** An ambiguous comment *)
type s = S
```

then it will be attached to both items:

```
type t = T
[@@ocaml.doc " An ambiguous comment "]
type s = S
[@@ocaml.doc " An ambiguous comment "]
```

and the compiler will emit warning 50.

7.27.3 Label comments

Comments which appear *immediately after* a labelled argument, record field, variant constructor, object method or polymorphic variant constructor are are converted into *attribute*s. Immediately after means that there must be no blank lines or other documentation comments between them. For example:

```
type t1 = lbl:int (** Labelled argument *) -> unit

type t2 = {
  fld: int; (** Record field *)
  fld2: float;
}

type t3 =
  | Cstr of string (** Variant constructor *)
  | Cstr2 of string

type t4 = < meth: int * int; (** Object method *) >

type t5 = [
  `PCstr (** Polymorphic variant constructor *)
]
```

will be converted to:

```
type t1 = lbl:(int [@ocaml.doc " Labelled argument "]) -> unit

type t2 = {
  fld: int [@ocaml.doc " Record field "];
  fld2: float;
}

type t3 =
  | Cstr of string [@ocaml.doc " Variant constructor "]
  | Cstr2 of string

type t4 = < meth : int * int [@ocaml.doc " Object method "] >

type t5 = [
  `PCstr [@ocaml.doc " Polymorphic variant constructor "]
]
```

Note that label comments take precedence over item comments, so:

```
type t = T of string
(** Attaches to T not t *)
```

will be converted to:

```
type t =  T of string [@ocaml.doc " Attaches to T not t "]
```

whilst:

```
type t = T of string
(** Attaches to T not t *)
(** Attaches to t *)
```

will be converted to:

```
type t =  T of string [@ocaml.doc " Attaches to T not t "]
[@@ocaml.doc " Attaches to t "]
```

In the absence of meaningful comment on the last constructor of a type, an empty comment `(**)` can be used instead:

```
type t = T of string
(**)
(** Attaches to t *)
```

will be converted directly to

```
type t =  T of string
[@@ocaml.doc " Attaches to t "]
```

Part III

The OCaml tools

Chapter 8

Batch compilation (ocamlc)

This chapter describes the OCaml batch compiler `ocamlc`, which compiles OCaml source files to bytecode object files and links these object files to produce standalone bytecode executable files. These executable files are then run by the bytecode interpreter `ocamlrun`.

8.1 Overview of the compiler

The `ocamlc` command has a command-line interface similar to the one of most C compilers. It accepts several types of arguments and processes them sequentially, after all options have been processed:

- Arguments ending in `.mli` are taken to be source files for compilation unit interfaces. Interfaces specify the names exported by compilation units: they declare value names with their types, define public data types, declare abstract data types, and so on. From the file *x*`.mli`, the `ocamlc` compiler produces a compiled interface in the file *x*`.cmi`.
- Arguments ending in `.ml` are taken to be source files for compilation unit implementations. Implementations provide definitions for the names exported by the unit, and also contain expressions to be evaluated for their side-effects. From the file *x*`.ml`, the `ocamlc` compiler produces compiled object bytecode in the file *x*`.cmo`.

  If the interface file *x*`.mli` exists, the implementation *x*`.ml` is checked against the corresponding compiled interface *x*`.cmi`, which is assumed to exist. If no interface *x*`.mli` is provided, the compilation of *x*`.ml` produces a compiled interface file *x*`.cmi` in addition to the compiled object code file *x*`.cmo`. The file *x*`.cmi` produced corresponds to an interface that exports everything that is defined in the implementation *x*`.ml`.
- Arguments ending in `.cmo` are taken to be compiled object bytecode. These files are linked together, along with the object files obtained by compiling `.ml` arguments (if any), and the OCaml standard library, to produce a standalone executable program. The order in which `.cmo` and `.ml` arguments are presented on the command line is relevant: compilation units are initialized in that order at run-time, and it is a link-time error to use a component of a unit before having initialized it. Hence, a given *x*`.cmo` file must come before all `.cmo` files that refer to the unit *x*.

- Arguments ending in `.cma` are taken to be libraries of object bytecode. A library of object bytecode packs in a single file a set of object bytecode files (`.cmo` files). Libraries are built with `ocamlc -a` (see the description of the `-a` option below). The object files contained in the library are linked as regular `.cmo` files (see above), in the order specified when the `.cma` file was built. The only difference is that if an object file contained in a library is not referenced anywhere in the program, then it is not linked in.
- Arguments ending in `.c` are passed to the C compiler, which generates a `.o` object file (`.obj` under Windows). This object file is linked with the program if the `-custom` flag is set (see the description of `-custom` below).
- Arguments ending in `.o` or `.a` (`.obj` or `.lib` under Windows) are assumed to be C object files and libraries. They are passed to the C linker when linking in `-custom` mode (see the description of `-custom` below).
- Arguments ending in `.so` (`.dll` under Windows) are assumed to be C shared libraries (DLLs). During linking, they are searched for external C functions referenced from the OCaml code, and their names are written in the generated bytecode executable. The run-time system `ocamlrun` then loads them dynamically at program start-up time.

The output of the linking phase is a file containing compiled bytecode that can be executed by the OCaml bytecode interpreter: the command named `ocamlrun`. If `a.out` is the name of the file produced by the linking phase, the command

`ocamlrun a.out` arg_1 arg_2 `...` arg_n

executes the compiled code contained in `a.out`, passing it as arguments the character strings arg_1 to arg_n. (See chapter 10 for more details.)

On most systems, the file produced by the linking phase can be run directly, as in:

`./a.out` arg_1 arg_2 `...` arg_n

The produced file has the executable bit set, and it manages to launch the bytecode interpreter by itself.

8.2 Options

The following command-line options are recognized by `ocamlc`. The options `-pack`, `-a`, `-c` and `-output-obj` are mutually exclusive.

`-a` Build a library (`.cma` file) with the object files (`.cmo` files) given on the command line, instead of linking them into an executable file. The name of the library must be set with the `-o` option.

If `-custom`, `-cclib` or `-ccopt` options are passed on the command line, these options are stored in the resulting `.cma` library. Then, linking with this library automatically adds back the `-custom`, `-cclib` and `-ccopt` options as if they had been provided on the command line, unless the `-noautolink` option is given.

`-absname`
: Force error messages to show absolute paths for file names.

`-annot`
: Dump detailed information about the compilation (types, bindings, tail-calls, etc). The information for file *src*`.ml` is put into file *src*`.annot`. In case of a type error, dump all the information inferred by the type-checker before the error. The *src*`.annot` file can be used with the emacs commands given in `emacs/caml-types.el` to display types and other annotations interactively.

`-bin-annot`
: Dump detailed information about the compilation (types, bindings, tail-calls, etc) in binary format. The information for file *src*`.ml` is put into file *src*`.cmt`. In case of a type error, dump all the information inferred by the type-checker before the error. The `*.cmt` files produced by `-bin-annot` contain more information and are much more compact than the files produced by `-annot`.

`-c` Compile only. Suppress the linking phase of the compilation. Source code files are turned into compiled files, but no executable file is produced. This option is useful to compile modules separately.

`-cc` *ccomp*
: Use *ccomp* as the C linker when linking in "custom runtime" mode (see the `-custom` option) and as the C compiler for compiling `.c` source files.

`-cclib -l`*libname*
: Pass the `-l`*libname* option to the C linker when linking in "custom runtime" mode (see the `-custom` option). This causes the given C library to be linked with the program.

`-ccopt` *option*
: Pass the given option to the C compiler and linker. When linking in "custom runtime" mode, for instance, `-ccopt -L`*dir* causes the C linker to search for C libraries in directory *dir*. (See the `-custom` option.)

`-color` *mode*
: Enable or disable colors in compiler messages (especially warnings and errors). The following modes are supported:

  `auto`
  : use heuristics to enable colors only if the output supports them (an ANSI-compatible tty terminal);

  `always`
  : enable colors unconditionally;

  `never`
  : disable color output.

  The default setting is 'auto', and the current heuristic checks that the `TERM` environment variable exists and is not empty or `dumb`, and that `isatty(stderr)` holds.

`-compat-32`
: Check that the generated bytecode executable can run on 32-bit platforms and signal an error if it cannot. This is useful when compiling bytecode on a 64-bit machine.

`-config`
: Print the version number of `ocamlc` and a detailed summary of its configuration, then exit.

`-custom`
: Link in "custom runtime" mode. In the default linking mode, the linker produces bytecode that is intended to be executed with the shared runtime system, `ocamlrun`. In the custom runtime mode, the linker produces an output file that contains both the runtime system and the bytecode for the program. The resulting file is larger, but it can be executed directly, even if the `ocamlrun` command is not installed. Moreover, the "custom runtime" mode enables static linking of OCaml code with user-defined C functions, as described in chapter 18.

  Unix:

  Never use the `strip` command on executables produced by `ocamlc -custom`, this would remove the bytecode part of the executable.

`-dllib -l`*libname*
: Arrange for the C shared library `dll`*libname*`.so` (`dll`*libname*`.dll` under Windows) to be loaded dynamically by the run-time system `ocamlrun` at program start-up time.

`-dllpath` *dir*
: Adds the directory *dir* to the run-time search path for shared C libraries. At link-time, shared libraries are searched in the standard search path (the one corresponding to the `-I` option). The `-dllpath` option simply stores *dir* in the produced executable file, where `ocamlrun` can find it and use it as described in section 10.3.

`-for-pack` *module-path*
: Generate an object file (`.cmo`) that can later be included as a sub-module (with the given access path) of a compilation unit constructed with `-pack`. For instance, `ocamlc -for-pack P -c A.ml` will generate `a.cmo` that can later be used with `ocamlc -pack -o P.cmo a.cmo`. Note: you can still pack a module that was compiled without `-for-pack` but in this case exceptions will be printed with the wrong names.

`-g` Add debugging information while compiling and linking. This option is required in order to be able to debug the program with `ocamldebug` (see chapter 15), and to produce stack backtraces when the program terminates on an uncaught exception (see section 10.2).

`-i` Cause the compiler to print all defined names (with their inferred types or their definitions) when compiling an implementation (`.ml` file). No compiled files (`.cmo` and `.cmi` files) are produced. This can be useful to check the types inferred by the compiler. Also, since the output follows the syntax of interfaces, it can help in writing an explicit interface (`.mli` file) for a file: just redirect the standard output of the compiler to a `.mli` file, and edit that file to remove all declarations of unexported names.

`-I` *directory*
: Add the given directory to the list of directories searched for compiled interface files (`.cmi`), compiled object code files (`.cmo`), libraries (`.cma`), and C libraries specified with `-cclib -lxxx`. By default, the current directory is searched first, then the standard library directory. Directories added with `-I` are searched after the current directory, in the order in which they were given on the command line, but before the standard library directory. See also option `-nostdlib`.

  If the given directory starts with `+`, it is taken relative to the standard library directory. For instance, `-I +labltk` adds the subdirectory `labltk` of the standard library to the search path.

`-impl` *filename*
: Compile the file *filename* as an implementation file, even if its extension is not `.ml`.

`-intf` *filename*
: Compile the file *filename* as an interface file, even if its extension is not `.mli`.

`-intf-suffix` *string*
: Recognize file names ending with *string* as interface files (instead of the default `.mli`).

`-labels`
: Labels are not ignored in types, labels may be used in applications, and labelled parameters can be given in any order. This is the default.

`-linkall`
: Force all modules contained in libraries to be linked in. If this flag is not given, unreferenced modules are not linked in. When building a library (option `-a`), setting the `-linkall` option forces all subsequent links of programs involving that library to link all the modules contained in the library.

`-make-runtime`
: Build a custom runtime system (in the file specified by option `-o`) incorporating the C object files and libraries given on the command line. This custom runtime system can be used later to execute bytecode executables produced with the `ocamlc -use-runtime` *runtime-name* option. See section 18.1.6 for more information.

`-no-alias-deps`
: Do not record dependencies for module aliases. See section 7.13 for more information.

`-no-app-funct`
: Deactivates the applicative behaviour of functors. With this option, each functor application generates new types in its result and applying the same functor twice to the same argument yields two incompatible structures.

`-noassert`
: Do not compile assertion checks. Note that the special form `assert false` is always compiled because it is typed specially. This flag has no effect when linking already-compiled files.

`-noautolink`
: When linking `.cma` libraries, ignore `-custom`, `-cclib` and `-ccopt` options potentially contained in the libraries (if these options were given when building the libraries). This can be useful if a library contains incorrect specifications of C libraries or C options; in this case, during linking, set `-noautolink` and pass the correct C libraries and options on the command line.

`-nolabels`
: Ignore non-optional labels in types. Labels cannot be used in applications, and parameter order becomes strict.

`-nostdlib`
: Do not include the standard library directory in the list of directories searched for compiled interface files (`.cmi`), compiled object code files (`.cmo`), libraries (`.cma`), and C libraries specified with `-cclib -lxxx`. See also option `-I`.

`-o` *exec-file*
: Specify the name of the output file produced by the compiler. The default output name is `a.out` under Unix and `camlprog.exe` under Windows. If the `-a` option is given, specify the name of the library produced. If the `-pack` option is given, specify the name of the packed object file produced. If the `-output-obj` option is given, specify the name of the output file produced. If the `-c` option is given, specify the name of the object file produced for the *next* source file that appears on the command line.

`-open` *Module*
: Opens the given module before processing the interface or implementation files. If several `-open` options are given, they are processed in order, just as if the statements `open!` *Module1*`;;` `... open!` *ModuleN*`;;` were added at the top of each file.

`-output-obj`
: Cause the linker to produce a C object file instead of a bytecode executable file. This is useful to wrap OCaml code as a C library, callable from any C program. See chapter 18, section 18.7.5. The name of the output object file must be set with the `-o` option. This option can also be used to produce a C source file (`.c` extension) or a compiled shared/dynamic library (`.so` extension, `.dll` under Windows).

`-pack`
: Build a bytecode object file (`.cmo` file) and its associated compiled interface (`.cmi`) that combines the object files given on the command line, making them appear as sub-modules of the output `.cmo` file. The name of the output `.cmo` file must be given with the `-o` option. For instance,

```
ocamlc -pack -o p.cmo a.cmo b.cmo c.cmo
```

  generates compiled files `p.cmo` and `p.cmi` describing a compilation unit having three sub-modules `A`, `B` and `C`, corresponding to the contents of the object files `a.cmo`, `b.cmo` and `c.cmo`. These contents can be referenced as `P.A`, `P.B` and `P.C` in the remainder of the program.

`-plugin` *plugin*
: Dynamically load the code of the given *plugin* (a `.cmo`, `.cma` or `.cmxs` file) in the compiler. *plugin* must exist in the same kind of code as the compiler (`ocamlc.byte` must load bytecode plugins, while `ocamlc.opt` must load native code plugins), and extension adaptation is done automatically for `.cma` files (to `.cmxs` files if the compiler is compiled in native code).

`-pp` *command*
: Cause the compiler to call the given *command* as a preprocessor for each source file. The output of *command* is redirected to an intermediate file, which is compiled. If there are no compilation errors, the intermediate file is deleted afterwards.

`-ppx` *command*
: After parsing, pipe the abstract syntax tree through the preprocessor *command*. The module `Ast_mapper`, described in chapter 22.1, implements the external interface of a preprocessor.

`-principal`
: Check information path during type-checking, to make sure that all types are derived in a principal way. When using labelled arguments and/or polymorphic methods, this flag is required to ensure future versions of the compiler will be able to infer types correctly, even if internal algorithms change. All programs accepted in `-principal` mode are also accepted in the default mode with equivalent types, but different binary signatures, and this may slow down type checking; yet it is a good idea to use it once before publishing source code.

`-rectypes`
: Allow arbitrary recursive types during type-checking. By default, only recursive types where the recursion goes through an object type are supported. Note that once you have created an interface using this flag, you must use it again for all dependencies.

`-runtime-variant` *suffix*
: Add the *suffix* string to the name of the runtime library used by the program. Currently, only one such suffix is supported: `d`, and only if the OCaml compiler was configured with option `-with-debug-runtime`. This suffix gives the debug version of the runtime, which is useful for debugging pointer problems in low-level code such as C stubs.

`-safe-string`
: Enforce the separation between types `string` and `bytes`, thereby making strings read-only. This will become the default in a future version of OCaml.

`-short-paths`
: When a type is visible under several module-paths, use the shortest one when printing the type's name in inferred interfaces and error and warning messages. Identifier names starting with an underscore `_` or containing double underscores `__` incur a penalty of +10 when computing their length.

`-strict-sequence`
: Force the left-hand part of each sequence to have type unit.

`-strict-formats`
: Reject invalid formats that were accepted in legacy format implementations. You should use

this flag to detect and fix such invalid formats, as they will be rejected by future OCaml versions.

`-thread`
: Compile or link multithreaded programs, in combination with the system `threads` library described in chapter 26.

`-unboxed-types`
: When a type is unboxable (i.e. a record with a single argument or a concrete datatype with a single constructor of one argument) it will be unboxed unless annotated with `[@@ocaml.boxed]`.

`-no-unboxed-types`
: When a type is unboxable it will be boxed unless annotated with `[@@ocaml.unboxed]`. This is the default.

`-unsafe`
: Turn bound checking off for array and string accesses (the `v.(i)` and `s.[i]` constructs). Programs compiled with `-unsafe` are therefore slightly faster, but unsafe: anything can happen if the program accesses an array or string outside of its bounds.

`-unsafe-string`
: Identify the types `string` and `bytes`, thereby making strings writable. For reasons of backward compatibility, this is the default setting for the moment, but this will change in a future version of OCaml.

`-use-runtime` *runtime-name*
: Generate a bytecode executable file that can be executed on the custom runtime system *runtime-name*, built earlier with `ocamlc -make-runtime` *runtime-name*. See section 18.1.6 for more information.

`-v` Print the version number of the compiler and the location of the standard library directory, then exit.

`-verbose`
: Print all external commands before they are executed, in particular invocations of the C compiler and linker in `-custom` mode. Useful to debug C library problems.

`-vmthread`
: Compile or link multithreaded programs, in combination with the VM-level `threads` library described in chapter 26.

`-version` **or** `-vnum`
: Print the version number of the compiler in short form (e.g. `3.11.0`), then exit.

`-w` *warning-list*
: Enable, disable, or mark as fatal the warnings specified by the argument *warning-list*. Each warning can be *enabled* or *disabled*, and each warning can be *fatal* or *non-fatal*. If a warning is disabled, it isn't displayed and doesn't affect compilation in any way (even if it is fatal).

If a warning is enabled, it is displayed normally by the compiler whenever the source code triggers it. If it is enabled and fatal, the compiler will also stop with an error after displaying it.

The *warning-list* argument is a sequence of warning specifiers, with no separators between them. A warning specifier is one of the following:

`+`*num*
: Enable warning number *num*.

`-`*num*
: Disable warning number *num*.

`@`*num*
: Enable and mark as fatal warning number *num*.

`+`*num1*`..`*num2*
: Enable warnings in the given range.

`-`*num1*`..`*num2*
: Disable warnings in the given range.

`@`*num1*`..`*num2*
: Enable and mark as fatal warnings in the given range.

`+`*letter*
: Enable the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

`-`*letter*
: Disable the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

`@`*letter*
: Enable and mark as fatal the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

uppercase-letter
: Enable the set of warnings corresponding to *uppercase-letter*.

lowercase-letter
: Disable the set of warnings corresponding to *lowercase-letter*.

Warning numbers and letters which are out of the range of warnings that are currently defined are ignored. The warnings are as follows.

1 Suspicious-looking start-of-comment mark.

2 Suspicious-looking end-of-comment mark.

3 Deprecated feature.

4 Fragile pattern matching: matching that will remain complete even if additional constructors are added to one of the variant types matched.

5 Partially applied function: expression whose result has function type and is ignored.

6 Label omitted in function application.

7 Method overridden.

8 Partial match: missing cases in pattern-matching.

9 Missing fields in a record pattern.

10 Expression on the left-hand side of a sequence that doesn't have type `unit` (and that is not a function, see warning number 5).

11 Redundant case in a pattern matching (unused match case).

12 Redundant sub-pattern in a pattern-matching.

13 Instance variable overridden.

14 Illegal backslash escape in a string constant.

15 Private method made public implicitly.

16 Unerasable optional argument.

17 Undeclared virtual method.

18 Non-principal type.

19 Type without principality.

20 Unused function argument.

21 Non-returning statement.

22 Preprocessor warning.

23 Useless record `with` clause.

24 Bad module name: the source file name is not a valid OCaml module name.

26 Suspicious unused variable: unused variable that is bound with `let` or `as`, and doesn't start with an underscore (`_`) character.

27 Innocuous unused variable: unused variable that is not bound with `let` nor `as`, and doesn't start with an underscore (`_`) character.

28 Wildcard pattern given as argument to a constant constructor.

29 Unescaped end-of-line in a string constant (non-portable code).

30 Two labels or constructors of the same name are defined in two mutually recursive types.

31 A module is linked twice in the same executable.

32 Unused value declaration.

33 Unused open statement.

34 Unused type declaration.

35 Unused for-loop index.

36 Unused ancestor variable.

37 Unused constructor.

38 Unused extension constructor.

39 Unused rec flag.

40 Constructor or label name used out of scope.

41 Ambiguous constructor or label name.

42 Disambiguated constructor or label name (compatibility warning).

43 Nonoptional label applied as optional.

44 Open statement shadows an already defined identifier.

45 Open statement shadows an already defined label or constructor.

46 Error in environment variable.

47 Illegal attribute payload.

48 Implicit elimination of optional arguments.

49 Absent cmi file when looking up module alias.

50 Unexpected documentation comment.

51 Warning on non-tail calls if @tailcall present.

52 (see 8.5.1)
Fragile constant pattern.

53 Attribute cannot appear in this context

54 Attribute used more than once on an expression

55 Inlining impossible

56 Unreachable case in a pattern-matching (based on type information).

57 (see 8.5.2)
Ambiguous or-pattern variables under guard

58 Missing cmx file

59 Assignment to non-mutable value

60 Unused module declaration

A all warnings

C warnings 1, 2.

D Alias for warning 3.

E Alias for warning 4.

F Alias for warning 5.

K warnings 32, 33, 34, 35, 36, 37, 38, 39.

L Alias for warning 6.

M Alias for warning 7.

P Alias for warning 8.

R Alias for warning 9.

S Alias for warning 10.

U warnings 11, 12.

V Alias for warning 13.

X warnings 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 30.

Y Alias for warning 26.

Z Alias for warning 27.

Some warnings are described in more detail in section 8.5.

The default setting is `-w +a-4-6-7-9-27-29-32..39-41..42-44-45-48-50`. It is displayed by `ocamlc -help`. Note that warnings 5 and 10 are not always triggered, depending on the internals of the type checker.

`-warn-error` *warning-list*
Mark as fatal the warnings specified in the argument *warning-list*. The compiler will stop with an error when one of these warnings is emitted. The *warning-list* has the same meaning as for the `-w` option: a `+` sign (or an uppercase letter) marks the corresponding warnings as fatal, a `-` sign (or a lowercase letter) turns them back into non-fatal warnings, and a `@` sign both enables and marks as fatal the corresponding warnings.

Note: it is not recommended to use warning sets (i.e. letters) as arguments to `-warn-error` in production code, because this can break your build when future versions of OCaml add some new warnings.

The default setting is `-warn-error -a+31` (only warning 31 is fatal).

`-warn-help`
Show the description of all available warning numbers.

`-where`
Print the location of the standard library, then exit.

`-` *file*
Process *file* as a file name, even if it starts with a dash (`-`) character.

`-help` **or** `--help`
Display a short usage summary and exit.

Contextual control of command-line options

The compiler command line can be modified "from the outside" with the following mechanisms. These are experimental and subject to change. They should be used only for experimental and development work, not in released packages.

`OCAMLPARAM` (environment variable)
Arguments that will be inserted before or after the arguments from the command line.

`ocaml_compiler_internal_params` (file in the stdlib directory)
A mapping of file names to lists of arguments that will be added to the command line (and `OCAMLPARAM`) arguments.

`OCAML_FLEXLINK` (environment variable)
Alternative executable to use on native Windows for `flexlink` instead of the configured value. Primarily used for bootstrapping.

8.3 Modules and the file system

This short section is intended to clarify the relationship between the names of the modules corresponding to compilation units and the names of the files that contain their compiled interface and compiled implementation.

The compiler always derives the module name by taking the capitalized base name of the source file (`.ml` or `.mli` file). That is, it strips the leading directory name, if any, as well as the `.ml` or `.mli` suffix; then, it set the first letter to uppercase, in order to comply with the requirement that module names must be capitalized. For instance, compiling the file `mylib/misc.ml` provides an implementation for the module named `Misc`. Other compilation units may refer to components defined in `mylib/misc.ml` under the names `Misc.`*name*; they can also do `open Misc`, then use unqualified names *name*.

The `.cmi` and `.cmo` files produced by the compiler have the same base name as the source file. Hence, the compiled files always have their base name equal (modulo capitalization of the first letter) to the name of the module they describe (for `.cmi` files) or implement (for `.cmo` files).

When the compiler encounters a reference to a free module identifier `Mod`, it looks in the search path for a file named `Mod.cmi` or `mod.cmi` and loads the compiled interface contained in that file. As a consequence, renaming `.cmi` files is not advised: the name of a `.cmi` file must always correspond to the name of the compilation unit it implements. It is admissible to move them to another directory, if their base name is preserved, and the correct `-I` options are given to the compiler. The compiler will flag an error if it loads a `.cmi` file that has been renamed.

Compiled bytecode files (`.cmo` files), on the other hand, can be freely renamed once created. That's because the linker never attempts to find by itself the `.cmo` file that implements a module with a given name: it relies instead on the user providing the list of `.cmo` files by hand.

8.4 Common errors

This section describes and explains the most frequently encountered error messages.

Cannot find file *filename*

The named file could not be found in the current directory, nor in the directories of the search path. The *filename* is either a compiled interface file (`.cmi` file), or a compiled bytecode file (`.cmo` file). If *filename* has the format *mod*`.cmi`, this means you are trying to compile a file that references identifiers from module *mod*, but you have not yet compiled an interface for module *mod*. Fix: compile *mod*`.mli` or *mod*`.ml` first, to create the compiled interface *mod*`.cmi`.

If *filename* has the format *mod*`.cmo`, this means you are trying to link a bytecode object file that does not exist yet. Fix: compile *mod*`.ml` first.

If your program spans several directories, this error can also appear because you haven't specified the directories to look into. Fix: add the correct `-I` options to the command line.

Corrupted compiled interface *filename*

The compiler produces this error when it tries to read a compiled interface file (`.cmi` file) that has the wrong structure. This means something went wrong when this `.cmi` file was written: the disk was full, the compiler was interrupted in the middle of the file creation, and so on.

This error can also appear if a `.cmi` file is modified after its creation by the compiler. Fix: remove the corrupted `.cmi` file, and rebuild it.

This expression has type t_1, but is used with type t_2
This is by far the most common type error in programs. Type t_1 is the type inferred for the expression (the part of the program that is displayed in the error message), by looking at the expression itself. Type t_2 is the type expected by the context of the expression; it is deduced by looking at how the value of this expression is used in the rest of the program. If the two types t_1 and t_2 are not compatible, then the error above is produced.

In some cases, it is hard to understand why the two types t_1 and t_2 are incompatible. For instance, the compiler can report that "expression of type `foo` cannot be used with type `foo`", and it really seems that the two types `foo` are compatible. This is not always true. Two type constructors can have the same name, but actually represent different types. This can happen if a type constructor is redefined. Example:

```
type foo = A | B
let f = function A -> 0 | B -> 1
type foo = C | D
f C
```

This result in the error message "expression `C` of type `foo` cannot be used with type `foo`".

The type of this expression, *t*, contains type variables that cannot be generalized
Type variables (`'a`, `'b`, ...) in a type t can be in either of two states: generalized (which means that the type t is valid for all possible instantiations of the variables) and not generalized (which means that the type t is valid only for one instantiation of the variables). In a `let` binding `let` *name* `=` *expr*, the type-checker normally generalizes as many type variables as possible in the type of *expr*. However, this leads to unsoundness (a well-typed program can crash) in conjunction with polymorphic mutable data structures. To avoid this, generalization is performed at `let` bindings only if the bound expression *expr* belongs to the class of "syntactic values", which includes constants, identifiers, functions, tuples of syntactic values, etc. In all other cases (for instance, *expr* is a function application), a polymorphic mutable could have been created and generalization is therefore turned off for all variables occurring in contravariant or non-variant branches of the type. For instance, if the type of a non-value is `'a list` the variable is generalizable (`list` is a covariant type constructor), but not in `'a list -> 'a list` (the left branch of `->` is contravariant) or `'a ref` (`ref` is non-variant).

Non-generalized type variables in a type cause no difficulties inside a given structure or compilation unit (the contents of a `.ml` file, or an interactive session), but they cannot be allowed inside signatures nor in compiled interfaces (`.cmi` file), because they could be used inconsistently later. Therefore, the compiler flags an error when a structure or compilation unit defines a value *name* whose type contains non-generalized type variables. There are two ways to fix this error:

- Add a type constraint or a `.mli` file to give a monomorphic type (without type variables) to *name*. For instance, instead of writing

```
let sort_int_list = Sort.list (<)
(* inferred type 'a list -> 'a list, with 'a not generalized *)
```

write

```
let sort_int_list = (Sort.list (<) : int list -> int list);;
```

- If you really need *name* to have a polymorphic type, turn its defining expression into a function by adding an extra parameter. For instance, instead of writing

```
let map_length = List.map Array.length
(* inferred type 'a array list -> int list, with 'a not generalized *)
```

write

```
let map_length lv = List.map Array.length lv
```

Reference to undefined global *mod*

This error appears when trying to link an incomplete or incorrectly ordered set of files. Either you have forgotten to provide an implementation for the compilation unit named *mod* on the command line (typically, the file named *mod*`.cmo`, or a library containing that file). Fix: add the missing `.ml` or `.cmo` file to the command line. Or, you have provided an implementation for the module named *mod*, but it comes too late on the command line: the implementation of *mod* must come before all bytecode object files that reference *mod*. Fix: change the order of `.ml` and `.cmo` files on the command line.

Of course, you will always encounter this error if you have mutually recursive functions across modules. That is, function `Mod1.f` calls function `Mod2.g`, and function `Mod2.g` calls function `Mod1.f`. In this case, no matter what permutations you perform on the command line, the program will be rejected at link-time. Fixes:

- Put `f` and `g` in the same module.
- Parameterize one function by the other. That is, instead of having

```
mod1.ml:    let f x = ... Mod2.g ...
mod2.ml:    let g y = ... Mod1.f ...
```

define

```
mod1.ml:    let f g x = ... g ...
mod2.ml:    let rec g y = ... Mod1.f g ...
```

and link `mod1.cmo` before `mod2.cmo`.

- Use a reference to hold one of the two functions, as in :

```
mod1.ml:    let forward_g =
                ref((fun x -> failwith "forward_g") : <type>)
            let f x = ... !forward_g ...
mod2.ml:    let g y = ... Mod1.f ...
            let _ = Mod1.forward_g := g
```

The external function *f* is not available
: This error appears when trying to link code that calls external functions written in C. As explained in chapter 18, such code must be linked with C libraries that implement the required *f* C function. If the C libraries in question are not shared libraries (DLLs), the code must be linked in "custom runtime" mode. Fix: add the required C libraries to the command line, and possibly the `-custom` option.

8.5 Warning reference

This section describes and explains in detail some warnings:

8.5.1 Warning 52: fragile constant pattern

Some constructors, such as the exception constructors `Failure` and `Invalid_argument`, take as parameter a `string` value holding a text message intended for the user.

These text messages are usually not stable over time: call sites building these constructors may refine the message in a future version to make it more explicit, etc. Therefore, it is dangerous to match over the precise value of the message. For example, until OCaml 4.02, `Array.iter2` would raise the exception

```
Invalid_argument "arrays must have the same length"
```

Since 4.03 it raises the more helpful message

```
Invalid_argument "Array.iter2: arrays must have the same length"
```

but this means that any code of the form

```
try ...
with Invalid_argument "arrays must have the same length" -> ...
```

is now broken and may suffer from uncaught exceptions.

Warning 52 is there to prevent users from writing such fragile code in the first place. It does not occur on every matching on a literal string, but only in the case in which library authors expressed their intent to possibly change the constructor parameter value in the future, by using the attribute `ocaml.warn_on_literal_pattern` (see the manual section on builtin attributes in 7.18.1):

```
type t =
  | Foo of string [@ocaml.warn_on_literal_pattern]
  | Bar of string

let no_warning = function
  | Bar "specific value" -> 0
  | _ -> 1

let warning = function
  | Foo "specific value" -> 0
  | _ -> 1
```

```
>    | Foo "specific value" -> 0
>          ^^^^^^^^^^^^^^^^
> Warning 52: Code should not depend on the actual values of
> this constructor's arguments. They are only for information
> and may change in future versions. (See manual section 8.5)
```

In particular, all built-in exceptions with a string argument have this attribute set: `Invalid_argument`, `Failure`, `Sys_error` will all raise this warning if you match for a specific string argument.

If your code raises this warning, you should *not* change the way you test for the specific string to avoid the warning (for example using a string equality inside the right-hand-side instead of a literal pattern), as your code would remain fragile. You should instead enlarge the scope of the pattern by matching on all possible values.

```
let warning = function
  | Foo _ -> 0
  | _ -> 1
```

This may require some care: if the scrutinee may return several different cases of the same pattern, or raise distinct instances of the same exception, you may need to modify your code to separate those several cases.

For example,

```
try (int_of_string count_str, bool_of_string choice_str) with
  | Failure "int_of_string" -> (0, true)
  | Failure "bool_of_string" -> (-1, false)
```

should be rewritten into more atomic tests. For example, using the `exception` patterns documented in Section 7.21, one can write:

```
match int_of_string count_str with
  | exception (Failure _) -> (0, true)
  | count ->
    begin match bool_of_string choice_str with
    | exception (Failure _) -> (-1, false)
    | choice -> (count, choice)
    end
```

The only case where that transformation is not possible is if a given function call may raises distinct exceptions with the same constructor but different string values. In this case, you will have to check for specific string values. This is dangerous API design and it should be discouraged: it's better to define more precise exception constructors than store useful information in strings.

8.5.2 Warning 57: Ambiguous or-pattern variables under guard

The semantics of or-patterns in OCaml is specified with a left-to-right bias: a value v matches the pattern p `|` q if it matches p or q, but if it matches both, the environment captured by the match is the environment captured by p, never the one captured by q.

While this property is generally intuitive, there is at least one specific case where a different semantics might be expected. Consider a pattern followed by a when-guard: `|` *p* `when` *g* `->` *e*, for example:

```
| ((Const x, _) | (_, Const x)) when is_neutral x -> branch
```

The semantics is clear: match the scrutinee against the pattern, if it matches, test the guard, and if the guard passes, take the branch. In particular, consider the input `(Const` *a*`, Const` *b*`)`, where *a* fails the test `is_neutral` *a*, while *b* passes the test `is_neutral` *b*. With the left-to-right semantics, the clause above is *not* taken by its input: matching `(Const` *a*`, Const` *b*`)` against the or-pattern succeeds in the left branch, it returns the environment *x* `->` *a*, and then the guard `is_neutral` *a* is tested and fails, the branch is not taken.

However, another semantics may be considered more natural here: any pair that has one side passing the test will take the branch. With this semantics the previous code fragment would be equivalent to

```
| (Const x, _) when is_neutral x -> branch
| (_, Const x) when is_neutral x -> branch
```

This is *not* the semantics adopted by OCaml.

Warning 57 is dedicated to these confusing cases where the specified left-to-right semantics is not equivalent to a non-deterministic semantics (any branch can be taken) relatively to a specific guard. More precisely, it warns when guard uses "ambiguous" variables, that are bound to different parts of the scrutinees by different sides of a or-pattern.

Chapter 9

The toplevel system (ocaml)

This chapter describes the toplevel system for OCaml, that permits interactive use of the OCaml system through a read-eval-print loop. In this mode, the system repeatedly reads OCaml phrases from the input, then typechecks, compile and evaluate them, then prints the inferred type and result value, if any. The system prints a `#` (sharp) prompt before reading each phrase.

Input to the toplevel can span several lines. It is terminated by `;;` (a double-semicolon). The toplevel input consists in one or several toplevel phrases, with the following syntax:

toplevel-input	::=	{*definition*}$^+$ `;;`
	|	*expr* `;;`
	|	`#` *ident* [*directive-argument*] `;;`
directive-argument	::=	*string-literal*
	|	*integer-literal*
	|	*value-path*
	|	`true` | `false`

A phrase can consist of a definition, like those found in implementations of compilation units or in `struct`...`end` module expressions. The definition can bind value names, type names, an exception, a module name, or a module type name. The toplevel system performs the bindings, then prints the types and values (if any) for the names thus defined.

A phrase may also consist in a value expression (section 6.7). It is simply evaluated without performing any bindings, and its value is printed.

Finally, a phrase can also consist in a toplevel directive, starting with `#` (the sharp sign). These directives control the behavior of the toplevel; they are listed below in section 9.2.

Unix:

The toplevel system is started by the command `ocaml`, as follows:

```
ocaml options objects                  # interactive mode
ocaml options objects scriptfile       # script mode
```

options are described below. *objects* are filenames ending in `.cmo` or `.cma`; they are loaded into the interpreter immediately after *options* are set. *scriptfile* is any file name not ending in `.cmo` or `.cma`.

If no *scriptfile* is given on the command line, the toplevel system enters interactive mode: phrases are read on standard input, results are printed on standard output, errors on standard error. End-of-file on standard input terminates `ocaml` (see also the `#quit` directive in section 9.2).

On start-up (before the first phrase is read), if the file `.ocamlinit` exists in the current directory, its contents are read as a sequence of OCaml phrases and executed as per the `#use` directive described in section 9.2. The evaluation outcode for each phrase are not displayed. If the current directory does not contain an `.ocamlinit` file, but the user's home directory (environment variable `HOME`) does, the latter is read and executed as described below.

The toplevel system does not perform line editing, but it can easily be used in conjunction with an external line editor such as `ledit`, `ocaml2` or `rlwrap` (see the Caml Hump `http://caml.inria.fr/humps/index_framed_caml.html`). Another option is to use `ocaml` under Gnu Emacs, which gives the full editing power of Emacs (command `run-caml` from library `inf-caml`).

At any point, the parsing, compilation or evaluation of the current phrase can be interrupted by pressing `ctrl-C` (or, more precisely, by sending the `INTR` signal to the `ocaml` process). The toplevel then immediately returns to the `#` prompt.

If *scriptfile* is given on the command-line to `ocaml`, the toplevel system enters script mode: the contents of the file are read as a sequence of OCaml phrases and executed, as per the `#use` directive (section 9.2). The outcome of the evaluation is not printed. On reaching the end of file, the `ocaml` command exits immediately. No commands are read from standard input. `Sys.argv` is transformed, ignoring all OCaml parameters, and starting with the script file name in `Sys.argv.(0)`.

In script mode, the first line of the script is ignored if it starts with `#!`. Thus, it should be possible to make the script itself executable and put as first line `#!/usr/local/bin/ocaml`, thus calling the toplevel system automatically when the script is run. However, `ocaml` itself is a `#!` script on most installations of OCaml, and Unix kernels usually do not handle nested `#!` scripts. A better solution is to put the following as the first line of the script:

```
#!/usr/local/bin/ocamlrun /usr/local/bin/ocaml
```

Windows:
In addition to the text-only command `ocaml.exe`, which works exactly as under Unix (see above), a graphical user interface for the toplevel is available under the name `ocamlwin.exe`. It should be launched from the Windows file manager or program manager. This interface provides a text window in which commands can be entered and edited, and the toplevel responses are printed.

9.1 Options

The following command-line options are recognized by the `ocaml` command.

`-absname`
Force error messages to show absolute paths for file names.

`-I` *directory*
: Add the given directory to the list of directories searched for source and compiled files. By default, the current directory is searched first, then the standard library directory. Directories added with `-I` are searched after the current directory, in the order in which they were given on the command line, but before the standard library directory.

  If the given directory starts with `+`, it is taken relative to the standard library directory. For instance, `-I +labltk` adds the subdirectory `labltk` of the standard library to the search path.

  Directories can also be added to the list once the toplevel is running with the `#directory` directive (section 9.2).

`-init` *file*
: Load the given file instead of the default initialization file. The default file is `.ocamlinit` in the current directory if it exists, otherwise `.ocamlinit` in the user's home directory.

`-labels`
: Labels are not ignored in types, labels may be used in applications, and labelled parameters can be given in any order. This is the default.

`-no-app-funct`
: Deactivates the applicative behaviour of functors. With this option, each functor application generates new types in its result and applying the same functor twice to the same argument yields two incompatible structures.

`-noassert`
: Do not compile assertion checks. Note that the special form `assert false` is always compiled because it is typed specially.

`-nolabels`
: Ignore non-optional labels in types. Labels cannot be used in applications, and parameter order becomes strict.

`-noprompt`
: Do not display any prompt when waiting for input.

`-nopromptcont`
: Do not display the secondary prompt when waiting for continuation lines in multi-line inputs. This should be used e.g. when running `ocaml` in an `emacs` window.

`-nostdlib`
: Do not include the standard library directory in the list of directories searched for source and compiled files.

`-ppx` *command*
: After parsing, pipe the abstract syntax tree through the preprocessor *command*. The module `Ast_mapper`, described in chapter 22.1, implements the external interface of a preprocessor.

`-principal`
: Check information paths during type-checking, to make sure that all types are derived in a principal way. When using labelled arguments and/or polymorphic methods, this flag is required to ensure future versions of the compiler will be able to infer types correctly, even if internal algorithms change. All programs accepted in `-principal` mode are also accepted in the default mode with equivalent types, but different binary signatures, and this may slow down type checking; yet it is a good idea to use it once before publishing source code.

`-rectypes`
: Allow arbitrary recursive types during type-checking. By default, only recursive types where the recursion goes through an object type are supported.

`-safe-string`
: Enforce the separation between types `string` and `bytes`, thereby making strings read-only. This will become the default in a future version of OCaml.

`-short-paths`
: When a type is visible under several module-paths, use the shortest one when printing the type's name in inferred interfaces and error and warning messages. Identifier names starting with an underscore `_` or containing double underscores `__` incur a penalty of +10 when computing their length.

`-stdin`
: Read the standard input as a script file rather than starting an interactive session.

`-strict-sequence`
: Force the left-hand part of each sequence to have type unit.

`-strict-formats`
: Reject invalid formats that were accepted in legacy format implementations. You should use this flag to detect and fix such invalid formats, as they will be rejected by future OCaml versions.

`-unsafe`
: See the corresponding option for `ocamlc`, chapter 8. Turn bound checking off on array and string accesses (the `v.(i)` and `s.[i]` constructs). Programs compiled with `-unsafe` are therefore slightly faster, but unsafe: anything can happen if the program accesses an array or string outside of its bounds.

`-unsafe-string`
: Identify the types `string` and `bytes`, thereby making strings writable. For reasons of backward compatibility, this is the default setting for the moment, but this will change in a future version of OCaml.

`-version`
: Print version string and exit.

`-vnum`
: Print short version number and exit.

`-no-version`
: Do not print the version banner at startup.

`-w` *warning-list*
: Enable or disable warnings according to the argument *warning-list*. See section 8.2 for the syntax of the argument.

`-warn-error` *warning-list*
: Mark as fatal the warnings enabled by the argument *warning-list*. See section 8.2 for the syntax of the argument.

`-warn-help`
: Show the description of all available warning numbers.

`-` *file*
: Use *file* as a script file name, even when it starts with a hyphen (-).

`-help` **or** `--help`
: Display a short usage summary and exit.

Unix:
: The following environment variables are also consulted:

`LC_CTYPE`
: If set to `iso_8859_1`, accented characters (from the ISO Latin-1 character set) in string and character literals are printed as is; otherwise, they are printed as decimal escape sequences (*ddd*).

`TERM`
: When printing error messages, the toplevel system attempts to underline visually the location of the error. It consults the `TERM` variable to determines the type of output terminal and look up its capabilities in the terminal database.

`HOME`
: Directory where the `.ocamlinit` file is searched.

9.2 Toplevel directives

The following directives control the toplevel behavior, load files in memory, and trace program execution.

Note: all directives start with a `#` (sharp) symbol. This `#` must be typed before the directive, and must not be confused with the `#` prompt displayed by the interactive loop. For instance, typing `#quit;;` will exit the toplevel loop, but typing `quit;;` will result in an "unbound value `quit`" error.

General

`#help;;`
: Prints a list of all available directives, with corresponding argument type if appropriate.

`#quit;;`
: Exit the toplevel loop and terminate the `ocaml` command.

Loading codes

`#cd "`*dir-name*`";;`
: Change the current working directory.

`#directory "`*dir-name*`";;`
: Add the given directory to the list of directories searched for source and compiled files.

`#remove_directory "`*dir-name*`";;`
: Remove the given directory from the list of directories searched for source and compiled files. Do nothing if the list does not contain the given directory.

`#load "`*file-name*`";;`
: Load in memory a bytecode object file (`.cmo` file) or library file (`.cma` file) produced by the batch compiler `ocamlc`.

`#load_rec "`*file-name*`";;`
: Load in memory a bytecode object file (`.cmo` file) or library file (`.cma` file) produced by the batch compiler `ocamlc`. When loading an object file that depends on other modules which have not been loaded yet, the .cmo files for these modules are searched and loaded as well, recursively. The loading order is not specified.

`#use "`*file-name*`";;`
: Read, compile and execute source phrases from the given file. This is textual inclusion: phrases are processed just as if they were typed on standard input. The reading of the file stops at the first error encountered.

`#mod_use "`*file-name*`";;`
: Similar to `#use` but also wrap the code into a top-level module of the same name as capitalized file name without extensions, following semantics of the compiler.

Environment queries

`#show_class` *class-path*`;;`
`#show_class_type` *class-path*`;;`
`#show_exception` *ident*`;;`
`#show_module` *module-path*`;;`
`#show_module_type` *modtype-path*`;;`
`#show_type` *typeconstr*`;;`
`#show_val` *value-path*`;;`
: Print the signature of the corresponding component.

`#show` *ident*`;;`
: Print the signatures of components with name *ident* in all the above categories.

Pretty-printing

`#install_printer` *printer-name*`;;`
: This directive registers the function named *printer-name* (a value path) as a printer for values whose types match the argument type of the function. That is, the toplevel loop will call *printer-name* when it has such a value to print.

  The printing function *printer-name* should have type `Format.formatter ->`*t* `-> unit`, where *t* is the type for the values to be printed, and should output its textual representation for the value of type *t* on the given formatter, using the functions provided by the `Format` library. For backward compatibility, *printer-name* can also have type *t*`-> unit` and should then output on the standard formatter, but this usage is deprecated.

`#print_depth` *n*`;;`
: Limit the printing of values to a maximal depth of *n*. The parts of values whose depth exceeds *n* are printed as `...` (ellipsis).

`#print_length` *n*`;;`
: Limit the number of value nodes printed to at most *n*. Remaining parts of values are printed as `...` (ellipsis).

`#remove_printer` *printer-name*`;;`
: Remove the named function from the table of toplevel printers.

Tracing

`#trace` *function-name*`;;`
: After executing this directive, all calls to the function named *function-name* will be "traced". That is, the argument and the result are displayed for each call, as well as the exceptions escaping out of the function, raised either by the function itself or by another function it calls. If the function is curried, each argument is printed as it is passed to the function.

`#untrace` *function-name*`;;`
: Stop tracing the given function.

`#untrace_all;;`
: Stop tracing all functions traced so far.

Compiler options

`#labels` *bool*`;;`
: Ignore labels in function types if argument is `false`, or switch back to default behaviour (commuting style) if argument is `true`.

`#ppx "`*file-name*`";;`
: After parsing, pipe the abstract syntax tree through the preprocessor command.

`#principal` *bool*`;;`
: If the argument is `true`, check information paths during type-checking, to make sure that all types are derived in a principal way. If the argument is `false`, do not check information paths.

`#rectypes;;`
: Allow arbitrary recursive types during type-checking. Note: once enabled, this option cannot be disabled because that would lead to unsoundness of the type system.

`#warn_error "`*warning-list*`";;`
: Treat as errors the warnings enabled by the argument and as normal warnings the warnings disabled by the argument.

`#warnings "`*warning-list*`";;`
: Enable or disable warnings according to the argument.

9.3 The toplevel and the module system

Toplevel phrases can refer to identifiers defined in compilation units with the same mechanisms as for separately compiled units: either by using qualified names (`Modulename.localname`), or by using the `open` construct and unqualified names (see section 6.3).

However, before referencing another compilation unit, an implementation of that unit must be present in memory. At start-up, the toplevel system contains implementations for all the modules in the the standard library. Implementations for user modules can be entered with the `#load` directive described above. Referencing a unit for which no implementation has been provided results in the error `Reference to undefined global `...'`.

Note that entering `open` *Mod* merely accesses the compiled interface (`.cmi` file) for *Mod*, but does not load the implementation of *Mod*, and does not cause any error if no implementation of *Mod* has been loaded. The error "reference to undefined global *Mod*" will occur only when executing a value or module definition that refers to *Mod*.

9.4 Common errors

This section describes and explains the most frequently encountered error messages.

Cannot find file *filename*
: The named file could not be found in the current directory, nor in the directories of the search path.

  If *filename* has the format *mod*`.cmi`, this means you have referenced the compilation unit *mod*, but its compiled interface could not be found. Fix: compile *mod*`.mli` or *mod*`.ml` first, to create the compiled interface *mod*`.cmi`.

  If *filename* has the format *mod*`.cmo`, this means you are trying to load with `#load` a bytecode object file that does not exist yet. Fix: compile *mod*`.ml` first.

  If your program spans several directories, this error can also appear because you haven't specified the directories to look into. Fix: use the `#directory` directive to add the correct directories to the search path.

This expression has type t_1**, but is used with type** t_2
: See section 8.4.

Reference to undefined global *mod*
: You have neglected to load in memory an implementation for a module with `#load`. See section 9.3 above.

9.5 Building custom toplevel systems: `ocamlmktop`

The `ocamlmktop` command builds OCaml toplevels that contain user code preloaded at start-up.

The `ocamlmktop` command takes as argument a set of `.cmo` and `.cma` files, and links them with the object files that implement the OCaml toplevel. The typical use is:

```
ocamlmktop -o mytoplevel foo.cmo bar.cmo gee.cmo
```

This creates the bytecode file `mytoplevel`, containing the OCaml toplevel system, plus the code from the three `.cmo` files. This toplevel is directly executable and is started by:

```
./mytoplevel
```

This enters a regular toplevel loop, except that the code from `foo.cmo`, `bar.cmo` and `gee.cmo` is already loaded in memory, just as if you had typed:

```
#load "foo.cmo";;
#load "bar.cmo";;
#load "gee.cmo";;
```

on entrance to the toplevel. The modules `Foo`, `Bar` and `Gee` are not opened, though; you still have to do

```
open Foo;;
```

yourself, if this is what you wish.

9.6 Options

The following command-line options are recognized by `ocamlmktop`.

`-cclib` *libname*
: Pass the `-l`*libname* option to the C linker when linking in "custom runtime" mode. See the corresponding option for `ocamlc`, in chapter 8.

`-ccopt` *option*
: Pass the given option to the C compiler and linker, when linking in "custom runtime" mode. See the corresponding option for `ocamlc`, in chapter 8.

`-custom`
: Link in "custom runtime" mode. See the corresponding option for `ocamlc`, in chapter 8.

`-I` *directory*
: Add the given directory to the list of directories searched for compiled object code files (`.cmo` and `.cma`).

`-o` *exec-file*
: Specify the name of the toplevel file produced by the linker. The default is `a.out`.

Chapter 10

The runtime system (ocamlrun)

The `ocamlrun` command executes bytecode files produced by the linking phase of the `ocamlc` command.

10.1 Overview

The `ocamlrun` command comprises three main parts: the bytecode interpreter, that actually executes bytecode files; the memory allocator and garbage collector; and a set of C functions that implement primitive operations such as input/output.

The usage for `ocamlrun` is:

`ocamlrun` *options bytecode-executable* arg_1 `...` arg_n

The first non-option argument is taken to be the name of the file containing the executable bytecode. (That file is searched in the executable path as well as in the current directory.) The remaining arguments are passed to the OCaml program, in the string array `Sys.argv`. Element 0 of this array is the name of the bytecode executable file; elements 1 to n are the remaining arguments arg_1 to arg_n.

As mentioned in chapter 8, the bytecode executable files produced by the `ocamlc` command are self-executable, and manage to launch the `ocamlrun` command on themselves automatically. That is, assuming `a.out` is a bytecode executable file,

`a.out` arg_1 `...` arg_n

works exactly as

`ocamlrun a.out` arg_1 `...` arg_n

Notice that it is not possible to pass options to `ocamlrun` when invoking `a.out` directly.

Windows:

Under several versions of Windows, bytecode executable files are self-executable only if their name ends in `.exe`. It is recommended to always give `.exe` names to bytecode executables, e.g. compile with `ocamlc -o myprog.exe ...` rather than `ocamlc -o myprog ...`.

10.2 Options

The following command-line options are recognized by `ocamlrun`.

`-b` When the program aborts due to an uncaught exception, print a detailed "back trace" of the execution, showing where the exception was raised and which function calls were outstanding at this point. The back trace is printed only if the bytecode executable contains debugging information, i.e. was compiled and linked with the `-g` option to `ocamlc` set. This is equivalent to setting the `b` flag in the `OCAMLRUNPARAM` environment variable (see below).

`-I` *dir*
Search the directory *dir* for dynamically-loaded libraries, in addition to the standard search path (see section 10.3).

`-p` Print the names of the primitives known to this version of `ocamlrun` and exit.

`-v` Direct the memory manager to print some progress messages on standard error. This is equivalent to setting `v=63` in the `OCAMLRUNPARAM` environment variable (see below).

`-version`
Print version string and exit.

`-vnum`
Print short version number and exit.

The following environment variables are also consulted:

`CAML_LD_LIBRARY_PATH`
Additional directories to search for dynamically-loaded libraries (see section 10.3).

`OCAMLLIB`
The directory containing the OCaml standard library. (If `OCAMLLIB` is not set, `CAMLLIB` will be used instead.) Used to locate the `ld.conf` configuration file for dynamic loading (see section 10.3). If not set, default to the library directory specified when compiling OCaml.

`OCAMLRUNPARAM`
Set the runtime system options and garbage collection parameters. (If `OCAMLRUNPARAM` is not set, `CAMLRUNPARAM` will be used instead.) This variable must be a sequence of parameter specifications separated by commas. A parameter specification is an option letter followed by an `=` sign, a decimal number (or an hexadecimal number prefixed by `0x`), and an optional multiplier. The options are documented below; the last six correspond to the fields of the `control` record documented in section 21.12.

- **b** (backtrace) Trigger the printing of a stack backtrace when an uncaught exception aborts the program. This option takes no argument.
- **p** (parser trace) Turn on debugging support for `ocamlyacc`-generated parsers. When this option is on, the pushdown automaton that executes the parsers prints a trace of its actions. This option takes no argument.

R (randomize) Turn on randomization of all hash tables by default (see section 21.14). This option takes no argument.

h The initial size of the major heap (in words).

a (`allocation_policy`) The policy used for allocating in the OCaml heap. Possible values are 0 for the next-fit policy, and 1 for the first-fit policy. Next-fit is usually faster, but first-fit is better for avoiding fragmentation and the associated heap compactions.

s (`minor_heap_size`) Size of the minor heap. (in words)

i (`major_heap_increment`) Default size increment for the major heap. (in words)

o (`space_overhead`) The major GC speed setting.

O (`max_overhead`) The heap compaction trigger setting.

l (`stack_limit`) The limit (in words) of the stack size.

v (`verbose`) What GC messages to print to stderr. This is a sum of values selected from the following:

1 (= 0x001)
Start of major GC cycle.

2 (= 0x002)
Minor collection and major GC slice.

4 (= 0x004)
Growing and shrinking of the heap.

8 (= 0x008)
Resizing of stacks and memory manager tables.

16 (= 0x010)
Heap compaction.

32 (= 0x020)
Change of GC parameters.

64 (= 0x040)
Computation of major GC slice size.

128 (= 0x080)
Calling of finalization functions

256 (= 0x100)
Startup messages (loading the bytecode executable file, resolving shared libraries).

512 (= 0x200)
Computation of compaction-triggering condition.

The multiplier is `k`, `M`, or `G`, for multiplication by 2^{10}, 2^{20}, and 2^{30} respectively.

If the option letter is not recognized, the whole parameter is ignored; if the equal sign or the number is missing, the value is taken as 1; if the multiplier is not recognized, it is ignored.

For example, on a 32-bit machine, under `bash` the command

```
export OCAMLRUNPARAM='b,s=256k,v=0x015'
```

tells a subsequent `ocamlrun` to print backtraces for uncaught exceptions, set its initial minor heap size to 1 megabyte and print a message at the start of each major GC cycle, when the heap size changes, and when compaction is triggered.

`CAMLRUNPARAM`
: If `OCAMLRUNPARAM` is not found in the environment, then `CAMLRUNPARAM` will be used instead. If `CAMLRUNPARAM` is also not found, then the default values will be used.

`PATH`
: List of directories searched to find the bytecode executable file.

10.3 Dynamic loading of shared libraries

On platforms that support dynamic loading, `ocamlrun` can link dynamically with C shared libraries (DLLs) providing additional C primitives beyond those provided by the standard runtime system. The names for these libraries are provided at link time as described in section 18.1.4), and recorded in the bytecode executable file; `ocamlrun`, then, locates these libraries and resolves references to their primitives when the bytecode executable program starts.

The `ocamlrun` command searches shared libraries in the following directories, in the order indicated:

1. Directories specified on the `ocamlrun` command line with the `-I` option.
2. Directories specified in the `CAML_LD_LIBRARY_PATH` environment variable.
3. Directories specified at link-time via the `-dllpath` option to `ocamlc`. (These directories are recorded in the bytecode executable file.)
4. Directories specified in the file `ld.conf`. This file resides in the OCaml standard library directory, and lists directory names (one per line) to be searched. Typically, it contains only one line naming the `stublibs` subdirectory of the OCaml standard library directory. Users can add there the names of other directories containing frequently-used shared libraries; however, for consistency of installation, we recommend that shared libraries are installed directly in the system `stublibs` directory, rather than adding lines to the `ld.conf` file.
5. Default directories searched by the system dynamic loader. Under Unix, these generally include `/lib` and `/usr/lib`, plus the directories listed in the file `/etc/ld.so.conf` and the environment variable `LD_LIBRARY_PATH`. Under Windows, these include the Windows system directories, plus the directories listed in the `PATH` environment variable.

10.4 Common errors

This section describes and explains the most frequently encountered error messages.

filename`: no such file or directory`
: If *filename* is the name of a self-executable bytecode file, this means that either that file does not exist, or that it failed to run the `ocamlrun` bytecode interpreter on itself. The second possibility indicates that OCaml has not been properly installed on your system.

`Cannot exec ocamlrun`
: (When launching a self-executable bytecode file.) The `ocamlrun` could not be found in the executable path. Check that OCaml has been properly installed on your system.

`Cannot find the bytecode file`
: The file that `ocamlrun` is trying to execute (e.g. the file given as first non-option argument to `ocamlrun`) either does not exist, or is not a valid executable bytecode file.

`Truncated bytecode file`
: The file that `ocamlrun` is trying to execute is not a valid executable bytecode file. Probably it has been truncated or mangled since created. Erase and rebuild it.

`Uncaught exception`
: The program being executed contains a "stray" exception. That is, it raises an exception at some point, and this exception is never caught. This causes immediate termination of the program. The name of the exception is printed, along with its string, byte sequence, and integer arguments (arguments of more complex types are not correctly printed). To locate the context of the uncaught exception, compile the program with the `-g` option and either run it again under the `ocamldebug` debugger (see chapter 15), or run it with `ocamlrun -b` or with the `OCAMLRUNPARAM` environment variable set to `b=1`.

`Out of memory`
: The program being executed requires more memory than available. Either the program builds excessively large data structures; or the program contains too many nested function calls, and the stack overflows. In some cases, your program is perfectly correct, it just requires more memory than your machine provides. In other cases, the "out of memory" message reveals an error in your program: non-terminating recursive function, allocation of an excessively large array, string or byte sequence, attempts to build an infinite list or other data structure, ...

  To help you diagnose this error, run your program with the `-v` option to `ocamlrun`, or with the `OCAMLRUNPARAM` environment variable set to `v=63`. If it displays lots of "`Growing stack...`" messages, this is probably a looping recursive function. If it displays lots of "`Growing heap...`" messages, with the heap size growing slowly, this is probably an attempt to construct a data structure with too many (infinitely many?) cells. If it displays few "`Growing heap...`" messages, but with a huge increment in the heap size, this is probably an attempt to build an excessively large array, string or byte sequence.

Chapter 11

Native-code compilation (ocamlopt)

This chapter describes the OCaml high-performance native-code compiler `ocamlopt`, which compiles OCaml source files to native code object files and link these object files to produce standalone executables.

The native-code compiler is only available on certain platforms. It produces code that runs faster than the bytecode produced by `ocamlc`, at the cost of increased compilation time and executable code size. Compatibility with the bytecode compiler is extremely high: the same source code should run identically when compiled with `ocamlc` and `ocamlopt`.

It is not possible to mix native-code object files produced by `ocamlopt` with bytecode object files produced by `ocamlc`: a program must be compiled entirely with `ocamlopt` or entirely with `ocamlc`. Native-code object files produced by `ocamlopt` cannot be loaded in the toplevel system `ocaml`.

11.1 Overview of the compiler

The `ocamlopt` command has a command-line interface very close to that of `ocamlc`. It accepts the same types of arguments, and processes them sequentially, after all options have been processed:

- Arguments ending in `.mli` are taken to be source files for compilation unit interfaces. Interfaces specify the names exported by compilation units: they declare value names with their types, define public data types, declare abstract data types, and so on. From the file *x*`.mli`, the `ocamlopt` compiler produces a compiled interface in the file *x*`.cmi`. The interface produced is identical to that produced by the bytecode compiler `ocamlc`.
- Arguments ending in `.ml` are taken to be source files for compilation unit implementations. Implementations provide definitions for the names exported by the unit, and also contain expressions to be evaluated for their side-effects. From the file *x*`.ml`, the `ocamlopt` compiler produces two files: *x*`.o`, containing native object code, and *x*`.cmx`, containing extra information for linking and optimization of the clients of the unit. The compiled implementation should always be referred to under the name *x*`.cmx` (when given a `.o` or `.obj` file, `ocamlopt` assumes that it contains code compiled from C, not from OCaml).

  The implementation is checked against the interface file *x*`.mli` (if it exists) as described in the manual for `ocamlc` (chapter 8).

- Arguments ending in `.cmx` are taken to be compiled object code. These files are linked together, along with the object files obtained by compiling `.ml` arguments (if any), and the OCaml standard library, to produce a native-code executable program. The order in which `.cmx` and `.ml` arguments are presented on the command line is relevant: compilation units are initialized in that order at run-time, and it is a link-time error to use a component of a unit before having initialized it. Hence, a given *x*`.cmx` file must come before all `.cmx` files that refer to the unit *x*.
- Arguments ending in `.cmxa` are taken to be libraries of object code. Such a library packs in two files (*lib*`.cmxa` and *lib*`.a`/`.lib`) a set of object files (`.cmx` and `.o`/`.obj` files). Libraries are build with `ocamlopt -a` (see the description of the `-a` option below). The object files contained in the library are linked as regular `.cmx` files (see above), in the order specified when the library was built. The only difference is that if an object file contained in a library is not referenced anywhere in the program, then it is not linked in.
- Arguments ending in `.c` are passed to the C compiler, which generates a `.o`/`.obj` object file. This object file is linked with the program.
- Arguments ending in `.o`, `.a` or `.so` (`.obj`, `.lib` and `.dll` under Windows) are assumed to be C object files and libraries. They are linked with the program.

The output of the linking phase is a regular Unix or Windows executable file. It does not need `ocamlrun` to run.

11.2 Options

The following command-line options are recognized by `ocamlopt`. The options `-pack`, `-a`, `-shared`, `-c` and `-output-obj` are mutually exclusive.

`-a` Build a library (`.cmxa` and `.a`/`.lib` files) with the object files (`.cmx` and `.o`/`.obj` files) given on the command line, instead of linking them into an executable file. The name of the library must be set with the `-o` option.

If `-cclib` or `-ccopt` options are passed on the command line, these options are stored in the resulting `.cmxa` library. Then, linking with this library automatically adds back the `-cclib` and `-ccopt` options as if they had been provided on the command line, unless the `-noautolink` option is given.

`-absname`
Force error messages to show absolute paths for file names.

`-annot`
Dump detailed information about the compilation (types, bindings, tail-calls, etc). The information for file *src*`.ml` is put into file *src*`.annot`. In case of a type error, dump all the information inferred by the type-checker before the error. The *src*`.annot` file can be used with the emacs commands given in `emacs/caml-types.el` to display types and other annotations interactively.

`-bin-annot`
: Dump detailed information about the compilation (types, bindings, tail-calls, etc) in binary format. The information for file *src*`.ml` is put into file *src*`.cmt`. In case of a type error, dump all the information inferred by the type-checker before the error. The `*.cmt` files produced by `-bin-annot` contain more information and are much more compact than the files produced by `-annot`.

`-c`
: Compile only. Suppress the linking phase of the compilation. Source code files are turned into compiled files, but no executable file is produced. This option is useful to compile modules separately.

`-cc` *ccomp*
: Use *ccomp* as the C linker called to build the final executable and as the C compiler for compiling `.c` source files.

`-cclib -l`*libname*
: Pass the `-l`*libname* option to the linker. This causes the given C library to be linked with the program.

`-ccopt` *option*
: Pass the given option to the C compiler and linker. For instance, `-ccopt -L`*dir* causes the C linker to search for C libraries in directory *dir*.

`-compact`
: Optimize the produced code for space rather than for time. This results in slightly smaller but slightly slower programs. The default is to optimize for speed.

`-config`
: Print the version number of `ocamlopt` and a detailed summary of its configuration, then exit.

`-for-pack` *module-path*
: Generate an object file (`.cmx` and `.o`/`.obj` files) that can later be included as a sub-module (with the given access path) of a compilation unit constructed with `-pack`. For instance, `ocamlopt -for-pack P -c A.ml` will generate `a.cmx` and `a.o` files that can later be used with `ocamlopt -pack -o P.cmx a.cmx`.

`-g`
: Add debugging information while compiling and linking. This option is required in order to produce stack backtraces when the program terminates on an uncaught exception (see section 10.2).

`-i`
: Cause the compiler to print all defined names (with their inferred types or their definitions) when compiling an implementation (`.ml` file). No compiled files (`.cmo` and `.cmi` files) are produced. This can be useful to check the types inferred by the compiler. Also, since the output follows the syntax of interfaces, it can help in writing an explicit interface (`.mli` file) for a file: just redirect the standard output of the compiler to a `.mli` file, and edit that file to remove all declarations of unexported names.

`-I` *directory*
: Add the given directory to the list of directories searched for compiled interface files (`.cmi`),

compiled object code files (`.cmx`), and libraries (`.cmxa`). By default, the current directory is searched first, then the standard library directory. Directories added with `-I` are searched after the current directory, in the order in which they were given on the command line, but before the standard library directory. See also option `-nostdlib`.

If the given directory starts with `+`, it is taken relative to the standard library directory. For instance, `-I +labltk` adds the subdirectory `labltk` of the standard library to the search path.

`-impl` *filename*
: Compile the file *filename* as an implementation file, even if its extension is not `.ml`.

`-inline` *n*
: Set aggressiveness of inlining to *n*, where *n* is a positive integer. Specifying `-inline 0` prevents all functions from being inlined, except those whose body is smaller than the call site. Thus, inlining causes no expansion in code size. The default aggressiveness, `-inline 1`, allows slightly larger functions to be inlined, resulting in a slight expansion in code size. Higher values for the `-inline` option cause larger and larger functions to become candidate for inlining, but can result in a serious increase in code size.

`-intf` *filename*
: Compile the file *filename* as an interface file, even if its extension is not `.mli`.

`-intf-suffix` *string*
: Recognize file names ending with *string* as interface files (instead of the default `.mli`).

`-labels`
: Labels are not ignored in types, labels may be used in applications, and labelled parameters can be given in any order. This is the default.

`-linkall`
: Force all modules contained in libraries to be linked in. If this flag is not given, unreferenced modules are not linked in. When building a library (`-a` flag), setting the `-linkall` flag forces all subsequent links of programs involving that library to link all the modules contained in the library.

`-no-app-funct`
: Deactivates the applicative behaviour of functors. With this option, each functor application generates new types in its result and applying the same functor twice to the same argument yields two incompatible structures.

`-noassert`
: Do not compile assertion checks. Note that the special form `assert false` is always compiled because it is typed specially. This flag has no effect when linking already-compiled files.

`-noautolink`
: When linking `.cmxa` libraries, ignore `-cclib` and `-ccopt` options potentially contained in the libraries (if these options were given when building the libraries). This can be useful if a library contains incorrect specifications of C libraries or C options; in this case, during linking, set `-noautolink` and pass the correct C libraries and options on the command line.

`-nodynlink`
: Allow the compiler to use some optimizations that are valid only for code that is never dynlinked.

`-nolabels`
: Ignore non-optional labels in types. Labels cannot be used in applications, and parameter order becomes strict.

`-nostdlib`
: Do not automatically add the standard library directory the list of directories searched for compiled interface files (`.cmi`), compiled object code files (`.cmx`), and libraries (`.cmxa`). See also option `-I`.

`-o` *exec-file*
: Specify the name of the output file produced by the linker. The default output name is `a.out` under Unix and `camlprog.exe` under Windows. If the `-a` option is given, specify the name of the library produced. If the `-pack` option is given, specify the name of the packed object file produced. If the `-output-obj` option is given, specify the name of the output file produced. If the `-shared` option is given, specify the name of plugin file produced.

`-output-obj`
: Cause the linker to produce a C object file instead of an executable file. This is useful to wrap OCaml code as a C library, callable from any C program. See chapter 18, section 18.7.5. The name of the output object file must be set with the `-o` option. This option can also be used to produce a compiled shared/dynamic library (`.so` extension, `.dll` under Windows).

`-p` Generate extra code to write profile information when the program is executed. The profile information can then be examined with the analysis program `gprof`. (See chapter 16 for more information on profiling.) The `-p` option must be given both at compile-time and at link-time. Linking object files not compiled with `-p` is possible, but results in less precise profiling.

Unix:

See the Unix manual page for `gprof(1)` for more information about the profiles.

Full support for `gprof` is only available for certain platforms (currently: Intel x86 32 and 64 bits under Linux, BSD and MacOS X). On other platforms, the `-p` option will result in a less precise profile (no call graph information, only a time profile).

Windows:

The `-p` option does not work under Windows.

`-pack`
: Build an object file (`.cmx` and `.o`/`.obj` files) and its associated compiled interface (`.cmi`)

that combines the `.cmx` object files given on the command line, making them appear as sub-modules of the output `.cmx` file. The name of the output `.cmx` file must be given with the `-o` option. For instance,

```
ocamlopt -pack -o P.cmx A.cmx B.cmx C.cmx
```

generates compiled files `P.cmx`, `P.o` and `P.cmi` describing a compilation unit having three sub-modules `A`, `B` and `C`, corresponding to the contents of the object files `A.cmx`, `B.cmx` and `C.cmx`. These contents can be referenced as `P.A`, `P.B` and `P.C` in the remainder of the program.

The `.cmx` object files being combined must have been compiled with the appropriate `-for-pack` option. In the example above, `A.cmx`, `B.cmx` and `C.cmx` must have been compiled with `ocamlopt -for-pack P`.

Multiple levels of packing can be achieved by combining `-pack` with `-for-pack`. Consider the following example:

```
ocamlopt -for-pack P.Q -c A.ml
ocamlopt -pack -o Q.cmx -for-pack P A.cmx
ocamlopt -for-pack P -c B.ml
ocamlopt -pack -o P.cmx Q.cmx B.cmx
```

The resulting `P.cmx` object file has sub-modules `P.Q`, `P.Q.A` and `P.B`.

`-plugin` *plugin*
: Dynamically load the code of the given *plugin* (a `.cmo`, `.cma` or `.cmxs` file) in the compiler. *plugin* must exist in the same kind of code as the compiler (`ocamlopt.byte` must load bytecode plugins, while `ocamlopt.opt` must load native code plugins), and extension adaptation is done automatically for `.cma` files (to `.cmxs` files if the compiler is compiled in native code).

`-pp` *command*
: Cause the compiler to call the given *command* as a preprocessor for each source file. The output of *command* is redirected to an intermediate file, which is compiled. If there are no compilation errors, the intermediate file is deleted afterwards.

`-ppx` *command*
: After parsing, pipe the abstract syntax tree through the preprocessor *command*. The module `Ast_mapper`, described in chapter 22.1, implements the external interface of a preprocessor.

`-principal`
: Check information path during type-checking, to make sure that all types are derived in a principal way. All programs accepted in `-principal` mode are also accepted in default mode with equivalent types, but different binary signatures.

`-rectypes`
: Allow arbitrary recursive types during type-checking. By default, only recursive types where the recursion goes through an object type are supported. Note that once you have created an interface using this flag, you must use it again for all dependencies.

`-runtime-variant` *suffix*
: Add the *suffix* string to the name of the runtime library used by the program. Currently, only one such suffix is supported: `d`, and only if the OCaml compiler was configured with option `-with-debug-runtime`. This suffix gives the debug version of the runtime, which is useful for debugging pointer problems in low-level code such as C stubs.

`-S`
: Keep the assembly code produced during the compilation. The assembly code for the source file *x*`.ml` is saved in the file *x*`.s`.

`-shared`
: Build a plugin (usually `.cmxs`) that can be dynamically loaded with the `Dynlink` module. The name of the plugin must be set with the `-o` option. A plugin can include a number of OCaml modules and libraries, and extra native objects (`.o`, `.obj`, `.a`, `.lib` files). Building native plugins is only supported for some operating system. Under some systems (currently, only Linux AMD 64), all the OCaml code linked in a plugin must have been compiled without the `-nodynlink` flag. Some constraints might also apply to the way the extra native objects have been compiled (under Linux AMD 64, they must contain only position-independent code).

`-safe-string`
: Enforce the separation between types `string` and `bytes`, thereby making strings read-only. This will become the default in a future version of OCaml.

`-short-paths`
: When a type is visible under several module-paths, use the shortest one when printing the type's name in inferred interfaces and error and warning messages. Identifier names starting with an underscore `_` or containing double underscores `__` incur a penalty of +10 when computing their length.

`-strict-sequence`
: Force the left-hand part of each sequence to have type unit.

`-strict-formats`
: Reject invalid formats that were accepted in legacy format implementations. You should use this flag to detect and fix such invalid formats, as they will be rejected by future OCaml versions.

`-thread`
: Compile or link multithreaded programs, in combination with the system `threads` library described in chapter 26.

`-unboxed-types`
: When a type is unboxable (i.e. a record with a single argument or a concrete datatype with a single constructor of one argument) it will be unboxed unless annotated with `[@@ocaml.boxed]`.

`-no-unboxed-types`
: When a type is unboxable it will be boxed unless annotated with `[@@ocaml.unboxed]`. This is the default.

`-unsafe`
: Turn bound checking off for array and string accesses (the `v.(i)` and `s.[i]` constructs). Programs compiled with `-unsafe` are therefore faster, but unsafe: anything can happen if the program accesses an array or string outside of its bounds. Additionally, turn off the check for zero divisor in integer division and modulus operations. With `-unsafe`, an integer division (or modulus) by zero can halt the program or continue with an unspecified result instead of raising a `Division_by_zero` exception.

`-unsafe-string`
: Identify the types `string` and `bytes`, thereby making strings writable. For reasons of backward compatibility, this is the default setting for the moment, but this will change in a future version of OCaml.

`-v`
: Print the version number of the compiler and the location of the standard library directory, then exit.

`-verbose`
: Print all external commands before they are executed, in particular invocations of the assembler, C compiler, and linker.

`-version` **or** `-vnum`
: Print the version number of the compiler in short form (e.g. `3.11.0`), then exit.

`-w` *warning-list*
: Enable, disable, or mark as fatal the warnings specified by the argument *warning-list*. Each warning can be *enabled* or *disabled*, and each warning can be *fatal* or *non-fatal*. If a warning is disabled, it isn't displayed and doesn't affect compilation in any way (even if it is fatal). If a warning is enabled, it is displayed normally by the compiler whenever the source code triggers it. If it is enabled and fatal, the compiler will also stop with an error after displaying it.

  The *warning-list* argument is a sequence of warning specifiers, with no separators between them. A warning specifier is one of the following:

  `+`*num*
  : Enable warning number *num*.

  `-`*num*
  : Disable warning number *num*.

  `@`*num*
  : Enable and mark as fatal warning number *num*.

  `+`*num1*`..`*num2*
  : Enable warnings in the given range.

  `-`*num1*`..`*num2*
  : Disable warnings in the given range.

  `@`*num1*`..`*num2*
  : Enable and mark as fatal warnings in the given range.

+*letter*
: Enable the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

-*letter*
: Disable the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

@*letter*
: Enable and mark as fatal the set of warnings corresponding to *letter*. The letter may be uppercase or lowercase.

uppercase-letter
: Enable the set of warnings corresponding to *uppercase-letter*.

lowercase-letter
: Disable the set of warnings corresponding to *lowercase-letter*.

Warning numbers and letters which are out of the range of warnings that are currently defined are ignored. The warning are as follows.

1 Suspicious-looking start-of-comment mark.

2 Suspicious-looking end-of-comment mark.

3 Deprecated feature.

4 Fragile pattern matching: matching that will remain complete even if additional constructors are added to one of the variant types matched.

5 Partially applied function: expression whose result has function type and is ignored.

6 Label omitted in function application.

7 Method overridden.

8 Partial match: missing cases in pattern-matching.

9 Missing fields in a record pattern.

10 Expression on the left-hand side of a sequence that doesn't have type `unit` (and that is not a function, see warning number 5).

11 Redundant case in a pattern matching (unused match case).

12 Redundant sub-pattern in a pattern-matching.

13 Instance variable overridden.

14 Illegal backslash escape in a string constant.

15 Private method made public implicitly.

16 Unerasable optional argument.

17 Undeclared virtual method.

18 Non-principal type.

19 Type without principality.

20 Unused function argument.

21 Non-returning statement.

22 Preprocessor warning.

23 Useless record `with` clause.

24 Bad module name: the source file name is not a valid OCaml module name.

26 Suspicious unused variable: unused variable that is bound with `let` or `as`, and doesn't start with an underscore (`_`) character.

27 Innocuous unused variable: unused variable that is not bound with `let` nor `as`, and doesn't start with an underscore (`_`) character.

28 Wildcard pattern given as argument to a constant constructor.

29 Unescaped end-of-line in a string constant (non-portable code).

30 Two labels or constructors of the same name are defined in two mutually recursive types.

31 A module is linked twice in the same executable.

32 Unused value declaration.

33 Unused open statement.

34 Unused type declaration.

35 Unused for-loop index.

36 Unused ancestor variable.

37 Unused constructor.

38 Unused extension constructor.

39 Unused rec flag.

40 Constructor or label name used out of scope.

41 Ambiguous constructor or label name.

42 Disambiguated constructor or label name (compatibility warning).

43 Nonoptional label applied as optional.

44 Open statement shadows an already defined identifier.

45 Open statement shadows an already defined label or constructor.

46 Error in environment variable.

47 Illegal attribute payload.

48 Implicit elimination of optional arguments.

49 Absent cmi file when looking up module alias.

50 Unexpected documentation comment.

51 Warning on non-tail calls if @tailcall present.

52 (see 8.5.1)
Fragile constant pattern.

53 Attribute cannot appear in this context

54 Attribute used more than once on an expression

55 Inlining impossible

56 Unreachable case in a pattern-matching (based on type information).

57 (see 8.5.2)
Ambiguous or-pattern variables under guard

58 Missing cmx file

59 Assignment to non-mutable value

60 Unused module declaration

A all warnings

C warnings 1, 2.

D Alias for warning 3.

E Alias for warning 4.

F Alias for warning 5.

K warnings 32, 33, 34, 35, 36, 37, 38, 39.

L Alias for warning 6.

M Alias for warning 7.

P Alias for warning 8.

R Alias for warning 9.

S Alias for warning 10.

U warnings 11, 12.

V Alias for warning 13.

X warnings 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 30.

Y Alias for warning 26.

Z Alias for warning 27.

The default setting is `-w +a-4-6-7-9-27-29-32..39-41..42-44-45-48-50`. It is displayed by `ocamlopt -help`. Note that warnings 5 and 10 are not always triggered, depending on the internals of the type checker.

`-warn-error` *warning-list*
Mark as fatal the warnings specified in the argument *warning-list*. The compiler will stop with an error when one of these warnings is emitted. The *warning-list* has the same meaning as for the `-w` option: a `+` sign (or an uppercase letter) marks the corresponding warnings as fatal, a `-` sign (or a lowercase letter) turns them back into non-fatal warnings, and a `@` sign both enables and marks as fatal the corresponding warnings.

Note: it is not recommended to use warning sets (i.e. letters) as arguments to `-warn-error` in production code, because this can break your build when future versions of OCaml add some new warnings.

The default setting is `-warn-error -a+31` (only warning 31 is fatal).

`-warn-help`
Show the description of all available warning numbers.

`-where`
Print the location of the standard library, then exit.

`-` *file*
Process *file* as a file name, even if it starts with a dash (-) character.

`-help` **or** `--help`
Display a short usage summary and exit.

Options for the IA32 architecture The IA32 code generator (Intel Pentium, AMD Athlon) supports the following additional option:

`-ffast-math`
Use the IA32 instructions to compute trigonometric and exponential functions, instead of calling the corresponding library routines. The functions affected are: `atan`, `atan2`, `cos`, `log`, `log10`, `sin`, `sqrt` and `tan`. The resulting code runs faster, but the range of supported arguments and the precision of the result can be reduced. In particular, trigonometric operations `cos`, `sin`, `tan` have their range reduced to $[-2^{64}, 2^{64}]$.

Options for the AMD64 architecture The AMD64 code generator (64-bit versions of Intel Pentium and AMD Athlon) supports the following additional options:

`-fPIC`
Generate position-independent machine code. This is the default.

`-fno-PIC`
Generate position-dependent machine code.

Options for the Sparc architecture The Sparc code generator supports the following additional options:

`-march=v8`
Generate SPARC version 8 code.

`-march=v9`
Generate SPARC version 9 code.

The default is to generate code for SPARC version 7, which runs on all SPARC processors.

Contextual control of command-line options

The compiler command line can be modified "from the outside" with the following mechanisms. These are experimental and subject to change. They should be used only for experimental and development work, not in released packages.

`OCAMLPARAM` (environment variable)
: Arguments that will be inserted before or after the arguments from the command line.

`ocaml_compiler_internal_params` (file in the stdlib directory)
: A mapping of file names to lists of arguments that will be added to the command line (and `OCAMLPARAM`) arguments.

`OCAML_FLEXLINK` (environment variable)
: Alternative executable to use on native Windows for `flexlink` instead of the configured value. Primarily used for bootstrapping.

11.3 Common errors

The error messages are almost identical to those of `ocamlc`. See section 8.4.

11.4 Running executables produced by ocamlopt

Executables generated by `ocamlopt` are native, stand-alone executable files that can be invoked directly. They do not depend on the `ocamlrun` bytecode runtime system nor on dynamically-loaded C/OCaml stub libraries.

During execution of an `ocamlopt`-generated executable, the following environment variables are also consulted:

`OCAMLRUNPARAM`
: Same usage as in `ocamlrun` (see section 10.2), except that option `l` is ignored (the operating system's stack size limit is used instead).

`CAMLRUNPARAM`
: If `OCAMLRUNPARAM` is not found in the environment, then `CAMLRUNPARAM` will be used instead. If `CAMLRUNPARAM` is not found, then the default values will be used.

11.5 Compatibility with the bytecode compiler

This section lists the known incompatibilities between the bytecode compiler and the native-code compiler. Except on those points, the two compilers should generate code that behave identically.

- Signals are detected only when the program performs an allocation in the heap. That is, if a signal is delivered while in a piece of code that does not allocate, its handler will not be called until the next heap allocation.
- Stack overflow, typically caused by excessively deep recursion, is handled in one of the following ways, depending on the platform used:
  - By raising a `Stack_overflow` exception, like the bytecode compiler does. (IA32/Linux, AMD64/Linux, PowerPC/MacOSX, MS Windows 32-bit ports).
  - By aborting the program on a "segmentation fault" signal. (All other Unix systems.)

  - By terminating the program silently. (MS Windows 64 bits).

- On IA32 processors only (Intel and AMD x86 processors in 32-bit mode), some intermediate results in floating-point computations are kept in extended precision rather than being rounded to double precision like the bytecode compiler always does. Floating-point results can therefore differ slightly between bytecode and native code.

Chapter 12

Lexer and parser generators (ocamllex, ocamlyacc)

This chapter describes two program generators: `ocamllex`, that produces a lexical analyzer from a set of regular expressions with associated semantic actions, and `ocamlyacc`, that produces a parser from a grammar with associated semantic actions.

These program generators are very close to the well-known `lex` and `yacc` commands that can be found in most C programming environments. This chapter assumes a working knowledge of `lex` and `yacc`: while it describes the input syntax for `ocamllex` and `ocamlyacc` and the main differences with `lex` and `yacc`, it does not explain the basics of writing a lexer or parser description in `lex` and `yacc`. Readers unfamiliar with `lex` and `yacc` are referred to "Compilers: principles, techniques, and tools" by Aho, Sethi and Ullman (Addison-Wesley, 1986), or "Lex & Yacc", by Levine, Mason and Brown (O'Reilly, 1992).

12.1 Overview of `ocamllex`

The `ocamllex` command produces a lexical analyzer from a set of regular expressions with attached semantic actions, in the style of `lex`. Assuming the input file is *lexer*`.mll`, executing

```
ocamllex lexer.mll
```

produces OCaml code for a lexical analyzer in file *lexer*`.ml`. This file defines one lexing function per entry point in the lexer definition. These functions have the same names as the entry points. Lexing functions take as argument a lexer buffer, and return the semantic attribute of the corresponding entry point.

Lexer buffers are an abstract data type implemented in the standard library module `Lexing`. The functions `Lexing.from_channel`, `Lexing.from_string` and `Lexing.from_function` create lexer buffers that read from an input channel, a character string, or any reading function, respectively. (See the description of module `Lexing` in chapter 21.)

When used in conjunction with a parser generated by `ocamlyacc`, the semantic actions compute a value belonging to the type `token` defined by the generated parsing module. (See the description of `ocamlyacc` below.)

12.1.1 Options

The following command-line options are recognized by `ocamllex`.

`-ml` Output code that does not use OCaml's built-in automata interpreter. Instead, the automaton is encoded by OCaml functions. This option mainly is useful for debugging `ocamllex`, using it for production lexers is not recommended.

`-o` *output-file*
Specify the name of the output file produced by `ocamllex`. The default is the input file name with its extension replaced by `.ml`.

`-q` Quiet mode. `ocamllex` normally outputs informational messages to standard output. They are suppressed if option `-q` is used.

`-v` **or** `-version`
Print version string and exit.

`-vnum`
Print short version number and exit.

`-help` **or** `--help`
Display a short usage summary and exit.

12.2 Syntax of lexer definitions

The format of lexer definitions is as follows:

```
{ header }
let ident = regexp ...
[refill { refill-handler }]
rule entrypoint [arg1... argn] =
  parse regexp { action }
      | ...
      | regexp { action }
and entrypoint [arg1... argn] =
  parse ...
and ...
{ trailer }
```

Comments are delimited by `(*` and `*)`, as in OCaml. The `parse` keyword, can be replaced by the `shortest` keyword, with the semantic consequences explained below.

Refill handlers are a recent (optional) feature introduced in 4.02, documented below in subsection 12.2.7.

12.2.1 Header and trailer

The *header* and *trailer* sections are arbitrary OCaml text enclosed in curly braces. Either or both can be omitted. If present, the header text is copied as is at the beginning of the output file and the trailer text at the end. Typically, the header section contains the `open` directives required by the actions, and possibly some auxiliary functions used in the actions.

12.2.2 Naming regular expressions

Between the header and the entry points, one can give names to frequently-occurring regular expressions. This is written `let` *ident* `=` *regexp*. In regular expressions that follow this declaration, the identifier *ident* can be used as shorthand for *regexp*.

12.2.3 Entry points

The names of the entry points must be valid identifiers for OCaml values (starting with a lowercase letter). Similarily, the arguments $arg_1 \ldots arg_n$ must be valid identifiers for OCaml. Each entry point becomes an OCaml function that takes $n + 1$ arguments, the extra implicit last argument being of type `Lexing.lexbuf`. Characters are read from the `Lexing.lexbuf` argument and matched against the regular expressions provided in the rule, until a prefix of the input matches one of the rule. The corresponding action is then evaluated and returned as the result of the function.

If several regular expressions match a prefix of the input, the "longest match" rule applies: the regular expression that matches the longest prefix of the input is selected. In case of tie, the regular expression that occurs earlier in the rule is selected.

However, if lexer rules are introduced with the `shortest` keyword in place of the `parse` keyword, then the "shortest match" rule applies: the shortest prefix of the input is selected. In case of tie, the regular expression that occurs earlier in the rule is still selected. This feature is not intended for use in ordinary lexical analyzers, it may facilitate the use of `ocamllex` as a simple text processing tool.

12.2.4 Regular expressions

The regular expressions are in the style of `lex`, with a more OCaml-like syntax.

regexp ::= ...

`'` *regular-char* | *escape-sequence* `'`
: A character constant, with the same syntax as OCaml character constants. Match the denoted character.

`_`
: (underscore) Match any character.

`eof`
: Match the end of the lexer input.
Note: On some systems, with interactive input, an end-of-file may be followed by more characters. However, `ocamllex` will not correctly handle regular expressions that contain `eof` followed by something else.

" {*string-character*} "
: A string constant, with the same syntax as OCaml string constants. Match the corresponding sequence of characters.

[*character-set*]
: Match any single character belonging to the given character set. Valid character sets are: single character constants 'c '; ranges of characters 'c_1 ' - 'c_2 ' (all characters between c_1 and c_2, inclusive); and the union of two or more character sets, denoted by concatenation.

[^ *character-set*]
: Match any single character not belonging to the given character set.

$regexp_1$ # $regexp_2$
: (difference of character sets) Regular expressions $regexp_1$ and $regexp_2$ must be character sets defined with [...] (or a a single character expression or underscore _). Match the difference of the two specified character sets.

regexp *
: (repetition) Match the concatenation of zero or more strings that match *regexp*.

regexp +
: (strict repetition) Match the concatenation of one or more strings that match *regexp*.

regexp ?
: (option) Match the empty string, or a string matching *regexp*.

$regexp_1$ | $regexp_2$
: (alternative) Match any string that matches $regexp_1$ or $regexp_2$

$regexp_1$ $regexp_2$
: (concatenation) Match the concatenation of two strings, the first matching $regexp_1$, the second matching $regexp_2$.

(*regexp*)
: Match the same strings as *regexp*.

ident
: Reference the regular expression bound to *ident* by an earlier let *ident* = *regexp* definition.

regexp as *ident*
: Bind the substring matched by *regexp* to identifier *ident*.

Concerning the precedences of operators, # has the highest precedence, followed by *, + and ?, then concatenation, then | (alternation), then as.

12.2.5 Actions

The actions are arbitrary OCaml expressions. They are evaluated in a context where the identifiers defined by using the as construct are bound to subparts of the matched string. Additionally, lexbuf is bound to the current lexer buffer. Some typical uses for lexbuf, in conjunction with the operations on lexer buffers provided by the Lexing standard library module, are listed below.

`Lexing.lexeme lexbuf`
: Return the matched string.

`Lexing.lexeme_char lexbuf` n
: Return the n^{th} character in the matched string. The first character corresponds to $n = 0$.

`Lexing.lexeme_start lexbuf`
: Return the absolute position in the input text of the beginning of the matched string (i.e. the offset of the first character of the matched string). The first character read from the input text has offset 0.

`Lexing.lexeme_end lexbuf`
: Return the absolute position in the input text of the end of the matched string (i.e. the offset of the first character after the matched string). The first character read from the input text has offset 0.

entrypoint [exp_1`...` exp_n] `lexbuf`
: (Where *entrypoint* is the name of another entry point in the same lexer definition.) Recursively call the lexer on the given entry point. Notice that `lexbuf` is the last argument. Useful for lexing nested comments, for example.

12.2.6 Variables in regular expressions

The `as` construct is similar to "*groups*" as provided by numerous regular expression packages. The type of these variables can be `string`, `char`, `string option` or `char option`.

We first consider the case of linear patterns, that is the case when all `as` bound variables are distinct. In *regexp* `as` *ident*, the type of *ident* normally is `string` (or `string option`) except when *regexp* is a character constant, an underscore, a string constant of length one, a character set specification, or an alternation of those. Then, the type of *ident* is `char` (or `char option`). Option types are introduced when overall rule matching does not imply matching of the bound sub-pattern. This is in particular the case of `(` *regexp* `as` *ident* `)?` and of $regexp_1$ `|` `(` $regexp_2$ `as` *ident* `)`.

There is no linearity restriction over `as` bound variables. When a variable is bound more than once, the previous rules are to be extended as follows:

- A variable is a `char` variable when all its occurrences bind `char` occurrences in the previous sense.
- A variable is an `option` variable when the overall expression can be matched without binding this variable.

For instance, in `('a' as x) | ( 'a' (_ as x) )` the variable `x` is of type `char`, whereas in `("ab" as x) | ( 'a' (_ as x) ? )` the variable `x` is of type `string option`.

In some cases, a successful match may not yield a unique set of bindings. For instance the matching of `aba` by the regular expression `(('a'|"ab") as x) (("ba"|'a') as y)` may result in binding either `x` to `"ab"` and `y` to `"a"`, or `x` to `"a"` and `y` to `"ba"`. The automata produced `ocamllex` on such ambiguous regular expressions will select one of the possible resulting sets of bindings. The selected set of bindings is purposely left unspecified.

12.2.7 Refill handlers

By default, when ocamllex reaches the end of its lexing buffer, it will silently call the `refill_buff` function of `lexbuf` structure and continue lexing. It is sometimes useful to be able to take control of refilling action; typically, if you use a library for asynchronous computation, you may want to wrap the refilling action in a delaying function to avoid blocking synchronous operations.

Since OCaml 4.02, it is possible to specify a *refill-handler*, a function that will be called when refill happens. It is passed the continuation of the lexing, on which it has total control. The OCaml expression used as refill action should have a type that is an instance of

```
(Lexing.lexbuf -> 'a) -> Lexing.lexbuf -> 'a
```

where the first argument is the continuation which captures the processing ocamllex would usually perform (refilling the buffer, then calling the lexing function again), and the result type that instantiates ['a] should unify with the result type of all lexing rules.

As an example, consider the following lexer that is parametrized over an arbitrary monad:

```
{
type token = EOL | INT of int | PLUS

module Make (M : sig
                type 'a t
                val return: 'a -> 'a t
                val bind: 'a t -> ('a -> 'b t) -> 'b t
                val fail : string -> 'a t

                (* Set up lexbuf *)
                val on_refill : Lexing.lexbuf -> unit t
              end)
= struct

let refill_handler k lexbuf =
    M.bind (M.on_refill lexbuf) (fun () -> k lexbuf)

}

refill {refill_handler}

rule token = parse
| [' ' '\t']
    { token lexbuf }
| '\n'
    { M.return EOL }
| ['0'-'9']+ as i
    { M.return (INT (int_of_string i)) }
| '+'
    { M.return PLUS }
```

```
| _
    { M.fail "unexpected character" }
{
end
}
```

12.2.8 Reserved identifiers

All identifiers starting with `__ocaml_lex` are reserved for use by `ocamllex`; do not use any such identifier in your programs.

12.3 Overview of `ocamlyacc`

The `ocamlyacc` command produces a parser from a context-free grammar specification with attached semantic actions, in the style of `yacc`. Assuming the input file is *grammar*`.mly`, executing

`ocamlyacc` *options grammar*`.mly`

produces OCaml code for a parser in the file *grammar*`.ml`, and its interface in file *grammar*`.mli`.

The generated module defines one parsing function per entry point in the grammar. These functions have the same names as the entry points. Parsing functions take as arguments a lexical analyzer (a function from lexer buffers to tokens) and a lexer buffer, and return the semantic attribute of the corresponding entry point. Lexical analyzer functions are usually generated from a lexer specification by the `ocamllex` program. Lexer buffers are an abstract data type implemented in the standard library module `Lexing`. Tokens are values from the concrete type `token`, defined in the interface file *grammar*`.mli` produced by `ocamlyacc`.

12.4 Syntax of grammar definitions

Grammar definitions have the following format:

```
%{
  header
%}
  declarations
%%
  rules
%%
  trailer
```

Comments are enclosed between `/*` and `*/` (as in C) in the "declarations" and "rules" sections, and between `(*` and `*)` (as in OCaml) in the "header" and "trailer" sections.

12.4.1 Header and trailer

The header and the trailer sections are OCaml code that is copied as is into file *grammar*`.ml`. Both sections are optional. The header goes at the beginning of the output file; it usually contains `open` directives and auxiliary functions required by the semantic actions of the rules. The trailer goes at the end of the output file.

12.4.2 Declarations

Declarations are given one per line. They all start with a `%` sign.

`%token` *constr* ... *constr*
: Declare the given symbols *constr* ... *constr* as tokens (terminal symbols). These symbols are added as constant constructors for the `token` concrete type.

`%token <` *typexpr* `>` *constr* ... *constr*
: Declare the given symbols *constr* ... *constr* as tokens with an attached attribute of the given type. These symbols are added as constructors with arguments of the given type for the `token` concrete type. The *typexpr* part is an arbitrary OCaml type expression, except that all type constructor names must be fully qualified (e.g. `Modname.typename`) for all types except standard built-in types, even if the proper `open` directives (e.g. `open Modname`) were given in the header section. That's because the header is copied only to the `.ml` output file, but not to the `.mli` output file, while the *typexpr* part of a `%token` declaration is copied to both.

`%start` *symbol* ... *symbol*
: Declare the given symbols as entry points for the grammar. For each entry point, a parsing function with the same name is defined in the output module. Non-terminals that are not declared as entry points have no such parsing function. Start symbols must be given a type with the `%type` directive below.

`%type <` *typexpr* `>` *symbol* ... *symbol*
: Specify the type of the semantic attributes for the given symbols. This is mandatory for start symbols only. Other nonterminal symbols need not be given types by hand: these types will be inferred when running the output files through the OCaml compiler (unless the `-s` option is in effect). The *typexpr* part is an arbitrary OCaml type expression, except that all type constructor names must be fully qualified, as explained above for `%token`.

`%left` *symbol* ... *symbol*

`%right` *symbol* ... *symbol*

`%nonassoc` *symbol* ... *symbol*

: Associate precedences and associativities to the given symbols. All symbols on the same line are given the same precedence. They have higher precedence than symbols declared before

in a `%left`, `%right` or `%nonassoc` line. They have lower precedence than symbols declared after in a `%left`, `%right` or `%nonassoc` line. The symbols are declared to associate to the left (`%left`), to the right (`%right`), or to be non-associative (`%nonassoc`). The symbols are usually tokens. They can also be dummy nonterminals, for use with the `%prec` directive inside the rules.

The precedence declarations are used in the following way to resolve reduce/reduce and shift/reduce conflicts:

- Tokens and rules have precedences. By default, the precedence of a rule is the precedence of its rightmost terminal. You can override this default by using the `%prec` directive in the rule.
- A reduce/reduce conflict is resolved in favor of the first rule (in the order given by the source file), and `ocamlyacc` outputs a warning.
- A shift/reduce conflict is resolved by comparing the precedence of the rule to be reduced with the precedence of the token to be shifted. If the precedence of the rule is higher, then the rule will be reduced; if the precedence of the token is higher, then the token will be shifted.
- A shift/reduce conflict between a rule and a token with the same precedence will be resolved using the associativity: if the token is left-associative, then the parser will reduce; if the token is right-associative, then the parser will shift. If the token is non-associative, then the parser will declare a syntax error.
- When a shift/reduce conflict cannot be resolved using the above method, then `ocamlyacc` will output a warning and the parser will always shift.

12.4.3 Rules

The syntax for rules is as usual:

```
nonterminal :
    symbol ... symbol { semantic-action }
  | ...
  | symbol ... symbol { semantic-action }
;
```

Rules can also contain the `%prec` *symbol* directive in the right-hand side part, to override the default precedence and associativity of the rule with the precedence and associativity of the given symbol.

Semantic actions are arbitrary OCaml expressions, that are evaluated to produce the semantic attribute attached to the defined nonterminal. The semantic actions can access the semantic attributes of the symbols in the right-hand side of the rule with the `$` notation: `$1` is the attribute for the first (leftmost) symbol, `$2` is the attribute for the second symbol, etc.

The rules may contain the special symbol `error` to indicate resynchronization points, as in `yacc`.

Actions occurring in the middle of rules are not supported.

Nonterminal symbols are like regular OCaml symbols, except that they cannot end with `'` (single quote).

12.4.4 Error handling

Error recovery is supported as follows: when the parser reaches an error state (no grammar rules can apply), it calls a function named `parse_error` with the string `"syntax error"` as argument. The default `parse_error` function does nothing and returns, thus initiating error recovery (see below). The user can define a customized `parse_error` function in the header section of the grammar file.

The parser also enters error recovery mode if one of the grammar actions raises the `Parsing.Parse_error` exception.

In error recovery mode, the parser discards states from the stack until it reaches a place where the error token can be shifted. It then discards tokens from the input until it finds three successive tokens that can be accepted, and starts processing with the first of these. If no state can be uncovered where the error token can be shifted, then the parser aborts by raising the `Parsing.Parse_error` exception.

Refer to documentation on `yacc` for more details and guidance in how to use error recovery.

12.5 Options

The `ocamlyacc` command recognizes the following options:

`-b`*prefix*
: Name the output files *prefix*`.ml`, *prefix*`.mli`, *prefix*`.output`, instead of the default naming convention.

`-q`
: This option has no effect.

`-v`
: Generate a description of the parsing tables and a report on conflicts resulting from ambiguities in the grammar. The description is put in file *grammar*`.output`.

`-version`
: Print version string and exit.

`-vnum`
: Print short version number and exit.

`-`
: Read the grammar specification from standard input. The default output file names are `stdin.ml` and `stdin.mli`.

`--` *file*
: Process *file* as the grammar specification, even if its name starts with a dash (-) character. This option must be the last on the command line.

At run-time, the `ocamlyacc`-generated parser can be debugged by setting the `p` option in the `OCAMLRUNPARAM` environment variable (see section 10.2). This causes the pushdown automaton executing the parser to print a trace of its action (tokens shifted, rules reduced, etc). The trace mentions rule numbers and state numbers that can be interpreted by looking at the file *grammar*`.output` generated by `ocamlyacc -v`.

12.6 A complete example

The all-time favorite: a desk calculator. This program reads arithmetic expressions on standard input, one per line, and prints their values. Here is the grammar definition:

```
/* File parser.mly */
%token <int> INT
%token PLUS MINUS TIMES DIV
%token LPAREN RPAREN
%token EOL
%left PLUS MINUS        /* lowest precedence */
%left TIMES DIV         /* medium precedence */
%nonassoc UMINUS        /* highest precedence */
%start main             /* the entry point */
%type <int> main
%%
main:
    expr EOL                { $1 }
;
expr:
    INT                     { $1 }
  | LPAREN expr RPAREN      { $2 }
  | expr PLUS expr          { $1 + $3 }
  | expr MINUS expr         { $1 - $3 }
  | expr TIMES expr         { $1 * $3 }
  | expr DIV expr           { $1 / $3 }
  | MINUS expr %prec UMINUS { - $2 }
;
```

Here is the definition for the corresponding lexer:

```
(* File lexer.mll *)
{
open Parser        (* The type token is defined in parser.mli *)
exception Eof
}
rule token = parse
    [' ' '\t']     { token lexbuf }     (* skip blanks *)
  | ['\n' ]        { EOL }
  | ['0'-'9']+ as lxm { INT(int_of_string lxm) }
  | '+'            { PLUS }
  | '-'            { MINUS }
  | '*'            { TIMES }
  | '/'            { DIV }
  | '('            { LPAREN }
  | ')'            { RPAREN }
  | eof            { raise Eof }
```

Here is the main program, that combines the parser with the lexer:

```
(* File calc.ml *)
let _ =
  try
    let lexbuf = Lexing.from_channel stdin in
    while true do
      let result = Parser.main Lexer.token lexbuf in
        print_int result; print_newline(); flush stdout
    done
  with Lexer.Eof ->
    exit 0
```

To compile everything, execute:

```
ocamllex lexer.mll       # generates lexer.ml
ocamlyacc parser.mly     # generates parser.ml and parser.mli
ocamlc -c parser.mli
ocamlc -c lexer.ml
ocamlc -c parser.ml
ocamlc -c calc.ml
ocamlc -o calc lexer.cmo parser.cmo calc.cmo
```

12.7 Common errors

ocamllex: transition table overflow, automaton is too big

The deterministic automata generated by `ocamllex` are limited to at most 32767 transitions. The message above indicates that your lexer definition is too complex and overflows this limit. This is commonly caused by lexer definitions that have separate rules for each of the alphabetic keywords of the language, as in the following example.

```
rule token = parse
  "keyword1"   { KWD1 }
| "keyword2"   { KWD2 }
| ...
| "keyword100" { KWD100 }
| ['A'-'Z' 'a'-'z'] ['A'-'Z' 'a'-'z' '0'-'9' '_'] * as id
               { IDENT id}
```

To keep the generated automata small, rewrite those definitions with only one general "identifier" rule, followed by a hashtable lookup to separate keywords from identifiers:

```
{ let keyword_table = Hashtbl.create 53
  let _ =
    List.iter (fun (kwd, tok) -> Hashtbl.add keyword_table kwd tok)
```

```
                [ "keyword1", KWD1;
                  "keyword2", KWD2; ...
                  "keyword100", KWD100 ]
}
rule token = parse
  ['A'-'Z' 'a'-'z'] ['A'-'Z' 'a'-'z' '0'-'9' '_'] * as id
               { try
                   Hashtbl.find keyword_table id
                 with Not_found ->
                   IDENT id }
```

ocamllex: Position memory overflow, too many bindings
The deterministic automata generated by `ocamllex` maintain a table of positions inside the scanned lexer buffer. The size of this table is limited to at most 255 cells. This error should not show up in normal situations.

12.8 Module `Depend` : Module dependencies.

```
module StringSet :
   Set.S  with type elt = string
module StringMap :
   Map.S  with type key = string
type map_tree =
  | Node of StringSet.t * bound_map
type bound_map = map_tree StringMap.t
val make_leaf : string -> map_tree
val make_node : bound_map -> map_tree
val weaken_map : StringSet.t -> map_tree -> map_tree
val free_structure_names : StringSet.t Pervasives.ref
val open_module : bound_map -> Longident.t -> bound_map
val add_use_file : bound_map -> Parsetree.toplevel_phrase list -> unit
val add_signature : bound_map -> Parsetree.signature -> unit
val add_implementation : bound_map -> Parsetree.structure -> unit
val add_implementation_binding :
  bound_map -> Parsetree.structure -> bound_map
val add_signature_binding : bound_map -> Parsetree.signature -> bound_map
```

Chapter 13

The browser/editor (ocamlbrowser)

Since OCaml version 4.02, the OCamlBrowser tool and the Labltk library are distributed separately from the OCaml compiler. The project is now hosted at `https://forge.ocamlcore.org/projects/lablt k/`.

Chapter 14

The documentation generator (ocamldoc)

This chapter describes OCamldoc, a tool that generates documentation from special comments embedded in source files. The comments used by OCamldoc are of the form `(**...*)` and follow the format described in section 14.2.

OCamldoc can produce documentation in various formats: HTML, LaTeX, TeXinfo, Unix man pages, and `dot` dependency graphs. Moreover, users can add their own custom generators, as explained in section 14.3.

In this chapter, we use the word *element* to refer to any of the following parts of an OCaml source file: a type declaration, a value, a module, an exception, a module type, a type constructor, a record field, a class, a class type, a class method, a class value or a class inheritance clause.

14.1 Usage

14.1.1 Invocation

OCamldoc is invoked via the command `ocamldoc`, as follows:

`ocamldoc` *options sourcefiles*

Options for choosing the output format

The following options determine the format for the generated documentation.

`-html`
: Generate documentation in HTML default format. The generated HTML pages are stored in the current directory, or in the directory specified with the `-d` option. You can customize the style of the generated pages by editing the generated `style.css` file, or by providing your own style sheet using option `-css-style`. The file `style.css` is not generated if it already exists or if -css-style is used.

`-latex`
: Generate documentation in LaTeX default format. The generated LaTeX document is saved in

file `ocamldoc.out`, or in the file specified with the `-o` option. The document uses the style file `ocamldoc.sty`. This file is generated when using the `-latex` option, if it does not already exist. You can change this file to customize the style of your LaTeX documentation.

`-texi`
Generate documentation in TeXinfo default format. The generated LaTeX document is saved in file `ocamldoc.out`, or in the file specified with the `-o` option.

`-man`
Generate documentation as a set of Unix `man` pages. The generated pages are stored in the current directory, or in the directory specified with the `-d` option.

`-dot`
Generate a dependency graph for the toplevel modules, in a format suitable for displaying and processing by `dot`. The `dot` tool is available from `http://www.research.att.com/sw/tools/graphviz/`. The textual representation of the graph is written to the file `ocamldoc.out`, or to the file specified with the `-o` option. Use `dot ocamldoc.out` to display it.

`-g` *file.cm[o,a,xs]*
Dynamically load the given file, which defines a custom documentation generator. See section 14.4.1. This option is supported by the `ocamldoc` command (to load `.cmo` and `.cma` files) and by its native-code version `ocamldoc.opt` (to load `.cmxs` files). If the given file is a simple one and does not exist in the current directory, then ocamldoc looks for it in the custom generators default directory, and in the directories specified with optional `-i` options.

`-customdir`
Display the custom generators default directory.

`-i` *directory*
Add the given directory to the path where to look for custom generators.

General options

`-d` *dir*
Generate files in directory *dir*, rather than the current directory.

`-dump` *file*
Dump collected information into *file*. This information can be read with the `-load` option in a subsequent invocation of `ocamldoc`.

`-hide` *modules*
Hide the given complete module names in the generated documentation. *modules* is a list of complete module names separated by '`,`', without blanks. For instance: `Pervasives,M2.M3`.

`-inv-merge-ml-mli`
Reverse the precedence of implementations and interfaces when merging. All elements in implementation files are kept, and the `-m` option indicates which parts of the comments in interface files are merged with the comments in implementation files.

`-keep-code`
: Always keep the source code for values, methods and instance variables, when available. The source code is always kept when a `.ml` file is given, but is by default discarded when a `.mli` is given. This option keeps the source code in all cases.

`-load` *file*
: Load information from *file*, which has been produced by `ocamldoc -dump`. Several `-load` options can be given.

`-m` *flags*
: Specify merge options between interfaces and implementations. (see section 14.1.2 for details). *flags* can be one or several of the following characters:

`d`	merge description
`a`	merge `@author`
`v`	merge `@version`
`l`	merge `@see`
`s`	merge `@since`
`b`	merge `@before`
`o`	merge `@deprecated`
`p`	merge `@param`
`e`	merge `@raise`
`r`	merge `@return`
`A`	merge everything

`-no-custom-tags`
: Do not allow custom @-tags (see section 14.2.5).

`-no-stop`
: Keep elements placed after/between the `(**/**)` special comment(s) (see section 14.2).

`-o` *file*
: Output the generated documentation to *file* instead of `ocamldoc.out`. This option is meaningful only in conjunction with the `-latex`, `-texi`, or `-dot` options.

`-pp` *command*
: Pipe sources through preprocessor *command*.

`-impl` *filename*
: Process the file *filename* as an implementation file, even if its extension is not `.ml`.

`-intf` *filename*
: Process the file *filename* as an interface file, even if its extension is not `.mli`.

`-text` *filename*
: Process the file *filename* as a text file, even if its extension is not `.txt`.

`-sort`
Sort the list of top-level modules before generating the documentation.

`-stars`
Remove blank characters until the first asterisk (’`*`’) in each line of comments.

`-t` *title*
Use *title* as the title for the generated documentation.

`-intro` *file*
Use content of *file* as ocamldoc text to use as introduction (HTML, LaTeX and TeXinfo only). For HTML, the file is used to create the whole `index.html` file.

`-v` Verbose mode. Display progress information.

`-version`
Print version string and exit.

`-vnum`
Print short version number and exit.

`-warn-error`
Treat Ocamldoc warnings as errors.

`-hide-warnings`
Do not print OCamldoc warnings.

`-help` **or** `--help`
Display a short usage summary and exit.

Type-checking options

OCamldoc calls the OCaml type-checker to obtain type information. The following options impact the type-checking phase. They have the same meaning as for the `ocamlc` and `ocamlopt` commands.

`-I` *directory*
Add *directory* to the list of directories search for compiled interface files (`.cmi` files).

`-nolabels`
Ignore non-optional labels in types.

`-rectypes`
Allow arbitrary recursive types. (See the `-rectypes` option to `ocamlc`.)

Options for generating HTML pages

The following options apply in conjunction with the `-html` option:

`-all-params`
Display the complete list of parameters for functions and methods.

`-charset` *charset*
: Add information about character encoding being *charset* (default is iso-8859-1).

`-colorize-code`
: Colorize the OCaml code enclosed in `[ ]` and `{[ ]}`, using colors to emphasize keywords, etc. If the code fragments are not syntactically correct, no color is added.

`-css-style` *filename*
: Use *filename* as the Cascading Style Sheet file.

`-index-only`
: Generate only index files.

`-short-functors`
: Use a short form to display functors:

```
module M : functor (A:Module) -> functor (B:Module2) -> sig .. end
```

: is displayed as:

```
module M (A:Module) (B:Module2) : sig .. end
```

Options for generating LaTeX files

The following options apply in conjunction with the `-latex` option:

`-latex-value-prefix` *prefix*
: Give a prefix to use for the labels of the values in the generated LaTeX document. The default prefix is the empty string. You can also use the options `-latex-type-prefix`, `-latex-exception-prefix`, `-latex-module-prefix`, `-latex-module-type-prefix`, `-latex-class-prefix`, `-latex-class-type-prefix`, `-latex-attribute-prefix` and `-latex-method-prefix`.

: These options are useful when you have, for example, a type and a value with the same name. If you do not specify prefixes, LaTeX will complain about multiply defined labels.

`-latextitle` *n,style*
: Associate style number *n* to the given LaTeX sectioning command *style*, e.g. `section` or `subsection`. (LaTeX only.) This is useful when including the generated document in another LaTeX document, at a given sectioning level. The default association is 1 for `section`, 2 for `subsection`, 3 for `subsubsection`, 4 for `paragraph` and 5 for `subparagraph`.

`-noheader`
: Suppress header in generated documentation.

`-notoc`
: Do not generate a table of contents.

`-notrailer`
: Suppress trailer in generated documentation.

`-sepfiles`
: Generate one `.tex` file per toplevel module, instead of the global `ocamldoc.out` file.

Options for generating TeXinfo files

The following options apply in conjunction with the `-texi` option:

`-esc8`
: Escape accented characters in Info files.

`-info-entry`
: Specify Info directory entry.

`-info-section`
: Specify section of Info directory.

`-noheader`
: Suppress header in generated documentation.

`-noindex`
: Do not build index for Info files.

`-notrailer`
: Suppress trailer in generated documentation.

Options for generating `dot` graphs

The following options apply in conjunction with the `-dot` option:

`-dot-colors` *colors*
: Specify the colors to use in the generated `dot` code. When generating module dependencies, `ocamldoc` uses different colors for modules, depending on the directories in which they reside. When generating types dependencies, `ocamldoc` uses different colors for types, depending on the modules in which they are defined. *colors* is a list of color names separated by '`,`', as in `Red,Blue,Green`. The available colors are the ones supported by the `dot` tool.

`-dot-include-all`
: Include all modules in the `dot` output, not only modules given on the command line or loaded with the `-load` option.

`-dot-reduce`
: Perform a transitive reduction of the dependency graph before outputting the `dot` code. This can be useful if there are a lot of transitive dependencies that clutter the graph.

`-dot-types`
: Output `dot` code describing the type dependency graph instead of the module dependency graph.

Options for generating man files

The following options apply in conjunction with the `-man` option:

`-man-mini`
: Generate man pages only for modules, module types, classes and class types, instead of pages for all elements.

`-man-suffix` *suffix*
: Set the suffix used for generated man filenames. Default is '`3o`', as in `List.3o`.

`-man-section` *section*
: Set the section number used for generated man filenames. Default is '`3`'.

14.1.2 Merging of module information

Information on a module can be extracted either from the `.mli` or `.ml` file, or both, depending on the files given on the command line. When both `.mli` and `.ml` files are given for the same module, information extracted from these files is merged according to the following rules:

- Only elements (values, types, classes, ...) declared in the `.mli` file are kept. In other terms, definitions from the `.ml` file that are not exported in the `.mli` file are not documented.
- Descriptions of elements and descriptions in @-tags are handled as follows. If a description for the same element or in the same @-tag of the same element is present in both files, then the description of the `.ml` file is concatenated to the one in the `.mli` file, if the corresponding `-m` flag is given on the command line. If a description is present in the `.ml` file and not in the `.mli` file, the `.ml` description is kept. In either case, all the information given in the `.mli` file is kept.

14.1.3 Coding rules

The following rules must be respected in order to avoid name clashes resulting in cross-reference errors:

- In a module, there must not be two modules, two module types or a module and a module type with the same name. In the default HTML generator, modules `ab` and `AB` will be printed to the same file on case insensitive file systems.
- In a module, there must not be two classes, two class types or a class and a class type with the same name.
- In a module, there must not be two values, two types, or two exceptions with the same name.
- Values defined in tuple, as in `let (x,y,z) = (1,2,3)` are not kept by OCamldoc.
- Avoid the following construction:

```
open Foo (* which has a module Bar with a value x *)
module Foo =
  struct
    module Bar =
      struct
        let x = 1
      end
  end
  let dummy = Bar.x
```

In this case, OCamldoc will associate `Bar.x` to the `x` of module `Foo` defined just above, instead of to the `Bar.x` defined in the opened module `Foo`.

14.2 Syntax of documentation comments

Comments containing documentation material are called *special comments* and are written between `(**` and `*)`. Special comments must start exactly with `(**`. Comments beginning with `(` and more than two `*` are ignored.

14.2.1 Placement of documentation comments

OCamldoc can associate comments to some elements of the language encountered in the source files. The association is made according to the locations of comments with respect to the language elements. The locations of comments in `.mli` and `.ml` files are different.

Comments in `.mli` files

A special comment is associated to an element if it is placed before or after the element.
A special comment before an element is associated to this element if :

- There is no blank line or another special comment between the special comment and the element. However, a regular comment can occur between the special comment and the element.
- The special comment is not already associated to the previous element.
- The special comment is not the first one of a toplevel module.

A special comment after an element is associated to this element if there is no blank line or comment between the special comment and the element.

There are two exceptions: for constructors and record fields in type definitions, the associated comment can only be placed after the constructor or field definition, without blank lines or other comments between them. The special comment for a constructor with another constructor following must be placed before the '`|`' character separating the two constructors.

The following sample interface file `foo.mli` illustrates the placement rules for comments in `.mli` files.

```
(** The first special comment of the file is the comment associated
    with the whole module.*)


(** Special comments can be placed between elements and are kept
    by the OCamldoc tool, but are not associated to any element.
    @-tags in these comments are ignored.*)

(**************************************************************)
(** Comments like the one above, with more than two asterisks,
    are ignored. *)

(** The comment for function f. *)
val f : int -> int -> int
(** The continuation of the comment for function f. *)

(** Comment for exception My_exception, even with a simple comment
    between the special comment and the exception.*)
(* Hello, I'm a simple comment :-) *)
exception My_exception of (int -> int) * int

(** Comment for type weather  *)
type weather =
| Rain of int (** The comment for constructor Rain *)
| Sun (** The comment for constructor Sun *)

(** Comment for type weather2  *)
type weather2 =
| Rain of int (** The comment for constructor Rain *)
| Sun (** The comment for constructor Sun *)
(** I can continue the comment for type weather2 here
  because there is already a comment associated to the last constructor.*)

(** The comment for type my_record *)
type my_record = {
    val foo : int ;    (** Comment for field foo *)
    val bar : string ; (** Comment for field bar *)
  }
  (** Continuation of comment for type my_record *)

(** Comment for foo *)
val foo : string
(** This comment is associated to foo and not to bar. *)
val bar : string
(** This comment is associated to bar. *)
```

```
(** The comment for class my_class *)
class my_class :
  object
    (** A comment to describe inheritance from cl *)
    inherit cl

    (** The comment for attribute tutu *)
    val mutable tutu : string

    (** The comment for attribute toto. *)
    val toto : int

    (** This comment is not attached to titi since
        there is a blank line before titi, but is kept
        as a comment in the class. *)

    val titi : string

    (** Comment for method toto *)
    method toto : string

    (** Comment for method m *)
    method m : float -> int
  end

(** The comment for the class type my_class_type *)
class type my_class_type =
  object
    (** The comment for variable x. *)
    val mutable x : int

    (** The commend for method m. *)
    method m : int -> int
end

(** The comment for module Foo *)
module Foo =
  struct
    (** The comment for x *)
    val x : int

    (** A special comment that is kept but not associated to any element *)
  end
```

```
(** The comment for module type my_module_type. *)
module type my_module_type =
  sig
    (** The comment for value x. *)
    val x : int

    (** The comment for module M. *)
    module M =
      struct
        (** The comment for value y. *)
        val y : int

        (* ... *)
      end

  end
```

Comments in `.ml` files

A special comment is associated to an element if it is placed before the element and there is no blank line between the comment and the element. Meanwhile, there can be a simple comment between the special comment and the element. There are two exceptions, for constructors and record fields in type definitions, whose associated comment must be placed after the constructor or field definition, without blank line between them. The special comment for a constructor with another constructor following must be placed before the '`|`' character separating the two constructors.

The following example of file `toto.ml` shows where to place comments in a `.ml` file.

```
(** The first special comment of the file is the comment associated
    to the whole module. *)

(** The comment for function f *)
let f x y = x + y

(** This comment is not attached to any element since there is another
    special comment just before the next element. *)

(** Comment for exception My_exception, even with a simple comment
    between the special comment and the exception.*)
(* A simple comment. *)
exception My_exception of (int -> int) * int

(** Comment for type weather  *)
type weather =
| Rain of int (** The comment for constructor Rain *)
| Sun (** The comment for constructor Sun *)
```

```
(** The comment for type my_record *)
type my_record = {
    val foo : int ;    (** Comment for field foo *)
    val bar : string ; (** Comment for field bar *)
  }

(** The comment for class my_class *)
class my_class =
    object
      (** A comment to describe inheritance from cl *)
      inherit cl

      (** The comment for the instance variable tutu *)
      val mutable tutu = "tutu"
      (** The comment for toto *)
      val toto = 1
      val titi = "titi"
      (** Comment for method toto *)
      method toto = tutu ^ "!"
      (** Comment for method m *)
      method m (f : float) = 1
    end

(** The comment for class type my_class_type *)
class type my_class_type =
  object
    (** The comment for the instance variable x. *)
    val mutable x : int
    (** The commend for method m. *)
    method m : int -> int
  end

(** The comment for module Foo *)
module Foo =
  struct
    (** The comment for x *)
    val x : int
    (** A special comment in the class, but not associated to any element. *)
  end

(** The comment for module type my_module_type. *)
module type my_module_type =
  sig
    (* Comment for value x. *)
```

```
    val x : int
    (* ... *)
  end
```

14.2.2 The Stop special comment

The special comment `(**/**)` tells OCamldoc to discard elements placed after this comment, up to the end of the current class, class type, module or module type, or up to the next stop comment. For instance:

```
class type foo =
  object
    (** comment for method m *)
    method m : string

    (**/**)

    (** This method won't appear in the documentation *)
    method bar : int
  end

(** This value appears in the documentation, since the Stop special comment
    in the class does not affect the parent module of the class.*)
val foo : string

(**/**)
(** The value bar does not appear in the documentation.*)
val bar : string
(**/**)

(** The type t appears since in the documentation since the previous stop comment
toggled off the "no documentation mode". *)
type t = string
```

The `-no-stop` option to `ocamldoc` causes the Stop special comments to be ignored.

14.2.3 Syntax of documentation comments

The inside of documentation comments `(**...*)` consists of free-form text with optional formatting annotations, followed by optional *tags* giving more specific information about parameters, version, authors, ... The tags are distinguished by a leading `@` character. Thus, a documentation comment has the following shape:

```
(** The comment begins with a description, which is text formatted
   according to the rules described in the next section.
   The description continues until the first non-escaped '@' character.
   @author Mr Smith
```

```
   @param x description for parameter x
*)
```

Some elements support only a subset of all @-tags. Tags that are not relevant to the documented element are simply ignored. For instance, all tags are ignored when documenting type constructors, record fields, and class inheritance clauses. Similarly, a `@param` tag on a class instance variable is ignored.

At last, `(**)` is the empty documentation comment.

14.2.4 Text formatting

Here is the BNF grammar for the simple markup language used to format text descriptions.

text ::= {*text-element*}$^+$

text-element ::=

`{` {`0`...`9`}$^+$ *text* `}`	format *text* as a section header; the integer following `{` indicates the sectioning level.
`{` {`0`...`9`}$^+$ `:` *label text* `}`	same, but also associate the name *label* to the current point. This point can be referenced by its fully-qualified label in a `{!` command, just like any other element.
`{b` *text* `}`	set *text* in bold.
`{i` *text* `}`	set *text* in italic.
`{e` *text* `}`	emphasize *text*.
`{C` *text* `}`	center *text*.
`{L` *text* `}`	left align *text*.
`{R` *text* `}`	right align *text*.
`{ul` *list* `}`	build a list.
`{ol` *list* `}`	build an enumerated list.
`{{:` *string* `}` *text* `}`	put a link to the given address (given as *string*) on the given *text*.
`[` *string* `]`	set the given *string* in source code style.
`{[` *string* `]}`	set the given *string* in preformatted source code style.
`{v` *string* `v}`	set the given *string* in verbatim style.
`{%` *string* `%}`	target-specific content (LaTeX code by default, see details in 14.2.4.4)
`{!` *string* `}`	insert a cross-reference to an element (see section 14.2.4.2 for the syntax of cross-references).
`{!modules:` *string string*... `}`	insert an index table for the given module names. Used in HTML only.
`{!indexlist}`	insert a table of links to the various indexes (types, values, modules, ...). Used in HTML only.
`{^` *text* `}`	set text in superscript.
`{_` *text* `}`	set text in subscript.
escaped-string	typeset the given string as is; special characters ('`{`', '`}`', '`[`', '`]`' and '`@`') must be escaped by a '`\`'
blank-line	force a new line.

14.2.4.1 List formatting

list ::=
| {`{-` *text* `}`}$^+$
| {`{li` *text* `}`}$^+$

A shortcut syntax exists for lists and enumerated lists:

```
(** Here is a {b list}
```

```
- item 1
- item 2
- item 3

The list is ended by the blank line.*)
```

is equivalent to:

```
(** Here is a {b list}
{ul {- item 1}
{- item 2}
{- item 3}}
The list is ended by the blank line.*)
```

The same shortcut is available for enumerated lists, using '+' instead of '-'. Note that only one list can be defined by this shortcut in nested lists.

14.2.4.2 Cross-reference formatting

Cross-references are fully qualified element names, as in the example `{!Foo.Bar.t}`. This is an ambiguous reference as it may designate a type name, a value name, a class name, etc. It is possible to make explicit the intended syntactic class, using `{!type:Foo.Bar.t}` to designate a type, and `{!val:Foo.Bar.t}` a value of the same name.

The list of possible syntactic class is as follows:

tag	syntactic class
`module:`	module
`modtype:`	module type
`class:`	class
`classtype:`	class type
`val:`	value
`type:`	type
`exception:`	exception
`attribute:`	attribute
`method:`	class method
`section:`	ocamldoc section
`const:`	variant constructor
`recfield:`	record field

In the case of variant constructors or record field, the constructor or field name should be preceded by the name of the correspond type – to avoid the ambiguity of several types having the same constructor names. For example, the constructor `Node` of the type `tree` will be referenced as `{!tree.Node}` or `{!const:tree.Node}`, or possibly `{!Mod1.Mod2.tree.Node}` from outside the module.

14.2.4.3 First sentence

In the description of a value, type, exception, module, module type, class or class type, the *first sentence* is sometimes used in indexes, or when just a part of the description is needed. The first sentence is composed of the first characters of the description, until

- the first dot followed by a blank, or
- the first blank line

outside of the following text formatting : `{ul` *list* `}`, `{ol` *list* `}`, `[` *string* `]`, `{[` *string* `]}`, `{v` *string* `v}`, `{%` *string* `%}`, `{!` *string* `}`, `{^` *text* `}`, `{_` *text* `}`.

14.2.4.4 Target-specific formatting

The content inside `{%foo: ... %}` is target-specific and will only be interpreted by the backend `foo`, and ignored by the others. The backends of the distribution are `latex`, `html`, `texi` and `man`. If no target is specified (syntax `{% ... %}`), `latex` is chosen by default. Custom generators may support their own target prefix.

14.2.4.5 Recognized HTML tags

The HTML tags `<b>..</b>`, `<code>..</code>`, `<i>..</i>`, `<ul>..</ul>`, `<ol>..</ol>`, `<li>..</li>`, `<center>..</center>` and `<h[0-9]>..</h[0-9]>` can be used instead of, respectively, `{b␣..}`, `[..]`, `{i␣..}`, `{ul␣..}`, `{ol␣..}`, `{li␣..}`, `{C␣..}` and `{[0-9] ..}`.

14.2.5 Documentation tags (@-tags)

Predefined tags

The following table gives the list of predefined @-tags, with their syntax and meaning.

`@author` *string*	The author of the element. One author per `@author` tag. There may be several `@author` tags for the same element.
`@deprecated` *text*	The *text* should describe when the element was deprecated, what to use as a replacement, and possibly the reason for deprecation.
`@param` *id text*	Associate the given description (*text*) to the given parameter name *id*. This tag is used for functions, methods, classes and functors.
`@raise` *Exc text*	Explain that the element may raise the exception *Exc*.
`@return` *text*	Describe the return value and its possible values. This tag is used for functions and methods.
`@see <` *URL* `>` *text*	Add a reference to the *URL* with the given *text* as comment.
`@see '`*filename*`'` *text*	Add a reference to the given file name (written between single quotes), with the given *text* as comment.
`@see "`*document-name*`"` *text*	Add a reference to the given document name (written between double quotes), with the given *text* as comment.
`@since` *string*	Indicate when the element was introduced.
`@before` *version text*	Associate the given description (*text*) to the given *version* in order to document compatibility issues.
`@version` *string*	The version number for the element.

Custom tags

You can use custom tags in the documentation comments, but they will have no effect if the generator used does not handle them. To use a custom tag, for example `foo`, just put `@foo` with some text in your comment, as in:

```
(** My comment to show you a custom tag.
@foo this is the text argument to the [foo] custom tag.
*)
```

To handle custom tags, you need to define a custom generator, as explained in section 14.3.2.

14.3 Custom generators

OCamldoc operates in two steps:

1. analysis of the source files;
2. generation of documentation, through a documentation generator, which is an object of class `Odoc_args.class_generator`.

Users can provide their own documentation generator to be used during step 2 instead of the default generators. All the information retrieved during the analysis step is available through the `Odoc_info` module, which gives access to all the types and functions representing the elements found in the given modules, with their associated description.

The files you can use to define custom generators are installed in the `ocamldoc` sub-directory of the OCaml standard library.

14.3.1 The generator modules

The type of a generator module depends on the kind of generated documentation. Here is the list of generator module types, with the name of the generator class in the module :

- for HTML : `Odoc_html.Html_generator` (class `html`),
- for LaTeX : `Odoc_latex.Latex_generator` (class `latex`),
- for TeXinfo : `Odoc_texi.Texi_generator` (class `texi`),
- for man pages : `Odoc_man.Man_generator` (class `man`),
- for graphviz (dot) : `Odoc_dot.Dot_generator` (class `dot`),
- for other kinds : `Odoc_gen.Base` (class `generator`).

That is, to define a new generator, one must implement a module with the expected signature, and with the given generator class, providing the `generate` method as entry point to make the generator generates documentation for a given list of modules :

```
method generate : Odoc_info.Module.t_module list -> unit
```

This method will be called with the list of analysed and possibly merged `Odoc_info.t_module` structures.

It is recommended to inherit from the current generator of the same kind as the one you want to define. Doing so, it is possible to load various custom generators to combine improvements brought by each one.

This is done using first class modules (see chapter 7.10).

The easiest way to define a custom generator is the following this example, here extending the current HTML generator. We don't have to know if this is the original HTML generator defined in ocamldoc or if it has been extended already by a previously loaded custom generator :

```
module Generator (G : Odoc_html.Html_generator) =
struct
  class html =
    object(self)
      inherit G.html as html
      (* ... *)

      method generate module_list =
        (* ... *)
        ()

      (* ... *)
  end
end;;

let _ = Odoc_args.extend_html_generator (module Generator : Odoc_gen.Html_functor);;
```

To know which methods to override and/or which methods are available, have a look at the different base implementations, depending on the kind of generator you are extending :

- for HTML : `odoc_html.ml`,
- for LaTeX : `odoc_latex.ml`,
- for TeXinfo : `odoc_texi.ml`,
- for man pages : `odoc_man.ml`,
- for graphviz (dot) : `odoc_dot.ml`.

14.3.2 Handling custom tags

Making a custom generator handle custom tags (see 14.2.5) is very simple.

For HTML

Here is how to develop a HTML generator handling your custom tags.

The class `Odoc_html.Generator.html` inherits from the class `Odoc_html.info`, containing a field `tag_functions` which is a list pairs composed of a custom tag (e.g. `"foo"`) and a function taking a `text` and returning HTML code (of type `string`). To handle a new tag `bar`, extend the current HTML generator and complete the `tag_functions` field:

```
module Generator (G : Odoc_html.Html_generator) =
struct
  class html =
    object(self)
      inherit G.html

      (** Return HTML code for the given text of a bar tag. *)
      method html_of_bar t = (* your code here *)

      initializer
        tag_functions <- ("bar", self#html_of_bar) :: tag_functions
  end
end
let _ = Odoc_args.extend_html_generator (module Generator : Odoc_gen.Html_functor);;
```

Another method of the class `Odoc_html.info` will look for the function associated to a custom tag and apply it to the text given to the tag. If no function is associated to a custom tag, then the method prints a warning message on `stderr`.

For other generators

You can act the same way for other kinds of generators.

14.4 Adding command line options

The command line analysis is performed after loading the module containing the documentation generator, thus allowing command line options to be added to the list of existing ones. Adding an option can be done with the function

```
Odoc_args.add_option : string * Arg.spec * string -> unit
```

Note: Existing command line options can be redefined using this function.

14.4.1 Compilation and usage

Defining a custom generator class in one file

Let `custom.ml` be the file defining a new generator class. Compilation of `custom.ml` can be performed by the following command :

```
ocamlc -I +ocamldoc -c custom.ml
```

The file `custom.cmo` is created and can be used this way :

```
ocamldoc -g custom.cmo other-options source-files
```

Options selecting a built-in generator to `ocamldoc`, such as `-html`, have no effect if a custom generator of the same kind is provided using `-g`. If the kinds do not match, the selected built-in generator is used and the custom one is ignored.

Defining a custom generator class in several files

It is possible to define a generator class in several modules, which are defined in several files *file*$_1$`.ml`[`i`], *file*$_2$`.ml`[`i`], ..., *file*$_n$`.ml`[`i`]. A `.cma` library file must be created, including all these files.

The following commands create the `custom.cma` file from files *file*$_1$`.ml`[`i`], ..., *file*$_n$`.ml`[`i`] :

```
ocamlc -I +ocamldoc -c file_1.ml[i]
ocamlc -I +ocamldoc -c file_2.ml[i]
...
ocamlc -I +ocamldoc -c file_n.ml[i]
ocamlc -o custom.cma -a file_1.cmo file_2.cmo ... file_n.cmo
```

Then, the following command uses `custom.cma` as custom generator:

```
ocamldoc -g custom.cma other-options source-files
```

Chapter 15

The debugger (ocamldebug)

This chapter describes the OCaml source-level replay debugger `ocamldebug`.

Unix:
The debugger is available on Unix systems that provide BSD sockets.

Windows:
The debugger is available under the Cygwin port of OCaml, but not under the native Win32 ports.

15.1 Compiling for debugging

Before the debugger can be used, the program must be compiled and linked with the `-g` option: all `.cmo` and `.cma` files that are part of the program should have been created with `ocamlc -g`, and they must be linked together with `ocamlc -g`.

Compiling with `-g` entails no penalty on the running time of programs: object files and bytecode executable files are bigger and take longer to produce, but the executable files run at exactly the same speed as if they had been compiled without `-g`.

15.2 Invocation

15.2.1 Starting the debugger

The OCaml debugger is invoked by running the program `ocamldebug` with the name of the bytecode executable file as first argument:

`ocamldebug` [*options*] *program* [*arguments*]

The arguments following *program* are optional, and are passed as command-line arguments to the program being debugged. (See also the `set arguments` command.)

The following command-line options are recognized:

`-c` *count*
Set the maximum number of simultaneously live checkpoints to *count*.

`-cd` *dir*
: Run the debugger program from the working directory *dir*, instead of the current directory. (See also the `cd` command.)

`-emacs`
: Tell the debugger it is executed under Emacs. (See section 15.10 for information on how to run the debugger under Emacs.)

`-I` *directory*
: Add *directory* to the list of directories searched for source files and compiled files. (See also the `directory` command.)

`-s` *socket*
: Use *socket* for communicating with the debugged program. See the description of the command `set socket` (section 15.8.6) for the format of *socket*.

`-version`
: Print version string and exit.

`-vnum`
: Print short version number and exit.

`-help` **or** `--help`
: Display a short usage summary and exit.

15.2.2 Initialization file

On start-up, the debugger will read commands from an initialization file before giving control to the user. The default file is `.ocamldebug` in the current directory if it exists, otherwise `.ocamldebug` in the user's home directory.

15.2.3 Exiting the debugger

The command `quit` exits the debugger. You can also exit the debugger by typing an end-of-file character (usually `ctrl-D`).

Typing an interrupt character (usually `ctrl-C`) will not exit the debugger, but will terminate the action of any debugger command that is in progress and return to the debugger command level.

15.3 Commands

A debugger command is a single line of input. It starts with a command name, which is followed by arguments depending on this name. Examples:

```
run
goto 1000
set arguments arg1 arg2
```

A command name can be truncated as long as there is no ambiguity. For instance, `go 1000` is understood as `goto 1000`, since there are no other commands whose name starts with `go`. For the most frequently used commands, ambiguous abbreviations are allowed. For instance, `r` stands for `run` even though there are others commands starting with `r`. You can test the validity of an abbreviation using the `help` command.

If the previous command has been successful, a blank line (typing just `RET`) will repeat it.

15.3.1 Getting help

The OCaml debugger has a simple on-line help system, which gives a brief description of each command and variable.

`help`
: Print the list of commands.

`help` *command*
: Give help about the command *command*.

`help set` *variable*, `help show` *variable*
: Give help about the variable *variable*. The list of all debugger variables can be obtained with `help set`.

`help info` *topic*
: Give help about *topic*. Use `help info` to get a list of known topics.

15.3.2 Accessing the debugger state

`set` *variable value*
: Set the debugger variable *variable* to the value *value*.

`show` *variable*
: Print the value of the debugger variable *variable*.

`info` *subject*
: Give information about the given subject. For instance, `info breakpoints` will print the list of all breakpoints.

15.4 Executing a program

15.4.1 Events

Events are "interesting" locations in the source code, corresponding to the beginning or end of evaluation of "interesting" sub-expressions. Events are the unit of single-stepping (stepping goes to the next or previous event encountered in the program execution). Also, breakpoints can only be set at events. Thus, events play the role of line numbers in debuggers for conventional languages.

During program execution, a counter is incremented at each event encountered. The value of this counter is referred as the *current time*. Thanks to reverse execution, it is possible to jump back and forth to any time of the execution.

Here is where the debugger events (written $\bowtie$) are located in the source code:

- Following a function application:

  `(f arg)`⋈

- On entrance to a function:

  `fun x y z ->` ⋈ `...`

- On each case of a pattern-matching definition (function, `match`...`with` construct, `try`...`with` construct):

```
function pat1 -> ⋈ expr1
       | ...
       | patN -> ⋈ exprN
```

- Between subexpressions of a sequence:

  `expr1;` ⋈ `expr2;` ⋈ `...;` ⋈ `exprN`

- In the two branches of a conditional expression:

  `if cond then` ⋈ `expr1 else` ⋈ `expr2`

- At the beginning of each iteration of a loop:

```
while cond do ⋈ body done
for i = a to b do ⋈ body done
```

Exceptions: A function application followed by a function return is replaced by the compiler by a jump (tail-call optimization). In this case, no event is put after the function application.

15.4.2 Starting the debugged program

The debugger starts executing the debugged program only when needed. This allows setting breakpoints or assigning debugger variables before execution starts. There are several ways to start execution:

`run` Run the program until a breakpoint is hit, or the program terminates.

`goto 0`
: Load the program and stop on the first event.

`goto` *time*
: Load the program and execute it until the given time. Useful when you already know approximately at what time the problem appears. Also useful to set breakpoints on function values that have not been computed at time 0 (see section 15.5).

The execution of a program is affected by certain information it receives when the debugger starts it, such as the command-line arguments to the program and its working directory. The debugger provides commands to specify this information (`set arguments` and `cd`). These commands must be used before program execution starts. If you try to change the arguments or the working directory after starting your program, the debugger will kill the program (after asking for confirmation).

15.4.3 Running the program

The following commands execute the program forward or backward, starting at the current time. The execution will stop either when specified by the command or when a breakpoint is encountered.

`run` Execute the program forward from current time. Stops at next breakpoint or when the program terminates.

`reverse`
Execute the program backward from current time. Mostly useful to go to the last breakpoint encountered before the current time.

`step` [*count*]
Run the program and stop at the next event. With an argument, do it *count* times. If *count* is 0, run until the program terminates or a breakpoint is hit.

`backstep` [*count*]
Run the program backward and stop at the previous event. With an argument, do it *count* times.

`next` [*count*]
Run the program and stop at the next event, skipping over function calls. With an argument, do it *count* times.

`previous` [*count*]
Run the program backward and stop at the previous event, skipping over function calls. With an argument, do it *count* times.

`finish`
Run the program until the current function returns.

`start`
Run the program backward and stop at the first event before the current function invocation.

15.4.4 Time travel

You can jump directly to a given time, without stopping on breakpoints, using the `goto` command.

As you move through the program, the debugger maintains an history of the successive times you stop at. The `last` command can be used to revisit these times: each `last` command moves one step back through the history. That is useful mainly to undo commands such as `step` and `next`.

`goto` *time*
Jump to the given time.

`last` [*count*]
Go back to the latest time recorded in the execution history. With an argument, do it *count* times.

`set history` *size*
Set the size of the execution history.

15.4.5 Killing the program

`kill`
: Kill the program being executed. This command is mainly useful if you wish to recompile the program without leaving the debugger.

15.5 Breakpoints

A breakpoint causes the program to stop whenever a certain point in the program is reached. It can be set in several ways using the `break` command. Breakpoints are assigned numbers when set, for further reference. The most comfortable way to set breakpoints is through the Emacs interface (see section 15.10).

`break`
: Set a breakpoint at the current position in the program execution. The current position must be on an event (i.e., neither at the beginning, nor at the end of the program).

`break` *function*
: Set a breakpoint at the beginning of *function*. This works only when the functional value of the identifier *function* has been computed and assigned to the identifier. Hence this command cannot be used at the very beginning of the program execution, when all identifiers are still undefined; use `goto` *time* to advance execution until the functional value is available.

`break @` [*module*] *line*
: Set a breakpoint in module *module* (or in the current module if *module* is not given), at the first event of line *line*.

`break @` [*module*] *line column*
: Set a breakpoint in module *module* (or in the current module if *module* is not given), at the event closest to line *line*, column *column*.

`break @` [*module*] `#` *character*
: Set a breakpoint in module *module* at the event closest to character number *character*.

`break` *address*
: Set a breakpoint at the code address *address*.

`delete` [*breakpoint-numbers*]
: Delete the specified breakpoints. Without argument, all breakpoints are deleted (after asking for confirmation).

`info breakpoints`
: Print the list of all breakpoints.

15.6 The call stack

Each time the program performs a function application, it saves the location of the application (the return address) in a block of data called a stack frame. The frame also contains the local variables

of the caller function. All the frames are allocated in a region of memory called the call stack. The command `backtrace` (or `bt`) displays parts of the call stack.

At any time, one of the stack frames is "selected" by the debugger; several debugger commands refer implicitly to the selected frame. In particular, whenever you ask the debugger for the value of a local variable, the value is found in the selected frame. The commands `frame`, `up` and `down` select whichever frame you are interested in.

When the program stops, the debugger automatically selects the currently executing frame and describes it briefly as the `frame` command does.

`frame`
: Describe the currently selected stack frame.

`frame` *frame-number*
: Select a stack frame by number and describe it. The frame currently executing when the program stopped has number 0; its caller has number 1; and so on up the call stack.

`backtrace` [*count*], `bt` [*count*]
: Print the call stack. This is useful to see which sequence of function calls led to the currently executing frame. With a positive argument, print only the innermost *count* frames. With a negative argument, print only the outermost -*count* frames.

`up` [*count*]
: Select and display the stack frame just "above" the selected frame, that is, the frame that called the selected frame. An argument says how many frames to go up.

`down` [*count*]
: Select and display the stack frame just "below" the selected frame, that is, the frame that was called by the selected frame. An argument says how many frames to go down.

15.7 Examining variable values

The debugger can print the current value of simple expressions. The expressions can involve program variables: all the identifiers that are in scope at the selected program point can be accessed.

Expressions that can be printed are a subset of OCaml expressions, as described by the following grammar:

simple-expr ::= *lowercase-ident*
| {*capitalized-ident* `.`} *lowercase-ident*
| `*`
| `$` *integer*
| *simple-expr* `.` *lowercase-ident*
| *simple-expr* `.(` *integer* `)`
| *simple-expr* `.[` *integer* `]`
| `!` *simple-expr*
| `(` *simple-expr* `)`

The first two cases refer to a value identifier, either unqualified or qualified by the path to the structure that define it. `*` refers to the result just computed (typically, the value of a function

application), and is valid only if the selected event is an "after" event (typically, a function application). `$` *integer* refer to a previously printed value. The remaining four forms select part of an expression: respectively, a record field, an array element, a string element, and the current contents of a reference.

`print` *variables*
: Print the values of the given variables. `print` can be abbreviated as `p`.

`display` *variables*
: Same as `print`, but limit the depth of printing to 1. Useful to browse large data structures without printing them in full. `display` can be abbreviated as `d`.

When printing a complex expression, a name of the form `$`*integer* is automatically assigned to its value. Such names are also assigned to parts of the value that cannot be printed because the maximal printing depth is exceeded. Named values can be printed later on with the commands `p $`*integer* or `d $`*integer*. Named values are valid only as long as the program is stopped. They are forgotten as soon as the program resumes execution.

`set print_depth` *d*
: Limit the printing of values to a maximal depth of *d*.

`set print_length` *l*
: Limit the printing of values to at most *l* nodes printed.

15.8 Controlling the debugger

15.8.1 Setting the program name and arguments

`set program` *file*
: Set the program name to *file*.

`set arguments` *arguments*
: Give *arguments* as command-line arguments for the program.

A shell is used to pass the arguments to the debugged program. You can therefore use wildcards, shell variables, and file redirections inside the arguments. To debug programs that read from standard input, it is recommended to redirect their input from a file (using `set arguments < input-file`), otherwise input to the program and input to the debugger are not properly separated, and inputs are not properly replayed when running the program backwards.

15.8.2 How programs are loaded

The `loadingmode` variable controls how the program is executed.

`set loadingmode direct`
: The program is run directly by the debugger. This is the default mode.

`set loadingmode runtime`
: The debugger execute the OCaml runtime `ocamlrun` on the program. Rarely useful; moreover it prevents the debugging of programs compiled in "custom runtime" mode.

`set loadingmode manual`
: The user starts manually the program, when asked by the debugger. Allows remote debugging (see section 15.8.6).

15.8.3 Search path for files

The debugger searches for source files and compiled interface files in a list of directories, the search path. The search path initially contains the current directory `.` and the standard library directory. The `directory` command adds directories to the path.

Whenever the search path is modified, the debugger will clear any information it may have cached about the files.

`directory` *directorynames*
: Add the given directories to the search path. These directories are added at the front, and will therefore be searched first.

`directory` *directorynames* `for` *modulename*
: Same as `directory` *directorynames*, but the given directories will be searched only when looking for the source file of a module that has been packed into *modulename*.

`directory`
: Reset the search path. This requires confirmation.

15.8.4 Working directory

Each time a program is started in the debugger, it inherits its working directory from the current working directory of the debugger. This working directory is initially whatever it inherited from its parent process (typically the shell), but you can specify a new working directory in the debugger with the `cd` command or the `-cd` command-line option.

`cd` *directory*
: Set the working directory for `ocamldebug` to *directory*.

`pwd` Print the working directory for `ocamldebug`.

15.8.5 Turning reverse execution on and off

In some cases, you may want to turn reverse execution off. This speeds up the program execution, and is also sometimes useful for interactive programs.

Normally, the debugger takes checkpoints of the program state from time to time. That is, it makes a copy of the current state of the program (using the Unix system call `fork`). If the variable *checkpoints* is set to `off`, the debugger will not take any checkpoints.

`set checkpoints` *on/off*
: Select whether the debugger makes checkpoints or not.

15.8.6 Communication between the debugger and the program

The debugger communicate with the program being debugged through a Unix socket. You may need to change the socket name, for example if you need to run the debugger on a machine and your program on another.

`set socket` *socket*
: Use *socket* for communication with the program. *socket* can be either a file name, or an Internet port specification *host*:*port*, where *host* is a host name or an Internet address in dot notation, and *port* is a port number on the host.

On the debugged program side, the socket name is passed through the `CAML_DEBUG_SOCKET` environment variable.

15.8.7 Fine-tuning the debugger

Several variables enables to fine-tune the debugger. Reasonable defaults are provided, and you should normally not have to change them.

`set processcount` *count*
: Set the maximum number of checkpoints to *count*. More checkpoints facilitate going far back in time, but use more memory and create more Unix processes.

As checkpointing is quite expensive, it must not be done too often. On the other hand, backward execution is faster when checkpoints are taken more often. In particular, backward single-stepping is more responsive when many checkpoints have been taken just before the current time. To fine-tune the checkpointing strategy, the debugger does not take checkpoints at the same frequency for long displacements (e.g. `run`) and small ones (e.g. `step`). The two variables `bigstep` and `smallstep` contain the number of events between two checkpoints in each case.

`set bigstep` *count*
: Set the number of events between two checkpoints for long displacements.

`set smallstep` *count*
: Set the number of events between two checkpoints for small displacements.

The following commands display information on checkpoints and events:

`info checkpoints`
: Print a list of checkpoints.

`info events` [*module*]
: Print the list of events in the given module (the current module, by default).

15.8.8 User-defined printers

Just as in the toplevel system (section 9.2), the user can register functions for printing values of certain types. For technical reasons, the debugger cannot call printing functions that reside in the program being debugged. The code for the printing functions must therefore be loaded explicitly in the debugger.

`load_printer "`*file-name*`"`
: Load in the debugger the indicated `.cmo` or `.cma` object file. The file is loaded in an environment consisting only of the OCaml standard library plus the definitions provided by object files previously loaded using `load_printer`. If this file depends on other object files not yet loaded, the debugger automatically loads them if it is able to find them in the search path. The loaded file does not have direct access to the modules of the program being debugged.

`install_printer` *printer-name*
: Register the function named *printer-name* (a value path) as a printer for objects whose types match the argument type of the function. That is, the debugger will call *printer-name* when it has such an object to print. The printing function *printer-name* must use the `Format` library module to produce its output, otherwise its output will not be correctly located in the values printed by the toplevel loop.

  The value path *printer-name* must refer to one of the functions defined by the object files loaded using `load_printer`. It cannot reference the functions of the program being debugged.

`remove_printer` *printer-name*
: Remove the named function from the table of value printers.

15.9 Miscellaneous commands

`list` [*module*] [*beginning*] [*end*]
: List the source of module *module*, from line number *beginning* to line number *end*. By default, 20 lines of the current module are displayed, starting 10 lines before the current position.

`source` *filename*
: Read debugger commands from the script *filename*.

15.10 Running the debugger under Emacs

The most user-friendly way to use the debugger is to run it under Emacs. See the file `emacs/README` in the distribution for information on how to load the Emacs Lisp files for OCaml support.

The OCaml debugger is started under Emacs by the command `M-x camldebug`, with argument the name of the executable file *progname* to debug. Communication with the debugger takes place in an Emacs buffer named `*camldebug-`*progname*`*`. The editing and history facilities of Shell mode are available for interacting with the debugger.

In addition, Emacs displays the source files containing the current event (the current position in the program execution) and highlights the location of the event. This display is updated synchronously with the debugger action.

The following bindings for the most common debugger commands are available in the `*camldebug-`*`progname`*`*` buffer:

`C-c C-s`
: (command `step`): execute the program one step forward.

`C-c C-k`
: (command `backstep`): execute the program one step backward.

`C-c C-n`
: (command `next`): execute the program one step forward, skipping over function calls.

Middle mouse button
: (command `display`): display named value. `$`*n* under mouse cursor (support incremental browsing of large data structures).

`C-c C-p`
: (command `print`): print value of identifier at point.

`C-c C-d`
: (command `display`): display value of identifier at point.

`C-c C-r`
: (command `run`): execute the program forward to next breakpoint.

`C-c C-v`
: (command `reverse`): execute the program backward to latest breakpoint.

`C-c C-l`
: (command `last`): go back one step in the command history.

`C-c C-t`
: (command `backtrace`): display backtrace of function calls.

`C-c C-f`
: (command `finish`): run forward till the current function returns.

`C-c <`
: (command `up`): select the stack frame below the current frame.

`C-c >`
: (command `down`): select the stack frame above the current frame.

In all buffers in OCaml editing mode, the following debugger commands are also available:

`C-x C-a C-b`
: (command `break`): set a breakpoint at event closest to point

`C-x C-a C-p`
: (command `print`): print value of identifier at point

`C-x C-a C-d`
: (command `display`): display value of identifier at point

Chapter 16

Profiling (ocamlprof)

This chapter describes how the execution of OCaml programs can be profiled, by recording how many times functions are called, branches of conditionals are taken, ...

16.1 Compiling for profiling

Before profiling an execution, the program must be compiled in profiling mode, using the `ocamlcp` front-end to the `ocamlc` compiler (see chapter 8) or the `ocamloptp` front-end to the `ocamlopt` compiler (see chapter 11). When compiling modules separately, `ocamlcp` or `ocamloptp` must be used when compiling the modules (production of `.cmo` or `.cmx` files), and can also be used (though this is not strictly necessary) when linking them together.

Note If a module (`.ml` file) doesn't have a corresponding interface (`.mli` file), then compiling it with `ocamlcp` will produce object files (`.cmi` and `.cmo`) that are not compatible with the ones produced by `ocamlc`, which may lead to problems (if the `.cmi` or `.cmo` is still around) when switching between profiling and non-profiling compilations. To avoid this problem, you should always have a `.mli` file for each `.ml` file. The same problem exists with `ocamloptp`.

Note To make sure your programs can be compiled in profiling mode, avoid using any identifier that begins with `__ocaml_prof`.

The amount of profiling information can be controlled through the `-P` option to `ocamlcp` or `ocamloptp`, followed by one or several letters indicating which parts of the program should be profiled:

`a` all options

`f` function calls : a count point is set at the beginning of each function body

`i` **if ... then ... else ...** : count points are set in both **then** branch and **else** branch

`l` **while, for** loops: a count point is set at the beginning of the loop body

`m` **match** branches: a count point is set at the beginning of the body of each branch

`t` **try ... with ...** branches: a count point is set at the beginning of the body of each branch

For instance, compiling with `ocamlcp -P film` profiles function calls, if... then... else..., loops and pattern matching.

Calling `ocamlcp` or `ocamloptp` without the `-P` option defaults to `-P fm`, meaning that only function calls and pattern matching are profiled.

Note For compatibility with previous releases, `ocamlcp` also accepts the `-p` option, with the same arguments and behaviour as `-P`.

The `ocamlcp` and `ocamloptp` commands also accept all the options of the corresponding `ocamlc` or `ocamlopt` compiler, except the `-pp` (preprocessing) option.

16.2 Profiling an execution

Running an executable that has been compiled with `ocamlcp` or `ocamloptp` records the execution counts for the specified parts of the program and saves them in a file called `ocamlprof.dump` in the current directory.

If the environment variable `OCAMLPROF_DUMP` is set when the program exits, its value is used as the file name instead of `ocamlprof.dump`.

The dump file is written only if the program terminates normally (by calling `exit` or by falling through). It is not written if the program terminates with an uncaught exception.

If a compatible dump file already exists in the current directory, then the profiling information is accumulated in this dump file. This allows, for instance, the profiling of several executions of a program on different inputs. Note that dump files produced by byte-code executables (compiled with `ocamlcp`) are compatible with the dump files produced by native executables (compiled with `ocamloptp`).

16.3 Printing profiling information

The `ocamlprof` command produces a source listing of the program modules where execution counts have been inserted as comments. For instance,

```
ocamlprof foo.ml
```

prints the source code for the `foo` module, with comments indicating how many times the functions in this module have been called. Naturally, this information is accurate only if the source file has not been modified after it was compiled.

The following options are recognized by `ocamlprof`:

`-f` *dumpfile*
: Specifies an alternate dump file of profiling information to be read.

`-F` *string*
: Specifies an additional string to be output with profiling information. By default, `ocamlprof` will annotate programs with comments of the form `(*` *n* `*)` where *n* is the counter value for a profiling point. With option `-F` *s*, the annotation will be `(*` *sn* `*)`.

`-impl` *filename*
: Process the file *filename* as an implementation file, even if its extension is not `.ml`.

`-intf` *filename*
: Process the file *filename* as an interface file, even if its extension is not `.mli`.

`-version`
: Print version string and exit.

`-vnum`
: Print short version number and exit.

`-help` **or** `--help`
: Display a short usage summary and exit.

16.4 Time profiling

Profiling with `ocamlprof` only records execution counts, not the actual time spent within each function. There is currently no way to perform time profiling on bytecode programs generated by `ocamlc`.

Native-code programs generated by `ocamlopt` can be profiled for time and execution counts using the `-p` option and the standard Unix profiler `gprof`. Just add the `-p` option when compiling and linking the program:

```
ocamlopt -o myprog -p other-options files
./myprog
gprof myprog
```

OCaml function names in the output of `gprof` have the following format:

Module-name_function-name_unique-number

Other functions shown are either parts of the OCaml run-time system or external C functions linked with the program.

The output of `gprof` is described in the Unix manual page for `gprof(1)`. It generally consists of two parts: a "flat" profile showing the time spent in each function and the number of invocation of each function, and a "hierarchical" profile based on the call graph. Currently, only the Intel x86 ports of `ocamlopt` under Linux, BSD and MacOS X support the two profiles. On other platforms, `gprof` will report only the "flat" profile with just time information. When reading the output of `gprof`, keep in mind that the accumulated times computed by `gprof` are based on heuristics and may not be exact.

Note The `ocamloptp` command also accepts the `-p` option. In that case, both kinds of profiling are performed by the program, and you can display the results with the `gprof` and `ocamlprof` commands, respectively.

Chapter 17

The ocamlbuild compilation manager

Since OCaml version 4.03, the ocamlbuild compilation manager is distributed separately from the OCaml compiler. The project is now hosted at `https://github.com/ocaml/ocamlbuild/`.

Chapter 18

Interfacing C with OCaml

This chapter describes how user-defined primitives, written in C, can be linked with OCaml code and called from OCaml functions, and how these C functions can call back to OCaml code.

18.1 Overview and compilation information

18.1.1 Declaring primitives

definition	::=	...
	|	`external` *value-name* `:` *typexpr* `=` *external-declaration*
external-declaration	::=	*string-literal* [*string-literal* [*string-literal*]]

User primitives are declared in an implementation file or `struct` ... `end` module expression using the `external` keyword:

`external` *name* `:` *type* `=` *C-function-name*

This defines the value name *name* as a function with type *type* that executes by calling the given C function. For instance, here is how the `input` primitive is declared in the standard library module `Pervasives`:

```
external input : in_channel -> bytes -> int -> int -> int
               = "input"
```

Primitives with several arguments are always curried. The C function does not necessarily have the same name as the ML function.

External functions thus defined can be specified in interface files or `sig` ... `end` signatures either as regular values

`val` *name* `:` *type*

thus hiding their implementation as C functions, or explicitly as "manifest" external functions

`external` *name* `:` *type* `=` *C-function-name*

The latter is slightly more efficient, as it allows clients of the module to call directly the C function instead of going through the corresponding OCaml function. On the other hand, it should not be used in library modules if they have side-effects at toplevel, as this direct call interferes with the linker's algorithm for removing unused modules from libraries at link-time.

The arity (number of arguments) of a primitive is automatically determined from its OCaml type in the `external` declaration, by counting the number of function arrows in the type. For instance, `input` above has arity 4, and the `input` C function is called with four arguments. Similarly,

```
external input2 : in_channel * bytes * int * int -> int = "input2"
```

has arity 1, and the `input2` C function receives one argument (which is a quadruple of OCaml values).

Type abbreviations are not expanded when determining the arity of a primitive. For instance,

```
type int_endo = int -> int
external f : int_endo -> int_endo = "f"
external g : (int -> int) -> (int -> int) = "f"
```

`f` has arity 1, but `g` has arity 2. This allows a primitive to return a functional value (as in the `f` example above): just remember to name the functional return type in a type abbreviation.

The language accepts external declarations with one or two flag strings in addition to the C function's name. These flags are reserved for the implementation of the standard library.

18.1.2 Implementing primitives

User primitives with arity $n \leq 5$ are implemented by C functions that take n arguments of type `value`, and return a result of type `value`. The type `value` is the type of the representations for OCaml values. It encodes objects of several base types (integers, floating-point numbers, strings, ...) as well as OCaml data structures. The type `value` and the associated conversion functions and macros are described in detail below. For instance, here is the declaration for the C function implementing the `input` primitive:

```
CAMLprim value input(value channel, value buffer, value offset, value length)
{
  ...
}
```

When the primitive function is applied in an OCaml program, the C function is called with the values of the expressions to which the primitive is applied as arguments. The value returned by the function is passed back to the OCaml program as the result of the function application.

User primitives with arity greater than 5 should be implemented by two C functions. The first function, to be used in conjunction with the bytecode compiler `ocamlc`, receives two arguments: a pointer to an array of OCaml values (the values for the arguments), and an integer which is the number of arguments provided. The other function, to be used in conjunction with the native-code compiler `ocamlopt`, takes its arguments directly. For instance, here are the two C functions for the 7-argument primitive `Nat.add_nat`:

```
CAMLprim value add_nat_native(value nat1, value ofs1, value len1,
                              value nat2, value ofs2, value len2,
                              value carry_in)
{
  ...
}
CAMLprim value add_nat_bytecode(value * argv, int argn)
{
  return add_nat_native(argv[0], argv[1], argv[2], argv[3],
                        argv[4], argv[5], argv[6]);
}
```

The names of the two C functions must be given in the primitive declaration, as follows:

```
external name : type =
         bytecode-C-function-name native-code-C-function-name
```

For instance, in the case of `add_nat`, the declaration is:

```
external add_nat: nat -> int -> int -> nat -> int -> int -> int
                  = "add_nat_bytecode" "add_nat_native"
```

Implementing a user primitive is actually two separate tasks: on the one hand, decoding the arguments to extract C values from the given OCaml values, and encoding the return value as an OCaml value; on the other hand, actually computing the result from the arguments. Except for very simple primitives, it is often preferable to have two distinct C functions to implement these two tasks. The first function actually implements the primitive, taking native C values as arguments and returning a native C value. The second function, often called the "stub code", is a simple wrapper around the first function that converts its arguments from OCaml values to C values, call the first function, and convert the returned C value to OCaml value. For instance, here is the stub code for the `input` primitive:

```
CAMLprim value input(value channel, value buffer, value offset, value length)
{
  return Val_long(getblock((struct channel *) channel,
                           &Byte(buffer, Long_val(offset)),
                           Long_val(length)));
}
```

(Here, `Val_long`, `Long_val` and so on are conversion macros for the type `value`, that will be described later. The `CAMLprim` macro expands to the required compiler directives to ensure that the function is exported and accessible from OCaml.) The hard work is performed by the function `getblock`, which is declared as:

```
long getblock(struct channel * channel, char * p, long n)
{
  ...
}
```

To write C code that operates on OCaml values, the following include files are provided:

Include file	Provides
`caml/mlvalues.h`	definition of the `value` type, and conversion macros
`caml/alloc.h`	allocation functions (to create structured OCaml objects)
`caml/memory.h`	miscellaneous memory-related functions and macros (for GC interface, in-place modification of structures, etc).
`caml/fail.h`	functions for raising exceptions (see section 18.4.5)
`caml/callback.h`	callback from C to OCaml (see section 18.7).
`caml/custom.h`	operations on custom blocks (see section 18.9).
`caml/intext.h`	operations for writing user-defined serialization and deserialization functions for custom blocks (see section 18.9).
`caml/threads.h`	operations for interfacing in the presence of multiple threads (see section 18.11).

These files reside in the `caml/` subdirectory of the OCaml standard library directory, which is returned by the command `ocamlc -where` (usually `/usr/local/lib/ocaml` or `/usr/lib/ocaml`).

By default, header files in the `caml/` subdirectory give only access to the public interface of the OCaml runtime. It is possible to define the macro `CAML_INTERNALS` to get access to a lower-level interface, but this lower-level interface is more likely to change and break programs that use it.

Note: It is recommended to define the macro `CAML_NAME_SPACE` before including these header files. If you do not define it, the header files will also define short names (without the `caml_` prefix) for most functions, which usually produce clashes with names defined by other C libraries that you might use. Including the header files without `CAML_NAME_SPACE` is only supported for backward compatibility.

18.1.3 Statically linking C code with OCaml code

The OCaml runtime system comprises three main parts: the bytecode interpreter, the memory manager, and a set of C functions that implement the primitive operations. Some bytecode instructions are provided to call these C functions, designated by their offset in a table of functions (the table of primitives).

In the default mode, the OCaml linker produces bytecode for the standard runtime system, with a standard set of primitives. References to primitives that are not in this standard set result in the "unavailable C primitive" error. (Unless dynamic loading of C libraries is supported – see section 18.1.4 below.)

In the "custom runtime" mode, the OCaml linker scans the object files and determines the set of required primitives. Then, it builds a suitable runtime system, by calling the native code linker with:

- the table of the required primitives;
- a library that provides the bytecode interpreter, the memory manager, and the standard primitives;
- libraries and object code files (`.o` files) mentioned on the command line for the OCaml linker, that provide implementations for the user's primitives.

This builds a runtime system with the required primitives. The OCaml linker generates bytecode for this custom runtime system. The bytecode is appended to the end of the custom runtime system, so that it will be automatically executed when the output file (custom runtime + bytecode) is launched.

To link in "custom runtime" mode, execute the `ocamlc` command with:

- the `-custom` option;
- the names of the desired OCaml object files (`.cmo` and `.cma` files) ;
- the names of the C object files and libraries (`.o` and `.a` files) that implement the required primitives. Under Unix and Windows, a library named `lib`*name*`.a` (respectively, `.lib`) residing in one of the standard library directories can also be specified as `-cclib -l`*name*.

If you are using the native-code compiler `ocamlopt`, the `-custom` flag is not needed, as the final linking phase of `ocamlopt` always builds a standalone executable. To build a mixed OCaml/C executable, execute the `ocamlopt` command with:

- the names of the desired OCaml native object files (`.cmx` and `.cmxa` files);
- the names of the C object files and libraries (`.o`, `.a`, `.so` or `.dll` files) that implement the required primitives.

Starting with Objective Caml 3.00, it is possible to record the `-custom` option as well as the names of C libraries in an OCaml library file `.cma` or `.cmxa`. For instance, consider an OCaml library `mylib.cma`, built from the OCaml object files `a.cmo` and `b.cmo`, which reference C code in `libmylib.a`. If the library is built as follows:

```
ocamlc -a -o mylib.cma -custom a.cmo b.cmo -cclib -lmylib
```

users of the library can simply link with `mylib.cma`:

```
ocamlc -o myprog mylib.cma ...
```

and the system will automatically add the `-custom` and `-cclib -lmylib` options, achieving the same effect as

```
ocamlc -o myprog -custom a.cmo b.cmo ... -cclib -lmylib
```

The alternative is of course to build the library without extra options:

```
ocamlc -a -o mylib.cma a.cmo b.cmo
```

and then ask users to provide the `-custom` and `-cclib -lmylib` options themselves at link-time:

```
ocamlc -o myprog -custom mylib.cma ... -cclib -lmylib
```

The former alternative is more convenient for the final users of the library, however.

18.1.4 Dynamically linking C code with OCaml code

Starting with Objective Caml 3.03, an alternative to static linking of C code using the `-custom` code is provided. In this mode, the OCaml linker generates a pure bytecode executable (no embedded custom runtime system) that simply records the names of dynamically-loaded libraries containing the C code. The standard OCaml runtime system `ocamlrun` then loads dynamically these libraries, and resolves references to the required primitives, before executing the bytecode.

This facility is currently supported and known to work well under Linux, MacOS X, and Windows. It is supported, but not fully tested yet, under FreeBSD, Tru64, Solaris and Irix. It is not supported yet under other Unixes.

To dynamically link C code with OCaml code, the C code must first be compiled into a shared library (under Unix) or DLL (under Windows). This involves 1- compiling the C files with appropriate C compiler flags for producing position-independent code (when required by the operating system), and 2- building a shared library from the resulting object files. The resulting shared library or DLL file must be installed in a place where `ocamlrun` can find it later at program start-up time (see section 10.3). Finally (step 3), execute the `ocamlc` command with

- the names of the desired OCaml object files (`.cmo` and `.cma` files) ;
- the names of the C shared libraries (`.so` or `.dll` files) that implement the required primitives. Under Unix and Windows, a library named `dll`*name*`.so` (respectively, `.dll`) residing in one of the standard library directories can also be specified as `-dllib -l`*name*.

Do *not* set the `-custom` flag, otherwise you're back to static linking as described in section 18.1.3. The `ocamlmklib` tool (see section 18.12) automates steps 2 and 3.

As in the case of static linking, it is possible (and recommended) to record the names of C libraries in an OCaml `.cma` library archive. Consider again an OCaml library `mylib.cma`, built from the OCaml object files `a.cmo` and `b.cmo`, which reference C code in `dllmylib.so`. If the library is built as follows:

```
ocamlc -a -o mylib.cma a.cmo b.cmo -dllib -lmylib
```

users of the library can simply link with `mylib.cma`:

```
ocamlc -o myprog mylib.cma ...
```

and the system will automatically add the `-dllib -lmylib` option, achieving the same effect as

```
ocamlc -o myprog a.cmo b.cmo ... -dllib -lmylib
```

Using this mechanism, users of the library `mylib.cma` do not need to known that it references C code, nor whether this C code must be statically linked (using `-custom`) or dynamically linked.

18.1.5 Choosing between static linking and dynamic linking

After having described two different ways of linking C code with OCaml code, we now review the pros and cons of each, to help developers of mixed OCaml/C libraries decide.

The main advantage of dynamic linking is that it preserves the platform-independence of bytecode executables. That is, the bytecode executable contains no machine code, and can therefore be

compiled on platform A and executed on other platforms B, C, ..., as long as the required shared libraries are available on all these platforms. In contrast, executables generated by `ocamlc -custom` run only on the platform on which they were created, because they embark a custom-tailored runtime system specific to that platform. In addition, dynamic linking results in smaller executables.

Another advantage of dynamic linking is that the final users of the library do not need to have a C compiler, C linker, and C runtime libraries installed on their machines. This is no big deal under Unix and Cygwin, but many Windows users are reluctant to install Microsoft Visual C just to be able to do `ocamlc -custom`.

There are two drawbacks to dynamic linking. The first is that the resulting executable is not stand-alone: it requires the shared libraries, as well as `ocamlrun`, to be installed on the machine executing the code. If you wish to distribute a stand-alone executable, it is better to link it statically, using `ocamlc -custom -ccopt -static` or `ocamlopt -ccopt -static`. Dynamic linking also raises the "DLL hell" problem: some care must be taken to ensure that the right versions of the shared libraries are found at start-up time.

The second drawback of dynamic linking is that it complicates the construction of the library. The C compiler and linker flags to compile to position-independent code and build a shared library vary wildly between different Unix systems. Also, dynamic linking is not supported on all Unix systems, requiring a fall-back case to static linking in the Makefile for the library. The `ocamlmklib` command (see section 18.12) tries to hide some of these system dependencies.

In conclusion: dynamic linking is highly recommended under the native Windows port, because there are no portability problems and it is much more convenient for the end users. Under Unix, dynamic linking should be considered for mature, frequently used libraries because it enhances platform-independence of bytecode executables. For new or rarely-used libraries, static linking is much simpler to set up in a portable way.

18.1.6 Building standalone custom runtime systems

It is sometimes inconvenient to build a custom runtime system each time OCaml code is linked with C libraries, like `ocamlc -custom` does. For one thing, the building of the runtime system is slow on some systems (that have bad linkers or slow remote file systems); for another thing, the platform-independence of bytecode files is lost, forcing to perform one `ocamlc -custom` link per platform of interest.

An alternative to `ocamlc -custom` is to build separately a custom runtime system integrating the desired C libraries, then generate "pure" bytecode executables (not containing their own runtime system) that can run on this custom runtime. This is achieved by the `-make-runtime` and `-use-runtime` flags to `ocamlc`. For example, to build a custom runtime system integrating the C parts of the "Unix" and "Threads" libraries, do:

```
ocamlc -make-runtime -o /home/me/ocamlunixrun unix.cma threads.cma
```

To generate a bytecode executable that runs on this runtime system, do:

```
ocamlc -use-runtime /home/me/ocamlunixrun -o myprog \
       unix.cma threads.cma your .cmo and .cma files
```

The bytecode executable `myprog` can then be launched as usual: `myprog` *args* or `/home/me/ocamlunixrun myprog` *args*.

Notice that the bytecode libraries `unix.cma` and `threads.cma` must be given twice: when building the runtime system (so that `ocamlc` knows which C primitives are required) and also when building the bytecode executable (so that the bytecode from `unix.cma` and `threads.cma` is actually linked in).

18.2 The `value` type

All OCaml objects are represented by the C type `value`, defined in the include file `caml/mlvalues.h`, along with macros to manipulate values of that type. An object of type `value` is either:

- an unboxed integer;
- a pointer to a block inside the heap (such as the blocks allocated through one of the `caml_alloc_*` functions below);
- a pointer to an object outside the heap (e.g., a pointer to a block allocated by `malloc`, or to a C variable).

18.2.1 Integer values

Integer values encode 63-bit signed integers (31-bit on 32-bit architectures). They are unboxed (unallocated).

18.2.2 Blocks

Blocks in the heap are garbage-collected, and therefore have strict structure constraints. Each block includes a header containing the size of the block (in words), and the tag of the block. The tag governs how the contents of the blocks are structured. A tag lower than `No_scan_tag` indicates a structured block, containing well-formed values, which is recursively traversed by the garbage collector. A tag greater than or equal to `No_scan_tag` indicates a raw block, whose contents are not scanned by the garbage collector. For the benefit of ad-hoc polymorphic primitives such as equality and structured input-output, structured and raw blocks are further classified according to their tags as follows:

Tag	Contents of the block
0 to `No_scan_tag` − 1	A structured block (an array of OCaml objects). Each field is a `value`.
`Closure_tag`	A closure representing a functional value. The first word is a pointer to a piece of code, the remaining words are `value` containing the environment.
`String_tag`	A character string or a byte sequence.
`Double_tag`	A double-precision floating-point number.
`Double_array_tag`	An array or record of double-precision floating-point numbers.
`Abstract_tag`	A block representing an abstract datatype.
`Custom_tag`	A block representing an abstract datatype with user-defined finalization, comparison, hashing, serialization and deserialization functions atttached.

18.2.3 Pointers outside the heap

Any word-aligned pointer to an address outside the heap can be safely cast to and from the type `value`. This includes pointers returned by `malloc`, and pointers to C variables (of size at least one word) obtained with the `&` operator.

Caution: if a pointer returned by `malloc` is cast to the type `value` and returned to OCaml, explicit deallocation of the pointer using `free` is potentially dangerous, because the pointer may still be accessible from the OCaml world. Worse, the memory space deallocated by `free` can later be reallocated as part of the OCaml heap; the pointer, formerly pointing outside the OCaml heap, now points inside the OCaml heap, and this can crash the garbage collector. To avoid these problems, it is preferable to wrap the pointer in a OCaml block with tag `Abstract_tag` or `Custom_tag`.

18.3 Representation of OCaml data types

This section describes how OCaml data types are encoded in the `value` type.

18.3.1 Atomic types

OCaml type	Encoding
`int`	Unboxed integer values.
`char`	Unboxed integer values (ASCII code).
`float`	Blocks with tag `Double_tag`.
`bytes`	Blocks with tag `String_tag`.
`string`	Blocks with tag `String_tag`.
`int32`	Blocks with tag `Custom_tag`.
`int64`	Blocks with tag `Custom_tag`.
`nativeint`	Blocks with tag `Custom_tag`.

18.3.2 Tuples and records

Tuples are represented by pointers to blocks, with tag 0.

Records are also represented by zero-tagged blocks. The ordering of labels in the record type declaration determines the layout of the record fields: the value associated to the label declared first is stored in field 0 of the block, the value associated to the second label goes in field 1, and so on.

As an optimization, records whose fields all have static type `float` are represented as arrays of floating-point numbers, with tag `Double_array_tag`. (See the section below on arrays.)

As another optimization, unboxable record types are represented specially; unboxable record types are the immutable record types that have only one field. An unboxable type will be represented in one of two ways: boxed or unboxed. Boxed record types are represented as described above (by a block with tag 0 or `Double_array_tag`). An unboxed record type is represented directly by the value of its field (i.e. there is no block to represent the record itself).

The representation is chosen according to the following, in decreasing order of priority:

- An attribute (`[@@boxed]` or `[@@unboxed]`) on the type declaration.
- A compiler option (`-unboxed-types` or `-no-unboxed-types`).
- The default representation. In the present version of OCaml, the default is the boxed representation.

18.3.3 Arrays

Arrays of integers and pointers are represented like tuples, that is, as pointers to blocks tagged 0. They are accessed with the `Field` macro for reading and the `caml_modify` function for writing.

Arrays of floating-point numbers (type `float array`) have a special, unboxed, more efficient representation. These arrays are represented by pointers to blocks with tag `Double_array_tag`. They should be accessed with the `Double_field` and `Store_double_field` macros.

18.3.4 Concrete data types

Constructed terms are represented either by unboxed integers (for constant constructors) or by blocks whose tag encode the constructor (for non-constant constructors). The constant constructors and the non-constant constructors for a given concrete type are numbered separately, starting from 0, in the order in which they appear in the concrete type declaration. A constant constructor is represented by the unboxed integer equal to its constructor number. A non-constant constructor declared with n arguments is represented by a block of size n, tagged with the constructor number; the n fields contain its arguments. Example:

Constructed term	Representation
`()`	`Val_int(0)`
`false`	`Val_int(0)`
`true`	`Val_int(1)`
`[]`	`Val_int(0)`
`h::t`	Block with size = 2 and tag = 0; first field contains `h`, second field `t`.

As a convenience, `caml/mlvalues.h` defines the macros `Val_unit`, `Val_false` and `Val_true` to refer to `()`, `false` and `true`.

The following example illustrates the assignment of integers and block tags to constructors:

```
type t =
  | A             (* First constant constructor -> integer "Val_int(0)" *)
  | B of string   (* First non-constant constructor -> block with tag 0 *)
  | C             (* Second constant constructor -> integer "Val_int(1)" *)
  | D of bool     (* Second non-constant constructor -> block with tag 1 *)
  | E of t * t    (* Third non-constant constructor -> block with tag 2 *)
```

As an optimization, unboxable concrete data types are represented specially; a concrete data type is unboxable if it has exactly one constructor and this constructor has exactly one argument. Unboxable concrete data types are represented in the same ways as unboxable record types: see the description in section 18.3.2.

18.3.5 Objects

Objects are represented as blocks with tag `Object_tag`. The first field of the block refers to the object's class and associated method suite, in a format that cannot easily be exploited from C. The second field contains a unique object ID, used for comparisons. The remaining fields of the object contain the values of the instance variables of the object. It is unsafe to access directly instance variables, as the type system provides no guarantee about the instance variables contained by an object.

One may extract a public method from an object using the C function `caml_get_public_method` (declared in `<caml/mlvalues.h>`.) Since public method tags are hashed in the same way as variant tags, and methods are functions taking self as first argument, if you want to do the method call `foo#bar` from the C side, you should call:

```
callback(caml_get_public_method(foo, hash_variant("bar")), foo);
```

18.3.6 Polymorphic variants

Like constructed terms, polymorphic variant values are represented either as integers (for polymorphic variants without argument), or as blocks (for polymorphic variants with an argument). Unlike constructed terms, variant constructors are not numbered starting from 0, but identified by a hash value (an OCaml integer), as computed by the C function `hash_variant` (declared in `<caml/mlvalues.h>`): the hash value for a variant constructor named, say, `VConstr` is `hash_variant("VConstr")`.

The variant value `` `VConstr `` is represented by `hash_variant("VConstr")`. The variant value `` `VConstr(`$v$`) `` is represented by a block of size 2 and tag 0, with field number 0 containing `hash_variant("VConstr")` and field number 1 containing v.

Unlike constructed values, polymorphic variant values taking several arguments are not flattened. That is, `` `VConstr(`$v$`, `$w$`) `` is represented by a block of size 2, whose field number 1 contains the representation of the pair `(`v`, `w`)`, rather than a block of size 3 containing v and w in fields 1 and 2.

18.4 Operations on values

18.4.1 Kind tests

- `Is_long(`v`)` is true if value v is an immediate integer, false otherwise
- `Is_block(`v`)` is true if value v is a pointer to a block, and false if it is an immediate integer.

18.4.2 Operations on integers

- `Val_long(`l`)` returns the value encoding the `long int` l.
- `Long_val(`v`)` returns the `long int` encoded in value v.
- `Val_int(`i`)` returns the value encoding the `int` i.
- `Int_val(`v`)` returns the `int` encoded in value v.
- `Val_bool(`x`)` returns the OCaml boolean representing the truth value of the C integer x.
- `Bool_val(`v`)` returns 0 if v is the OCaml boolean `false`, 1 if v is `true`.
- `Val_true`, `Val_false` represent the OCaml booleans `true` and `false`.

18.4.3 Accessing blocks

- `Wosize_val(`v`)` returns the size of the block v, in words, excluding the header.
- `Tag_val(`v`)` returns the tag of the block v.
- `Field(`v`, `n`)` returns the value contained in the n^{th} field of the structured block v. Fields are numbered from 0 to `Wosize_val`$(v) - 1$.
- `Store_field(`b`, `n`, `v`)` stores the value v in the field number n of value b, which must be a structured block.
- `Code_val(`v`)` returns the code part of the closure v.
- `caml_string_length(`v`)` returns the length (number of bytes) of the string or byte sequence v.
- `Byte(`v`, `n`)` returns the n^{th} byte of the string or byte sequence v, with type `char`. Bytes are numbered from 0 to `string_length`$(v) - 1$.
- `Byte_u(`v`, `n`)` returns the n^{th} byte of the string or byte sequence v, with type `unsigned char`. Bytes are numbered from 0 to `string_length`$(v) - 1$.
- `String_val(`v`)` returns a pointer to the first byte of the string or byte sequence v, with type `char *`. This pointer is a valid C string: there is a null byte after the last byte in the string. However, OCaml strings and byte sequences can contain embedded null bytes, which will confuse the usual C functions over strings.

- `Double_val(`*v*`)` returns the floating-point number contained in value *v*, with type `double`.
- `Double_field(`*v*`, `*n*`)` returns the n^{th} element of the array of floating-point numbers *v* (a block tagged `Double_array_tag`).
- `Store_double_field(`*v*`, `*n*`, `*d*`)` stores the double precision floating-point number *d* in the n^{th} element of the array of floating-point numbers *v*.
- `Data_custom_val(`*v*`)` returns a pointer to the data part of the custom block *v*. This pointer has type `void *` and must be cast to the type of the data contained in the custom block.
- `Int32_val(`*v*`)` returns the 32-bit integer contained in the `int32` *v*.
- `Int64_val(`*v*`)` returns the 64-bit integer contained in the `int64` *v*.
- `Nativeint_val(`*v*`)` returns the long integer contained in the `nativeint` *v*.
- `caml_field_unboxed(`*v*`)` returns the value of the field of a value *v* of any unboxed type (record or concrete data type).
- `caml_field_boxed(`*v*`)` returns the value of the field of a value *v* of any boxed type (record or concrete data type).
- `caml_field_unboxable(`*v*`)` calls either `caml_field_unboxed` or `caml_field_boxed` according to the default representation of unboxable types in the current version of OCaml.

The expressions `Field(`*v*`, `*n*`)`, `Byte(`*v*`, `*n*`)` and `Byte_u(`*v*`, `*n*`)` are valid l-values. Hence, they can be assigned to, resulting in an in-place modification of value *v*. Assigning directly to `Field(`*v*`, `*n*`)` must be done with care to avoid confusing the garbage collector (see below).

18.4.4 Allocating blocks

Simple interface

- `Atom(`*t*`)` returns an "atom" (zero-sized block) with tag *t*. Zero-sized blocks are preallocated outside of the heap. It is incorrect to try and allocate a zero-sized block using the functions below. For instance, `Atom(0)` represents the empty array.
- `caml_alloc(`*n*`, `*t*`)` returns a fresh block of size *n* with tag *t*. If *t* is less than `No_scan_tag`, then the fields of the block are initialized with a valid value in order to satisfy the GC constraints.
- `caml_alloc_tuple(`*n*`)` returns a fresh block of size *n* words, with tag 0.
- `caml_alloc_string(`*n*`)` returns a byte sequence (or string) value of length *n* bytes. The sequence initially contains uninitialized bytes.
- `caml_copy_string(`*s*`)` returns a string or byte sequence value containing a copy of the null-terminated C string *s* (a `char *`).
- `caml_copy_double(`*d*`)` returns a floating-point value initialized with the `double` *d*.

- `caml_copy_int32(`*i*`)`, `caml_copy_int64(`*i*`)` and `caml_copy_nativeint(`*i*`)` return a value of OCaml type `int32`, `int64` and `nativeint`, respectively, initialized with the integer *i*.
- `caml_alloc_array(`*f*`,` *a*`)` allocates an array of values, calling function *f* over each element of the input array *a* to transform it into a value. The array *a* is an array of pointers terminated by the null pointer. The function *f* receives each pointer as argument, and returns a value. The zero-tagged block returned by `alloc_array(`*f*`,` *a*`)` is filled with the values returned by the successive calls to *f*. (This function must not be used to build an array of floating-point numbers.)
- `caml_copy_string_array(`*p*`)` allocates an array of strings or byte sequences, copied from the pointer to a string array *p* (a `char **`). *p* must be NULL-terminated.
- `caml_alloc_float_array(`*n*`)` allocates an array of floating point numbers of size *n*. The array initially contains uninitialized values.
- `caml_alloc_unboxed(`*v*`)` returns the value (of any unboxed type) whose field is the value *v*.
- `caml_alloc_boxed(`*v*`)` allocates and returns a value (of any boxed type) whose field is the value *v*.
- `caml_alloc_unboxable(`*v*`)` calls either `caml_alloc_unboxed` or `caml_alloc_boxed` according to the default representation of unboxable types in the current version of OCaml.

Low-level interface

The following functions are slightly more efficient than `caml_alloc`, but also much more difficult to use.

From the standpoint of the allocation functions, blocks are divided according to their size as zero-sized blocks, small blocks (with size less than or equal to `Max_young_wosize`), and large blocks (with size greater than `Max_young_wosize`). The constant `Max_young_wosize` is declared in the include file `mlvalues.h`. It is guaranteed to be at least 64 (words), so that any block with constant size less than or equal to 64 can be assumed to be small. For blocks whose size is computed at run-time, the size must be compared against `Max_young_wosize` to determine the correct allocation procedure.

- `caml_alloc_small(`*n*`,` *t*`)` returns a fresh small block of size $n \leq$ `Max_young_wosize` words, with tag *t*. If this block is a structured block (i.e. if $t <$ `No_scan_tag`), then the fields of the block (initially containing garbage) must be initialized with legal values (using direct assignment to the fields of the block) before the next allocation.
- `caml_alloc_shr(`*n*`,` *t*`)` returns a fresh block of size *n*, with tag *t*. The size of the block can be greater than `Max_young_wosize`. (It can also be smaller, but in this case it is more efficient to call `caml_alloc_small` instead of `caml_alloc_shr`.) If this block is a structured block (i.e. if $t <$ `No_scan_tag`), then the fields of the block (initially containing garbage) must be initialized with legal values (using the `caml_initialize` function described below) before the next allocation.

18.4.5 Raising exceptions

Two functions are provided to raise two standard exceptions:

- `caml_failwith(`*s*`)`, where *s* is a null-terminated C string (with type `char *`), raises exception `Failure` with argument *s*.
- `caml_invalid_argument(`*s*`)`, where *s* is a null-terminated C string (with type `char *`), raises exception `Invalid_argument` with argument *s*.

Raising arbitrary exceptions from C is more delicate: the exception identifier is dynamically allocated by the OCaml program, and therefore must be communicated to the C function using the registration facility described below in section 18.7.3. Once the exception identifier is recovered in C, the following functions actually raise the exception:

- `caml_raise_constant(`*id*`)` raises the exception *id* with no argument;
- `caml_raise_with_arg(`*id*`, `*v*`)` raises the exception *id* with the OCaml value *v* as argument;
- `caml_raise_with_args(`*id*`, `*n*`, `*v*`)` raises the exception *id* with the OCaml values *v*`[0]`, ..., *v*`[`*n*`-1]` as arguments;
- `caml_raise_with_string(`*id*`, `*s*`)`, where *s* is a null-terminated C string, raises the exception *id* with a copy of the C string *s* as argument.

18.5 Living in harmony with the garbage collector

Unused blocks in the heap are automatically reclaimed by the garbage collector. This requires some cooperation from C code that manipulates heap-allocated blocks.

18.5.1 Simple interface

All the macros described in this section are declared in the `memory.h` header file.

Rule 1 *A function that has parameters or local variables of type* `value` *must begin with a call to one of the* `CAMLparam` *macros and return with* `CAMLreturn`*,* `CAMLreturn0`*, or* `CAMLreturnT`*. In particular,* `CAMLlocal` *and* `CAMLxparam` *can only be called* after `CAMLparam`*.*

There are six `CAMLparam` macros: `CAMLparam0` to `CAMLparam5`, which take zero to five arguments respectively. If your function has no more than 5 parameters of type `value`, use the corresponding macros with these parameters as arguments. If your function has more than 5 parameters of type `value`, use `CAMLparam5` with five of these parameters, and use one or more calls to the `CAMLxparam` macros for the remaining parameters (`CAMLxparam1` to `CAMLxparam5`).

The macros `CAMLreturn`, `CAMLreturn0`, and `CAMLreturnT` are used to replace the C keyword `return`. Every occurrence of `return x` must be replaced by `CAMLreturn (x)` if `x` has type `value`, or `CAMLreturnT (t, x)` (where `t` is the type of `x`); every occurrence of `return` without argument must be replaced by `CAMLreturn0`. If your C function is a procedure (i.e. if it returns void), you must insert `CAMLreturn0` at the end (to replace C's implicit `return`).

Note: some C compilers give bogus warnings about unused variables `caml__dummy_xxx` at each use of `CAMLparam` and `CAMLlocal`. You should ignore them.

Example:

```
void foo (value v1, value v2, value v3)
{
  CAMLparam3 (v1, v2, v3);
  ...
  CAMLreturn0;
}
```

Note: if your function is a primitive with more than 5 arguments for use with the byte-code runtime, its arguments are not `value`s and must not be declared (they have types `value *` and `int`).

Rule 2 *Local variables of type* `value` *must be declared with one of the* `CAMLlocal` *macros. Arrays of* `value`*s are declared with* `CAMLlocalN`*. These macros must be used at the beginning of the function, not in a nested block.*

The macros `CAMLlocal1` to `CAMLlocal5` declare and initialize one to five local variables of type `value`. The variable names are given as arguments to the macros. `CAMLlocalN(`x`, `n`)` declares and initializes a local variable of type `value [`n`]`. You can use several calls to these macros if you have more than 5 local variables.

Example:

```
value bar (value v1, value v2, value v3)
{
  CAMLparam3 (v1, v2, v3);
  CAMLlocal1 (result);
  result = caml_alloc (3, 0);
  ...
  CAMLreturn (result);
}
```

Rule 3 *Assignments to the fields of structured blocks must be done with the* `Store_field` *macro (for normal blocks) or* `Store_double_field` *macro (for arrays and records of floating-point numbers). Other assignments must not use* `Store_field` *nor* `Store_double_field`*.*

`Store_field (`b`, `n`, `v`)` stores the value v in the field number n of value b, which must be a block (i.e. `Is_block(`b`)` must be true).

Example:

```
value bar (value v1, value v2, value v3)
{
  CAMLparam3 (v1, v2, v3);
  CAMLlocal1 (result);
  result = caml_alloc (3, 0);
  Store_field (result, 0, v1);
  Store_field (result, 1, v2);
```

```
  Store_field (result, 2, v3);
  CAMLreturn (result);
}
```

Warning: The first argument of `Store_field` and `Store_double_field` must be a variable declared by `CAMLparam*` or a parameter declared by `CAMLlocal*` to ensure that a garbage collection triggered by the evaluation of the other arguments will not invalidate the first argument after it is computed.

Use with CAMLlocalN: Arrays of values declared using `CAMLlocalN` must not be written to using `Store_field`. Use the normal C array syntax instead.

Rule 4 *Global variables containing values must be registered with the garbage collector using the* `caml_register_global_root` *function.*

Registration of a global variable `v` is achieved by calling `caml_register_global_root(&v)` just before or just after a valid value is stored in `v` for the first time. You must not call any of the OCaml runtime functions or macros between registering and storing the value.

A registered global variable `v` can be un-registered by calling `caml_remove_global_root(&v)`.

If the contents of the global variable `v` are seldom modified after registration, better performance can be achieved by calling `caml_register_generational_global_root(&v)` to register `v` (after its initialization with a valid `value`, but before any allocation or call to the GC functions), and `caml_remove_generational_global_root(&v)` to un-register it. In this case, you must not modify the value of `v` directly, but you must use `caml_modify_generational_global_root(&v,x)` to set it to `x`. The garbage collector takes advantage of the guarantee that `v` is not modified between calls to `caml_modify_generational_global_root` to scan it less often. This improves performance if the modifications of `v` happen less often than minor collections.

Note: The `CAML` macros use identifiers (local variables, type identifiers, structure tags) that start with `caml__`. Do not use any identifier starting with `caml__` in your programs.

18.5.2 Low-level interface

We now give the GC rules corresponding to the low-level allocation functions `caml_alloc_small` and `caml_alloc_shr`. You can ignore those rules if you stick to the simplified allocation function `caml_alloc`.

Rule 5 *After a structured block (a block with tag less than* `No_scan_tag`*) is allocated with the low-level functions, all fields of this block must be filled with well-formed values before the next allocation operation. If the block has been allocated with* `caml_alloc_small`*, filling is performed by direct assignment to the fields of the block:*

`Field(`v`, `n`) = `v_n`;`

If the block has been allocated with `caml_alloc_shr`*, filling is performed through the* `caml_initialize` *function:*

```
caml_initialize(&Field(v, n), v_n);
```

The next allocation can trigger a garbage collection. The garbage collector assumes that all structured blocks contain well-formed values. Newly created blocks contain random data, which generally do not represent well-formed values.

If you really need to allocate before the fields can receive their final value, first initialize with a constant value (e.g. `Val_unit`), then allocate, then modify the fields with the correct value (see rule 6).

Rule 6 *Direct assignment to a field of a block, as in*

```
Field(v, n) = w;
```

is safe only if v is a block newly allocated by `caml_alloc_small`*; that is, if no allocation took place between the allocation of v and the assignment to the field. In all other cases, never assign directly. If the block has just been allocated by* `caml_alloc_shr`*, use* `caml_initialize` *to assign a value to a field for the first time:*

```
caml_initialize(&Field(v, n), w);
```

Otherwise, you are updating a field that previously contained a well-formed value; then, call the `caml_modify` *function:*

```
caml_modify(&Field(v, n), w);
```

To illustrate the rules above, here is a C function that builds and returns a list containing the two integers given as parameters. First, we write it using the simplified allocation functions:

```
value alloc_list_int(int i1, int i2)
{
  CAMLparam0 ();
  CAMLlocal2 (result, r);

  r = caml_alloc(2, 0);                   /* Allocate a cons cell */
  Store_field(r, 0, Val_int(i2));         /* car = the integer i2 */
  Store_field(r, 1, Val_int(0));          /* cdr = the empty list [] */
  result = caml_alloc(2, 0);              /* Allocate the other cons cell */
  Store_field(result, 0, Val_int(i1));    /* car = the integer i1 */
  Store_field(result, 1, r);              /* cdr = the first cons cell */
  CAMLreturn (result);
}
```

Here, the registering of `result` is not strictly needed, because no allocation takes place after it gets its value, but it's easier and safer to simply register all the local variables that have type `value`.

Here is the same function written using the low-level allocation functions. We notice that the cons cells are small blocks and can be allocated with `caml_alloc_small`, and filled by direct assignments on their fields.

```
value alloc_list_int(int i1, int i2)
{
  CAMLparam0 ();
  CAMLlocal2 (result, r);

  r = caml_alloc_small(2, 0);             /* Allocate a cons cell */
  Field(r, 0) = Val_int(i2);              /* car = the integer i2 */
  Field(r, 1) = Val_int(0);               /* cdr = the empty list [] */
  result = caml_alloc_small(2, 0);        /* Allocate the other cons cell */
  Field(result, 0) = Val_int(i1);         /* car = the integer i1 */
  Field(result, 1) = r;                   /* cdr = the first cons cell */
  CAMLreturn (result);
}
```

In the two examples above, the list is built bottom-up. Here is an alternate way, that proceeds top-down. It is less efficient, but illustrates the use of `caml_modify`.

```
value alloc_list_int(int i1, int i2)
{
  CAMLparam0 ();
  CAMLlocal2 (tail, r);

  r = caml_alloc_small(2, 0);             /* Allocate a cons cell */
  Field(r, 0) = Val_int(i1);              /* car = the integer i1 */
  Field(r, 1) = Val_int(0);               /* A dummy value
  tail = caml_alloc_small(2, 0);          /* Allocate the other cons cell */
  Field(tail, 0) = Val_int(i2);           /* car = the integer i2 */
  Field(tail, 1) = Val_int(0);            /* cdr = the empty list [] */
  caml_modify(&Field(r, 1), tail);        /* cdr of the result = tail */
  CAMLreturn (r);
}
```

It would be incorrect to perform `Field(r, 1) = tail` directly, because the allocation of `tail` has taken place since `r` was allocated.

18.6 A complete example

This section outlines how the functions from the Unix `curses` library can be made available to OCaml programs. First of all, here is the interface `curses.mli` that declares the `curses` primitives and data types:

```
(* File curses.ml -- declaration of primitives and data types *)
type window                    (* The type "window" remains abstract *)
external initscr: unit -> window = "caml_curses_initscr"
external endwin: unit -> unit = "caml_curses_endwin"
external refresh: unit -> unit = "caml_curses_refresh"
```

```
external wrefresh : window -> unit = "caml_curses_wrefresh"
external newwin: int -> int -> int -> int -> window = "caml_curses_newwin"
external addch: char -> unit = "caml_curses_addch"
external mvwaddch: window -> int -> int -> char -> unit = "caml_curses_mvwaddch"
external addstr: string -> unit = "caml_curses_addstr"
external mvwaddstr: window -> int -> int -> string -> unit
         = "caml_curses_mvwaddstr"
(* lots more omitted *)
```

To compile this interface:

```
ocamlc -c curses.ml
```

To implement these functions, we just have to provide the stub code; the core functions are already implemented in the `curses` library. The stub code file, `curses_stubs.c`, looks like this:

```
/* File curses_stubs.c -- stub code for curses */
#include <curses.h>
#include <caml/mlvalues.h>
#include <caml/memory.h>
#include <caml/alloc.h>
#include <caml/custom.h>

/* Encapsulation of opaque window handles (of type WINDOW *)
   as OCaml custom blocks. */

static struct custom_operations curses_window_ops = {
  "fr.inria.caml.curses_windows",
  custom_finalize_default,
  custom_compare_default,
  custom_hash_default,
  custom_serialize_default,
  custom_deserialize_default,
  custom_compare_ext_default
};

/* Accessing the WINDOW * part of an OCaml custom block */
#define Window_val(v) (*((WINDOW **) Data_custom_val(v)))

/* Allocating an OCaml custom block to hold the given WINDOW * */
static value alloc_window(WINDOW * w)
{
  value v = alloc_custom(&curses_window_ops, sizeof(WINDOW *), 0, 1);
  Window_val(v) = w;
  return v;
}
```

```
value caml_curses_initscr(value unit)
{
  CAMLparam1 (unit);
  CAMLreturn (alloc_window(initscr()));
}

value caml_curses_endwin(value unit)
{
  CAMLparam1 (unit);
  endwin();
  CAMLreturn (Val_unit);
}

value caml_curses_refresh(value unit)
{
  CAMLparam1 (unit);
  refresh();
  CAMLreturn (Val_unit);
}

value caml_curses_wrefresh(value win)
{
  CAMLparam1 (win);
  wrefresh(Window_val(win));
  CAMLreturn (Val_unit);
}

value caml_curses_newwin(value nlines, value ncols, value x0, value y0)
{
  CAMLparam4 (nlines, ncols, x0, y0);
  CAMLreturn (alloc_window(newwin(Int_val(nlines), Int_val(ncols),
                                  Int_val(x0), Int_val(y0))));
}

value caml_curses_addch(value c)
{
  CAMLparam1 (c);
  addch(Int_val(c));            /* Characters are encoded like integers */
  CAMLreturn (Val_unit);
}

value caml_curses_mvwaddch(value win, value x, value y, value c)
{
  CAMLparam4 (win, x, y, c);
  mvwaddch(Window_val(win), Int_val(x), Int_val(y), Int_val(c));
```

```
  CAMLreturn (Val_unit);
}

value caml_curses_addstr(value s)
{
  CAMLparam1 (s);
  addstr(String_val(s));
  CAMLreturn (Val_unit);
}

value caml_curses_mvwaddstr(value win, value x, value y, value s)
{
  CAMLparam4 (win, x, y, s);
  mvwaddstr(Window_val(win), Int_val(x), Int_val(y), String_val(s));
  CAMLreturn (Val_unit);
}

/* This goes on for pages. */
```

The file `curses_stubs.c` can be compiled with:

```
cc -c -I`ocamlc -where` curses_stubs.c
```

or, even simpler,

```
ocamlc -c curses_stubs.c
```

(When passed a `.c` file, the `ocamlc` command simply calls the C compiler on that file, with the right `-I` option.)

Now, here is a sample OCaml program `prog.ml` that uses the `curses` module:

```
(* File prog.ml -- main program using curses *)
open Curses;;
let main_window = initscr () in
let small_window = newwin 10 5 20 10 in
  mvwaddstr main_window 10 2 "Hello";
  mvwaddstr small_window 4 3 "world";
  refresh();
  Unix.sleep 5;
  endwin()
```

To compile and link this program, run:

```
ocamlc -custom -o prog unix.cma curses.cmo prog.ml curses_stubs.o -cclib -lcurses
```

(On some machines, you may need to put `-cclib -lcurses -cclib -ltermcap` or `-cclib -ltermcap` instead of `-cclib -lcurses`.)

18.7 Advanced topic: callbacks from C to OCaml

So far, we have described how to call C functions from OCaml. In this section, we show how C functions can call OCaml functions, either as callbacks (OCaml calls C which calls OCaml), or with the main program written in C.

18.7.1 Applying OCaml closures from C

C functions can apply OCaml function values (closures) to OCaml values. The following functions are provided to perform the applications:

- `caml_callback(`*f, a*`)` applies the functional value *f* to the value *a* and returns the value returned by *f*.
- `caml_callback2(`*f, a, b*`)` applies the functional value *f* (which is assumed to be a curried OCaml function with two arguments) to *a* and *b*.
- `caml_callback3(`*f, a, b, c*`)` applies the functional value *f* (a curried OCaml function with three arguments) to *a*, *b* and *c*.
- `caml_callbackN(`*f, n, args*`)` applies the functional value *f* to the *n* arguments contained in the array of values *args*.

If the function *f* does not return, but raises an exception that escapes the scope of the application, then this exception is propagated to the next enclosing OCaml code, skipping over the C code. That is, if an OCaml function *f* calls a C function *g* that calls back an OCaml function *h* that raises a stray exception, then the execution of *g* is interrupted and the exception is propagated back into *f*.

If the C code wishes to catch exceptions escaping the OCaml function, it can use the functions `caml_callback_exn`, `caml_callback2_exn`, `caml_callback3_exn`, `caml_callbackN_exn`. These functions take the same arguments as their non-`_exn` counterparts, but catch escaping exceptions and return them to the C code. The return value *v* of the `caml_callback*_exn` functions must be tested with the macro `Is_exception_result(`*v*`)`. If the macro returns "false", no exception occured, and *v* is the value returned by the OCaml function. If `Is_exception_result(`*v*`)` returns "true", an exception escaped, and its value (the exception descriptor) can be recovered using `Extract_exception(`*v*`)`.

Warning: If the OCaml function returned with an exception, `Extract_exception` should be applied to the exception result prior to calling a function that may trigger garbage collection. Otherwise, if *v* is reachable during garbage collection, the runtime can crash since *v* does not contain a valid value.

Example:

```
value call_caml_f_ex(value closure, value arg)
{
  CAMLparam2(closure, arg);
  CAMLlocal2(res, tmp);
  res = caml_callback_exn(closure, arg);
```

```
  if(Is_exception_result(res)) {
    res = Extract_exception(res);
    tmp = caml_alloc(3, 0); /* Safe to allocate: res contains valid value. */
    ...
  }
  CAMLreturn (res);
}
```

18.7.2 Obtaining or registering OCaml closures for use in C functions

There are two ways to obtain OCaml function values (closures) to be passed to the `callback` functions described above. One way is to pass the OCaml function as an argument to a primitive function. For example, if the OCaml code contains the declaration

```
external apply : ('a -> 'b) -> 'a -> 'b = "caml_apply"
```

the corresponding C stub can be written as follows:

```
CAMLprim value caml_apply(value vf, value vx)
{
  CAMLparam2(vf, vx);
  CAMLlocal1(vy);
  vy = caml_callback(vf, vx);
  CAMLreturn(vy);
}
```

Another possibility is to use the registration mechanism provided by OCaml. This registration mechanism enables OCaml code to register OCaml functions under some global name, and C code to retrieve the corresponding closure by this global name.

On the OCaml side, registration is performed by evaluating `Callback.register` n v. Here, n is the global name (an arbitrary string) and v the OCaml value. For instance:

```
let f x = print_string "f is applied to "; print_int x; print_newline()
let _ = Callback.register "test function" f
```

On the C side, a pointer to the value registered under name n is obtained by calling `caml_named_value`(n). The returned pointer must then be dereferenced to recover the actual OCaml value. If no value is registered under the name n, the null pointer is returned. For example, here is a C wrapper that calls the OCaml function `f` above:

```
void call_caml_f(int arg)
{
    caml_callback(*caml_named_value("test function"), Val_int(arg));
}
```

The pointer returned by `caml_named_value` is constant and can safely be cached in a C variable to avoid repeated name lookups. On the other hand, the value pointed to can change during garbage collection and must always be recomputed at the point of use. Here is a more efficient variant of `call_caml_f` above that calls `caml_named_value` only once:

```
void call_caml_f(int arg)
{
    static value * closure_f = NULL;
    if (closure_f == NULL) {
        /* First time around, look up by name */
        closure_f = caml_named_value("test function");
    }
    caml_callback(*closure_f, Val_int(arg));
}
```

18.7.3 Registering OCaml exceptions for use in C functions

The registration mechanism described above can also be used to communicate exception identifiers from OCaml to C. The OCaml code registers the exception by evaluating `Callback.register_exception` *n exn*, where *n* is an arbitrary name and *exn* is an exception value of the exception to register. For example:

```
exception Error of string
let _ = Callback.register_exception "test exception" (Error "any string")
```

The C code can then recover the exception identifier using `caml_named_value` and pass it as first argument to the functions `raise_constant`, `raise_with_arg`, and `raise_with_string` (described in section 18.4.5) to actually raise the exception. For example, here is a C function that raises the `Error` exception with the given argument:

```
void raise_error(char * msg)
{
    caml_raise_with_string(*caml_named_value("test exception"), msg);
}
```

18.7.4 Main program in C

In normal operation, a mixed OCaml/C program starts by executing the OCaml initialization code, which then may proceed to call C functions. We say that the main program is the OCaml code. In some applications, it is desirable that the C code plays the role of the main program, calling OCaml functions when needed. This can be achieved as follows:

- The C part of the program must provide a `main` function, which will override the default `main` function provided by the OCaml runtime system. Execution will start in the user-defined `main` function just like for a regular C program.
- At some point, the C code must call `caml_main(argv)` to initialize the OCaml code. The `argv` argument is a C array of strings (type `char **`), terminated with a `NULL` pointer, which represents the command-line arguments, as passed as second argument to `main`. The OCaml array `Sys.argv` will be initialized from this parameter. For the bytecode compiler, `argv[0]` and `argv[1]` are also consulted to find the file containing the bytecode.

- The call to `caml_main` initializes the OCaml runtime system, loads the bytecode (in the case of the bytecode compiler), and executes the initialization code of the OCaml program. Typically, this initialization code registers callback functions using `Callback.register`. Once the OCaml initialization code is complete, control returns to the C code that called `caml_main`.
- The C code can then invoke OCaml functions using the callback mechanism (see section 18.7.1).

18.7.5 Embedding the OCaml code in the C code

The bytecode compiler in custom runtime mode (`ocamlc -custom`) normally appends the bytecode to the executable file containing the custom runtime. This has two consequences. First, the final linking step must be performed by `ocamlc`. Second, the OCaml runtime library must be able to find the name of the executable file from the command-line arguments. When using `caml_main(argv)` as in section 18.7.4, this means that `argv[0]` or `argv[1]` must contain the executable file name.

An alternative is to embed the bytecode in the C code. The `-output-obj` option to `ocamlc` is provided for this purpose. It causes the `ocamlc` compiler to output a C object file (`.o` file, `.obj` under Windows) containing the bytecode for the OCaml part of the program, as well as a `caml_startup` function. The C object file produced by `ocamlc -output-obj` can then be linked with C code using the standard C compiler, or stored in a C library.

The `caml_startup` function must be called from the main C program in order to initialize the OCaml runtime and execute the OCaml initialization code. Just like `caml_main`, it takes one `argv` parameter containing the command-line parameters. Unlike `caml_main`, this `argv` parameter is used only to initialize `Sys.argv`, but not for finding the name of the executable file.

The `-output-obj` option can also be used to obtain the C source file. More interestingly, the same option can also produce directly a shared library (`.so` file, `.dll` under Windows) that contains the OCaml code, the OCaml runtime system and any other static C code given to `ocamlc` (`.o`, `.a`, respectively, `.obj`, `.lib`). This use of `-output-obj` is very similar to a normal linking step, but instead of producing a main program that automatically runs the OCaml code, it produces a shared library that can run the OCaml code on demand. The three possible behaviors of `-output-obj` are selected according to the extension of the resulting file (given with `-o`).

The native-code compiler `ocamlopt` also supports the `-output-obj` option, causing it to output a C object file or a shared library containing the native code for all OCaml modules on the command-line, as well as the OCaml startup code. Initialization is performed by calling `caml_startup` as in the case of the bytecode compiler.

For the final linking phase, in addition to the object file produced by `-output-obj`, you will have to provide the OCaml runtime library (`libcamlrun.a` for bytecode, `libasmrun.a` for native-code), as well as all C libraries that are required by the OCaml libraries used. For instance, assume the OCaml part of your program uses the Unix library. With `ocamlc`, you should do:

```
ocamlc -output-obj -o camlcode.o unix.cma other .cmo and .cma files
cc -o myprog C objects and libraries \
   camlcode.o -L‘ocamlc -where‘ -lunix -lcamlrun
```

With `ocamlopt`, you should do:

```
ocamlopt -output-obj -o camlcode.o unix.cmxa other .cmx and .cmxa files
```

```
cc -o myprog C objects and libraries \
   camlcode.o -L`ocamlc -where` -lunix -lasmrun
```

Warning: On some ports, special options are required on the final linking phase that links together the object file produced by the `-output-obj` option and the remainder of the program. Those options are shown in the configuration file `config/Makefile` generated during compilation of OCaml, as the variables `BYTECCLINKOPTS` (for object files produced by `ocamlc -output-obj`) and `NATIVECCLINKOPTS` (for object files produced by `ocamlopt -output-obj`).

- Windows with the MSVC compiler: the object file produced by OCaml have been compiled with the `/MD` flag, and therefore all other object files linked with it should also be compiled with `/MD`.
- other systems: you may have to add one or more of `-lcurses`, `-lm`, `-ldl`, depending on your OS and C compiler.

Stack backtraces. When OCaml bytecode produced by `ocamlc -g` is embedded in a C program, no debugging information is included, and therefore it is impossible to print stack backtraces on uncaught exceptions. This is not the case when native code produced by `ocamlopt -g` is embedded in a C program: stack backtrace information is available, but the backtrace mechanism needs to be turned on programmatically. This can be achieved from the OCaml side by calling `Printexc.record_backtrace true` in the initialization of one of the OCaml modules. This can also be achieved from the C side by calling `caml_record_backtrace(Val_int(1));` in the OCaml-C glue code.

18.8 Advanced example with callbacks

This section illustrates the callback facilities described in section 18.7. We are going to package some OCaml functions in such a way that they can be linked with C code and called from C just like any C functions. The OCaml functions are defined in the following `mod.ml` OCaml source:

```
(* File mod.ml -- some "useful" OCaml functions *)

let rec fib n = if n < 2 then 1 else fib(n-1) + fib(n-2)

let format_result n = Printf.sprintf "Result is: %d\n" n

(* Export those two functions to C *)

let _ = Callback.register "fib" fib
let _ = Callback.register "format_result" format_result
```

Here is the C stub code for calling these functions from C:

```
/* File modwrap.c -- wrappers around the OCaml functions */
```

```
#include <stdio.h>
#include <string.h>
#include <caml/mlvalues.h>
#include <caml/callback.h>

int fib(int n)
{
  static value * fib_closure = NULL;
  if (fib_closure == NULL) fib_closure = caml_named_value("fib");
  return Int_val(caml_callback(*fib_closure, Val_int(n)));
}

char * format_result(int n)
{
  static value * format_result_closure = NULL;
  if (format_result_closure == NULL)
    format_result_closure = caml_named_value("format_result");
  return strdup(String_val(caml_callback(*format_result_closure, Val_int(n))));
  /* We copy the C string returned by String_val to the C heap
     so that it remains valid after garbage collection. */
}
```

We now compile the OCaml code to a C object file and put it in a C library along with the stub code in `modwrap.c` and the OCaml runtime system:

```
ocamlc -custom -output-obj -o modcaml.o mod.ml
ocamlc -c modwrap.c
cp `ocamlc -where`/libcamlrun.a mod.a && chmod +w mod.a
ar r mod.a modcaml.o modwrap.o
```

(One can also use `ocamlopt -output-obj` instead of `ocamlc -custom -output-obj`. In this case, replace `libcamlrun.a` (the bytecode runtime library) by `libasmrun.a` (the native-code runtime library).)

Now, we can use the two functions `fib` and `format_result` in any C program, just like regular C functions. Just remember to call `caml_startup` once before.

```
/* File main.c -- a sample client for the OCaml functions */

#include <stdio.h>
#include <caml/callback.h>

extern int fib(int n);
extern char * format_result(int n);

int main(int argc, char ** argv)
{
```

```
  int result;

  /* Initialize OCaml code */
  caml_startup(argv);
  /* Do some computation */
  result = fib(10);
  printf("fib(10) = %s\n", format_result(result));
  return 0;
}
```

To build the whole program, just invoke the C compiler as follows:

```
cc -o prog -I `ocamlc -where` main.c mod.a -lcurses
```

(On some machines, you may need to put `-ltermcap` or `-lcurses -ltermcap` instead of `-lcurses`.)

18.9 Advanced topic: custom blocks

Blocks with tag `Custom_tag` contain both arbitrary user data and a pointer to a C struct, with type `struct custom_operations`, that associates user-provided finalization, comparison, hashing, serialization and deserialization functions to this block.

18.9.1 The `struct custom_operations`

The `struct custom_operations` is defined in `<caml/custom.h>` and contains the following fields:

- `char *identifier`
  A zero-terminated character string serving as an identifier for serialization and deserialization operations.

- `void (*finalize)(value v)`
  The `finalize` field contains a pointer to a C function that is called when the block becomes unreachable and is about to be reclaimed. The block is passed as first argument to the function. The `finalize` field can also be `custom_finalize_default` to indicate that no finalization function is associated with the block.

- `int (*compare)(value v1, value v2)`
  The `compare` field contains a pointer to a C function that is called whenever two custom blocks are compared using OCaml's generic comparison operators (`=`, `<>`, `<=`, `>=`, `<`, `>` and `compare`). The C function should return 0 if the data contained in the two blocks are structurally equal, a negative integer if the data from the first block is less than the data from the second block, and a positive integer if the data from the first block is greater than the data from the second block.

  The `compare` field can be set to `custom_compare_default`; this default comparison function simply raises `Failure`.

- `int (*compare_ext)(value v1, value v2)`
  (Since 3.12.1) The `compare_ext` field contains a pointer to a C function that is called whenever one custom block and one unboxed integer are compared using OCaml's generic comparison operators (`=`, `<>`, `<=`, `>=`, `<`, `>` and `compare`). As in the case of the `compare` field, the C function should return 0 if the two arguments are structurally equal, a negative integer if the first argument compares less than the second argument, and a positive integer if the first argument compares greater than the second argument.

  The `compare_ext` field can be set to `custom_compare_ext_default`; this default comparison function simply raises `Failure`.

- `intnat (*hash)(value v)`
  The `hash` field contains a pointer to a C function that is called whenever OCaml's generic hash operator (see module `Hashtbl`) is applied to a custom block. The C function can return an arbitrary integer representing the hash value of the data contained in the given custom block. The hash value must be compatible with the `compare` function, in the sense that two structurally equal data (that is, two custom blocks for which `compare` returns 0) must have the same hash value.

  The `hash` field can be set to `custom_hash_default`, in which case the custom block is ignored during hash computation.

- `void (*serialize)(value v, uintnat * wsize_32, uintnat * wsize_64)`
  The `serialize` field contains a pointer to a C function that is called whenever the custom block needs to be serialized (marshaled) using the OCaml functions `output_value` or `Marshal.to_...`. For a custom block, those functions first write the identifier of the block (as given by the `identifier` field) to the output stream, then call the user-provided `serialize` function. That function is responsible for writing the data contained in the custom block, using the `serialize_...` functions defined in `<caml/intext.h>` and listed below. The user-provided `serialize` function must then store in its `wsize_32` and `wsize_64` parameters the sizes in bytes of the data part of the custom block on a 32-bit architecture and on a 64-bit architecture, respectively.

  The `serialize` field can be set to `custom_serialize_default`, in which case the `Failure` exception is raised when attempting to serialize the custom block.

- `uintnat (*deserialize)(void * dst)`
  The `deserialize` field contains a pointer to a C function that is called whenever a custom block with identifier `identifier` needs to be deserialized (un-marshaled) using the OCaml functions `input_value` or `Marshal.from_...`. This user-provided function is responsible for reading back the data written by the `serialize` operation, using the `deserialize_...` functions defined in `<caml/intext.h>` and listed below. It must then rebuild the data part of the custom block and store it at the pointer given as the `dst` argument. Finally, it returns the size in bytes of the data part of the custom block. This size must be identical to the `wsize_32` result of the `serialize` operation if the architecture is 32 bits, or `wsize_64` if the architecture is 64 bits.

  The `deserialize` field can be set to `custom_deserialize_default` to indicate that deserialization is not supported. In this case, do not register the `struct custom_operations` with

the deserializer using `register_custom_operations` (see below).

Note: the `finalize`, `compare`, `hash`, `serialize` and `deserialize` functions attached to custom block descriptors must never trigger a garbage collection. Within these functions, do not call any of the OCaml allocation functions, and do not perform a callback into OCaml code. Do not use `CAMLparam` to register the parameters to these functions, and do not use `CAMLreturn` to return the result.

18.9.2 Allocating custom blocks

Custom blocks must be allocated via the `caml_alloc_custom` function:

`caml_alloc_custom(`*ops*`,` *size*`,` *used*`,` *max*`)`

returns a fresh custom block, with room for *size* bytes of user data, and whose associated operations are given by *ops* (a pointer to a `struct custom_operations`, usually statically allocated as a C global variable).

The two parameters *used* and *max* are used to control the speed of garbage collection when the finalized object contains pointers to out-of-heap resources. Generally speaking, the OCaml incremental major collector adjusts its speed relative to the allocation rate of the program. The faster the program allocates, the harder the GC works in order to reclaim quickly unreachable blocks and avoid having large amount of "floating garbage" (unreferenced objects that the GC has not yet collected).

Normally, the allocation rate is measured by counting the in-heap size of allocated blocks. However, it often happens that finalized objects contain pointers to out-of-heap memory blocks and other resources (such as file descriptors, X Windows bitmaps, etc.). For those blocks, the in-heap size of blocks is not a good measure of the quantity of resources allocated by the program.

The two arguments *used* and *max* give the GC an idea of how much out-of-heap resources are consumed by the finalized block being allocated: you give the amount of resources allocated to this object as parameter *used*, and the maximum amount that you want to see in floating garbage as parameter *max*. The units are arbitrary: the GC cares only about the ratio $used/max$.

For instance, if you are allocating a finalized block holding an X Windows bitmap of w by h pixels, and you'd rather not have more than 1 mega-pixels of unreclaimed bitmaps, specify $used = w * h$ and $max = 1000000$.

Another way to describe the effect of the *used* and *max* parameters is in terms of full GC cycles. If you allocate many custom blocks with $used/max = 1/N$, the GC will then do one full cycle (examining every object in the heap and calling finalization functions on those that are unreachable) every N allocations. For instance, if $used = 1$ and $max = 1000$, the GC will do one full cycle at least every 1000 allocations of custom blocks.

If your finalized blocks contain no pointers to out-of-heap resources, or if the previous discussion made little sense to you, just take $used = 0$ and $max = 1$. But if you later find that the finalization functions are not called "often enough", consider increasing the $used/max$ ratio.

18.9.3 Accessing custom blocks

The data part of a custom block v can be accessed via the pointer `Data_custom_val(`v`)`. This pointer has type `void *` and should be cast to the actual type of the data stored in the custom block.

The contents of custom blocks are not scanned by the garbage collector, and must therefore not contain any pointer inside the OCaml heap. In other terms, never store an OCaml `value` in a custom block, and do not use `Field`, `Store_field` nor `caml_modify` to access the data part of a custom block. Conversely, any C data structure (not containing heap pointers) can be stored in a custom block.

18.9.4 Writing custom serialization and deserialization functions

The following functions, defined in `<caml/intext.h>`, are provided to write and read back the contents of custom blocks in a portable way. Those functions handle endianness conversions when e.g. data is written on a little-endian machine and read back on a big-endian machine.

Function	Action
`caml_serialize_int_1`	Write a 1-byte integer
`caml_serialize_int_2`	Write a 2-byte integer
`caml_serialize_int_4`	Write a 4-byte integer
`caml_serialize_int_8`	Write a 8-byte integer
`caml_serialize_float_4`	Write a 4-byte float
`caml_serialize_float_8`	Write a 8-byte float
`caml_serialize_block_1`	Write an array of 1-byte quantities
`caml_serialize_block_2`	Write an array of 2-byte quantities
`caml_serialize_block_4`	Write an array of 4-byte quantities
`caml_serialize_block_8`	Write an array of 8-byte quantities
`caml_deserialize_uint_1`	Read an unsigned 1-byte integer
`caml_deserialize_sint_1`	Read a signed 1-byte integer
`caml_deserialize_uint_2`	Read an unsigned 2-byte integer
`caml_deserialize_sint_2`	Read a signed 2-byte integer
`caml_deserialize_uint_4`	Read an unsigned 4-byte integer
`caml_deserialize_sint_4`	Read a signed 4-byte integer
`caml_deserialize_uint_8`	Read an unsigned 8-byte integer
`caml_deserialize_sint_8`	Read a signed 8-byte integer
`caml_deserialize_float_4`	Read a 4-byte float
`caml_deserialize_float_8`	Read an 8-byte float
`caml_deserialize_block_1`	Read an array of 1-byte quantities
`caml_deserialize_block_2`	Read an array of 2-byte quantities
`caml_deserialize_block_4`	Read an array of 4-byte quantities
`caml_deserialize_block_8`	Read an array of 8-byte quantities
`caml_deserialize_error`	Signal an error during deserialization; `input_value` or `Marshal.from_...` raise a `Failure` exception after cleaning up their internal data structures

Serialization functions are attached to the custom blocks to which they apply. Obviously, deserialization functions cannot be attached this way, since the custom block does not exist yet when deserialization begins! Thus, the `struct custom_operations` that contain deserialization functions must be registered with the deserializer in advance, using the `register_custom_operations` function declared in `<caml/custom.h>`. Deserialization proceeds by reading the identifier off the input

stream, allocating a custom block of the size specified in the input stream, searching the registered `struct custom_operation` blocks for one with the same identifier, and calling its `deserialize` function to fill the data part of the custom block.

18.9.5 Choosing identifiers

Identifiers in `struct custom_operations` must be chosen carefully, since they must identify uniquely the data structure for serialization and deserialization operations. In particular, consider including a version number in the identifier; this way, the format of the data can be changed later, yet backward-compatible deserialisation functions can be provided.

Identifiers starting with `_` (an underscore character) are reserved for the OCaml runtime system; do not use them for your custom data. We recommend to use a URL (`http://mymachine.mydomain.com/mylibrary/version-number`) or a Java-style package name (`com.mydomain.mymachine.mylibrary.version-number`) as identifiers, to minimize the risk of identifier collision.

18.9.6 Finalized blocks

Custom blocks generalize the finalized blocks that were present in OCaml prior to version 3.00. For backward compatibility, the format of custom blocks is compatible with that of finalized blocks, and the `alloc_final` function is still available to allocate a custom block with a given finalization function, but default comparison, hashing and serialization functions. `caml_alloc_final(`*n*`,` *f*`,` *used*`,` *max*`)` returns a fresh custom block of size *n* words, with finalization function *f*. The first word is reserved for storing the custom operations; the other *n*-1 words are available for your data. The two parameters *used* and *max* are used to control the speed of garbage collection, as described for `caml_alloc_custom`.

18.10 Advanced topic: cheaper C call

This section describe how to make calling C functions cheaper.

Note: this only applies to the native compiler. So whenever you use any of these methods, you have to provide an alternative byte-code stub that ignores all the special annotations.

18.10.1 Passing unboxed values

We said earlier that all OCaml objects are represented by the C type `value`, and one has to use macros such as `Int_val` to decode data from the `value` type. It is however possible to tell OCaml to do this for us and pass arguments unboxed to the C function. Similarly it is possible to tell OCaml to expect the result unboxed and box it for us.

The motivation is that, by letting the OCaml compiler deal with boxing, it can often decide to suppress it entirely.

For instance let's consider this example:

```
external foo : float -> float -> float = "foo"

let f a b =
```

```
  let len = Array.length a in
  assert (Array.length b = len);
  let res = Array.make len 0. in
  for i = 0 to len - 1 do
    res.(i) <- foo a.(i) b.(i)
  done
```

Float arrays are unboxed in OCaml, however the C function `foo` expect its arguments as boxed floats and returns a boxed float. Hence the OCaml compiler has no choice but to box `a.(i)` and `b.(i)` and unbox the result of `foo`. This results in the allocation of `3 * len` temporary float values.

Now if we annotate the arguments and result with `[@unboxed]`, the compiler will be able to avoid all these allocations:

```
external foo
  :  (float [@unboxed])
  -> (float [@unboxed])
  -> (float [@unboxed])
  = "foo_byte" "foo"
```

In this case the C functions must look like:

```
CAMLprim double foo(double a, double b)
{
  ...
}

CAMLprim value foo_byte(value a, value b)
{
  return caml_copy_double(foo(Double_val(a), Double_val(b)))
}
```

For convenicence, when all arguments and the result are annotated with `[@unboxed]`, it is possible to put the attribute only once on the declaration itself. So we can also write instead:

```
external foo : float -> float -> float = "foo_byte" "foo" [@@unboxed]
```

The following table summarize what OCaml types can be unboxed, and what C types should be used in correspondence:

OCaml type	C type
`float`	`double`
`int32`	`int32_t`
`int64`	`int64_t`
`nativeint`	`intnat`

Similarly, it is possible to pass untagged OCaml integers between OCaml and C. This is done by annotating the arguments and/or result with `[@untagged]`:

```
external f : string -> (int [@untagged]) = "f_byte" "f"
```

The corresponding C type must be `intnat`.

Note: do not use the C `int` type in correspondence with `(int [@untagged])`. This is because they often differ in size.

18.10.2 Direct C call

In order to be able to run the garbage collector in the middle of a C function, the OCaml compiler generates some bookkeeping code around C calls. Technically it wraps every C call with the C function `caml_c_call` which is part of the OCaml runtime.

For small functions that are called repeatedly, this indirection can have a big impact on performances. However this is not needed if we know that the C function doesn't allocate and doesn't raise exceptions. We can instruct the OCaml compiler of this fact by annotating the external declaration with the attribute `[@@noalloc]`:

```
external bar : int -> int -> int = "foo" [@@noalloc]
```

In this case calling `bar` from OCaml is as cheap as calling any other OCaml function, except for the fact that the OCaml compiler can't inline C functions...

18.10.3 Example: calling C library functions without indirection

Using these attributes, it is possible to call C library functions with no indirection. For instance many math functions are defined this way in the OCaml standard library:

```
external sqrt : float -> float = "caml_sqrt_float" "sqrt"
  [@@unboxed] [@@noalloc]
(** Square root. *)

external exp : float -> float = "caml_exp_float" "exp" [@@unboxed] [@@noalloc]
(** Exponential. *)

external log : float -> float = "caml_log_float" "log" [@@unboxed] [@@noalloc]
(** Natural logarithm. *)
```

18.11 Advanced topic: multithreading

Using multiple threads (shared-memory concurrency) in a mixed OCaml/C application requires special precautions, which are described in this section.

18.11.1 Registering threads created from C

Callbacks from C to OCaml are possible only if the calling thread is known to the OCaml run-time system. Threads created from OCaml (through the `Thread.create` function of the system threads library) are automatically known to the run-time system. If the application creates additional threads from C and wishes to callback into OCaml code from these threads, it must first

register them with the run-time system. The following functions are declared in the include file `<caml/threads.h>`.

- `caml_c_thread_register()` registers the calling thread with the OCaml run-time system. Returns 1 on success, 0 on error. Registering an already-register thread does nothing and returns 0.
- `caml_c_thread_unregister()` must be called before the thread terminates, to unregister it from the OCaml run-time system. Returns 1 on success, 0 on error. If the calling thread was not previously registered, does nothing and returns 0.

18.11.2 Parallel execution of long-running C code

The OCaml run-time system is not reentrant: at any time, at most one thread can be executing OCaml code or C code that uses the OCaml run-time system. Technically, this is enforced by a "master lock" that any thread must hold while executing such code.

When OCaml calls the C code implementing a primitive, the master lock is held, therefore the C code has full access to the facilities of the run-time system. However, no other thread can execute OCaml code concurrently with the C code of the primitive.

If a C primitive runs for a long time or performs potentially blocking input-output operations, it can explicitly release the master lock, enabling other OCaml threads to run concurrently with its operations. The C code must re-acquire the master lock before returning to OCaml. This is achieved with the following functions, declared in the include file `<caml/threads.h>`.

- `caml_release_runtime_system()` The calling thread releases the master lock and other OCaml resources, enabling other threads to run OCaml code in parallel with the execution of the calling thread.
- `caml_acquire_runtime_system()` The calling thread re-acquires the master lock and other OCaml resources. It may block until no other thread uses the OCaml run-time system.

After `caml_release_runtime_system()` was called and until `caml_acquire_runtime_system()` is called, the C code must not access any OCaml data, nor call any function of the run-time system, nor call back into OCaml code. Consequently, arguments provided by OCaml to the C primitive must be copied into C data structures before calling `caml_release_runtime_system()`, and results to be returned to OCaml must be encoded as OCaml values after `caml_acquire_runtime_system()` returns.

Example: the following C primitive invokes `gethostbyname` to find the IP address of a host name. The `gethostbyname` function can block for a long time, so we choose to release the OCaml run-time system while it is running.

```
CAMLprim stub_gethostbyname(value vname)
{
  CAMLparam1 (vname);
  CAMLlocal1 (vres);
  struct hostent * h;
```

```
  /* Copy the string argument to a C string, allocated outside the
     OCaml heap. */
  name = stat_alloc(caml_string_length(vname) + 1);
  name = caml_strdup (String_val(vname));
  /* Release the OCaml run-time system */
  caml_release_runtime_system();
  /* Resolve the name */
  h = gethostbyname(name);
  /* Re-acquire the OCaml run-time system */
  caml_acquire_runtime_system();
  /* Encode the relevant fields of h as the OCaml value vres */
  ... /* Omitted */
  /* Return to OCaml */
  CAMLreturn (vres);
}
```

Callbacks from C to OCaml must be performed while holding the master lock to the OCaml run-time system. This is naturally the case if the callback is performed by a C primitive that did not release the run-time system. If the C primitive released the run-time system previously, or the callback is performed from other C code that was not invoked from OCaml (e.g. an event loop in a GUI application), the run-time system must be acquired before the callback and released after:

```
  caml_acquire_runtime_system();
  /* Resolve OCaml function vfun to be invoked */
  /* Build OCaml argument varg to the callback */
  vres = callback(vfun, varg);
  /* Copy relevant parts of result vres to C data structures */
  caml_release_runtime_system();
```

Note: the `acquire` and `release` functions described above were introduced in OCaml 3.12. Older code uses the following historical names, declared in `<caml/signals.h>`:

- `caml_enter_blocking_section` as an alias for `caml_release_runtime_system`
- `caml_leave_blocking_section` as an alias for `caml_acquire_runtime_system`

Intuition: a "blocking section" is a piece of C code that does not use the OCaml run-time system, typically a blocking input/output operation.

18.12 Building mixed C/OCaml libraries: `ocamlmklib`

The `ocamlmklib` command facilitates the construction of libraries containing both OCaml code and C code, and usable both in static linking and dynamic linking modes. This command is available under Windows since Objective Caml 3.11 and under other operating systems since Objective Caml 3.03.

The `ocamlmklib` command takes three kinds of arguments:

- OCaml source files and object files (`.cmo`, `.cmx`, `.ml`) comprising the OCaml part of the library;
- C object files (`.o`, `.a`, respectively, `.obj`, `.lib`) comprising the C part of the library;
- Support libraries for the C part (`-l`*lib*).

It generates the following outputs:

- An OCaml bytecode library `.cma` incorporating the `.cmo` and `.ml` OCaml files given as arguments, and automatically referencing the C library generated with the C object files.
- An OCaml native-code library `.cmxa` incorporating the `.cmx` and `.ml` OCaml files given as arguments, and automatically referencing the C library generated with the C object files.
- If dynamic linking is supported on the target platform, a `.so` (respectively, `.dll`) shared library built from the C object files given as arguments, and automatically referencing the support libraries.
- A C static library `.a`(respectively, `.lib`) built from the C object files.

In addition, the following options are recognized:

`-cclib`, `-ccopt`, `-I`, `-linkall`
: These options are passed as is to `ocamlc` or `ocamlopt`. See the documentation of these commands.

`-rpath`, `-R`, `-Wl,-rpath`, `-Wl,-R`
: These options are passed as is to the C compiler. Refer to the documentation of the C compiler.

`-custom`
: Force the construction of a statically linked library only, even if dynamic linking is supported.

`-failsafe`
: Fall back to building a statically linked library if a problem occurs while building the shared library (e.g. some of the support libraries are not available as shared libraries).

`-L`*dir*
: Add *dir* to the search path for support libraries (`-l`*lib*).

`-ocamlc` *cmd*
: Use *cmd* instead of `ocamlc` to call the bytecode compiler.

`-ocamlopt` *cmd*
: Use *cmd* instead of `ocamlopt` to call the native-code compiler.

`-o` *output*
: Set the name of the generated OCaml library. `ocamlmklib` will generate *output*`.cma` and/or *output*`.cmxa`. If not specified, defaults to `a`.

`-oc` *outputc*
: Set the name of the generated C library. `ocamlmklib` will generate `lib`*outputc*`.so` (if shared libraries are supported) and `lib`*outputc*`.a`. If not specified, defaults to the output name given with `-o`.

On native Windows, the following environment variable is also consulted:

`OCAML_FLEXLINK`
: Alternative executable to use instead of the configured value. Primarily used for bootstrapping.

Example Consider an OCaml interface to the standard `libz` C library for reading and writing compressed files. Assume this library resides in `/usr/local/zlib`. This interface is composed of an OCaml part `zip.cmo`/`zip.cmx` and a C part `zipstubs.o` containing the stub code around the `libz` entry points. The following command builds the OCaml libraries `zip.cma` and `zip.cmxa`, as well as the companion C libraries `dllzip.so` and `libzip.a`:

```
ocamlmklib -o zip zip.cmo zip.cmx zipstubs.o -lz -L/usr/local/zlib
```

If shared libraries are supported, this performs the following commands:

```
ocamlc -a -o zip.cma zip.cmo -dllib -lzip \
       -cclib -lzip -cclib -lz -ccopt -L/usr/local/zlib
ocamlopt -a -o zip.cmxa zip.cmx -cclib -lzip \
       -cclib -lzip -cclib -lz -ccopt -L/usr/local/zlib
gcc -shared -o dllzip.so zipstubs.o -lz -L/usr/local/zlib
ar rc libzip.a zipstubs.o
```

Note: This example is on a Unix system. The exact command lines may be different on other systems.

If shared libraries are not supported, the following commands are performed instead:

```
ocamlc -a -custom -o zip.cma zip.cmo -cclib -lzip \
       -cclib -lz -ccopt -L/usr/local/zlib
ocamlopt -a -o zip.cmxa zip.cmx -lzip \
       -cclib -lz -ccopt -L/usr/local/zlib
ar rc libzip.a zipstubs.o
```

Instead of building simultaneously the bytecode library, the native-code library and the C libraries, `ocamlmklib` can be called three times to build each separately. Thus,

```
ocamlmklib -o zip zip.cmo -lz -L/usr/local/zlib
```

builds the bytecode library `zip.cma`, and

```
ocamlmklib -o zip zip.cmx -lz -L/usr/local/zlib
```

builds the native-code library `zip.cmxa`, and

```
ocamlmklib -o zip zipstubs.o -lz -L/usr/local/zlib
```

builds the C libraries `dllzip.so` and `libzip.a`. Notice that the support libraries (`-lz`) and the corresponding options (`-L/usr/local/zlib`) must be given on all three invocations of `ocamlmklib`, because they are needed at different times depending on whether shared libraries are supported.

Chapter 19

Optimisation with Flambda

19.1 Overview

Flambda is the term used to describe a series of optimisation passes provided by the native code compilers as of OCaml 4.03.

Flambda aims to make it easier to write idiomatic OCaml code without incurring performance penalties.

To use the Flambda optimisers it is necessary to pass the `-flambda` option to the OCaml `configure` script. (There is no support for a single compiler that can operate in both Flambda and non-Flambda modes.) Code compiled with Flambda cannot be linked into the same program as code compiled without Flambda. Attempting to do this will result in a compiler error.

Whether or not a particular `ocamlopt` uses Flambda may be determined by invoking it with the `-config` option and looking for any line starting with "`flambda:`". If such a line is present and says "`true`", then Flambda is supported, otherwise it is not.

Flambda provides full optimisation across different compilation units, so long as the `.cmx` files for the dependencies of the unit currently being compiled are available. (A compilation unit corresponds to a single `.ml` source file.) However it does not yet act entirely as a whole-program compiler: for example, elimination of dead code across a complete set of compilation units is not supported.

Optimisation with Flambda is not currently supported when generating bytecode.

Flambda should not in general affect the semantics of existing programs. Two exceptions to this rule are: possible elimination of pure code that is being benchmarked (see section 19.14) and changes in behaviour of code using unsafe operations (see section 19.15).

Flambda does not yet optimise array or string bounds checks. Neither does it take hints for optimisation from any assertions written by the user in the code.

Consult the *Glossary* at the end of this chapter for definitions of technical terms used below.

19.2 Command-line flags

The Flambda optimisers provide a variety of command-line flags that may be used to control their behaviour. Detailed descriptions of each flag are given in the referenced sections. Those sections also describe any arguments which the particular flags take.

Commonly-used options:

`-O2` Perform more optimisation than usual. Compilation times may be lengthened. (This flag is an abbreviation for a certain set of parameters described in section 19.5.)

`-O3` Perform even more optimisation than usual, possibly including unrolling of recursive functions. Compilation times may be significantly lengthened.

`-Oclassic`
Make inlining decisions at the point of definition of a function rather than at the call site(s). This mirrors the behaviour of OCaml compilers not using Flambda. Compared to compilation using the new Flambda inlining heuristics (for example at `-O2`) it produces smaller `.cmx` files, shorter compilation times and code that probably runs rather slower. When using `-Oclassic`, only the following options described in this section are relevant: `-inlining-report` and `-inline`. If any other of the options described in this section are used, the behaviour is undefined and may cause an error in future versions of the compiler.

`-inlining-report`
Emit `.inlining` files (one per round of optimisation) showing all of the inliner's decisions.

Less commonly-used options:

`-remove-unused-arguments`
Remove unused function arguments even when the argument is not specialised. This may have a small performance penalty. See section 19.10.3.

`-unbox-closures`
Pass free variables via specialised arguments rather than closures (an optimisation for reducing allocation). See section 19.9.3. This may have a small performance penalty.

Advanced options, only needed for detailed tuning:

`-inline`
The behaviour depends on whether `-Oclassic` is used.

- When not in `-Oclassic` mode, `-inline` limits the total size of functions considered for inlining during any speculative inlining search. (See section 19.3.6.) Note that this parameter does **not** control the assessment as to whether any particular function may be inlined. Raising it to excessive amounts will not necessarily cause more functions to be inlined.
- When in `-Oclassic` mode, `-inline` behaves as in previous versions of the compiler: it is the maximum size of function to be considered for inlining. See section 19.3.1.

`-inline-toplevel`
The equivalent of `-inline` but used when speculative inlining starts at toplevel. See section 19.3.6. Not used in `-Oclassic` mode.

`-inline-branch-factor`
Controls how the inliner assesses whether a code path is likely to be hot or cold. See section 19.3.5.

`-inline-alloc-cost`, `-inline-branch-cost`, `-inline-call-cost`
: Controls how the inliner assesses the runtime performance penalties associated with various operations. See section 19.3.5.

`-inline-indirect-cost`, `-inline-prim-cost`
: Likewise.

`-inline-lifting-benefit`
: Controls inlining of functors at toplevel. See section 19.3.5.

`-inline-max-depth`
: The maximum depth of any speculative inlining search. See section 19.3.6.

`-inline-max-unroll`
: The maximum depth of any unrolling of recursive functions during any speculative inlining search. See section 19.3.6.

`-no-unbox-free-vars-of-closures`
: Do not unbox closure variables. See section 19.9.1.

`-no-unbox-specialised-args`
: Do not unbox arguments to which functions have been specialised. See section 19.9.2.

`-rounds`
: How many rounds of optimisation to perform. See section 19.2.1.

`-unbox-closures-factor`
: Scaling factor for benefit calculation when using `-unbox-closures`. See section 19.9.3.

Notes

- The set of command line flags relating to optimisation should typically be specified to be the same across an entire project. Flambda does not currently record the requested flags in the `.cmx` files. As such, inlining of functions from previously-compiled units will subject their code to the optimisation parameters of the unit currently being compiled, rather than those specified when they were previously compiled. It is hoped to rectify this deficiency in the future.

- Flambda-specific flags do not affect linking with the exception of affecting the optimisation of code in the startup file (containing generated functions such as currying helpers). Typically such optimisation will not be significant, so eliding such flags at link time might be reasonable.

- Flambda-specific flags are silently accepted even when the `-flambda` option was not provided to the `configure` script. (There is no means provided to change this behaviour.) This is intended to make it more straightforward to run benchmarks with and without the Flambda optimisers in effect.

- Some of the Flambda flags may be subject to change in future releases.

19.2.1 Specification of optimisation parameters by round

Flambda operates in *rounds*: one round consists of a certain sequence of transformations that may then be repeated in order to achieve more satisfactory results. The number of rounds can be set manually using the `-rounds` parameter (although this is not necessary when using predefined optimisation levels such as with `-O2` and `-O3`). For high optimisation the number of rounds might be set at 3 or 4.

Command-line flags that may apply per round, for example those with `-cost` in the name, accept arguments of the form:

n | *round*=*n*[,...]

- If the first form is used, with a single integer specified, the value will apply to all rounds.
- If the second form is used, zero-based *round* integers specify values which are to be used only for those rounds.

The flags `-Oclassic`, `-O2` and `-O3` are applied before all other flags, meaning that certain parameters may be overridden without having to specify every parameter usually invoked by the given optimisation level.

19.3 Inlining

Inlining refers to the copying of the code of a function to a place where the function is called. The code of the function will be surrounded by bindings of its parameters to the corresponding arguments.

The aims of inlining are:

- to reduce the runtime overhead caused by function calls (including setting up for such calls and returning afterwards);
- to reduce instruction cache misses by expressing frequently-taken paths through the program using fewer machine instructions; and
- to reduce the amount of allocation (especially of closures).

These goals are often reached not just by inlining itself but also by other optimisations that the compiler is able to perform as a result of inlining.

When a recursive call to a function (within the definition of that function or another in the same mutually-recursive group) is inlined, the procedure is also known as *unrolling*. This is somewhat akin to loop peeling. For example, given the following code:

```
let rec fact x =
  if x = 0 then
    1
  else
    x * fact (x - 1)

let n = fact 4
```

unrolling once at the call site `fact 4` produces (with the body of `fact` unchanged):

```
let n =
  if 4 = 0 then
    1
  else
    4 * fact (4 - 1)
```

This simplifies to:

```
let n = 4 * fact 3
```

Flambda provides significantly enhanced inlining capabilities relative to previous versions of the compiler.

Aside: when inlining is performed

Inlining is performed together with all of the other Flambda optimisation passes, that is to say, after closure conversion. This has three particular advantages over a potentially more straightforward implementation prior to closure conversion:

- It permits higher-order inlining, for example when a non-inlinable function always returns the same function yet with different environments of definition. Not all such cases are supported yet, but it is intended that such support will be improved in future.
- It is easier to integrate with cross-module optimisation, since imported information about other modules is already in the correct intermediate language.
- It becomes more straightforward to optimise closure allocations since the layout of closures does not have to be estimated in any way: it is known. Similarly, it becomes more straightforward to control which variables end up in which closures, helping to avoid closure bloat.

19.3.1 Classic inlining heuristic

In `-Oclassic` mode the behaviour of the Flambda inliner mimics previous versions of the compiler. (Code may still be subject to further optimisations not performed by previous versions of the compiler: functors may be inlined, constants are lifted and unused code is eliminated all as described elsewhere in this chapter. See sections 19.3.3, 19.8.1 and 19.10. At the definition site of a function, the body of the function is measured. It will then be marked as eligible for inlining (and hence inlined at every direct call site) if:

- the measured size (in unspecified units) is smaller than that of a function call plus the argument of the `-inline` command-line flag; and
- the function is not recursive.

Non-Flambda versions of the compiler cannot inline functions that contain a definition of another function. However `-Oclassic` does permit this. Further, non-Flambda versions also cannot inline functions that are only themselves exposed as a result of a previous pass of inlining, but again this is permitted by `-Oclassic`. For example:

```
module M : sig
  val i : int
end = struct
  let f x =
    let g y = x + y in
    g
  let h = f 3
  let i = h 4  (* h is correctly discovered to be g and inlined *)
end
```

All of this contrasts with the normal Flambda mode, that is to say without `-Oclassic`, where:

- the inlining decision is made at the **call site**; and
- recursive functions can be handled, by *specialisation* (see below).

The Flambda mode is described in the next section.

19.3.2 Overview of "Flambda" inlining heuristics

The Flambda inlining heuristics, used whenever the compiler is configured for Flambda and `-Oclassic` was not specified, make inlining decisions at call sites. This helps in situations where the context is important. For example:

```
let f b x =
  if b then
    x
  else
    ... big expression ...

let g x = f true x
```

In this case, we would like to inline `f` into `g`, because a conditional jump can be eliminated and the code size should reduce. If the inlining decision has been made after the declaration of `f` without seeing the use, its size would have probably made it ineligible for inlining; but at the call site, its final size can be known. Further, this function should probably not be inlined systematically: if `b` is unknown, or indeed `false`, there is little benefit to trade off against a large increase in code size. In the existing non-Flambda inliner this isn't a great problem because chains of inlining were cut off fairly quickly. However it has led to excessive use of overly-large inlining parameters such as `-inline 10000`.

In more detail, at each call site the following procedure is followed:

- Determine whether it is clear that inlining would be beneficial without, for the moment, doing any inlining within the function itself. (The exact assessment of *benefit* is described below.) If so, the function is inlined.
- If inlining the function is not clearly beneficial, then inlining will be performed *speculatively* inside the function itself. The search for speculative inlining possibilities is controlled by two parameters: the *inlining threshold* and the *inlining depth*. (These are described in more detail below.)

- If such speculation shows that performing some inlining inside the function would be beneficial, then such inlining is performed and the resulting function inlined at the original call site.
- Otherwise, nothing happens.

Inlining within recursive functions of calls to other functions in the same mutually-recursive group is kept in check by an *unrolling depth*, described below. This ensures that functions are not unrolled to excess. (Unrolling is only enabled if `-O3` optimisation level is selected and/or the `-inline-max-unroll` flag is passed with an argument greater than zero.)

19.3.3 Handling of specific language constructs

Functors

There is nothing particular about functors that inhibits inlining compared to normal functions. To the inliner, these both look the same, except that functors are marked as such.

Applications of functors at toplevel are biased in favour of inlining. (This bias may be adjusted: see the documentation for `-inline-lifting-benefit` below.)

Applications of functors not at toplevel, for example in a local module inside some other expression, are treated by the inliner identically to normal function calls.

First-class modules

The inliner will be able to consider inlining a call to a function in a first class module if it knows which particular function is going to be called. The presence of the first-class module record that wraps the set of functions in the module does not per se inhibit inlining.

Objects

Method calls to objects are not at present inlined by Flambda.

19.3.4 Inlining reports

If the `-inlining-report` option is provided to the compiler then a file will be emitted corresponding to each round of optimisation. For the OCaml source file *basename*`.ml` the files are named *basename*`.`*round*`.inlining.org`, with *round* a zero-based integer. Inside the files, which are formatted as "org mode", will be found English prose describing the decisions that the inliner took.

19.3.5 Assessment of inlining benefit

Inlining typically results in an increase in code size, which if left unchecked, may not only lead to grossly large executables and excessive compilation times but also a decrease in performance due to worse locality. As such, the Flambda inliner trades off the change in code size against the expected runtime performance benefit, with the benefit being computed based on the number of operations that the compiler observes may be removed as a result of inlining.

For example given the following code:

```
let f b x =
  if b then
    x
  else
    ... big expression ...

let g x = f true x
```

it would be observed that inlining of `f` would remove:

- one direct call;
- one conditional branch.

Formally, an estimate of runtime performance benefit is computed by first summing the cost of the operations that are known to be removed as a result of the inlining and subsequent simplification of the inlined body. The individual costs for the various kinds of operations may be adjusted using the various `-inline-...-cost` flags as follows. Costs are specified as integers. All of these flags accept a single argument describing such integers using the conventions detailed in section 19.2.1.

`-inline-alloc-cost`
: The cost of an allocation.

`-inline-branch-cost`
: The cost of a branch.

`-inline-call-cost`
: The cost of a direct function call.

`-inline-indirect-cost`
: The cost of an indirect function call.

`-inline-prim-cost`
: The cost of a *primitive*. Primitives encompass operations including arithmetic and memory access.

(Default values are described in section 19.5 below.)

The initial benefit value is then scaled by a factor that attempts to compensate for the fact that the current point in the code, if under some number of conditional branches, may be cold. (Flambda does not currently compute hot and cold paths.) The factor—the estimated probability that the inliner really is on a *hot* path—is calculated as $(\frac{1}{1+f})^d$, where f is set by `-inline-branch-factor` and d is the nesting depth of branches at the current point. As the inliner descends into more deeply-nested branches, the benefit of inlining thus lessens.

The resulting benefit value is known as the *estimated benefit*.

The change in code size is also estimated: morally speaking it should be the change in machine code size, but since that is not available to the inliner, an approximation is used.

If the estimated benefit exceeds the increase in code size then the inlined version of the function will be kept. Otherwise the function will not be inlined.

Applications of functors at toplevel will be given an additional benefit (which may be controlled by the `-inline-lifting-benefit` flag) to bias inlining in such situations towards keeping the inlined version.

19.3.6 Control of speculation

As described above, there are three parameters that restrict the search for inlining opportunities during speculation:

- the *inlining threshold*;
- the *inlining depth*;
- the *unrolling depth*.

These parameters are ultimately bounded by the arguments provided to the corresponding command-line flags (or their default values):

- `-inline` (or, if the call site that triggered speculation is at toplevel, `-inline-toplevel`);
- `-inline-max-depth`;
- `-inline-max-unroll`.

Note in particular that `-inline` does not have the meaning that it has in the previous compiler or in `-Oclassic` mode. In both of those situations `-inline` was effectively some kind of basic assessment of inlining benefit. However in Flambda inlining mode it corresponds to a constraint on the search; the assessment of benefit is independent, as described above.

When speculation starts the inlining threshold starts at the value set by `-inline` (or `-inline-toplevel` if appropriate, see above). Upon making a speculative inlining decision the threshold is reduced by the code size of the function being inlined. If the threshold becomes exhausted, at or below zero, no further speculation will be performed.

The inlining depth starts at zero and is increased by one every time the inliner descends into another function. It is then decreased by one every time the inliner leaves such function. If the depth exceeds the value set by `-inline-max-depth` then speculation stops. This parameter is intended as a general backstop for situations where the inlining threshold does not control the search sufficiently.

The unrolling depth applies to calls within the same mutually-recursive group of functions. Each time an inlining of such a call is performed the depth is incremented by one when examining the resulting body. If the depth reaches the limit set by `-inline-max-unroll` then speculation stops.

19.4 Specialisation

The inliner may discover a call site to a recursive function where something is known about the arguments: for example, they may be equal to some other variables currently in scope. In this situation it may be beneficial to *specialise* the function to those arguments. This is done by copying the declaration of the function (and any others involved in any same mutually-recursive declaration) and noting the extra information about the arguments. The arguments augmented by this information are known as *specialised arguments*. In order to try to ensure that specialisation is not performed uselessly, arguments are only specialised if it can be shown that they are *invariant*: in other words, during the execution of the recursive function(s) themselves, the arguments never change.

Unless overridden by an attribute (see below), specialisation of a function will not be attempted if:

- the compiler is in `-Oclassic` mode;
- the function is not obviously recursive;
- the function is not closed.

The compiler can prove invariance of function arguments across multiple functions within a recursive group (although this has some limitations, as shown by the example below).

It should be noted that the *unboxing of closures* pass (see below) can introduce specialised arguments on non-recursive functions. (No other place in the compiler currently does this.)

Example: the well-known `List.iter` function This function might be written like so:

```
let rec iter f l =
  match l with
  | [] -> ()
  | h :: t ->
    f h;
    iter f t
```

and used like this:

```
let print_int x =
  print_endline (string_of_int x)

let run xs =
  iter print_int (List.rev xs)
```

The argument `f` to `iter` is invariant so the function may be specialised:

```
let run xs =
  let rec iter' f l =
    (* The compiler knows: f holds the same value as foo throughout iter'. *)
    match l with
    | [] -> ()
    | h :: t ->
      f h;
      iter' f t
  in
  iter' print_int (List.rev xs)
```

The compiler notes down that for the function `iter'`, the argument `f` is specialised to the constant closure `print_int`. This means that the body of `iter'` may be simplified:

```
let run xs =
  let rec iter' f l =
    (* The compiler knows: f holds the same value as foo throughout iter'. *)
    match l with
    | [] -> ()
    | h :: t ->
      print_int h;  (* this is now a direct call *)
      iter' f t
  in
  iter' print_int (List.rev xs)
```

The call to `print_int` can indeed be inlined:

```
let run xs =
  let rec iter' f l =
    (* The compiler knows: f holds the same value as foo throughout iter'. *)
    match l with
    | [] -> ()
    | h :: t ->
      print_endline (string_of_int h);
      iter' f t
  in
  iter' print_int (List.rev xs)
```

The unused specialised argument `f` may now be removed, leaving:

```
let run xs =
  let rec iter' l =
    match l with
    | [] -> ()
    | h :: t ->
      print_endline (string_of_int h);
      iter' t
  in
  iter' (List.rev xs)
```

Aside on invariant parameters. The compiler cannot currently detect invariance in cases such as the following.

```
let rec iter_swap f g l =
  match l with
  | [] -> ()
  | 0 :: t ->
    iter_swap g f l
  | h :: t ->
    f h;
    iter_swap f g t
```

19.4.1 Assessment of specialisation benefit

The benefit of specialisation is assessed in a similar way as for inlining. Specialised argument information may mean that the body of the function being specialised can be simplified: the removed operations are accumulated into a benefit. This, together with the size of the duplicated (specialised) function declaration, is then assessed against the size of the call to the original function.

19.5 Default settings of parameters

The default settings (when not using `-Oclassic`) are for one round of optimisation using the following parameters.

Parameter	Setting
`-inline`	10
`-inline-branch-factor`	0.1
`-inline-alloc-cost`	7
`-inline-branch-cost`	5
`-inline-call-cost`	5
`-inline-indirect-cost`	4
`-inline-prim-cost`	3
`-inline-lifting-benefit`	1300
`-inline-toplevel`	160
`-inline-max-depth`	1
`-inline-max-unroll`	0
`-unbox-closures-factor`	10

19.5.1 Settings at -O2 optimisation level

When `-O2` is specified two rounds of optimisation are performed. The first round uses the default parameters (see above). The second uses the following parameters.

Parameter	Setting
`-inline`	25
`-inline-branch-factor`	Same as default
`-inline-alloc-cost`	Double the default
`-inline-branch-cost`	Double the default
`-inline-call-cost`	Double the default
`-inline-indirect-cost`	Double the default
`-inline-prim-cost`	Double the default
`-inline-lifting-benefit`	Same as default
`-inline-toplevel`	400
`-inline-max-depth`	2
`-inline-max-unroll`	Same as default
`-unbox-closures-factor`	Same as default

19.5.2 Settings at -O3 optimisation level

When `-O3` is specified three rounds of optimisation are performed. The first two rounds are as for `-O2`. The third round uses the following parameters.

Parameter	Setting
`-inline`	50
`-inline-branch-factor`	Same as default
`-inline-alloc-cost`	Triple the default
`-inline-branch-cost`	Triple the default
`-inline-call-cost`	Triple the default
`-inline-indirect-cost`	Triple the default
`-inline-prim-cost`	Triple the default
`-inline-lifting-benefit`	Same as default
`-inline-toplevel`	800
`-inline-max-depth`	3
`-inline-max-unroll`	1
`-unbox-closures-factor`	Same as default

19.6 Manual control of inlining and specialisation

Should the inliner prove recalcitrant and refuse to inline a particular function, or if the observed inlining decisions are not to the programmer's satisfaction for some other reason, inlining behaviour can be dictated by the programmer directly in the source code. One example where this might be appropriate is when the programmer, but not the compiler, knows that a particular function call is on a cold code path. It might be desirable to prevent inlining of the function so that the code size along the hot path is kept smaller, so as to increase locality.

The inliner is directed using attributes. For non-recursive functions (and one-step unrolling of recursive functions, although `@unroll` is more clear for this purpose) the following are supported:

`@@inline always` or `@@inline never`
: Attached to a *declaration* of a function or functor, these direct the inliner to either always or never inline, irrespective of the size/benefit calculation. (If the function is recursive then the body is substituted and no special action is taken for the recursive call site(s).) `@@inline` with no argument is equivalent to `@@inline always`.

`@inlined always` or `@inlined never`
: Attached to a function *application*, these direct the inliner likewise. These attributes at call sites override any other attribute that may be present on the corresponding declaration. `@inlined` with no argument is equivalent to `@inlined always`.

For recursive functions the relevant attributes are:

`@@specialise always` or `@@specialise never`
: Attached to a declaration of a function or functor, this directs the inliner to either always or never specialise the function so long as it has appropriate contextual knowledge, irrespective of the size/benefit calculation. `@@specialise` with no argument is equivalent to `@@specialise always`.

`@specialised always` **or** `@specialised never`

Attached to a function application, this directs the inliner likewise. This attribute at a call site overrides any other attribute that may be present on the corresponding declaration. (Note that the function will still only be specialised if there exist one or more invariant parameters whose values are known.) `@specialised` with no argument is equivalent to `@specialised always`.

`@unrolled` n

This attribute is attached to a function application and always takes an integer argument. Each time the inliner sees the attribute it behaves as follows:

- If n is zero or less, nothing happens.
- Otherwise the function being called is substituted at the call site with its body having been rewritten such that any recursive calls to that function *or any others in the same mutually-recursive group* are annotated with the attribute `unrolled(`$n-1$`)`. Inlining may continue on that body.

As such, n behaves as the "maximum depth of unrolling".

A compiler warning will be emitted if it was found impossible to obey an annotation from an `@inlined` or `@specialised` attribute.

Example showing correct placement of attributes

```
module F (M : sig type t end) = struct
  let[@inline never] bar x =
    x * 3

  let foo x =
    (bar [@inlined]) (42 + x)
end [@@inline never]

module X = F [@inlined] (struct type t = int end)
```

19.7 Simplification

Simplification, which is run in conjunction with inlining, propagates information (known as *approximations*) about which variables hold what values at runtime. Certain relationships between variables and symbols are also tracked: for example, some variable may be known to always hold the same value as some other variable; or perhaps some variable may be known to always hold the value pointed to by some symbol.

The propagation can help to eliminate allocations in cases such as:

```
let f x y =
  ...
  let p = x, y in
  ...
  ... (fst p) ... (snd p) ...
```

The projections from `p` may be replaced by uses of the variables `x` and `y`, potentially meaning that `p` becomes unused.

The propagation performed by the simplification pass is also important for discovering which functions flow to indirect call sites. This can enable the transformation of such call sites into direct call sites, which makes them eligible for an inlining transformation.

Note that no information is propagated about the contents of strings, even in `safe-string` mode, because it cannot yet be guaranteed that they are immutable throughout a given program.

19.8 Other code motion transformations

19.8.1 Lifting of constants

Expressions found to be constant will be lifted to symbol bindings—that is to say, they will be statically allocated in the object file—when they evaluate to boxed values. Such constants may be straightforward numeric constants, such as the floating-point number `42.0`, or more complicated values such as constant closures.

Lifting of constants to toplevel reduces allocation at runtime.

The compiler aims to share constants lifted to toplevel such that there are no duplicate definitions. However if `.cmx` files are hidden from the compiler then maximal sharing may not be possible.

Notes about float arrays The following language semantics apply specifically to constant float arrays. (By "constant float array" is meant an array consisting entirely of floating point numbers that are known at compile time. A common case is a literal such as `[| 42.0; 43.0; |]`.

- Constant float arrays at the toplevel are mutable and never shared. (That is to say, for each such definition there is a distinct symbol in the data section of the object file pointing at the array.)
- Constant float arrays not at toplevel are mutable and are created each time the expression is evaluated. This can be thought of as an operation that takes an immutable array (which in the source code has no associated name; let us call it the *initialising array*) and duplicates it into a fresh mutable array.
  - If the array is of size four or less, the expression will create a fresh block and write the values into it one by one. There is no reference to the initialising array as a whole.
  - Otherwise, the initialising array is lifted out and subject to the normal constant sharing procedure; creation of the array consists of bulk copying the initialising array into a fresh value on the OCaml heap.

19.8.2 Lifting of toplevel let bindings

Toplevel `let`-expressions may be lifted to symbol bindings to ensure that the corresponding bound variables are not captured by closures. If the defining expression of a given binding is found to be constant, it is bound as such (the technical term is a *let-symbol* binding).

Otherwise, the symbol is bound to a (statically-allocated) *preallocated block* containing one field. At runtime, the defining expression will be evaluated and the first field of the block filled with the resulting value. This *initialise-symbol* binding causes one extra indirection but ensures, by virtue of the symbol's address being known at compile time, that uses of the value are not captured by closures.

It should be noted that the blocks corresponding to initialise-symbol bindings are kept alive forever, by virtue of them occurring in a static table of GC roots within the object file. This extended lifetime of expressions may on occasion be surprising. If it is desired to create some non-constant value (for example when writing GC tests) that does not have this extended lifetime, then it may be created and used inside a function, with the application point of that function (perhaps at toplevel)—or indeed the function declaration itself—marked as to never be inlined. This technique prevents lifting of the definition of the value in question (assuming of course that it is not constant).

19.9 Unboxing transformations

The transformations in this section relate to the splitting apart of *boxed* (that is to say, non-immediate) values. They are largely intended to reduce allocation, which tends to result in a runtime performance profile with lower variance and smaller tails.

19.9.1 Unboxing of closure variables

This transformation is enabled unless `-no-unbox-free-vars-of-closures` is provided.

Variables that appear in closure environments may themselves be boxed values. As such, they may be split into further closure variables, each of which corresponds to some projection from the original closure variable(s). This transformation is called *unboxing of closure variables* or *unboxing of free variables of closures*. It is only applied when there is reasonable certainty that there are no uses of the boxed free variable itself within the corresponding function bodies.

Example: In the following code, the compiler observes that the closure returned from the function `f` contains a variable `pair` (free in the body of `f`) that may be split into two separate variables.

```
let f x0 x1 =
  let pair = x0, x1 in
  Printf.printf "foo\n";
  fun y ->
    fst pair + snd pair + y
```

After some simplification one obtains:

```
let f x0 x1 =
  let pair_0 = x0 in
  let pair_1 = x1 in
  Printf.printf "foo\n";
  fun y ->
    pair_0 + pair_1 + y
```

and then:

```
let f x0 x1 =
  Printf.printf "foo\n";
  fun y ->
    x0 + x1 + y
```

The allocation of the pair has been eliminated.

This transformation does not operate if it would cause the closure to contain more than twice as many closure variables as it did beforehand.

19.9.2 Unboxing of specialised arguments

This transformation is enabled unless `-no-unbox-specialised-args` is provided.

It may become the case during compilation that one or more invariant arguments to a function become specialised to a particular value. When such values are themselves boxed the corresponding specialised arguments may be split into more specialised arguments corresponding to the projections out of the boxed value that occur within the function body. This transformation is called *unboxing of specialised arguments*. It is only applied when there is reasonable certainty that the boxed argument itself is unused within the function.

If the function in question is involved in a recursive group then unboxing of specialised arguments may be immediately replicated across the group based on the dataflow between invariant arguments.

Example: Having been given the following code, the compiler will inline `loop` into `f`, and then observe `inv` being invariant and always the pair formed by adding `42` and `43` to the argument `x` of the function `f`.

```
let rec loop inv xs =
  match xs with
  | [] -> fst inv + snd inv
  | x::xs -> x + loop2 xs inv
and loop2 ys inv =
  match ys with
  | [] -> 4
  | y::ys -> y - loop inv ys

let f x =
  Printf.printf "%d\n" (loop (x + 42, x + 43) [1; 2; 3])
```

Since the functions have sufficiently few arguments, more specialised arguments will be added. After some simplification one obtains:

```
let f x =
  let rec loop' xs inv_0 inv_1 =
    match xs with
    | [] -> inv_0 + inv_1
    | x::xs -> x + loop2' xs inv_0 inv_1
```

```
  and loop2' ys inv_0 inv_1 =
    match ys with
    | [] -> 4
    | y::ys -> y - loop' ys inv_0 inv_1
  in
  Printf.printf "%d\n" (loop' (x + 42) (x + 43) [1; 2; 3])
```

The allocation of the pair within `f` has been removed. (Since the two closures for `loop'` and `loop2'` are constant they will also be lifted to toplevel with no runtime allocation penalty. This would also happen without having run the transformation to unbox specialise arguments.)

The transformation to unbox specialised arguments never introduces extra allocation.

The transformation will not unbox arguments if it would result in the original function having sufficiently many arguments so as to inhibit tail-call optimisation.

The transformation is implemented by creating a wrapper function that accepts the original arguments. Meanwhile, the original function is renamed and extra arguments are added corresponding to the unboxed specialised arguments; this new function is called from the wrapper. The wrapper will then be inlined at direct call sites. Indeed, all call sites will be direct unless `-unbox-closures` is being used, since they will have been generated by the compiler when originally specialising the function. (In the case of `-unbox-closures` other functions may appear with specialised arguments; in this case there may be indirect calls and these will incur a small penalty owing to having to bounce through the wrapper. The technique of *direct call surrogates* used for `-unbox-closures` is not used by the transformation to unbox specialised arguments.)

19.9.3 Unboxing of closures

This transformation is *not* enabled by default. It may be enabled using the `-unbox-closures` flag.

The transformation replaces closure variables by specialised arguments. The aim is to cause more closures to become closed. It is particularly applicable, as a means of reducing allocation, where the function concerned cannot be inlined or specialised. For example, some non-recursive function might be too large to inline; or some recursive function might offer no opportunities for specialisation perhaps because its only argument is one of type `unit`.

At present there may be a small penalty in terms of actual runtime performance when this transformation is enabled, although more stable performance may be obtained due to reduced allocation. It is recommended that developers experiment to determine whether the option is beneficial for their code. (It is expected that in the future it will be possible for the performance degradation to be removed.)

Simple example: In the following code (which might typically occur when `g` is too large to inline) the value of `x` would usually be communicated to the application of the `+` function via the closure of `g`.

```
let f x =
  let g y =
    x + y
  in
  (g [@inlined never]) 42
```

Unboxing of the closure causes the value for `x` inside `g` to be passed as an argument to `g` rather than through its closure. This means that the closure of `g` becomes constant and may be lifted to toplevel, eliminating the runtime allocation.

The transformation is implemented by adding a new wrapper function in the manner of that used when unboxing specialised arguments. The closure variables are still free in the wrapper, but the intention is that when the wrapper is inlined at direct call sites, the relevant values are passed directly to the main function via the new specialised arguments.

Adding such a wrapper will penalise indirect calls to the function (which might exist in arbitrary places; remember that this transformation is not for example applied only on functions the compiler has produced as a result of specialisation) since such calls will bounce through the wrapper. To mitigate this, if a function is small enough when weighed up against the number of free variables being removed, it will be duplicated by the transformation to obtain two versions: the original (used for indirect calls, since we can do no better) and the wrapper/rewritten function pair as described in the previous paragraph. The wrapper/rewritten function pair will only be used at direct call sites of the function. (The wrapper in this case is known as a *direct call surrogate*, since it takes the place of another function—the unchanged version used for indirect calls—at direct call sites.)

The `-unbox-closures-factor` command line flag, which takes an integer, may be used to adjust the point at which a function is deemed large enough to be ineligible for duplication. The benefit of duplication is scaled by the integer before being evaluated against the size.

Harder example: In the following code, there are two closure variables that would typically cause closure allocations. One is called `fv` and occurs inside the function `baz`; the other is called `z` and occurs inside the function `bar`. In this toy (yet sophisticated) example we again use an attribute to simulate the typical situation where the first argument of `baz` is too large to inline.

```
let foo c =
  let rec bar zs fv =
    match zs with
    | [] -> []
    | z::zs ->
      let rec baz f = function
        | [] -> []
        | a::l -> let r = fv + ((f [@inlined never]) a) in r :: baz f l
      in
      (map2 (fun y -> z + y) [z; 2; 3; 4]) @ bar zs fv
  in
  Printf.printf "%d" (List.length (bar [1; 2; 3; 4] c))
```

The code resulting from applying `-O3 -unbox-closures` to this code passes the free variables via function arguments in order to eliminate all closure allocation in this example (aside from any that might be performed inside `printf`).

19.10 Removal of unused code and values

19.10.1 Removal of redundant let expressions

The simplification pass removes unused `let` bindings so long as their corresponding defining expressions have "no effects". See the section "Treatment of effects" below for the precise definition of this term.

19.10.2 Removal of redundant program constructs

This transformation is analogous to the removal of `let`-expressions whose defining expressions have no effects. It operates instead on symbol bindings, removing those that have no effects.

19.10.3 Removal of unused arguments

This transformation is only enabled by default for specialised arguments. It may be enabled for all arguments using the `-remove-unused-arguments` flag.

The pass analyses functions to determine which arguments are unused. Removal is effected by creating a wrapper function, which will be inlined at every direct call site, that accepts the original arguments and then discards the unused ones before calling the original function. As a consequence, this transformation may be detrimental if the original function is usually indirectly called, since such calls will now bounce through the wrapper. (The technique of *direct call surrogates* used to reduce this penalty during unboxing of closure variables (see above) does not yet apply to the pass that removes unused arguments.)

19.10.4 Removal of unused closure variables

This transformation performs an analysis across the whole compilation unit to determine whether there exist closure variables that are never used. Such closure variables are then eliminated. (Note that this has to be a whole-unit analysis because a projection of a closure variable from some particular closure may have propagated to an arbitrary location within the code due to inlining.)

19.11 Other code transformations

19.11.1 Transformation of non-escaping references into mutable variables

Flambda performs a simple analysis analogous to that performed elsewhere in the compiler that can transform `ref`s into mutable variables that may then be held in registers (or on the stack as appropriate) rather than being allocated on the OCaml heap. This only happens so long as the reference concerned can be shown to not escape from its defining scope.

19.11.2 Substitution of closure variables for specialised arguments

This transformation discovers closure variables that are known to be equal to specialised arguments. Such closure variables are replaced by the specialised arguments; the closure variables may then be removed by the "removal of unused closure variables" pass (see below).

19.12 Treatment of effects

The Flambda optimisers classify expressions in order to determine whether an expression:

- does not need to be evaluated at all; and/or
- may be duplicated.

This is done by forming judgements on the *effects* and the *coeffects* that might be performed were the expression to be executed. Effects talk about how the expression might affect the world; coeffects talk about how the world might affect the expression.

Effects are classified as follows:

No effects:
The expression does not change the observable state of the world. For example, it must not write to any mutable storage, call arbitrary external functions or change control flow (e.g. by raising an exception). Note that allocation is *not* classed as having "no effects" (see below).

- It is assumed in the compiler that expressions with no effects, whose results are not used, may be eliminated. (This typically happens where the expression in question is the defining expression of a `let`; in such cases the `let`-expression will be eliminated.) It is further assumed that such expressions with no effects may be duplicated (and thus possibly executed more than once).
- Exceptions arising from allocation points, for example "out of memory" or exceptions propagated from finalizers or signal handlers, are treated as "effects out of the ether" and thus ignored for our determination here of effectfulness. The same goes for floating point operations that may cause hardware traps on some platforms.

Only generative effects:
The expression does not change the observable state of the world save for possibly affecting the state of the garbage collector by performing an allocation. Expressions that only have generative effects and whose results are unused may be eliminated by the compiler. However, unlike expressions with "no effects", such expressions will never be eligible for duplication.

Arbitrary effects:
All other expressions.

There is a single classification for coeffects:

No coeffects:
The expression does not observe the effects (in the sense described above) of other expressions. For example, it must not read from any mutable storage or call arbitrary external functions.

It is assumed in the compiler that, subject to data dependencies, expressions with neither effects nor coeffects may be reordered with respect to other expressions.

19.13 Compilation of statically-allocated modules

Compilation of modules that are able to be statically allocated (for example, the module corresponding to an entire compilation unit, as opposed to a first class module dependent on values computed at runtime) initially follows the strategy used for bytecode. A sequence of `let`-bindings, which may be interspersed with arbitrary effects, surrounds a record creation that becomes the module block. The Flambda-specific transformation follows: these bindings are lifted to toplevel symbols, as described above.

19.14 Inhibition of optimisation

Especially when writing benchmarking suites that run non-side-effecting algorithms in loops, it may be found that the optimiser entirely elides the code being benchmarked. This behaviour can be prevented by using the `Sys.opaque_identity` function (which indeed behaves as a normal OCaml function and does not possess any "magic" semantics). The documentation of the `Sys` module should be consulted for further details.

19.15 Use of unsafe operations

The behaviour of the Flambda simplification pass means that certain unsafe operations, which may without Flambda or when using previous versions of the compiler be safe, must not be used. This specifically refers to functions found in the `Obj` module.

In particular, it is forbidden to change any value (for example using `Obj.set_field` or `Obj.set_tag`) that is not mutable. (Values returned from C stubs are always treated as mutable.) The compiler will emit warning 59 if it detects such a write—but it cannot warn in all cases. Here is an example of code that will trigger the warning:

```
let f x =
  let a = 42, x in
  (Obj.magic a : int ref) := 1;
  fst a
```

The reason this is unsafe is because the simplification pass believes that `fst a` holds the value `42`; and indeed it must, unless type soundness has been broken via unsafe operations.

If it must be the case that code has to be written that triggers warning 59, but the code is known to actually be correct (for some definition of correct), then `Sys.opaque_identity` may be used to wrap the value before unsafe operations are performed upon it. Great care must be taken when doing this to ensure that the opacity is added at the correct place. It must be emphasised that this use of `Sys.opaque_identity` is only for **exceptional** cases. It should not be used in normal code or to try to guide the optimiser.

As an example, this code will return the integer `1`:

```
let f x =
  let a = Sys.opaque_identity (42, x) in
  (Obj.magic a : int ref) := 1;
  fst a
```

However the following code will still return `42`:

```
let f x =
  let a = 42, x in
  Sys.opaque_identity (Obj.magic a : int ref) := 1;
  fst a
```

High levels of inlining performed by Flambda may expose bugs in code thought previously to be correct. Take care, for example, not to add type annotations that claim some mutable value is always immediate if it might be possible for an unsafe operation to update it to a boxed value.

19.16 Glossary

The following terminology is used in this chapter of the manual.

Call site
: See *direct call site* and *indirect call site* below.

Closed function
: A function whose body has no free variables except its parameters and any to which are bound other functions within the same (possibly mutually-recursive) declaration.

Closure
: The runtime representation of a function. This includes pointers to the code of the function together with the values of any variables that are used in the body of the function but actually defined outside of the function, in the enclosing scope. The values of such variables, collectively known as the *environment*, are required because the function may be invoked from a place where the original bindings of such variables are no longer in scope. A group of possibly mutually-recursive functions defined using *let rec* all share a single closure. (Note to developers: in the Flambda source code a *closure* always corresponds to a single function; a *set of closures* refers to a group of such.)

Closure variable
: A member of the environment held within the closure of a given function.

Constant
: Some entity (typically an expression) the value of which is known by the compiler at compile time. Constantness may be explicit from the source code or inferred by the Flambda optimisers.

Constant closure
: A closure that is statically allocated in an object file. It is almost always the case that the environment portion of such a closure is empty.

Defining expression
: The expression `e` in `let x = e in e'`.

Direct call site
A place in a program's code where a function is called and it is known at compile time which function it will always be.

Indirect call site
A place in a program's code where a function is called but is not known to be a *direct call site*.

Program
A collection of *symbol bindings* forming the definition of a single compilation unit (i.e. `.cmx` file).

Specialised argument
An argument to a function that is known to always hold a particular value at runtime. These are introduced by the inliner when specialising recursive functions; and the `unbox-closures` pass. (See section 19.4.)

Symbol
A name referencing a particular place in an object file or executable image. At that particular place will be some constant value. Symbols may be examined using operating system-specific tools (for example `objdump` on Linux).

Symbol binding
Analogous to a `let`-expression but working at the level of symbols defined in the object file. The address of a symbol is fixed, but it may be bound to both constant and non-constant expressions.

Toplevel
An expression in the current program which is not enclosed within any function declaration.

Variable
A named entity to which some OCaml value is bound by a `let` expression, pattern-matching construction, or similar.

19.17 Module `Spacetime` : Profiling of a program's space behaviour over time.

Currently only supported on x86-64 platforms running 64-bit code.

To use the functions in this module you must:

- configure the compiler with "-spacetime";
- compile to native code. Without these conditions being satisfied the functions in this module will have no effect.

Instead of manually taking profiling heap snapshots with this module it is possible to use an automatic snapshot facility that writes profiling information at fixed intervals to a file. To enable this, all that needs to be done is to build the relevant program using a compiler configured with

-spacetime; and set the environment variable OCAML_SPACETIME_INTERVAL to an integer number of milliseconds giving the interval between profiling heap snapshots. This interval should not be made excessively small relative to the running time of the program. A typical interval to start with might be 1/100 of the running time of the program. The program must exit "normally" (i.e. by calling `exit`, with whatever exit code, rather than being abnormally terminated by a signal) so that the snapshot file is correctly completed.

When using the automatic snapshot mode the profiling output is written to a file called "spacetime-<pid>" where <pid> is the process ID of the program. (If the program forks and continues executing then multiple files may be produced with different pid numbers.) The profiling output is by default written to the current working directory when the program starts. This may be customised by setting the OCAML_SPACETIME_SNAPSHOT_DIR environment variable to the name of the desired directory.

If using automatic snapshots the presence of the `save_event_for_automatic_snapshots` function, below, should be noted.

The functions in this module are thread safe.

For functions to decode the information recorded by the profiler, see the Spacetime offline library in otherlibs/.

```
module Series :
  sig
```

```
    type t
```

Type representing a file that will hold a series of heap snapshots together with additional information required to interpret those snapshots.

```
    val create : path:string -> t
```

`create ~path` creates a series file at `path`.

```
    val save_event : ?time:float -> t -> event_name:string -> unit
```

`save_event` writes an event, which is an arbitrary string, into the given series file. This may be used for identifying particular points during program execution when analysing the profile. The optional `time` parameter is as for `Snapshot.take`.

```
    val save_and_close : ?time:float -> t -> unit
```

`save_and_close series` writes information into `series` required for interpeting the snapshots that `series` contains and then closes the `series` file. This function must be called to produce a valid series file. The optional `time` parameter is as for `Snapshot.take`.

```
  end

module Snapshot :
  sig
    val take : ?time:float -> Spacetime.Series.t -> unit
```

`take series` takes a snapshot of the profiling annotations on the values in the minor and major heaps, together with GC stats, and write the result to the `series` file. This function triggers a minor GC but does not allocate any memory itself. If the optional `time` is specified, it will be used instead of the result of `Sys.time` as the timestamp of the snapshot. Such `time`s should start from zero and be monotonically increasing. This parameter is intended to be used so that snapshots can be correlated against wall clock time (which is not supported in the standard library) rather than elapsed CPU time.

```
  end
```

```
val save_event_for_automatic_snapshots : event_name:string -> unit
```

Like `Series.save_event`, but writes to the automatic snapshot file. This function is a no-op if OCAML_SPACETIME_INTERVAL was not set.

Part IV

The OCaml library

Chapter 20

The core library

This chapter describes the OCaml core library, which is composed of declarations for built-in types and exceptions, plus the module `Pervasives` that provides basic operations on these built-in types. The `Pervasives` module is special in two ways:

- It is automatically linked with the user's object code files by the `ocamlc` command (chapter 8).
- It is automatically "opened" when a compilation starts, or when the toplevel system is launched. Hence, it is possible to use unqualified identifiers to refer to the functions provided by the `Pervasives` module, without adding a `open Pervasives` directive.

Conventions

The declarations of the built-in types and the components of module `Pervasives` are printed one by one in typewriter font, followed by a short comment. All library modules and the components they provide are indexed at the end of this report.

20.1 Built-in types and predefined exceptions

The following built-in types and predefined exceptions are always defined in the compilation environment, but are not part of any module. As a consequence, they can only be referred by their short names.

Built-in types

`type int`

The type of integer numbers.

`type char`

The type of characters.

`type bytes`

The type of (writable) byte sequences.

`type string`
: The type of (read-only) character strings.

`type float`
: The type of floating-point numbers.

`type bool = false | true`
: The type of booleans (truth values).

`type unit = ()`
: The type of the unit value.

`type exn`
: The type of exception values.

`type 'a array`
: The type of arrays whose elements have type `'a`.

`type 'a list = [] | :: of 'a * 'a list`
: The type of lists whose elements have type `'a`.

`type 'a option = None | Some of 'a`
: The type of optional values of type `'a`.

`type int32`
: The type of signed 32-bit integers. See the `Int32`[21.15] module.

`type int64`
: The type of signed 64-bit integers. See the `Int64`[21.16] module.

`type nativeint`
: The type of signed, platform-native integers (32 bits on 32-bit processors, 64 bits on 64-bit processors). See the `Nativeint`[21.23] module.

`type ('a, 'b, 'c, 'd, 'e, 'f) format6`
: The type of format strings. `'a` is the type of the parameters of the format, `'f` is the result type for the `printf`-style functions, `'b` is the type of the first argument given to `%a` and `%t` printing functions (see module `Printf`[21.27]), `'c` is the result type of these functions, and also the type of the argument transmitted to the first argument of `kprintf`-style functions, `'d` is the result type for the `scanf`-style functions (see module `Scanf`[21.30]), and `'e` is the type of the receiver function for the `scanf`-style functions.

`type 'a lazy_t`
: This type is used to implement the `Lazy`[21.17] module. It should not be used directly.

Predefined exceptions

`exception Match_failure of (string * int * int)`

Exception raised when none of the cases of a pattern-matching apply. The arguments are the location of the `match` keyword in the source code (file name, line number, column number).

`exception Assert_failure of (string * int * int)`

Exception raised when an assertion fails. The arguments are the location of the `assert` keyword in the source code (file name, line number, column number).

`exception Invalid_argument of string`

Exception raised by library functions to signal that the given arguments do not make sense. The string gives some information to the programmer. As a general rule, this exception should not be caught, it denotes a programming error and the code should be modified not to trigger it.

`exception Failure of string`

Exception raised by library functions to signal that they are undefined on the given arguments. The string is meant to give some information to the programmer; you must *not* pattern match on the string literal because it may change in future versions (use `Failure _` instead).

`exception Not_found`

Exception raised by search functions when the desired object could not be found.

`exception Out_of_memory`

Exception raised by the garbage collector when there is insufficient memory to complete the computation.

`exception Stack_overflow`

Exception raised by the bytecode interpreter when the evaluation stack reaches its maximal size. This often indicates infinite or excessively deep recursion in the user's program. (Not fully implemented by the native-code compiler; see section 11.5.)

`exception Sys_error of string`

Exception raised by the input/output functions to report an operating system error. The string is meant to give some information to the programmer; you must *not* pattern match on the string literal because it may change in future versions (use `Sys_error _` instead).

`exception End_of_file`

Exception raised by input functions to signal that the end of file has been reached.

`exception Division_by_zero`

Exception raised by integer division and remainder operations when their second argument is zero.

`exception Sys_blocked_io`

A special case of `Sys_error` raised when no I/O is possible on a non-blocking I/O channel.

`exception Undefined_recursive_module of (string * int * int)`

Exception raised when an ill-founded recursive module definition is evaluated. (See section 7.4.) The arguments are the location of the definition in the source code (file name, line number, column number).

20.2 Module `Pervasives` : The initially opened module.

This module provides the basic operations over the built-in types (numbers, booleans, byte sequences, strings, exceptions, references, lists, arrays, input-output channels, ...).

This module is automatically opened at the beginning of each compilation. All components of this module can therefore be referred by their short name, without prefixing them by `Pervasives`.

Exceptions

`val raise : exn -> 'a`

Raise the given exception value

`val raise_notrace : exn -> 'a`

A faster version `raise` which does not record the backtrace.

Since: 4.02.0

`val invalid_arg : string -> 'a`

Raise exception `Invalid_argument` with the given string.

`val failwith : string -> 'a`

Raise exception `Failure` with the given string.

`exception Exit`

The `Exit` exception is not raised by any library function. It is provided for use in your programs.

Comparisons

`val (=) : 'a -> 'a -> bool`

`e1 = e2` tests for structural equality of `e1` and `e2`. Mutable structures (e.g. references and arrays) are equal if and only if their current contents are structurally equal, even if the two mutable objects are not the same physical object. Equality between functional values raises `Invalid_argument`. Equality between cyclic data structures may not terminate.

`val (<>) : 'a -> 'a -> bool`

Negation of `Pervasives.(=)`[20.2].

`val (<) : 'a -> 'a -> bool`

See `Pervasives.(>=)`[20.2].

`val (>) : 'a -> 'a -> bool`

See `Pervasives.(>=)`[20.2].

`val (<=) : 'a -> 'a -> bool`

See `Pervasives.(>=)`[20.2].

`val (>=) : 'a -> 'a -> bool`

Structural ordering functions. These functions coincide with the usual orderings over integers, characters, strings, byte sequences and floating-point numbers, and extend them to a total ordering over all types. The ordering is compatible with `( = )`. As in the case of `( = )`, mutable structures are compared by contents. Comparison between functional values raises `Invalid_argument`. Comparison between cyclic structures may not terminate.

`val compare : 'a -> 'a -> int`

`compare x y` returns `0` if `x` is equal to `y`, a negative integer if `x` is less than `y`, and a positive integer if `x` is greater than `y`. The ordering implemented by `compare` is compatible with the comparison predicates `=`, `<` and `>` defined above, with one difference on the treatment of the float value `Pervasives.nan`[20.2]. Namely, the comparison predicates treat `nan` as different from any other float value, including itself; while `compare` treats `nan` as equal to itself and less than any other float value. This treatment of `nan` ensures that `compare` defines a total ordering relation.

`compare` applied to functional values may raise `Invalid_argument`. `compare` applied to cyclic structures may not terminate.

The `compare` function can be used as the comparison function required by the `Set.Make`[21.31] and `Map.Make`[21.20] functors, as well as the `List.sort`[21.19] and `Array.sort`[21.2] functions.

`val min : 'a -> 'a -> 'a`

Return the smaller of the two arguments. The result is unspecified if one of the arguments contains the float value `nan`.

`val max : 'a -> 'a -> 'a`

Return the greater of the two arguments. The result is unspecified if one of the arguments contains the float value `nan`.

`val (==) : 'a -> 'a -> bool`

`e1 == e2` tests for physical equality of `e1` and `e2`. On mutable types such as references, arrays, byte sequences, records with mutable fields and objects with mutable instance variables, `e1 == e2` is true if and only if physical modification of `e1` also affects `e2`. On non-mutable types, the behavior of `( == )` is implementation-dependent; however, it is guaranteed that `e1 == e2` implies `compare e1 e2 = 0`.

`val (!=) : 'a -> 'a -> bool`

Negation of `Pervasives.(==)`[20.2].

Boolean operations

`val not : bool -> bool`

The boolean negation.

`val (&&) : bool -> bool -> bool`

The boolean 'and'. Evaluation is sequential, left-to-right: in `e1 && e2`, `e1` is evaluated first, and if it returns `false`, `e2` is not evaluated at all.

`val (&) : bool -> bool -> bool`

Deprecated. `Pervasives.(&&)`[20.2] should be used instead.

`val (||) : bool -> bool -> bool`

The boolean 'or'. Evaluation is sequential, left-to-right: in `e1 || e2`, `e1` is evaluated first, and if it returns `true`, `e2` is not evaluated at all.

`val (or) : bool -> bool -> bool`

Deprecated. `Pervasives.(||)`[20.2] should be used instead.

Debugging

`val __LOC__ : string`

`__LOC__` returns the location at which this expression appears in the file currently being parsed by the compiler, with the standard error format of OCaml: "File %S, line %d, characters %d-%d".

Since: 4.02.0

`val __FILE__ : string`

`__FILE__` returns the name of the file currently being parsed by the compiler.

Since: 4.02.0

`val __LINE__ : int`

`__LINE__` returns the line number at which this expression appears in the file currently being parsed by the compiler.

Since: 4.02.0

`val __MODULE__ : string`

`__MODULE__` returns the module name of the file being parsed by the compiler.

Since: 4.02.0

`val __POS__ : string * int * int * int`

`__POS__` returns a tuple `(file,lnum,cnum,enum)`, corresponding to the location at which this expression appears in the file currently being parsed by the compiler. `file` is the current filename, `lnum` the line number, `cnum` the character position in the line and `enum` the last character position in the line.

Since: 4.02.0

`val __LOC_OF__ : 'a -> string * 'a`

`__LOC_OF__ expr` returns a pair `(loc, expr)` where `loc` is the location of `expr` in the file currently being parsed by the compiler, with the standard error format of OCaml: "File %S, line %d, characters %d-%d".

Since: 4.02.0

`val __LINE_OF__ : 'a -> int * 'a`

`__LINE__ expr` returns a pair `(line, expr)`, where `line` is the line number at which the expression `expr` appears in the file currently being parsed by the compiler.

Since: 4.02.0

`val __POS_OF__ : 'a -> (string * int * int * int) * 'a`

`__POS_OF__ expr` returns a pair `(loc,expr)`, where `loc` is a tuple `(file,lnum,cnum,enum)` corresponding to the location at which the expression `expr` appears in the file currently being parsed by the compiler. `file` is the current filename, `lnum` the line number, `cnum` the character position in the line and `enum` the last character position in the line.

Since: 4.02.0

Composition operators

`val (|>) : 'a -> ('a -> 'b) -> 'b`

Reverse-application operator: `x |> f |> g` is exactly equivalent to `g (f (x))`.

Since: 4.01

`val (@@) : ('a -> 'b) -> 'a -> 'b`

Application operator: `g @@ f @@ x` is exactly equivalent to `g (f (x))`.

Since: 4.01

Integer arithmetic

Integers are 31 bits wide (or 63 bits on 64-bit processors). All operations are taken modulo 2^{31} (or 2^{63}). They do not fail on overflow.

`val (~-) : int -> int`

Unary negation. You can also write `- e` instead of `~- e`.

`val (~+) : int -> int`

Unary addition. You can also write `+ e` instead of `~+ e`.

Since: 3.12.0

`val succ : int -> int`

`succ x` is `x + 1`.

`val pred : int -> int`

`pred x` is `x - 1`.

`val (+) : int -> int -> int`

Integer addition.

`val (-) : int -> int -> int`

Integer subtraction.

`val ( * ) : int -> int -> int`

Integer multiplication.

`val (/) : int -> int -> int`

Integer division. Raise `Division_by_zero` if the second argument is 0. Integer division rounds the real quotient of its arguments towards zero. More precisely, if `x >= 0` and `y > 0`, `x / y` is the greatest integer less than or equal to the real quotient of `x` by `y`. Moreover, `(- x) / y = x / (- y) = - (x / y)`.

`val (mod) : int -> int -> int`

Integer remainder. If `y` is not zero, the result of `x mod y` satisfies the following properties: `x = (x / y) * y + x mod y` and `abs(x mod y) <= abs(y) - 1`. If `y = 0`, `x mod y` raises `Division_by_zero`. Note that `x mod y` is negative only if `x < 0`. Raise `Division_by_zero` if `y` is zero.

`val abs : int -> int`

Return the absolute value of the argument. Note that this may be negative if the argument is `min_int`.

`val max_int : int`

The greatest representable integer.

`val min_int : int`

The smallest representable integer.

Bitwise operations

`val (land) : int -> int -> int`

Bitwise logical and.

`val (lor) : int -> int -> int`

Bitwise logical or.

`val (lxor) : int -> int -> int`

Bitwise logical exclusive or.

`val lnot : int -> int`

Bitwise logical negation.

`val (lsl) : int -> int -> int`

`n lsl m` shifts `n` to the left by `m` bits. The result is unspecified if `m < 0` or `m >= bitsize`, where `bitsize` is `32` on a 32-bit platform and `64` on a 64-bit platform.

`val (lsr) : int -> int -> int`

`n lsr m` shifts `n` to the right by `m` bits. This is a logical shift: zeroes are inserted regardless of the sign of `n`. The result is unspecified if `m < 0` or `m >= bitsize`.

`val (asr) : int -> int -> int`

`n asr m` shifts `n` to the right by `m` bits. This is an arithmetic shift: the sign bit of `n` is replicated. The result is unspecified if `m < 0` or `m >= bitsize`.

Floating-point arithmetic

OCaml's floating-point numbers follow the IEEE 754 standard, using double precision (64 bits) numbers. Floating-point operations never raise an exception on overflow, underflow, division by zero, etc. Instead, special IEEE numbers are returned as appropriate, such as `infinity` for `1.0 /. 0.0`, `neg_infinity` for `-1.0 /. 0.0`, and `nan` ('not a number') for `0.0 /. 0.0`. These special numbers then propagate through floating-point computations as expected: for instance, `1.0 /. infinity` is `0.0`, and any arithmetic operation with `nan` as argument returns `nan` as result.

`val (~-.) : float -> float`

Unary negation. You can also write `-. e` instead of `~-. e`.

`val (~+.) : float -> float`

Unary addition. You can also write `+. e` instead of `~+. e`.

Since: 3.12.0

`val (+.) : float -> float -> float`

Floating-point addition

`val (-.) : float -> float -> float`
Floating-point subtraction

`val ( *. ) : float -> float -> float`
Floating-point multiplication

`val (/.) : float -> float -> float`
Floating-point division.

`val ( ** ) : float -> float -> float`
Exponentiation.

`val sqrt : float -> float`
Square root.

`val exp : float -> float`
Exponential.

`val log : float -> float`
Natural logarithm.

`val log10 : float -> float`
Base 10 logarithm.

`val expm1 : float -> float`
`expm1 x` computes `exp x -. 1.0`, giving numerically-accurate results even if `x` is close to `0.0`.
Since: 3.12.0

`val log1p : float -> float`
`log1p x` computes `log(1.0 +. x)` (natural logarithm), giving numerically-accurate results even if `x` is close to `0.0`.
Since: 3.12.0

`val cos : float -> float`
Cosine. Argument is in radians.

`val sin : float -> float`
Sine. Argument is in radians.

`val tan : float -> float`
Tangent. Argument is in radians.

`val acos : float -> float`

Arc cosine. The argument must fall within the range `[-1.0, 1.0]`. Result is in radians and is between `0.0` and `pi`.

`val asin : float -> float`

Arc sine. The argument must fall within the range `[-1.0, 1.0]`. Result is in radians and is between `-pi/2` and `pi/2`.

`val atan : float -> float`

Arc tangent. Result is in radians and is between `-pi/2` and `pi/2`.

`val atan2 : float -> float -> float`

`atan2 y x` returns the arc tangent of `y /. x`. The signs of `x` and `y` are used to determine the quadrant of the result. Result is in radians and is between `-pi` and `pi`.

`val hypot : float -> float -> float`

`hypot x y` returns `sqrt(x *. x + y *. y)`, that is, the length of the hypotenuse of a right-angled triangle with sides of length `x` and `y`, or, equivalently, the distance of the point `(x,y)` to origin. If one of `x` or `y` is infinite, returns `infinity` even if the other is `nan`.

Since: 4.00.0

`val cosh : float -> float`

Hyperbolic cosine. Argument is in radians.

`val sinh : float -> float`

Hyperbolic sine. Argument is in radians.

`val tanh : float -> float`

Hyperbolic tangent. Argument is in radians.

`val ceil : float -> float`

Round above to an integer value. `ceil f` returns the least integer value greater than or equal to `f`. The result is returned as a float.

`val floor : float -> float`

Round below to an integer value. `floor f` returns the greatest integer value less than or equal to `f`. The result is returned as a float.

`val abs_float : float -> float`

`abs_float f` returns the absolute value of `f`.

`val copysign : float -> float -> float`

`copysign x y` returns a float whose absolute value is that of `x` and whose sign is that of `y`. If `x` is `nan`, returns `nan`. If `y` is `nan`, returns either `x` or `-. x`, but it is not specified which.

Since: 4.00.0

`val mod_float : float -> float -> float`

`mod_float a b` returns the remainder of `a` with respect to `b`. The returned value is `a -. n *. b`, where `n` is the quotient `a /. b` rounded towards zero to an integer.

`val frexp : float -> float * int`

`frexp f` returns the pair of the significant and the exponent of `f`. When `f` is zero, the significant `x` and the exponent `n` of `f` are equal to zero. When `f` is non-zero, they are defined by `f = x *. 2 ** n` and `0.5 <= x < 1.0`.

`val ldexp : float -> int -> float`

`ldexp x n` returns `x *. 2 ** n`.

`val modf : float -> float * float`

`modf f` returns the pair of the fractional and integral part of `f`.

`val float : int -> float`

Same as `Pervasives.float_of_int`[20.2].

`val float_of_int : int -> float`

Convert an integer to floating-point.

`val truncate : float -> int`

Same as `Pervasives.int_of_float`[20.2].

`val int_of_float : float -> int`

Truncate the given floating-point number to an integer. The result is unspecified if the argument is `nan` or falls outside the range of representable integers.

`val infinity : float`

Positive infinity.

`val neg_infinity : float`

Negative infinity.

`val nan : float`

A special floating-point value denoting the result of an undefined operation such as `0.0 /. 0.0`. Stands for 'not a number'. Any floating-point operation with `nan` as argument returns `nan` as result. As for floating-point comparisons, `=`, `<`, `<=`, `>` and `>=` return `false` and `<>` returns `true` if one or both of their arguments is `nan`.

`val max_float : float`

The largest positive finite value of type `float`.

`val min_float : float`

The smallest positive, non-zero, non-denormalized value of type `float`.

`val epsilon_float : float`

The difference between `1.0` and the smallest exactly representable floating-point number greater than `1.0`.

`type fpclass =`

— FP_normal
: Normal number, none of the below

— FP_subnormal
: Number very close to 0.0, has reduced precision

— FP_zero
: Number is 0.0 or -0.0

— FP_infinite
: Number is positive or negative infinity

— FP_nan
: Not a number: result of an undefined operation

The five classes of floating-point numbers, as determined by the `Pervasives.classify_float`[20.2] function.

`val classify_float : float -> fpclass`

Return the class of the given floating-point number: normal, subnormal, zero, infinite, or not a number.

String operations

More string operations are provided in module `String`[21.37].

`val (^) : string -> string -> string`

String concatenation.

Character operations

More character operations are provided in module `Char`[21.6].

`val int_of_char : char -> int`

Return the ASCII code of the argument.

`val char_of_int : int -> char`

Return the character with the given ASCII code. Raise `Invalid_argument "char_of_int"` if the argument is outside the range 0–255.

Unit operations

`val ignore : 'a -> unit`

Discard the value of its argument and return `()`. For instance, `ignore(f x)` discards the result of the side-effecting function `f`. It is equivalent to `f x; ()`, except that the latter may generate a compiler warning; writing `ignore(f x)` instead avoids the warning.

String conversion functions

`val string_of_bool : bool -> string`

Return the string representation of a boolean. As the returned values may be shared, the user should not modify them directly.

`val bool_of_string : string -> bool`

Convert the given string to a boolean. Raise `Invalid_argument "bool_of_string"` if the string is not `"true"` or `"false"`.

`val string_of_int : int -> string`

Return the string representation of an integer, in decimal.

`val int_of_string : string -> int`

Convert the given string to an integer. The string is read in decimal (by default), in hexadecimal (if it begins with `0x` or `0X`), in octal (if it begins with `0o` or `0O`), or in binary (if it begins with `0b` or `0B`). The `_` (underscore) character can appear anywhere in the string and is ignored. Raise `Failure "int_of_string"` if the given string is not a valid representation of an integer, or if the integer represented exceeds the range of integers representable in type `int`.

`val string_of_float : float -> string`

Return the string representation of a floating-point number.

`val float_of_string : string -> float`

Convert the given string to a float. The string is read in decimal (by default) or in hexadecimal (marked by `0x` or `0X`). The format of decimal floating-point numbers is `[-] dd.ddd (e|E) [+|-] dd` , where `d` stands for a decimal digit. The format of hexadecimal floating-point numbers is `[-] 0(x|X) hh.hhh (p|P) [+|-] dd` , where `h` stands for an hexadecimal digit and `d` for a decimal digit. In both cases, at least one of the integer and fractional parts must be given; the exponent part is optional. The `_` (underscore) character can appear anywhere in the string and is ignored. Depending on the execution platforms, other representations of floating-point numbers can be accepted, but should not be relied upon. Raise `Failure "float_of_string"` if the given string is not a valid representation of a float.

Pair operations

`val fst : 'a * 'b -> 'a`
Return the first component of a pair.

`val snd : 'a * 'b -> 'b`
Return the second component of a pair.

List operations

More list operations are provided in module `List`[21.19].

`val (@) : 'a list -> 'a list -> 'a list`
List concatenation. Not tail-recursive (length of the first argument).

Input/output

Note: all input/output functions can raise `Sys_error` when the system calls they invoke fail.

`type in_channel`
The type of input channel.

`type out_channel`
The type of output channel.

`val stdin : in_channel`
The standard input for the process.

`val stdout : out_channel`
The standard output for the process.

`val stderr : out_channel`
The standard error output for the process.

Output functions on standard output

`val print_char : char -> unit`
Print a character on standard output.

`val print_string : string -> unit`
Print a string on standard output.

`val print_bytes : bytes -> unit`
Print a byte sequence on standard output.
Since: 4.02.0

`val print_int : int -> unit`

Print an integer, in decimal, on standard output.

`val print_float : float -> unit`

Print a floating-point number, in decimal, on standard output.

`val print_endline : string -> unit`

Print a string, followed by a newline character, on standard output and flush standard output.

`val print_newline : unit -> unit`

Print a newline character on standard output, and flush standard output. This can be used to simulate line buffering of standard output.

Output functions on standard error

`val prerr_char : char -> unit`

Print a character on standard error.

`val prerr_string : string -> unit`

Print a string on standard error.

`val prerr_bytes : bytes -> unit`

Print a byte sequence on standard error.

Since: 4.02.0

`val prerr_int : int -> unit`

Print an integer, in decimal, on standard error.

`val prerr_float : float -> unit`

Print a floating-point number, in decimal, on standard error.

`val prerr_endline : string -> unit`

Print a string, followed by a newline character on standard error and flush standard error.

`val prerr_newline : unit -> unit`

Print a newline character on standard error, and flush standard error.

Input functions on standard input

`val read_line : unit -> string`

Flush standard output, then read characters from standard input until a newline character is encountered. Return the string of all characters read, without the newline character at the end.

`val read_int : unit -> int`

Flush standard output, then read one line from standard input and convert it to an integer. Raise `Failure "int_of_string"` if the line read is not a valid representation of an integer.

`val read_float : unit -> float`

Flush standard output, then read one line from standard input and convert it to a floating-point number. The result is unspecified if the line read is not a valid representation of a floating-point number.

General output functions

`type open_flag =`

— Open_rdonly
: open for reading.

— Open_wronly
: open for writing.

— Open_append
: open for appending: always write at end of file.

— Open_creat
: create the file if it does not exist.

— Open_trunc
: empty the file if it already exists.

— Open_excl
: fail if Open_creat and the file already exists.

— Open_binary
: open in binary mode (no conversion).

— Open_text
: open in text mode (may perform conversions).

— Open_nonblock
: open in non-blocking mode.

Opening modes for `Pervasives.open_out_gen`[20.2] and `Pervasives.open_in_gen`[20.2].

`val open_out : string -> out_channel`

Open the named file for writing, and return a new output channel on that file, positioned at the beginning of the file. The file is truncated to zero length if it already exists. It is created if it does not already exists.

`val open_out_bin : string -> out_channel`

Same as `Pervasives.open_out`[20.2], but the file is opened in binary mode, so that no translation takes place during writes. On operating systems that do not distinguish between text mode and binary mode, this function behaves like `Pervasives.open_out`[20.2].

`val open_out_gen : open_flag list -> int -> string -> out_channel`

`open_out_gen mode perm filename` opens the named file for writing, as described above. The extra argument `mode` specify the opening mode. The extra argument `perm` specifies the file permissions, in case the file must be created. `Pervasives.open_out`[20.2] and `Pervasives.open_out_bin`[20.2] are special cases of this function.

`val flush : out_channel -> unit`

Flush the buffer associated with the given output channel, performing all pending writes on that channel. Interactive programs must be careful about flushing standard output and standard error at the right time.

`val flush_all : unit -> unit`

Flush all open output channels; ignore errors.

`val output_char : out_channel -> char -> unit`

Write the character on the given output channel.

`val output_string : out_channel -> string -> unit`

Write the string on the given output channel.

`val output_bytes : out_channel -> bytes -> unit`

Write the byte sequence on the given output channel.

Since: 4.02.0

`val output : out_channel -> bytes -> int -> int -> unit`

`output oc buf pos len` writes `len` characters from byte sequence `buf`, starting at offset `pos`, to the given output channel `oc`. Raise `Invalid_argument "output"` if `pos` and `len` do not designate a valid range of `buf`.

`val output_substring : out_channel -> string -> int -> int -> unit`

Same as `output` but take a string as argument instead of a byte sequence.

Since: 4.02.0

`val output_byte : out_channel -> int -> unit`

Write one 8-bit integer (as the single character with that code) on the given output channel. The given integer is taken modulo 256.

`val output_binary_int : out_channel -> int -> unit`

Write one integer in binary format (4 bytes, big-endian) on the given output channel. The given integer is taken modulo 2^{32}. The only reliable way to read it back is through the `Pervasives.input_binary_int`[20.2] function. The format is compatible across all machines for a given version of OCaml.

`val output_value : out_channel -> 'a -> unit`

Write the representation of a structured value of any type to a channel. Circularities and sharing inside the value are detected and preserved. The object can be read back, by the function `Pervasives.input_value`[20.2]. See the description of module `Marshal`[21.21] for more information. `Pervasives.output_value`[20.2] is equivalent to `Marshal.to_channel`[21.21] with an empty list of flags.

`val seek_out : out_channel -> int -> unit`

`seek_out chan pos` sets the current writing position to `pos` for channel `chan`. This works only for regular files. On files of other kinds (such as terminals, pipes and sockets), the behavior is unspecified.

`val pos_out : out_channel -> int`

Return the current writing position for the given channel. Does not work on channels opened with the `Open_append` flag (returns unspecified results).

`val out_channel_length : out_channel -> int`

Return the size (number of characters) of the regular file on which the given channel is opened. If the channel is opened on a file that is not a regular file, the result is meaningless.

`val close_out : out_channel -> unit`

Close the given channel, flushing all buffered write operations. Output functions raise a `Sys_error` exception when they are applied to a closed output channel, except `close_out` and `flush`, which do nothing when applied to an already closed channel. Note that `close_out` may raise `Sys_error` if the operating system signals an error when flushing or closing.

`val close_out_noerr : out_channel -> unit`

Same as `close_out`, but ignore all errors.

`val set_binary_mode_out : out_channel -> bool -> unit`

`set_binary_mode_out oc true` sets the channel `oc` to binary mode: no translations take place during output. `set_binary_mode_out oc false` sets the channel `oc` to text mode: depending on the operating system, some translations may take place during output. For instance, under Windows, end-of-lines will be translated from `\n` to `\r\n`. This function has no effect under operating systems that do not distinguish between text mode and binary mode.

General input functions

`val open_in : string -> in_channel`

Open the named file for reading, and return a new input channel on that file, positioned at the beginning of the file.

`val open_in_bin : string -> in_channel`

Same as `Pervasives.open_in`[20.2], but the file is opened in binary mode, so that no translation takes place during reads. On operating systems that do not distinguish between text mode and binary mode, this function behaves like `Pervasives.open_in`[20.2].

`val open_in_gen : open_flag list -> int -> string -> in_channel`

`open_in_gen mode perm filename` opens the named file for reading, as described above. The extra arguments `mode` and `perm` specify the opening mode and file permissions. `Pervasives.open_in`[20.2] and `Pervasives.open_in_bin`[20.2] are special cases of this function.

`val input_char : in_channel -> char`

Read one character from the given input channel. Raise `End_of_file` if there are no more characters to read.

`val input_line : in_channel -> string`

Read characters from the given input channel, until a newline character is encountered. Return the string of all characters read, without the newline character at the end. Raise `End_of_file` if the end of the file is reached at the beginning of line.

`val input : in_channel -> bytes -> int -> int -> int`

`input ic buf pos len` reads up to `len` characters from the given channel `ic`, storing them in byte sequence `buf`, starting at character number `pos`. It returns the actual number of characters read, between 0 and `len` (inclusive). A return value of 0 means that the end of file was reached. A return value between 0 and `len` exclusive means that not all requested `len` characters were read, either because no more characters were available at that time, or because the implementation found it convenient to do a partial read; `input` must be called again to read the remaining characters, if desired. (See also `Pervasives.really_input`[20.2] for reading exactly `len` characters.) Exception `Invalid_argument "input"` is raised if `pos` and `len` do not designate a valid range of `buf`.

`val really_input : in_channel -> bytes -> int -> int -> unit`

`really_input ic buf pos len` reads `len` characters from channel `ic`, storing them in byte sequence `buf`, starting at character number `pos`. Raise `End_of_file` if the end of file is reached before `len` characters have been read. Raise `Invalid_argument "really_input"` if `pos` and `len` do not designate a valid range of `buf`.

`val really_input_string : in_channel -> int -> string`

`really_input_string ic len` reads `len` characters from channel `ic` and returns them in a new string. Raise `End_of_file` if the end of file is reached before `len` characters have been read.

Since: 4.02.0

`val input_byte : in_channel -> int`

Same as `Pervasives.input_char`[20.2], but return the 8-bit integer representing the character. Raise `End_of_file` if an end of file was reached.

`val input_binary_int : in_channel -> int`

Read an integer encoded in binary format (4 bytes, big-endian) from the given input channel. See `Pervasives.output_binary_int`[20.2]. Raise `End_of_file` if an end of file was reached while reading the integer.

`val input_value : in_channel -> 'a`

Read the representation of a structured value, as produced by `Pervasives.output_value`[20.2], and return the corresponding value. This function is identical to `Marshal.from_channel`[21.21]; see the description of module `Marshal`[21.21] for more information, in particular concerning the lack of type safety.

`val seek_in : in_channel -> int -> unit`

`seek_in chan pos` sets the current reading position to `pos` for channel `chan`. This works only for regular files. On files of other kinds, the behavior is unspecified.

`val pos_in : in_channel -> int`

Return the current reading position for the given channel.

`val in_channel_length : in_channel -> int`

Return the size (number of characters) of the regular file on which the given channel is opened. If the channel is opened on a file that is not a regular file, the result is meaningless. The returned size does not take into account the end-of-line translations that can be performed when reading from a channel opened in text mode.

`val close_in : in_channel -> unit`

Close the given channel. Input functions raise a `Sys_error` exception when they are applied to a closed input channel, except `close_in`, which does nothing when applied to an already closed channel.

`val close_in_noerr : in_channel -> unit`

Same as `close_in`, but ignore all errors.

`val set_binary_mode_in : in_channel -> bool -> unit`

`set_binary_mode_in ic true` sets the channel `ic` to binary mode: no translations take place during input. `set_binary_mode_out ic false` sets the channel `ic` to text mode: depending on the operating system, some translations may take place during input. For instance, under Windows, end-of-lines will be translated from `\r\n` to `\n`. This function has no effect under operating systems that do not distinguish between text mode and binary mode.

Operations on large files

```
module LargeFile :
  sig
    val seek_out : Pervasives.out_channel -> int64 -> unit
    val pos_out : Pervasives.out_channel -> int64
    val out_channel_length : Pervasives.out_channel -> int64
    val seek_in : Pervasives.in_channel -> int64 -> unit
    val pos_in : Pervasives.in_channel -> int64
    val in_channel_length : Pervasives.in_channel -> int64
  end
```

Operations on large files. This sub-module provides 64-bit variants of the channel functions that manipulate file positions and file sizes. By representing positions and sizes by 64-bit integers (type `int64`) instead of regular integers (type `int`), these alternate functions allow operating on files whose sizes are greater than `max_int`.

References

```
type 'a ref =
{  mutable contents : 'a ;
}
```

The type of references (mutable indirection cells) containing a value of type `'a`.

```
val ref : 'a -> 'a ref
```

Return a fresh reference containing the given value.

```
val (!) : 'a ref -> 'a
```

`!r` returns the current contents of reference `r`. Equivalent to `fun r -> r.contents`.

```
val (:=) : 'a ref -> 'a -> unit
```

`r := a` stores the value of `a` in reference `r`. Equivalent to `fun r v -> r.contents <- v`.

```
val incr : int ref -> unit
```

Increment the integer contained in the given reference. Equivalent to `fun r -> r := succ !r`.

```
val decr : int ref -> unit
```

Decrement the integer contained in the given reference. Equivalent to `fun r -> r := pred !r`.

Result type

```
type ('a, 'b) result =
  | Ok of 'a
  | Error of 'b
```

Operations on format strings

Format strings are character strings with special lexical conventions that defines the functionality of formatted input/output functions. Format strings are used to read data with formatted input functions from module `Scanf`[21.30] and to print data with formatted output functions from modules `Printf`[21.27] and `Format`[21.11].

Format strings are made of three kinds of entities:

- *conversions specifications*, introduced by the special character `'%'` followed by one or more characters specifying what kind of argument to read or print,
- *formatting indications*, introduced by the special character `'@'` followed by one or more characters specifying how to read or print the argument,
- *plain characters* that are regular characters with usual lexical conventions. Plain characters specify string literals to be read in the input or printed in the output.

There is an additional lexical rule to escape the special characters `'%'` and `'@'` in format strings: if a special character follows a `'%'` character, it is treated as a plain character. In other words, `"%%"` is considered as a plain `'%'` and `"%@"` as a plain `'@'`.

For more information about conversion specifications and formatting indications available, read the documentation of modules `Scanf`[21.30], `Printf`[21.27] and `Format`[21.11].

Format strings have a general and highly polymorphic type `('a, 'b, 'c, 'd, 'e, 'f) format6`. The two simplified types, `format` and `format4` below are included for backward compatibility with earlier releases of OCaml.

The meaning of format string type parameters is as follows:

- `'a` is the type of the parameters of the format for formatted output functions (`printf`-style functions); `'a` is the type of the values read by the format for formatted input functions (`scanf`-style functions).
- `'b` is the type of input source for formatted input functions and the type of output target for formatted output functions. For `printf`-style functions from module `Printf`, `'b` is typically `out_channel`; for `printf`-style functions from module `Format`, `'b` is

typically `Format.formatter`; for `scanf`-style functions from module `Scanf`, `'b` is typically `Scanf.Scanning.in_channel`.

Type argument `'b` is also the type of the first argument given to user's defined printing functions for `%a` and `%t` conversions, and user's defined reading functions for `%r` conversion.

- `'c` is the type of the result of the `%a` and `%t` printing functions, and also the type of the argument transmitted to the first argument of `kprintf`-style functions or to the `kscanf`-style functions.
- `'d` is the type of parameters for the `scanf`-style functions.
- `'e` is the type of the receiver function for the `scanf`-style functions.
- `'f` is the final result type of a formatted input/output function invocation: for the `printf`-style functions, it is typically `unit`; for the `scanf`-style functions, it is typically the result type of the receiver function.

```
type ('a, 'b, 'c, 'd, 'e, 'f) format6 = ('a, 'b, 'c, 'd, 'e, 'f) CamlinternalFormatBasics.forma
type ('a, 'b, 'c, 'd) format4 = ('a, 'b, 'c, 'c, 'c, 'd) format6
type ('a, 'b, 'c) format = ('a, 'b, 'c, 'c) format4
val string_of_format : ('a, 'b, 'c, 'd, 'e, 'f) format6 -> string
```

Converts a format string into a string.

```
val format_of_string :
  ('a, 'b, 'c, 'd, 'e, 'f) format6 ->
  ('a, 'b, 'c, 'd, 'e, 'f) format6
```

`format_of_string s` returns a format string read from the string literal `s`. Note: `format_of_string` can not convert a string argument that is not a literal. If you need this functionality, use the more general `Scanf.format_from_string`[21.30] function.

```
val (^^) :
  ('a, 'b, 'c, 'd, 'e, 'f) format6 ->
  ('f, 'b, 'c, 'e, 'g, 'h) format6 ->
  ('a, 'b, 'c, 'd, 'g, 'h) format6
```

`f1 ^^ f2` catenates format strings `f1` and `f2`. The result is a format string that behaves as the concatenation of format strings `f1` and `f2`: in case of formatted output, it accepts arguments from `f1`, then arguments from `f2`; in case of formatted input, it returns results from `f1`, then results from `f2`.

Program termination

```
val exit : int -> 'a
```

Terminate the process, returning the given status code to the operating system: usually 0 to indicate no errors, and a small positive integer to indicate failure. All open output channels are flushed with `flush_all`. An implicit `exit 0` is performed each time a program terminates normally. An implicit `exit 2` is performed if the program terminates early because of an uncaught exception.

```
val at_exit : (unit -> unit) -> unit
```

Register the given function to be called at program termination time. The functions registered with `at_exit` will be called when the program executes `Pervasives.exit`[20.2], or terminates, either normally or because of an uncaught exception. The functions are called in 'last in, first out' order: the function most recently added with `at_exit` is called first.

Chapter 21

The standard library

This chapter describes the functions provided by the OCaml standard library. The modules from the standard library are automatically linked with the user's object code files by the `ocamlc` command. Hence, these modules can be used in standalone programs without having to add any `.cmo` file on the command line for the linking phase. Similarly, in interactive use, these globals can be used in toplevel phrases without having to load any `.cmo` file in memory.

Unlike the `Pervasives` module from the core library, the modules from the standard library are not automatically "opened" when a compilation starts, or when the toplevel system is launched. Hence it is necessary to use qualified identifiers to refer to the functions provided by these modules, or to add `open` directives.

Conventions

For easy reference, the modules are listed below in alphabetical order of module names. For each module, the declarations from its signature are printed one by one in typewriter font, followed by a short comment. All modules and the identifiers they export are indexed at the end of this report.

Overview

Here is a short listing, by theme, of the standard library modules.

Data structures:

`String`	p. 502	string operations
`Bytes`	p. 389	operations on byte sequences
`Array`	p. 382	array operations
`List`	p. 449	list operations
`StdLabels`	p. 500	labelized versions of the above 4 modules
`Char`	p. 396	character operations
`Uchar`	p. 513	Unicode characters
`Sort`	p. 496	(deprecated)
`Hashtbl`	p. 432	hash tables and hash functions
`Random`	p. 480	pseudo-random number generator
`Set`	p. 492	sets over ordered types
`Map`	p. 454	association tables over ordered types
`MoreLabels`	p. 461	labelized versions of `Hashtbl`, `Set`, and `Map`
`Oo`	p. 469	useful functions on objects
`Stack`	p. 499	last-in first-out stacks
`Queue`	p. 479	first-in first-out queues
`Buffer`	p. 386	buffers that grow on demand
`Lazy`	p. 445	delayed evaluation
`Weak`	p. 514	references that don't prevent objects from being garbage-collected
`Ephemeron`	p. 400	ephemerons and weak hash tables

Arithmetic:

`Complex`	p. 397	Complex numbers
`Int32`	p. 439	operations on 32-bit integers
`Int64`	p. 442	operations on 64-bit integers
`Nativeint`	p. 466	operations on platform-native integers

Input/output:

`Format`	p. 410	pretty printing with automatic indentation and line breaking
`Marshal`	p. 459	marshaling of data structures
`Printf`	p. 476	formatting printing functions
`Scanf`	p. 483	formatted input functions
`Digest`	p. 398	MD5 message digest

Parsing:

`Genlex`	p. 431	a generic lexer over streams
`Lexing`	p. 447	the run-time library for lexers generated by `ocamllex`
`Parsing`	p. 470	the run-time library for parsers generated by `ocamlyacc`
`Stream`	p. 500	basic functions over streams

System interface:

`Arg`	p. 379	parsing of command line arguments
`Callback`	p. 395	registering OCaml functions to be called from C
`Filename`	p. 408	operations on file names
`Gc`	p. 425	memory management control and statistics
`Printexc`	p. 471	a catch-all exception handler
`Spacetime`	p. 497	memory profiler
`Sys`	p. 506	system interface

21.1 Module `Arg` : Parsing of command line arguments.

This module provides a general mechanism for extracting options and arguments from the command line to the program.

Syntax of command lines: A keyword is a character string starting with a `-`. An option is a keyword alone or followed by an argument. The types of keywords are: `Unit`, `Bool`, `Set`, `Clear`, `String`, `Set_string`, `Int`, `Set_int`, `Float`, `Set_float`, `Tuple`, `Symbol`, and `Rest`. `Unit`, `Set` and `Clear` keywords take no argument. A `Rest` keyword takes the remaining of the command line as arguments. Every other keyword takes the following word on the command line as argument. For compatibility with GNU getopt_long, `keyword=arg` is also allowed. Arguments not preceded by a keyword are called anonymous arguments.

Examples (`cmd` is assumed to be the command name):

- `cmd -flag` (a unit option)
- `cmd -int 1` (an int option with argument `1`)
- `cmd -string foobar` (a string option with argument `"foobar"`)
- `cmd -float 12.34` (a float option with argument `12.34`)
- `cmd a b c` (three anonymous arguments: `"a"`, `"b"`, and `"c"`)
- `cmd a b -- c d` (two anonymous arguments and a rest option with two arguments)

```
type spec =
  | Unit of (unit -> unit)
```

Call the function with unit argument

```
  | Bool of (bool -> unit)
```

Call the function with a bool argument

```
  | Set of bool Pervasives.ref
```

Set the reference to true

```
  | Clear of bool Pervasives.ref
```

Set the reference to false

| `String of (string -> unit)`
  Call the function with a string argument

| `Set_string of string Pervasives.ref`
  Set the reference to the string argument

| `Int of (int -> unit)`
  Call the function with an int argument

| `Set_int of int Pervasives.ref`
  Set the reference to the int argument

| `Float of (float -> unit)`
  Call the function with a float argument

| `Set_float of float Pervasives.ref`
  Set the reference to the float argument

| `Tuple of spec list`
  Take several arguments according to the spec list

| `Symbol of string list * (string -> unit)`
  Take one of the symbols as argument and call the function with the symbol

| `Rest of (string -> unit)`
  Stop interpreting keywords and call the function with each remaining argument

The concrete type describing the behavior associated with a keyword.

```
type key = string
type doc = string
type usage_msg = string
type anon_fun = string -> unit
val parse : (key * spec * doc) list -> anon_fun -> usage_msg -> unit
```

`Arg.parse speclist anon_fun usage_msg` parses the command line. `speclist` is a list of triples `(key, spec, doc)`. `key` is the option keyword, it must start with a `'-'` character. `spec` gives the option type and the function to call when this option is found on the command line. `doc` is a one-line description of this option. `anon_fun` is called on anonymous arguments. The functions in `spec` and `anon_fun` are called in the same order as their arguments appear on the command line.

If an error occurs, `Arg.parse` exits the program, after printing to standard error an error message as follows:

- The reason for the error: unknown option, invalid or missing argument, etc.
- `usage_msg`
- The list of options, each followed by the corresponding `doc` string. Beware: options that have an empty `doc` string will not be included in the list.

For the user to be able to specify anonymous arguments starting with a `-`, include for example `("-", String anon_fun, doc)` in `speclist`.

By default, `parse` recognizes two unit options, `-help` and `--help`, which will print to standard output `usage_msg` and the list of options, and exit the program. You can override this behaviour by specifying your own `-help` and `--help` options in `speclist`.

```
val parse_dynamic :
  (key * spec * doc) list Pervasives.ref ->
  anon_fun -> usage_msg -> unit
```

Same as `Arg.parse`[21.1], except that the `speclist` argument is a reference and may be updated during the parsing. A typical use for this feature is to parse command lines of the form:

- command subcommand `options` where the list of options depends on the value of the subcommand argument.

```
val parse_argv :
  ?current:int Pervasives.ref ->
  string array ->
  (key * spec * doc) list -> anon_fun -> usage_msg -> unit
```

`Arg.parse_argv ~current args speclist anon_fun usage_msg` parses the array `args` as if it were the command line. It uses and updates the value of `~current` (if given), or `Arg.current`. You must set it before calling `parse_argv`. The initial value of `current` is the index of the program name (argument 0) in the array. If an error occurs, `Arg.parse_argv` raises `Arg.Bad` with the error message as argument. If option `-help` or `--help` is given, `Arg.parse_argv` raises `Arg.Help` with the help message as argument.

```
val parse_argv_dynamic :
  ?current:int Pervasives.ref ->
  string array ->
  (key * spec * doc) list Pervasives.ref ->
  anon_fun -> string -> unit
```

Same as `Arg.parse_argv`[21.1], except that the `speclist` argument is a reference and may be updated during the parsing. See `Arg.parse_dynamic`[21.1].

```
exception Help of string
```

Raised by `Arg.parse_argv` when the user asks for help.

```
exception Bad of string
```

Functions in `spec` or `anon_fun` can raise `Arg.Bad` with an error message to reject invalid arguments. `Arg.Bad` is also raised by `Arg.parse_argv` in case of an error.

```
val usage : (key * spec * doc) list -> usage_msg -> unit
```

`Arg.usage speclist usage_msg` prints to standard error an error message that includes the list of valid options. This is the same message that `Arg.parse`[21.1] prints in case of error. `speclist` and `usage_msg` are the same as for `Arg.parse`.

```
val usage_string : (key * spec * doc) list -> usage_msg -> string
```

Returns the message that would have been printed by `Arg.usage`[21.1], if provided with the same parameters.

```
val align :
  ?limit:int ->
  (key * spec * doc) list -> (key * spec * doc) list
```

Align the documentation strings by inserting spaces at the first space, according to the length of the keyword. Use a space as the first character in a doc string if you want to align the whole string. The doc strings corresponding to `Symbol` arguments are aligned on the next line.

```
val current : int Pervasives.ref
```

Position (in `Sys.argv`[21.38]) of the argument being processed. You can change this value, e.g. to force `Arg.parse`[21.1] to skip some arguments. `Arg.parse`[21.1] uses the initial value of `Arg.current`[21.1] as the index of argument 0 (the program name) and starts parsing arguments at the next element.

21.2 Module `Array` : Array operations.

```
val length : 'a array -> int
```

Return the length (number of elements) of the given array.

```
val get : 'a array -> int -> 'a
```

`Array.get a n` returns the element number `n` of array `a`. The first element has number 0. The last element has number `Array.length a - 1`. You can also write `a.(n)` instead of `Array.get a n`.

Raise `Invalid_argument "index out of bounds"` if `n` is outside the range 0 to `(Array.length a - 1)`.

```
val set : 'a array -> int -> 'a -> unit
```

`Array.set a n x` modifies array `a` in place, replacing element number `n` with `x`. You can also write `a.(n) <- x` instead of `Array.set a n x`.

Raise `Invalid_argument "index out of bounds"` if `n` is outside the range 0 to `Array.length a - 1`.

```
val make : int -> 'a -> 'a array
```

`Array.make n x` returns a fresh array of length `n`, initialized with `x`. All the elements of this new array are initially physically equal to `x` (in the sense of the `==` predicate). Consequently, if `x` is mutable, it is shared among all elements of the array, and modifying `x` through one of the array entries will modify all other entries at the same time.

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_array_length`. If the value of `x` is a floating-point number, then the maximum size is only `Sys.max_array_length / 2`.

`val create : int -> 'a -> 'a array`

Deprecated. `Array.create` is an alias for `Array.make`[21.2].

`val create_float : int -> float array`

`Array.create_float n` returns a fresh float array of length `n`, with uninitialized data.

Since: 4.03

`val make_float : int -> float array`

Deprecated. `Array.make_float` is an alias for `Array.create_float`[21.2].

`val init : int -> (int -> 'a) -> 'a array`

`Array.init n f` returns a fresh array of length `n`, with element number `i` initialized to the result of `f i`. In other terms, `Array.init n f` tabulates the results of `f` applied to the integers `0` to `n-1`.

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_array_length`. If the return type of `f` is `float`, then the maximum size is only `Sys.max_array_length / 2`.

`val make_matrix : int -> int -> 'a -> 'a array array`

`Array.make_matrix dimx dimy e` returns a two-dimensional array (an array of arrays) with first dimension `dimx` and second dimension `dimy`. All the elements of this new matrix are initially physically equal to `e`. The element `(x,y)` of a matrix `m` is accessed with the notation `m.(x).(y)`.

Raise `Invalid_argument` if `dimx` or `dimy` is negative or greater than `Sys.max_array_length`. If the value of `e` is a floating-point number, then the maximum size is only `Sys.max_array_length / 2`.

`val create_matrix : int -> int -> 'a -> 'a array array`

Deprecated. `Array.create_matrix` is an alias for `Array.make_matrix`[21.2].

`val append : 'a array -> 'a array -> 'a array`

`Array.append v1 v2` returns a fresh array containing the concatenation of the arrays `v1` and `v2`.

`val concat : 'a array list -> 'a array`

Same as `Array.append`, but concatenates a list of arrays.

`val sub : 'a array -> int -> int -> 'a array`

`Array.sub a start len` returns a fresh array of length `len`, containing the elements number `start` to `start + len - 1` of array `a`.

Raise `Invalid_argument "Array.sub"` if `start` and `len` do not designate a valid subarray of `a`; that is, if `start < 0`, or `len < 0`, or `start + len > Array.length a`.

`val copy : 'a array -> 'a array`

`Array.copy a` returns a copy of `a`, that is, a fresh array containing the same elements as `a`.

`val fill : 'a array -> int -> int -> 'a -> unit`

`Array.fill a ofs len x` modifies the array `a` in place, storing `x` in elements number `ofs` to `ofs + len - 1`.

Raise `Invalid_argument "Array.fill"` if `ofs` and `len` do not designate a valid subarray of `a`.

`val blit : 'a array -> int -> 'a array -> int -> int -> unit`

`Array.blit v1 o1 v2 o2 len` copies `len` elements from array `v1`, starting at element number `o1`, to array `v2`, starting at element number `o2`. It works correctly even if `v1` and `v2` are the same array, and the source and destination chunks overlap.

Raise `Invalid_argument "Array.blit"` if `o1` and `len` do not designate a valid subarray of `v1`, or if `o2` and `len` do not designate a valid subarray of `v2`.

`val to_list : 'a array -> 'a list`

`Array.to_list a` returns the list of all the elements of `a`.

`val of_list : 'a list -> 'a array`

`Array.of_list l` returns a fresh array containing the elements of `l`.

Iterators

`val iter : ('a -> unit) -> 'a array -> unit`

`Array.iter f a` applies function `f` in turn to all the elements of `a`. It is equivalent to `f a.(0); f a.(1); ...; f a.(Array.length a - 1); ()`.

`val iteri : (int -> 'a -> unit) -> 'a array -> unit`

Same as `Array.iter`[21.2], but the function is applied with the index of the element as first argument, and the element itself as second argument.

`val map : ('a -> 'b) -> 'a array -> 'b array`

`Array.map f a` applies function `f` to all the elements of `a`, and builds an array with the results returned by `f`: `[| f a.(0); f a.(1); ...; f a.(Array.length a - 1) |]`.

`val mapi : (int -> 'a -> 'b) -> 'a array -> 'b array`

Same as `Array.map`[21.2], but the function is applied to the index of the element as first argument, and the element itself as second argument.

`val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b array -> 'a`

`Array.fold_left f x a` computes `f (... (f (f x a.(0)) a.(1)) ...) a.(n-1)`, where `n` is the length of the array `a`.

`val fold_right : ('b -> 'a -> 'a) -> 'b array -> 'a -> 'a`

`Array.fold_right f a x` computes `f a.(0) (f a.(1) ( ... (f a.(n-1) x) ...))`, where `n` is the length of the array `a`.

Iterators on two arrays

`val iter2 : ('a -> 'b -> unit) -> 'a array -> 'b array -> unit`

`Array.iter2 f a b` applies function `f` to all the elements of `a` and `b`. Raise `Invalid_argument` if the arrays are not the same size.

Since: 4.03.0

`val map2 : ('a -> 'b -> 'c) -> 'a array -> 'b array -> 'c array`

`Array.map2 f a b` applies function `f` to all the elements of `a` and `b`, and builds an array with the results returned by `f`: `[| f a.(0) b.(0); ...; f a.(Array.length a - 1) b.(Array.length b - 1)|]`. Raise `Invalid_argument` if the arrays are not the same size.

Since: 4.03.0

Array scanning

`val for_all : ('a -> bool) -> 'a array -> bool`

`Array.for_all p [|a1; ...; an|]` checks if all elements of the array satisfy the predicate `p`. That is, it returns `(p a1) && (p a2) && ... && (p an)`.

Since: 4.03.0

`val exists : ('a -> bool) -> 'a array -> bool`

`Array.exists p [|a1; ...; an|]` checks if at least one element of the array satisfies the predicate `p`. That is, it returns `(p a1) || (p a2) || ... || (p an)`.

Since: 4.03.0

`val mem : 'a -> 'a array -> bool`

`mem a l` is true if and only if `a` is equal to an element of `l`.

Since: 4.03.0

`val memq : 'a -> 'a array -> bool`

Same as `Array.mem`[21.2], but uses physical equality instead of structural equality to compare array elements.

Since: 4.03.0

Sorting

`val sort : ('a -> 'a -> int) -> 'a array -> unit`

Sort an array in increasing order according to a comparison function. The comparison function must return 0 if its arguments compare as equal, a positive integer if the first is greater, and a negative integer if the first is smaller (see below for a complete specification). For example, `Pervasives.compare`[20.2] is a suitable comparison function, provided there are no floating-point NaN values in the data. After calling `Array.sort`, the array is sorted in place in increasing order. `Array.sort` is guaranteed to run in constant heap space and (at most) logarithmic stack space.

The current implementation uses Heap Sort. It runs in constant stack space.

Specification of the comparison function: Let `a` be the array and `cmp` the comparison function. The following must be true for all x, y, z in a :

- `cmp x y` > 0 if and only if `cmp y x` < 0
- if `cmp x y` ≥ 0 and `cmp y z` ≥ 0 then `cmp x z` ≥ 0

When `Array.sort` returns, `a` contains the same elements as before, reordered in such a way that for all i and j valid indices of `a` :

- `cmp a.(i) a.(j)` ≥ 0 if and only if i $\geq$ j

`val stable_sort : ('a -> 'a -> int) -> 'a array -> unit`

Same as `Array.sort`[21.2], but the sorting algorithm is stable (i.e. elements that compare equal are kept in their original order) and not guaranteed to run in constant heap space.

The current implementation uses Merge Sort. It uses `n/2` words of heap space, where `n` is the length of the array. It is usually faster than the current implementation of `Array.sort`[21.2].

`val fast_sort : ('a -> 'a -> int) -> 'a array -> unit`

Same as `Array.sort`[21.2] or `Array.stable_sort`[21.2], whichever is faster on typical input.

21.3 Module `Buffer` : Extensible buffers.

This module implements buffers that automatically expand as necessary. It provides accumulative concatenation of strings in quasi-linear time (instead of quadratic time when strings are concatenated pairwise).

`type t`

The abstract type of buffers.

`val create : int -> t`

`create n` returns a fresh buffer, initially empty. The `n` parameter is the initial size of the internal byte sequence that holds the buffer contents. That byte sequence is automatically reallocated when more than `n` characters are stored in the buffer, but shrinks back to `n` characters when `reset` is called. For best performance, `n` should be of the same order of magnitude as the number of characters that are expected to be stored in the buffer (for instance, 80 for a buffer that holds one output line). Nothing bad will happen if the buffer grows beyond that limit, however. In doubt, take `n = 16` for instance. If `n` is not between 1 and `Sys.max_string_length`[21.38], it will be clipped to that interval.

`val contents : t -> string`

Return a copy of the current contents of the buffer. The buffer itself is unchanged.

`val to_bytes : t -> bytes`

Return a copy of the current contents of the buffer. The buffer itself is unchanged.

Since: 4.02

`val sub : t -> int -> int -> string`

`Buffer.sub b off len` returns a copy of `len` bytes from the current contents of the buffer `b`, starting at offset `off`.

Raise `Invalid_argument` if `srcoff` and `len` do not designate a valid range of `b`.

`val blit : t -> int -> bytes -> int -> int -> unit`

`Buffer.blit src srcoff dst dstoff len` copies `len` characters from the current contents of the buffer `src`, starting at offset `srcoff` to `dst`, starting at character `dstoff`.

Raise `Invalid_argument` if `srcoff` and `len` do not designate a valid range of `src`, or if `dstoff` and `len` do not designate a valid range of `dst`.

Since: 3.11.2

`val nth : t -> int -> char`

Get the n-th character of the buffer. Raise `Invalid_argument` if index out of bounds

`val length : t -> int`

Return the number of characters currently contained in the buffer.

`val clear : t -> unit`

Empty the buffer.

`val reset : t -> unit`

Empty the buffer and deallocate the internal byte sequence holding the buffer contents, replacing it with the initial internal byte sequence of length `n` that was allocated by `Buffer.create`[21.3] `n`. For long-lived buffers that may have grown a lot, `reset` allows faster reclamation of the space used by the buffer.

`val add_char : t -> char -> unit`

`add_char b c` appends the character `c` at the end of buffer `b`.

`val add_string : t -> string -> unit`

`add_string b s` appends the string `s` at the end of buffer `b`.

`val add_bytes : t -> bytes -> unit`

`add_bytes b s` appends the byte sequence `s` at the end of buffer `b`.

Since: 4.02

`val add_substring : t -> string -> int -> int -> unit`

`add_substring b s ofs len` takes `len` characters from offset `ofs` in string `s` and appends them at the end of buffer `b`.

`val add_subbytes : t -> bytes -> int -> int -> unit`

`add_subbytes b s ofs len` takes `len` characters from offset `ofs` in byte sequence `s` and appends them at the end of buffer `b`.

Since: 4.02

`val add_substitute : t -> (string -> string) -> string -> unit`

`add_substitute b f s` appends the string pattern `s` at the end of buffer `b` with substitution. The substitution process looks for variables into the pattern and substitutes each variable name by its value, as obtained by applying the mapping `f` to the variable name. Inside the string pattern, a variable name immediately follows a non-escaped `$` character and is one of the following:

- a non empty sequence of alphanumeric or `_` characters,
- an arbitrary sequence of characters enclosed by a pair of matching parentheses or curly brackets. An escaped `$` character is a `$` that immediately follows a backslash character; it then stands for a plain `$`. Raise `Not_found` if the closing character of a parenthesized variable cannot be found.

`val add_buffer : t -> t -> unit`

`add_buffer b1 b2` appends the current contents of buffer `b2` at the end of buffer `b1`. `b2` is not modified.

`val add_channel : t -> Pervasives.in_channel -> int -> unit`

`add_channel b ic n` reads at most `n` characters from the input channel `ic` and stores them at the end of buffer `b`. Raise `End_of_file` if the channel contains fewer than `n` characters. In this case, the characters are still added to the buffer, so as to avoid loss of data.

`val output_buffer : Pervasives.out_channel -> t -> unit`

`output_buffer oc b` writes the current contents of buffer `b` on the output channel `oc`.

21.4 Module `Bytes` : Byte sequence operations.

A byte sequence is a mutable data structure that contains a fixed-length sequence of bytes. Each byte can be indexed in constant time for reading or writing.

Given a byte sequence `s` of length `l`, we can access each of the `l` bytes of `s` via its index in the sequence. Indexes start at `0`, and we will call an index valid in `s` if it falls within the range `[0...l-1]` (inclusive). A position is the point between two bytes or at the beginning or end of the sequence. We call a position valid in `s` if it falls within the range `[0...l]` (inclusive). Note that the byte at index `n` is between positions `n` and `n+1`.

Two parameters `start` and `len` are said to designate a valid range of `s` if `len >= 0` and `start` and `start+len` are valid positions in `s`.

Byte sequences can be modified in place, for instance via the `set` and `blit` functions described below. See also strings (module `String`[21.37]), which are almost the same data structure, but cannot be modified in place.

Bytes are represented by the OCaml type `char`.

Since: 4.02.0

`val length : bytes -> int`

Return the length (number of bytes) of the argument.

`val get : bytes -> int -> char`

`get s n` returns the byte at index `n` in argument `s`.

Raise `Invalid_argument` if `n` not a valid index in `s`.

`val set : bytes -> int -> char -> unit`

`set s n c` modifies `s` in place, replacing the byte at index `n` with `c`.

Raise `Invalid_argument` if `n` is not a valid index in `s`.

`val create : int -> bytes`

`create n` returns a new byte sequence of length `n`. The sequence is uninitialized and contains arbitrary bytes.

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_string_length`[21.38].

`val make : int -> char -> bytes`

`make n c` returns a new byte sequence of length `n`, filled with the byte `c`.

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_string_length`[21.38].

`val init : int -> (int -> char) -> bytes`

`Bytes.init n f` returns a fresh byte sequence of length `n`, with character `i` initialized to the result of `f i` (in increasing index order).

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_string_length`[21.38].

`val empty : bytes`

A byte sequence of size 0.

`val copy : bytes -> bytes`

Return a new byte sequence that contains the same bytes as the argument.

`val of_string : string -> bytes`

Return a new byte sequence that contains the same bytes as the given string.

`val to_string : bytes -> string`

Return a new string that contains the same bytes as the given byte sequence.

`val sub : bytes -> int -> int -> bytes`

`sub s start len` returns a new byte sequence of length `len`, containing the subsequence of `s` that starts at position `start` and has length `len`.

Raise `Invalid_argument` if `start` and `len` do not designate a valid range of `s`.

`val sub_string : bytes -> int -> int -> string`

Same as `sub` but return a string instead of a byte sequence.

`val extend : bytes -> int -> int -> bytes`

`extend s left right` returns a new byte sequence that contains the bytes of `s`, with `left` uninitialized bytes prepended and `right` uninitialized bytes appended to it. If `left` or `right` is negative, then bytes are removed (instead of appended) from the corresponding side of `s`.

Raise `Invalid_argument` if the result length is negative or longer than `Sys.max_string_length`[21.38] bytes.

`val fill : bytes -> int -> int -> char -> unit`

`fill s start len c` modifies `s` in place, replacing `len` characters with `c`, starting at `start`.

Raise `Invalid_argument` if `start` and `len` do not designate a valid range of `s`.

`val blit : bytes -> int -> bytes -> int -> int -> unit`

`blit src srcoff dst dstoff len` copies `len` bytes from sequence `src`, starting at index `srcoff`, to sequence `dst`, starting at index `dstoff`. It works correctly even if `src` and `dst` are the same byte sequence, and the source and destination intervals overlap.

Raise `Invalid_argument` if `srcoff` and `len` do not designate a valid range of `src`, or if `dstoff` and `len` do not designate a valid range of `dst`.

`val blit_string : string -> int -> bytes -> int -> int -> unit`

`blit src srcoff dst dstoff len` copies `len` bytes from string `src`, starting at index `srcoff`, to byte sequence `dst`, starting at index `dstoff`.

Raise `Invalid_argument` if `srcoff` and `len` do not designate a valid range of `src`, or if `dstoff` and `len` do not designate a valid range of `dst`.

`val concat : bytes -> bytes list -> bytes`

`concat sep sl` concatenates the list of byte sequences `sl`, inserting the separator byte sequence `sep` between each, and returns the result as a new byte sequence.

Raise `Invalid_argument` if the result is longer than `Sys.max_string_length`[21.38] bytes.

`val cat : bytes -> bytes -> bytes`

`cat s1 s2` concatenates `s1` and `s2` and returns the result as new byte sequence.

Raise `Invalid_argument` if the result is longer than `Sys.max_string_length`[21.38] bytes.

`val iter : (char -> unit) -> bytes -> unit`

`iter f s` applies function `f` in turn to all the bytes of `s`. It is equivalent to `f (get s 0); f (get s 1); ...; f (get s (length s - 1)); ()`.

`val iteri : (int -> char -> unit) -> bytes -> unit`

Same as `Bytes.iter`[21.4], but the function is applied to the index of the byte as first argument and the byte itself as second argument.

`val map : (char -> char) -> bytes -> bytes`

`map f s` applies function `f` in turn to all the bytes of `s` (in increasing index order) and stores the resulting bytes in a new sequence that is returned as the result.

`val mapi : (int -> char -> char) -> bytes -> bytes`

`mapi f s` calls `f` with each character of `s` and its index (in increasing index order) and stores the resulting bytes in a new sequence that is returned as the result.

`val trim : bytes -> bytes`

Return a copy of the argument, without leading and trailing whitespace. The bytes regarded as whitespace are the ASCII characters `' '`, `'\012'`, `'\n'`, `'\r'`, and `'\t'`.

`val escaped : bytes -> bytes`

Return a copy of the argument, with special characters represented by escape sequences, following the lexical conventions of OCaml. All characters outside the ASCII printable range (32..126) are escaped, as well as backslash and double-quote.

Raise `Invalid_argument` if the result is longer than `Sys.max_string_length`[21.38] bytes.

`val index : bytes -> char -> int`

`index s c` returns the index of the first occurrence of byte `c` in `s`.

Raise `Not_found` if `c` does not occur in `s`.

`val rindex : bytes -> char -> int`

`rindex s c` returns the index of the last occurrence of byte `c` in `s`.

Raise `Not_found` if `c` does not occur in `s`.

`val index_from : bytes -> int -> char -> int`

`index_from s i c` returns the index of the first occurrence of byte `c` in `s` after position `i`. `Bytes.index s c` is equivalent to `Bytes.index_from s 0 c`.

Raise `Invalid_argument` if `i` is not a valid position in `s`. Raise `Not_found` if `c` does not occur in `s` after position `i`.

`val rindex_from : bytes -> int -> char -> int`

`rindex_from s i c` returns the index of the last occurrence of byte `c` in `s` before position `i+1`. `rindex s c` is equivalent to `rindex_from s (Bytes.length s - 1) c`.

Raise `Invalid_argument` if `i+1` is not a valid position in `s`. Raise `Not_found` if `c` does not occur in `s` before position `i+1`.

`val contains : bytes -> char -> bool`

`contains s c` tests if byte `c` appears in `s`.

`val contains_from : bytes -> int -> char -> bool`

`contains_from s start c` tests if byte `c` appears in `s` after position `start`. `contains s c` is equivalent to `contains_from s 0 c`.

Raise `Invalid_argument` if `start` is not a valid position in `s`.

`val rcontains_from : bytes -> int -> char -> bool`

`rcontains_from s stop c` tests if byte `c` appears in `s` before position `stop+1`.

Raise `Invalid_argument` if `stop < 0` or `stop+1` is not a valid position in `s`.

`val uppercase : bytes -> bytes`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with all lowercase letters translated to uppercase, including accented letters of the ISO Latin-1 (8859-1) character set.

`val lowercase : bytes -> bytes`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with all uppercase letters translated to lowercase, including accented letters of the ISO Latin-1 (8859-1) character set.

`val capitalize : bytes -> bytes`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with the first character set to uppercase, using the ISO Latin-1 (8859-1) character set..

`val uncapitalize : bytes -> bytes`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with the first character set to lowercase, using the ISO Latin-1 (8859-1) character set..

`val uppercase_ascii : bytes -> bytes`

Return a copy of the argument, with all lowercase letters translated to uppercase, using the US-ASCII character set.

Since: 4.03.0

`val lowercase_ascii : bytes -> bytes`

Return a copy of the argument, with all uppercase letters translated to lowercase, using the US-ASCII character set.

Since: 4.03.0

`val capitalize_ascii : bytes -> bytes`

Return a copy of the argument, with the first character set to uppercase, using the US-ASCII character set.

Since: 4.03.0

`val uncapitalize_ascii : bytes -> bytes`

Return a copy of the argument, with the first character set to lowercase, using the US-ASCII character set.

Since: 4.03.0

`type t = bytes`

An alias for the type of byte sequences.

`val compare : t -> t -> int`

The comparison function for byte sequences, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `Bytes` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

`val equal : t -> t -> bool`

The equality function for byte sequences.

Since: 4.03.0

Unsafe conversions (for advanced users)

This section describes unsafe, low-level conversion functions between `bytes` and `string`. They do not copy the internal data; used improperly, they can break the immutability invariant on strings provided by the `-safe-string` option. They are available for expert library authors, but for most purposes you should use the always-correct `Bytes.to_string`[21.4] and `Bytes.of_string`[21.4] instead.

`val unsafe_to_string : bytes -> string`

Unsafely convert a byte sequence into a string.

To reason about the use of `unsafe_to_string`, it is convenient to consider an "ownership" discipline. A piece of code that manipulates some data "owns" it; there are several disjoint ownership modes, including:

- Unique ownership: the data may be accessed and mutated
- Shared ownership: the data has several owners, that may only access it, not mutate it.

Unique ownership is linear: passing the data to another piece of code means giving up ownership (we cannot write the data again). A unique owner may decide to make the data shared (giving up mutation rights on it), but shared data may not become uniquely-owned again.

`unsafe_to_string s` can only be used when the caller owns the byte sequence `s` – either uniquely or as shared immutable data. The caller gives up ownership of `s`, and gains ownership of the returned string.

There are two valid use-cases that respect this ownership discipline:

1. Creating a string by initializing and mutating a byte sequence that is never changed after initialization is performed.

```
let string_init len f : string =
  let s = Bytes.create len in
  for i = 0 to len - 1 do Bytes.set s i (f i) done;
  Bytes.unsafe_to_string s
```

This function is safe because the byte sequence `s` will never be accessed or mutated after `unsafe_to_string` is called. The `string_init` code gives up ownership of `s`, and returns the ownership of the resulting string to its caller.

Note that it would be unsafe if `s` was passed as an additional parameter to the function `f` as it could escape this way and be mutated in the future – `string_init` would give up ownership of `s` to pass it to `f`, and could not call `unsafe_to_string` safely.

We have provided the `String.init`[21.37], `String.map`[21.37] and `String.mapi`[21.37] functions to cover most cases of building new strings. You should prefer those over `to_string` or `unsafe_to_string` whenever applicable.

2. Temporarily giving ownership of a byte sequence to a function that expects a uniquely owned string and returns ownership back, so that we can mutate the sequence again after the call ended.

```
let bytes_length (s : bytes) =
  String.length (Bytes.unsafe_to_string s)
```

In this use-case, we do not promise that `s` will never be mutated after the call to `bytes_length s`. The `String.length`[21.37] function temporarily borrows unique ownership of the byte sequence (and sees it as a `string`), but returns this ownership back to the caller, which may assume that `s` is still a valid byte sequence after the call. Note that this is only correct because we know that `String.length`[21.37] does not capture its argument – it could escape by a side-channel such as a memoization combinator.

The caller may not mutate `s` while the string is borrowed (it has temporarily given up ownership). This affects concurrent programs, but also higher-order functions: if `String.length` returned a closure to be called later, `s` should not be mutated until this closure is fully applied and returns ownership.

`val unsafe_of_string : string -> bytes`

Unsafely convert a shared string to a byte sequence that should not be mutated.

The same ownership discipline that makes `unsafe_to_string` correct applies to `unsafe_of_string`: you may use it if you were the owner of the `string` value, and you will own the return `bytes` in the same mode.

In practice, unique ownership of string values is extremely difficult to reason about correctly. You should always assume strings are shared, never uniquely owned.

For example, string literals are implicitly shared by the compiler, so you never uniquely own them.

```
let incorrect = Bytes.unsafe_of_string "hello"
let s = Bytes.of_string "hello"
```

The first declaration is incorrect, because the string literal `"hello"` could be shared by the compiler with other parts of the program, and mutating `incorrect` is a bug. You must always use the second version, which performs a copy and is thus correct.

Assuming unique ownership of strings that are not string literals, but are (partly) built from string literals, is also incorrect. For example, mutating `unsafe_of_string ("foo" ^ s)` could mutate the shared string `"foo"` – assuming a rope-like representation of strings. More generally, functions operating on strings will assume shared ownership, they do not preserve unique ownership. It is thus incorrect to assume unique ownership of the result of `unsafe_of_string`.

The only case we have reasonable confidence is safe is if the produced `bytes` is shared – used as an immutable byte sequence. This is possibly useful for incremental migration of low-level programs that manipulate immutable sequences of bytes (for example `Marshal.from_bytes`[21.21]) and previously used the `string` type for this purpose.

21.5 Module `Callback` : Registering OCaml values with the C runtime.

This module allows OCaml values to be registered with the C runtime under a symbolic name, so that C code can later call back registered OCaml functions, or raise registered OCaml exceptions.

`val register : string -> 'a -> unit`

`Callback.register n v` registers the value `v` under the name `n`. C code can later retrieve a handle to `v` by calling `caml_named_value(n)`.

`val register_exception : string -> exn -> unit`

`Callback.register_exception n exn` registers the exception contained in the exception value `exn` under the name `n`. C code can later retrieve a handle to the exception by calling `caml_named_value(n)`. The exception value thus obtained is suitable for passing as first argument to `raise_constant` or `raise_with_arg`.

21.6 Module `Char` : Character operations.

`val code : char -> int`

Return the ASCII code of the argument.

`val chr : int -> char`

Return the character with the given ASCII code. Raise `Invalid_argument "Char.chr"` if the argument is outside the range 0–255.

`val escaped : char -> string`

Return a string representing the given character, with special characters escaped following the lexical conventions of OCaml. All characters outside the ASCII printable range (32..126) are escaped, as well as backslash, double-quote, and single-quote.

`val lowercase : char -> char`

Deprecated. Functions operating on Latin-1 character set are deprecated.Convert the given character to its equivalent lowercase character, using the ISO Latin-1 (8859-1) character set.

`val uppercase : char -> char`

Deprecated. Functions operating on Latin-1 character set are deprecated.Convert the given character to its equivalent uppercase character, using the ISO Latin-1 (8859-1) character set.

`val lowercase_ascii : char -> char`

Convert the given character to its equivalent lowercase character, using the US-ASCII character set.

Since: 4.03.0

`val uppercase_ascii : char -> char`

Convert the given character to its equivalent uppercase character, using the US-ASCII character set.

Since: 4.03.0

`type t = char`

An alias for the type of characters.

`val compare : t -> t -> int`

The comparison function for characters, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `Char` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

```
val equal : t -> t -> bool
```

The equal function for chars.

Since: 4.03.0

21.7 Module `Complex` : Complex numbers.

This module provides arithmetic operations on complex numbers. Complex numbers are represented by their real and imaginary parts (cartesian representation). Each part is represented by a double-precision floating-point number (type `float`).

```
type t =
{  re : float ;
  im : float ;
}
```

The type of complex numbers. `re` is the real part and `im` the imaginary part.

```
val zero : t
```

The complex number `0`.

```
val one : t
```

The complex number `1`.

```
val i : t
```

The complex number `i`.

```
val neg : t -> t
```

Unary negation.

```
val conj : t -> t
```

Conjugate: given the complex `x + i.y`, returns `x - i.y`.

```
val add : t -> t -> t
```

Addition

```
val sub : t -> t -> t
```

Subtraction

```
val mul : t -> t -> t
```

Multiplication

`val inv : t -> t`

Multiplicative inverse (`1/z`).

`val div : t -> t -> t`

Division

`val sqrt : t -> t`

Square root. The result `x + i.y` is such that `x > 0` or `x = 0` and `y >= 0`. This function has a discontinuity along the negative real axis.

`val norm2 : t -> float`

Norm squared: given `x + i.y`, returns `x^2 + y^2`.

`val norm : t -> float`

Norm: given `x + i.y`, returns `sqrt(x^2 + y^2)`.

`val arg : t -> float`

Argument. The argument of a complex number is the angle in the complex plane between the positive real axis and a line passing through zero and the number. This angle ranges from `-pi` to `pi`. This function has a discontinuity along the negative real axis.

`val polar : float -> float -> t`

`polar norm arg` returns the complex having norm `norm` and argument `arg`.

`val exp : t -> t`

Exponentiation. `exp z` returns `e` to the `z` power.

`val log : t -> t`

Natural logarithm (in base `e`).

`val pow : t -> t -> t`

Power function. `pow z1 z2` returns `z1` to the `z2` power.

21.8 Module `Digest` : MD5 message digest.

This module provides functions to compute 128-bit 'digests' of arbitrary-length strings or files. The digests are of cryptographic quality: it is very hard, given a digest, to forge a string having that digest. The algorithm used is MD5. This module should not be used for secure and sensitive cryptographic applications. For these kind of applications more recent and stronger cryptographic primitives should be used instead.

`type t = string`

The type of digests: 16-character strings.

`val compare : t -> t -> int`

The comparison function for 16-character digest, with the same specification as `Pervasives.compare`[20.2] and the implementation shared with `String.compare`[21.37]. Along with the type `t`, this function `compare` allows the module `Digest` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

Since: 4.00.0

`val equal : t -> t -> bool`

The equal function for 16-character digest.

Since: 4.03.0

`val string : string -> t`

Return the digest of the given string.

`val bytes : bytes -> t`

Return the digest of the given byte sequence.

Since: 4.02.0

`val substring : string -> int -> int -> t`

`Digest.substring s ofs len` returns the digest of the substring of `s` starting at index `ofs` and containing `len` characters.

`val subbytes : bytes -> int -> int -> t`

`Digest.subbytes s ofs len` returns the digest of the subsequence of `s` starting at index `ofs` and containing `len` bytes.

Since: 4.02.0

`val channel : Pervasives.in_channel -> int -> t`

If `len` is nonnegative, `Digest.channel ic len` reads `len` characters from channel `ic` and returns their digest, or raises `End_of_file` if end-of-file is reached before `len` characters are read. If `len` is negative, `Digest.channel ic len` reads all characters from `ic` until end-of-file is reached and return their digest.

`val file : string -> t`

Return the digest of the file whose name is given.

`val output : Pervasives.out_channel -> t -> unit`

Write a digest on the given output channel.

`val input : Pervasives.in_channel -> t`

Read a digest from the given input channel.

`val to_hex : t -> string`

Return the printable hexadecimal representation of the given digest.

`val from_hex : string -> t`

Convert a hexadecimal representation back into the corresponding digest. Raise `Invalid_argument` if the argument is not exactly 32 hexadecimal characters.

Since: 4.00.0

21.9 Module `Ephemeron` : Ephemerons and weak hash table

Ephemerons and weak hash table

Ephemerons and weak hash table are useful when one wants to cache or memorize the computation of a function, as long as the arguments and the function are used, without creating memory leaks by continuously keeping old computation results that are not useful anymore because one argument or the function is freed. An implementation using is not suitable because all associations would keep in memory the arguments and the result.

Ephemerons can also be used for "adding" a field to an arbitrary boxed ocaml value: you can attach an information to a value created by an external library without memory leaks.

Ephemerons hold some keys and one or no data. They are all boxed ocaml values. The keys of an ephemeron have the same behavior than weak pointers according to the garbage collector. In fact ocaml weak pointers are implemented as ephemerons without data.

The keys and data of an ephemeron are said to be full if they point to a value, empty if the value have never been set, have been unset, or was erased by the GC. In the function that accesses the keys or data these two states are represented by the `option` type.

The data is considered by the garbage collector alive if all the full keys are alive and if the ephemeron is alive. When one of the keys is not considered alive anymore by the GC, the data is emptied from the ephemeron. The data could be alive for another reason and in that case the GC will not free it, but the ephemeron will not hold the data anymore.

The ephemerons complicate the notion of liveness of values, because it is not anymore an equivalence with the reachability from root value by usual pointers (not weak and not ephemerons). With ephemerons the notion of liveness is constructed by the least fixpoint of: A value is alive if:

- it is a root value
- it is reachable from alive value by usual pointers
- it is the data of an alive ephemeron with all its full keys alive

Notes:

- All the types defined in this module cannot be marshaled using `Pervasives.output_value`[20.2] or the functions of the `Marshal`[21.21] module.

Ephemerons are defined in a language agnostic way in this paper: B. Hayes, Ephemerons: a New Finalization Mechanism, OOPSLA'9

```
module type S =
  sig
```

Propose the same interface as usual hash table. However since the bindings are weak, even if `mem h k` is true, a subsequent `find h k` may raise `Not_found` because the garbage collector can run between the two.

Moreover, the table shouldn't be modified during a call to `iter`. Use `filter_map_inplace` in this case.

```
include Hashtbl.S
```

```
val clean : 'a t -> unit
```

remove all dead bindings. Done automatically during automatic resizing.

```
val stats_alive : 'a t -> Hashtbl.statistics
```

same as `Hashtbl.SeededS.stats`[21.14] but only count the alive bindings

```
end
```

The output signature of the functor `Ephemeron.K1.Make`[21.9] and `Ephemeron.K2.Make`[21.9]. These hash tables are weak in the keys. If all the keys of a binding are alive the binding is kept, but if one of the keys of the binding is dead then the binding is removed.

```
module type SeededS =
  sig
```

```
include Hashtbl.SeededS
```

```
val clean : 'a t -> unit
```

remove all dead bindings. Done automatically during automatic resizing.

```
val stats_alive : 'a t -> Hashtbl.statistics
```

same as `Hashtbl.SeededS.stats`[21.14] but only count the alive bindings

```
  end
```

The output signature of the functor `Ephemeron.K1.MakeSeeded`[21.9] and `Ephemeron.K2.MakeSeeded`[21.9].

```
module K1 :
  sig
```

```
type ('k, 'd) t
```

an ephemeron with one key

```
val create : unit -> ('k, 'd) t
```

`Ephemeron.K1.create ()` creates an ephemeron with one key. The data and the key are empty

```
val get_key : ('k, 'd) t -> 'k option
```

Ephemeron.K1.get_key eph returns None if the key of eph is empty, Some x (where x is the key) if it is full.

```
val get_key_copy : ('k, 'd) t -> 'k option
```

Ephemeron.K1.get_key_copy eph returns None if the key of eph is empty, Some x (where x is a (shallow) copy of the key) if it is full. This function has the same GC friendliness as Weak.get_copy[21.40]

```
val set_key : ('k, 'd) t -> 'k -> unit
```

Ephemeron.K1.set_key eph el sets the key of eph to be a (full) key to el

```
val unset_key : ('k, 'd) t -> unit
```

Ephemeron.K1.unset_key eph el sets the key of eph to be an empty key. Since there is only one key, the ephemeron starts behaving like a reference on the data.

```
val check_key : ('k, 'd) t -> bool
```

Ephemeron.K1.check_key eph returns true if the key of the eph is full, false if it is empty. Note that even if Ephemeron.K1.check_key eph returns true, a subsequent Ephemeron.K1.get_key[21.9]eph can return None.

```
val blit_key : ('k, 'a) t -> ('k, 'b) t -> unit
```

Ephemeron.K1.blit_key eph1 eph2 sets the key of eph2 with the key of eph1. Contrary to using Ephemeron.K1.get_key followed by Ephemeron.K1.set_key or Ephemeon.K1.unset_key this function does not prevent the incremental GC from erasing the value in its current cycle.

```
val get_data : ('k, 'd) t -> 'd option
```

Ephemeron.K1.get_data eph returns None if the data of eph is empty, Some x (where x is the data) if it is full.

```
val get_data_copy : ('k, 'd) t -> 'd option
```

Ephemeron.K1.get_data_copy eph returns None if the data of eph is empty, Some x (where x is a (shallow) copy of the data) if it is full. This function has the same GC friendliness as Weak.get_copy[21.40]

```
val set_data : ('k, 'd) t -> 'd -> unit
```

Ephemeron.K1.set_data eph el sets the data of eph to be a (full) data to el

```
val unset_data : ('k, 'd) t -> unit
```

Ephemeron.K1.unset_key eph el sets the key of eph to be an empty key. The ephemeron starts behaving like a weak pointer.

```
    val check_data : ('k, 'd) t -> bool
```

Ephemeron.K1.check_data eph returns true if the data of the eph is full, false if it is empty. Note that even if Ephemeron.K1.check_data eph returns true, a subsequent Ephemeron.K1.get_data[21.9]eph can return None.

```
    val blit_data : ('a, 'd) t -> ('b, 'd) t -> unit
```

Ephemeron.K1.blit_data eph1 eph2 sets the data of eph2 with the data of eph1. Contrary to using Ephemeron.K1.get_data followed by Ephemeron.K1.set_data or Ephemeon.K1.unset_data this function does not prevent the incremental GC from erasing the value in its current cycle.

```
    module Make :
    functor (H : Hashtbl.HashedType) -> Ephemeron.S  with type key = H.t
```

Functor building an implementation of a weak hash table

```
    module MakeSeeded :
    functor (H : Hashtbl.SeededHashedType) -> Ephemeron.SeededS  with type key =
    H.t
```

Functor building an implementation of a weak hash table. The seed is similar to the one of Hashtbl.MakeSeeded[21.14].

```
  end
module K2 :
  sig
    type ('k1, 'k2, 'd) t
```

an ephemeron with two keys

```
    val create : unit -> ('k1, 'k2, 'd) t
```

Same as Ephemeron.K1.create[21.9]

```
    val get_key1 : ('k1, 'k2, 'd) t -> 'k1 option
```

Same as Ephemeron.K1.get_key[21.9]

```
    val get_key1_copy : ('k1, 'k2, 'd) t -> 'k1 option
```

Same as Ephemeron.K1.get_key_copy[21.9]

```
    val set_key1 : ('k1, 'k2, 'd) t -> 'k1 -> unit
```

Same as Ephemeron.K1.set_key[21.9]

```
    val unset_key1 : ('k1, 'k2, 'd) t -> unit
```

Same as `Ephemeron.K1.unset_key`[21.9]

```
val check_key1 : ('k1, 'k2, 'd) t -> bool
```

Same as `Ephemeron.K1.check_key`[21.9]

```
val get_key2 : ('k1, 'k2, 'd) t -> 'k2 option
```

Same as `Ephemeron.K1.get_key`[21.9]

```
val get_key2_copy : ('k1, 'k2, 'd) t -> 'k2 option
```

Same as `Ephemeron.K1.get_key_copy`[21.9]

```
val set_key2 : ('k1, 'k2, 'd) t -> 'k2 -> unit
```

Same as `Ephemeron.K1.get_key`[21.9]

```
val unset_key2 : ('k1, 'k2, 'd) t -> unit
```

Same as `Ephemeron.K1.unset_key`[21.9]

```
val check_key2 : ('k1, 'k2, 'd) t -> bool
```

Same as `Ephemeron.K1.check_key`[21.9]

```
val blit_key1 : ('k1, 'a, 'b) t -> ('k1, 'c, 'd) t -> unit
```

Same as `Ephemeron.K1.blit_key`[21.9]

```
val blit_key2 : ('a, 'k2, 'b) t -> ('c, 'k2, 'd) t -> unit
```

Same as `Ephemeron.K1.blit_key`[21.9]

```
val blit_key12 : ('k1, 'k2, 'a) t -> ('k1, 'k2, 'b) t -> unit
```

Same as `Ephemeron.K1.blit_key`[21.9]

```
val get_data : ('k1, 'k2, 'd) t -> 'd option
```

Same as `Ephemeron.K1.get_data`[21.9]

```
val get_data_copy : ('k1, 'k2, 'd) t -> 'd option
```

Same as `Ephemeron.K1.get_data_copy`[21.9]

```
val set_data : ('k1, 'k2, 'd) t -> 'd -> unit
```

Same as `Ephemeron.K1.set_data`[21.9]

```
val unset_data : ('k1, 'k2, 'd) t -> unit
```

Same as `Ephemeron.K1.unset_data`[21.9]

```
val check_data : ('k1, 'k2, 'd) t -> bool
```

Same as `Ephemeron.K1.check_data`[21.9]

```
val blit_data : ('k1, 'k2, 'd) t -> ('k1, 'k2, 'd) t -> unit
```

Same as `Ephemeron.K1.blit_data`[21.9]

```
module Make :
functor (H1 :  Hashtbl.HashedType) -> functor (H2 :  Hashtbl.HashedType) ->
Ephemeron.S  with type key = H1.t * H2.t
```

Functor building an implementation of a weak hash table

```
module MakeSeeded :
functor (H1 :  Hashtbl.SeededHashedType) -> functor (H2 :  Hashtbl.SeededHashedType)
-> Ephemeron.SeededS  with type key = H1.t * H2.t
```

Functor building an implementation of a weak hash table. The seed is similar to the one of `Hashtbl.MakeSeeded`[21.14].

```
  end
module Kn :
  sig
```

```
type ('k, 'd) t
```

an ephemeron with an arbitrary number of keys of the same type

```
val create : int -> ('k, 'd) t
```

Same as `Ephemeron.K1.create`[21.9]

```
val get_key : ('k, 'd) t -> int -> 'k option
```

Same as `Ephemeron.K1.get_key`[21.9]

```
val get_key_copy : ('k, 'd) t -> int -> 'k option
```

Same as `Ephemeron.K1.get_key_copy`[21.9]

```
val set_key : ('k, 'd) t -> int -> 'k -> unit
```

Same as `Ephemeron.K1.set_key`[21.9]

```
val unset_key : ('k, 'd) t -> int -> unit
```

Same as `Ephemeron.K1.unset_key`[21.9]

```
val check_key : ('k, 'd) t -> int -> bool
```

Same as `Ephemeron.K1.check_key`[21.9]

```
val blit_key : ('k, 'a) t ->
  int -> ('k, 'b) t -> int -> int -> unit
```

Same as `Ephemeron.K1.blit_key`[21.9]

```
val get_data : ('k, 'd) t -> 'd option
```

Same as `Ephemeron.K1.get_data`[21.9]

```
val get_data_copy : ('k, 'd) t -> 'd option
```

Same as `Ephemeron.K1.get_data_copy`[21.9]

```
val set_data : ('k, 'd) t -> 'd -> unit
```

Same as `Ephemeron.K1.set_data`[21.9]

```
val unset_data : ('k, 'd) t -> unit
```

Same as `Ephemeron.K1.unset_data`[21.9]

```
val check_data : ('k, 'd) t -> bool
```

Same as `Ephemeron.K1.check_data`[21.9]

```
val blit_data : ('k, 'd) t -> ('k, 'd) t -> unit
```

Same as `Ephemeron.K1.blit_data`[21.9]

```
module Make :
functor (H : Hashtbl.HashedType) -> Ephemeron.S  with type key = H.t array
```

Functor building an implementation of a weak hash table

```
module MakeSeeded :
functor (H : Hashtbl.SeededHashedType) -> Ephemeron.SeededS  with type key =
H.t array
```

Functor building an implementation of a weak hash table. The seed is similar to the one of `Hashtbl.MakeSeeded`[21.14].

```
  end
module GenHashTable :
  sig
```

Define a hash table on generic containers which have a notion of "death" and aliveness. If a binding is dead the hash table can automatically remove it.

```
type equal =
```

— ETrue — EFalse — EDead

the container is dead

```
module MakeSeeded :
functor (H :   sig
```

```
type t
```
keys

```
type 'a container
```
contains keys and the associated data

```
val hash : int -> t -> int
```
same as `Hashtbl.SeededHashedType`

```
val equal : 'a container ->
  t -> Ephemeron.GenHashTable.equal
```
equality predicate used to compare a key with the one in a container. Can return `EDead` if the keys in the container are dead

```
val create : t ->
  'a -> 'a container
```
`create key data` creates a container from some initials keys and one data

```
val get_key : 'a container ->
  t option
```
`get_key cont` returns the keys if they are all alive

```
val get_data : 'a container -> 'a option
```
`get_data cont` return the data if it is alive

```
val set_key_data : 'a container ->
  t -> 'a -> unit
```
`set_key_data cont` modify the key and data

```
val check_key : 'a container -> bool
```
`check_key cont` checks if all the keys contained in the data are alive

```
end ) -> Ephemeron.SeededS  with type key = H.t
```

Functor building an implementation of an hash table that use the container for keeping the information given

```
end
```

21.10 Module `Filename` : Operations on file names.

`val current_dir_name : string`

The conventional name for the current directory (e.g. `.` in Unix).

`val parent_dir_name : string`

The conventional name for the parent of the current directory (e.g. `..` in Unix).

`val dir_sep : string`

The directory separator (e.g. `/` in Unix).

Since: 3.11.2

`val concat : string -> string -> string`

`concat dir file` returns a file name that designates file `file` in directory `dir`.

`val is_relative : string -> bool`

Return `true` if the file name is relative to the current directory, `false` if it is absolute (i.e. in Unix, starts with `/`).

`val is_implicit : string -> bool`

Return `true` if the file name is relative and does not start with an explicit reference to the current directory (`./` or `../` in Unix), `false` if it starts with an explicit reference to the root directory or the current directory.

`val check_suffix : string -> string -> bool`

`check_suffix name suff` returns `true` if the filename `name` ends with the suffix `suff`.

`val chop_suffix : string -> string -> string`

`chop_suffix name suff` removes the suffix `suff` from the filename `name`. The behavior is undefined if `name` does not end with the suffix `suff`.

`val extension : string -> string`

`extension name` is the shortest suffix `ext` of `name0` where:

- `name0` is the longest suffix of `name` that does not contain a directory separator;
- `ext` starts with a period;
- `ext` is preceded by at least one non-period character in `name0`.

If such a suffix does not exist, `extension name` is the empty string.

Since: 4.04

`val remove_extension : string -> string`

Return the given file name without its extension, as defined in `Filename.extension`[21.10]. If the extension is empty, the function returns the given file name.

The following invariant holds for any file name `s`:

```
remove_extension s ^ extension s = s
```

Since: 4.04

```
val chop_extension : string -> string
```

Same as `Filename.remove_extension`[21.10], but raise `Invalid_argument` if the given name has an empty extension.

```
val basename : string -> string
```

Split a file name into directory name / base file name. If `name` is a valid file name, then `concat (dirname name) (basename name)` returns a file name which is equivalent to `name`. Moreover, after setting the current directory to `dirname name` (with `Sys.chdir`[21.38]), references to `basename name` (which is a relative file name) designate the same file as `name` before the call to `Sys.chdir`[21.38].

This function conforms to the specification of POSIX.1-2008 for the `basename` utility.

```
val dirname : string -> string
```

See `Filename.basename`[21.10]. This function conforms to the specification of POSIX.1-2008 for the `dirname` utility.

```
val temp_file : ?temp_dir:string -> string -> string -> string
```

`temp_file prefix suffix` returns the name of a fresh temporary file in the temporary directory. The base name of the temporary file is formed by concatenating `prefix`, then a suitably chosen integer number, then `suffix`. The optional argument `temp_dir` indicates the temporary directory to use, defaulting to the current result of `Filename.get_temp_dir_name`[21.10]. The temporary file is created empty, with permissions `0o600` (readable and writable only by the file owner). The file is guaranteed to be different from any other file that existed when `temp_file` was called. Raise `Sys_error` if the file could not be created.

Before 3.11.2 no ?temp_dir optional argument

```
val open_temp_file :
  ?mode:Pervasives.open_flag list ->
  ?perms:int ->
  ?temp_dir:string -> string -> string -> string * Pervasives.out_channel
```

Same as `Filename.temp_file`[21.10], but returns both the name of a fresh temporary file, and an output channel opened (atomically) on this file. This function is more secure than `temp_file`: there is no risk that the temporary file will be modified (e.g. replaced by a symbolic link) before the program opens it. The optional argument `mode` is a list of additional flags to control the opening of the file. It can contain one or several of `Open_append`, `Open_binary`, and `Open_text`. The default is `[Open_text]` (open in text

mode). The file is created with permissions `perms` (defaults to readable and writable only by the file owner, `0o600`).

Before 4.03.0 no ?perms optional argument

Before 3.11.2 no ?temp_dir optional argument

Raises `Sys_error` if the file could not be opened.

`val get_temp_dir_name : unit -> string`

The name of the temporary directory: Under Unix, the value of the `TMPDIR` environment variable, or "/tmp" if the variable is not set. Under Windows, the value of the `TEMP` environment variable, or "." if the variable is not set. The temporary directory can be changed with `Filename.set_temp_dir_name`[21.10].

Since: 4.00.0

`val set_temp_dir_name : string -> unit`

Change the temporary directory returned by `Filename.get_temp_dir_name`[21.10] and used by `Filename.temp_file`[21.10] and `Filename.open_temp_file`[21.10].

Since: 4.00.0

`val temp_dir_name : string`

Deprecated. You should use `Filename.get_temp_dir_name`[21.10] instead.The name of the initial temporary directory: Under Unix, the value of the `TMPDIR` environment variable, or "/tmp" if the variable is not set. Under Windows, the value of the `TEMP` environment variable, or "." if the variable is not set.

Since: 3.09.1

`val quote : string -> string`

Return a quoted version of a file name, suitable for use as one argument in a command line, escaping all meta-characters. Warning: under Windows, the output is only suitable for use with programs that follow the standard Windows quoting conventions.

21.11 Module `Format` : Pretty printing.

This module implements a pretty-printing facility to format values within 'pretty-printing boxes'. The pretty-printer splits lines at specified break hints, and indents lines according to the box structure.

For a gentle introduction to the basics of pretty-printing using `Format`, read http://caml.inria.fr/resources/doc/guides/format.en.html[`http://caml.inria.fr/resources/doc/guides/f`

You may consider this module as providing an extension to the `printf` facility to provide automatic line splitting. The addition of pretty-printing annotations to your regular `printf` formats gives you fancy indentation and line breaks. Pretty-printing annotations are described below in the documentation of the function `Format.fprintf`[21.11].

You may also use the explicit box management and printing functions provided by this module. This style is more basic but more verbose than the `fprintf` concise formats.

For instance, the sequence `open_box 0; print_string "x ="; print_space (); print_int 1; close_box (); print_newline ()` that prints `x = 1` within a pretty-printing box, can be abbreviated as `printf "@[%s@ %i@]@." "x =" 1`, or even shorter `printf "@[x =@ %i@]@." 1`.

Rule of thumb for casual users of this library:

- use simple boxes (as obtained by `open_box 0`);
- use simple break hints (as obtained by `print_cut ()` that outputs a simple break hint, or by `print_space ()` that outputs a space indicating a break hint);
- once a box is opened, display its material with basic printing functions (e. g. `print_int` and `print_string`);
- when the material for a box has been printed, call `close_box ()` to close the box;
- at the end of your routine, flush the pretty-printer to display all the remaining material, e.g. evaluate `print_newline ()`.

The behaviour of pretty-printing commands is unspecified if there is no opened pretty-printing box. Each box opened via one of the `open_` functions below must be closed using `close_box` for proper formatting. Otherwise, some of the material printed in the boxes may not be output, or may be formatted incorrectly.

In case of interactive use, the system closes all opened boxes and flushes all pending text (as with the `print_newline` function) after each phrase. Each phrase is therefore executed in the initial state of the pretty-printer.

Warning: the material output by the following functions is delayed in the pretty-printer queue in order to compute the proper line splitting. Hence, you should not mix calls to the printing functions of the basic I/O system with calls to the functions of this module: this could result in some strange output seemingly unrelated with the evaluation order of printing commands.

Boxes

```
val open_box : int -> unit
```

`open_box d` opens a new pretty-printing box with offset `d`.

This box prints material as much as possible on every line.

A break hint splits the line if there is no more room on the line to print the remainder of the box. A break hint also splits the line if the splitting "moves to the left" (i.e. it gives an indentation smaller than the one of the current line).

This box is the general purpose pretty-printing box.

If the pretty-printer splits the line in the box, offset `d` is added to the current indentation.

```
val close_box : unit -> unit
```

Closes the most recently opened pretty-printing box.

Formatting functions

`val print_string : string -> unit`

`print_string str` prints `str` in the current box.

`val print_as : int -> string -> unit`

`print_as len str` prints `str` in the current box. The pretty-printer formats `str` as if it were of length `len`.

`val print_int : int -> unit`

Prints an integer in the current box.

`val print_float : float -> unit`

Prints a floating point number in the current box.

`val print_char : char -> unit`

Prints a character in the current box.

`val print_bool : bool -> unit`

Prints a boolean in the current box.

Break hints

A 'break hint' tells the pretty-printer to output some space or split the line whichever way is more appropriate to the current box splitting rules.

Break hints are used to separate printing items and are mandatory to let the pretty-printer correctly split lines and indent items.

Simple break hints are:

- the 'space': output a space or split the line if appropriate,
- the 'cut': split the line if appropriate.

Note: the notions of space and line splitting are abstract for the pretty-printing engine, since those notions can be completely defined by the programmer. However, in the pretty-printer default setting, "output a space" simply means printing a space character (ASCII code 32) and "split the line" is printing a newline character (ASCII code 10).

`val print_space : unit -> unit`

`print_space ()` the 'space' break hint: the pretty-printer may split the line at this point, otherwise it prints one space. It is equivalent to `print_break 1 0`.

`val print_cut : unit -> unit`

`print_cut ()` the 'cut' break hint: the pretty-printer may split the line at this point, otherwise it prints nothing. It is equivalent to `print_break 0 0`.

`val print_break : int -> int -> unit`

`print_break nspaces offset` the 'full' break hint: the pretty-printer may split the line at this point, otherwise it prints `nspaces` spaces.

If the pretty-printer splits the line, `offset` is added to the current indentation.

`val print_flush : unit -> unit`

Flushes the pretty printer: all opened boxes are closed, and all pending text is displayed.

`val print_newline : unit -> unit`

Equivalent to `print_flush` followed by a new line.

`val force_newline : unit -> unit`

Forces a new line in the current box. Not the normal way of pretty-printing, since the new line does not reset the current line count. You should prefer using break hints within a vertcal box.

`val print_if_newline : unit -> unit`

Executes the next formatting command if the preceding line has just been split. Otherwise, ignore the next formatting command.

Margin

`val set_margin : int -> unit`

`set_margin d` sets the right margin to `d` (in characters): the pretty-printer splits lines that overflow the right margin according to the break hints given. Nothing happens if `d` is smaller than 2. If `d` is too large, the right margin is set to the maximum admissible value (which is greater than `10^9`).

`val get_margin : unit -> int`

Returns the position of the right margin.

Maximum indentation limit

`val set_max_indent : int -> unit`

`set_max_indent d` sets the maximum indentation limit of lines to `d` (in characters): once this limit is reached, new boxes are rejected to the left, if they do not fit on the current line. Nothing happens if `d` is smaller than 2. If `d` is too large, the limit is set to the maximum admissible value (which is greater than `10 ^ 9`).

`val get_max_indent : unit -> int`

Return the maximum indentation limit (in characters).

Formatting depth: maximum number of boxes allowed before ellipsis

`val set_max_boxes : int -> unit`

`set_max_boxes max` sets the maximum number of boxes simultaneously opened. Material inside boxes nested deeper is printed as an ellipsis (more precisely as the text returned by `get_ellipsis_text ()`). Nothing happens if `max` is smaller than 2.

`val get_max_boxes : unit -> int`

Returns the maximum number of boxes allowed before ellipsis.

`val over_max_boxes : unit -> bool`

Tests if the maximum number of boxes allowed have already been opened.

Advanced formatting

`val open_hbox : unit -> unit`

`open_hbox ()` opens a new 'horizontal' pretty-printing box.

This box prints material on a single line.

Break hints in a horizontal box never split the line. (Line splitting may still occur inside boxes nested deeper).

`val open_vbox : int -> unit`

`open_vbox d` opens a new 'vertical' pretty-printing box with offset `d`.

This box prints material on as many lines as break hints in the box.

Every break hint in a vertical box splits the line.

If the pretty-printer splits the line in the box, `d` is added to the current indentation.

`val open_hvbox : int -> unit`

`open_hvbox d` opens a new 'horizontal-vertical' pretty-printing box with offset `d`.

This box behaves as an horizontal box if it fits on a single line, otherwise it behaves as a vertical box.

If the pretty-printer splits the line in the box, `d` is added to the current indentation.

`val open_hovbox : int -> unit`

`open_hovbox d` opens a new 'horizontal-or-vertical' pretty-printing box with offset `d`.

This box prints material as much as possible on every line.

A break hint splits the line if there is no more room on the line to print the remainder of the box.

If the pretty-printer splits the line in the box, `d` is added to the current indentation.

Ellipsis

`val set_ellipsis_text : string -> unit`

Set the text of the ellipsis printed when too many boxes are opened (a single dot, `.`, by default).

`val get_ellipsis_text : unit -> string`

Return the text of the ellipsis.

Semantic Tags

`type tag = string`

Semantic tags (or simply *tags*) are used to decorate printed entities for user's defined purposes, e.g. setting font and giving size indications for a display device, or marking delimitation of semantic entities (e.g. HTML or TeX elements or terminal escape sequences).

By default, those tags do not influence line splitting calculation: the tag 'markers' are not considered as part of the printing material that drives line splitting (in other words, the length of those strings is considered as zero for line splitting).

Thus, tag handling is in some sense transparent to pretty-printing and does not interfere with usual indentation. Hence, a single pretty printing routine can output both simple 'verbatim' material or richer decorated output depending on the treatment of tags. By default, tags are not active, hence the output is not decorated with tag information. Once `set_tags` is set to `true`, the pretty printer engine honours tags and decorates the output accordingly.

When a tag has been opened (or closed), it is both and successively 'printed' and 'marked'. Printing a tag means calling a formatter specific function with the name of the tag as argument: that 'tag printing' function can then print any regular material to the formatter (so that this material is enqueued as usual in the formatter queue for further line splitting computation). Marking a tag means to output an arbitrary string (the 'tag marker'), directly into the output device of the formatter. Hence, the formatter specific 'tag marking' function must return the tag marker string associated to its tag argument. Being flushed directly into the output device of the formatter, tag marker strings are not considered as part of the printing material that drives line splitting (in other words, the length of the strings corresponding to tag markers is considered as zero for line splitting). In addition, advanced users may take advantage of the specificity of tag markers to be precisely output when the pretty printer has already decided where to split the lines, and precisely when the queue is flushed into the output device.

In the spirit of HTML tags, the default tag marking functions output tags enclosed in "<" and ">": hence, the opening marker of tag `t` is `"<t>"` and the closing marker `"</t>"`.

Default tag printing functions just do nothing.

Tag marking and tag printing functions are user definable and can be set by calling `set_formatter_tag_functions`.

`val open_tag : tag -> unit`

`open_tag t` opens the tag named `t`; the `print_open_tag` function of the formatter is called with `t` as argument; the tag marker `mark_open_tag t` will be flushed into the output device of the formatter.

`val close_tag : unit -> unit`

`close_tag ()` closes the most recently opened tag `t`. In addition, the `print_close_tag` function of the formatter is called with `t` as argument. The marker `mark_close_tag t` will be flushed into the output device of the formatter.

`val set_tags : bool -> unit`

`set_tags b` turns on or off the treatment of tags (default is off).

`val set_print_tags : bool -> unit`

`set_print_tags b` turns on or off the printing of tags.

`val set_mark_tags : bool -> unit`

`set_mark_tags b` turns on or off the output of tag markers.

`val get_print_tags : unit -> bool`

Return the current status of tags printing.

`val get_mark_tags : unit -> bool`

Return the current status of tags marking.

Redirecting the standard formatter output

`val set_formatter_out_channel : Pervasives.out_channel -> unit`

Redirect the pretty-printer output to the given channel. (All the output functions of the standard formatter are set to the default output functions printing to the given channel.)

```
val set_formatter_output_functions :
  (string -> int -> int -> unit) -> (unit -> unit) -> unit
```

`set_formatter_output_functions out flush` redirects the pretty-printer output functions to the functions `out` and `flush`.

The `out` function performs all the pretty-printer string output. It is called with a string `s`, a start position `p`, and a number of characters `n`; it is supposed to output characters `p` to `p + n - 1` of `s`.

The `flush` function is called whenever the pretty-printer is flushed (via conversion `%!`, or pretty-printing indications `@?` or `@.`, or using low level functions `print_flush` or `print_newline`).

```
val get_formatter_output_functions :
  unit -> (string -> int -> int -> unit) * (unit -> unit)
```

Return the current output functions of the pretty-printer.

Changing the meaning of standard formatter pretty printing

The `Format` module is versatile enough to let you completely redefine the meaning of pretty printing: you may provide your own functions to define how to handle indentation, line splitting, and even printing of all the characters that have to be printed!

```
type formatter_out_functions =
{  out_string : string -> int -> int -> unit ;
  out_flush : unit -> unit ;
  out_newline : unit -> unit ;
  out_spaces : int -> unit ;
}
```

```
val set_formatter_out_functions : formatter_out_functions -> unit
```

`set_formatter_out_functions f` Redirect the pretty-printer output to the functions `f.out_string` and `f.out_flush` as described in `set_formatter_output_functions`. In addition, the pretty-printer function that outputs a newline is set to the function `f.out_newline` and the function that outputs indentation spaces is set to the function `f.out_spaces`.

This way, you can change the meaning of indentation (which can be something else than just printing space characters) and the meaning of new lines opening (which can be connected to any other action needed by the application at hand). The two functions `f.out_spaces` and `f.out_newline` are normally connected to `f.out_string` and `f.out_flush`: respective default values for `f.out_space` and `f.out_newline` are `f.out_string (String.make n ' ') 0 n` and `f.out_string "\n" 0 1`.

```
val get_formatter_out_functions : unit -> formatter_out_functions
```

Return the current output functions of the pretty-printer, including line splitting and indentation functions. Useful to record the current setting and restore it afterwards.

Changing the meaning of printing semantic tags

```
type formatter_tag_functions =
{  mark_open_tag : tag -> string ;
  mark_close_tag : tag -> string ;
  print_open_tag : tag -> unit ;
  print_close_tag : tag -> unit ;
}
```

The tag handling functions specific to a formatter: `mark` versions are the 'tag marking' functions that associate a string marker to a tag in order for the pretty-printing engine to flush those markers as 0 length tokens in the output device of the formatter. `print` versions are the 'tag printing' functions that can perform regular printing when a tag is closed or opened.

```
val set_formatter_tag_functions : formatter_tag_functions -> unit
```

`set_formatter_tag_functions tag_funs` changes the meaning of opening and closing tags to use the functions in `tag_funs`.

When opening a tag name `t`, the string `t` is passed to the opening tag marking function (the `mark_open_tag` field of the record `tag_funs`), that must return the opening tag marker for that name. When the next call to `close_tag ()` happens, the tag name `t` is sent back to the closing tag marking function (the `mark_close_tag` field of record `tag_funs`), that must return a closing tag marker for that name.

The `print_` field of the record contains the functions that are called at tag opening and tag closing time, to output regular material in the pretty-printer queue.

`val get_formatter_tag_functions : unit -> formatter_tag_functions`

Return the current tag functions of the pretty-printer.

Multiple formatted output

`type formatter`

Abstract data corresponding to a pretty-printer (also called a formatter) and all its machinery.

Defining new pretty-printers permits unrelated output of material in parallel on several output channels. All the parameters of a pretty-printer are local to a formatter: margin, maximum indentation limit, maximum number of boxes simultaneously opened, ellipsis, and so on, are specific to each pretty-printer and may be fixed independently. Given a `Pervasives.out_channel` output channel `oc`, a new formatter writing to that channel is simply obtained by calling `formatter_of_out_channel oc`. Alternatively, the `make_formatter` function allocates a new formatter with explicit output and flushing functions (convenient to output material to strings for instance).

`val formatter_of_out_channel : Pervasives.out_channel -> formatter`

`formatter_of_out_channel oc` returns a new formatter that writes to the corresponding channel `oc`.

`val std_formatter : formatter`

The standard formatter used by the formatting functions above. It is defined as `formatter_of_out_channel stdout`.

`val err_formatter : formatter`

A formatter to use with formatting functions below for output to standard error. It is defined as `formatter_of_out_channel stderr`.

`val formatter_of_buffer : Buffer.t -> formatter`

`formatter_of_buffer b` returns a new formatter writing to buffer `b`. As usual, the formatter has to be flushed at the end of pretty printing, using `pp_print_flush` or `pp_print_newline`, to display all the pending material.

`val stdbuf : Buffer.t`

The string buffer in which `str_formatter` writes.

`val str_formatter : formatter`

A formatter to use with formatting functions below for output to the `stdbuf` string buffer. `str_formatter` is defined as `formatter_of_buffer stdbuf`.

`val flush_str_formatter : unit -> string`

Returns the material printed with `str_formatter`, flushes the formatter and resets the corresponding buffer.

```
val make_formatter :
  (string -> int -> int -> unit) -> (unit -> unit) -> formatter
```

`make_formatter out flush` returns a new formatter that writes according to the output function `out`, and the flushing function `flush`. For instance, a formatter to the `Pervasives.out_channel oc` is returned by `make_formatter (Pervasives.output oc) (fun () -> Pervasives.flush oc)`.

Basic functions to use with formatters

```
val pp_open_hbox : formatter -> unit -> unit
val pp_open_vbox : formatter -> int -> unit
val pp_open_hvbox : formatter -> int -> unit
val pp_open_hovbox : formatter -> int -> unit
val pp_open_box : formatter -> int -> unit
val pp_close_box : formatter -> unit -> unit
val pp_open_tag : formatter -> string -> unit
val pp_close_tag : formatter -> unit -> unit
val pp_print_string : formatter -> string -> unit
val pp_print_as : formatter -> int -> string -> unit
val pp_print_int : formatter -> int -> unit
val pp_print_float : formatter -> float -> unit
val pp_print_char : formatter -> char -> unit
val pp_print_bool : formatter -> bool -> unit
val pp_print_break : formatter -> int -> int -> unit
val pp_print_cut : formatter -> unit -> unit
val pp_print_space : formatter -> unit -> unit
val pp_force_newline : formatter -> unit -> unit
val pp_print_flush : formatter -> unit -> unit
val pp_print_newline : formatter -> unit -> unit
```

```
val pp_print_if_newline : formatter -> unit -> unit
val pp_set_tags : formatter -> bool -> unit
val pp_set_print_tags : formatter -> bool -> unit
val pp_set_mark_tags : formatter -> bool -> unit
val pp_get_print_tags : formatter -> unit -> bool
val pp_get_mark_tags : formatter -> unit -> bool
val pp_set_margin : formatter -> int -> unit
val pp_get_margin : formatter -> unit -> int
val pp_set_max_indent : formatter -> int -> unit
val pp_get_max_indent : formatter -> unit -> int
val pp_set_max_boxes : formatter -> int -> unit
val pp_get_max_boxes : formatter -> unit -> int
val pp_over_max_boxes : formatter -> unit -> bool
val pp_set_ellipsis_text : formatter -> string -> unit
val pp_get_ellipsis_text : formatter -> unit -> string
val pp_set_formatter_out_channel :
  formatter -> Pervasives.out_channel -> unit
val pp_set_formatter_output_functions :
  formatter -> (string -> int -> int -> unit) -> (unit -> unit) -> unit
val pp_get_formatter_output_functions :
  formatter -> unit -> (string -> int -> int -> unit) * (unit -> unit)
val pp_set_formatter_tag_functions :
  formatter -> formatter_tag_functions -> unit
val pp_get_formatter_tag_functions :
  formatter -> unit -> formatter_tag_functions
val pp_set_formatter_out_functions :
  formatter -> formatter_out_functions -> unit
val pp_get_formatter_out_functions :
  formatter -> unit -> formatter_out_functions
```

These functions are the basic ones: usual functions operating on the standard formatter are defined via partial evaluation of these primitives. For instance, `print_string` is equal to `pp_print_string std_formatter`.

```
val pp_flush_formatter : formatter -> unit
```

`pp_flush_formatter fmt` flushes `fmt`'s internal queue, ensuring that all the printing and flushing actions have been performed. In addition, this operation will close all boxes and reset the state of the formatter.

This will not flush `fmt`'s output. In most cases, the user may want to use `Format.pp_print_flush`[21.11] instead.

Convenience formatting functions.

```
val pp_print_list :
  ?pp_sep:(formatter -> unit -> unit) ->
  (formatter -> 'a -> unit) -> formatter -> 'a list -> unit
```

`pp_print_list ?pp_sep pp_v ppf l` prints items of list `l`, using `pp_v` to print each item, and calling `pp_sep` between items (`pp_sep` defaults to `Format.pp_print_cut`[21.11]). Does nothing on empty lists.

Since: 4.02.0

```
val pp_print_text : formatter -> string -> unit
```

`pp_print_text ppf s` prints `s` with spaces and newlines respectively printed with `Format.pp_print_space`[21.11] and `Format.pp_force_newline`[21.11].

Since: 4.02.0

`printf` like functions for pretty-printing.

```
val fprintf : formatter -> ('a, formatter, unit) Pervasives.format -> 'a
```

`fprintf ff fmt arg1 ... argN` formats the arguments `arg1` to `argN` according to the format string `fmt`, and outputs the resulting string on the formatter `ff`.

The format `fmt` is a character string which contains three types of objects: plain characters and conversion specifications as specified in the `Printf` module, and pretty-printing indications specific to the `Format` module.

The pretty-printing indication characters are introduced by a `@` character, and their meanings are:

- `@[`: open a pretty-printing box. The type and offset of the box may be optionally specified with the following syntax: the `<` character, followed by an optional box type indication, then an optional integer offset, and the closing `>` character. Box type is one of `h`, `v`, `hv`, `b`, or `hov`. '`h`' stands for an 'horizontal' box, '`v`' stands for a 'vertical' box, '`hv`' stands for an 'horizontal-vertical' box, '`b`' stands for an 'horizontal-or-vertical' box demonstrating indentation, '`hov`' stands a simple 'horizontal-or-vertical' box. For instance, `@[<hov 2>` opens an 'horizontal-or-vertical' box with indentation 2 as obtained with `open_hovbox 2`. For more details about boxes, see the various box opening functions `open_*box`.
- `@]`: close the most recently opened pretty-printing box.
- `@,`: output a 'cut' break hint, as with `print_cut ()`.
- `@ `: output a 'space' break hint, as with `print_space ()`.
- `@;`: output a 'full' break hint as with `print_break`. The `nspaces` and `offset` parameters of the break hint may be optionally specified with the following syntax: the `<` character, followed by an integer `nspaces` value, then an integer `offset`, and a closing `>` character. If no parameters are provided, the good break defaults to a 'space' break hint.

- `@.`: flush the pretty printer and split the line, as with `print_newline ()`.
- `@<n>`: print the following item as if it were of length `n`. Hence, `printf "@<0>%s" arg` prints `arg` as a zero length string. If `@<n>` is not followed by a conversion specification, then the following character of the format is printed as if it were of length `n`.
- `@{`: open a tag. The name of the tag may be optionally specified with the following syntax: the `<` character, followed by an optional string specification, and the closing `>` character. The string specification is any character string that does not contain the closing character `'>'`. If omitted, the tag name defaults to the empty string. For more details about tags, see the functions `open_tag` and `close_tag`.
- `@}`: close the most recently opened tag.
- `@?`: flush the pretty printer as with `print_flush ()`. This is equivalent to the conversion `%!`.
- `@\n`: force a newline, as with `force_newline ()`, not the normal way of pretty-printing, you should prefer using break hints inside a vertical box.

Note: If you need to prevent the interpretation of a `@` character as a pretty-printing indication, you must escape it with a `%` character. Old quotation mode `@@` is deprecated since it is not compatible with formatted input interpretation of character `'@'`.

Example: `printf "@[%s@ %d@]@." "x =" 1` is equivalent to `open_box (); print_string "x ="; print_space (); print_int 1; close_box (); print_newline ()`. It prints `x = 1` within a pretty-printing 'horizontal-or-vertical' box.

`val printf : ('a, formatter, unit) Pervasives.format -> 'a`

Same as `fprintf` above, but output on `std_formatter`.

`val eprintf : ('a, formatter, unit) Pervasives.format -> 'a`

Same as `fprintf` above, but output on `err_formatter`.

`val sprintf : ('a, unit, string) Pervasives.format -> 'a`

Same as `printf` above, but instead of printing on a formatter, returns a string containing the result of formatting the arguments. Note that the pretty-printer queue is flushed at the end of *each call* to `sprintf`.

In case of multiple and related calls to `sprintf` to output material on a single string, you should consider using `fprintf` with the predefined formatter `str_formatter` and call `flush_str_formatter ()` to get the final result.

Alternatively, you can use `Format.fprintf` with a formatter writing to a buffer of your own: flushing the formatter and the buffer at the end of pretty-printing returns the desired string.

`val asprintf : ('a, formatter, unit, string) Pervasives.format4 -> 'a`

Same as `printf` above, but instead of printing on a formatter, returns a string containing the result of formatting the arguments. The type of `asprintf` is general enough to interact nicely with `%a` conversions.

Since: 4.01.0

```
val ifprintf : formatter -> ('a, formatter, unit) Pervasives.format -> 'a
```

Same as `fprintf` above, but does not print anything. Useful to ignore some material when conditionally printing.

Since: 3.10.0

Formatted output functions with continuations.

```
val kfprintf :
  (formatter -> 'a) ->
  formatter -> ('b, formatter, unit, 'a) Pervasives.format4 -> 'b
```

Same as `fprintf` above, but instead of returning immediately, passes the formatter to its first argument at the end of printing.

```
val ikfprintf :
  (formatter -> 'a) ->
  formatter -> ('b, formatter, unit, 'a) Pervasives.format4 -> 'b
```

Same as `kfprintf` above, but does not print anything. Useful to ignore some material when conditionally printing.

Since: 3.12.0

```
val ksprintf :
  (string -> 'a) -> ('b, unit, string, 'a) Pervasives.format4 -> 'b
```

Same as `sprintf` above, but instead of returning the string, passes it to the first argument.

```
val kasprintf :
  (string -> 'a) -> ('b, formatter, unit, 'a) Pervasives.format4 -> 'b
```

Same as `asprintf` above, but instead of returning the string, passes it to the first argument.

Since: 4.03

Deprecated

```
val bprintf : Buffer.t -> ('a, formatter, unit) Pervasives.format -> 'a
```

Deprecated. This function is error prone. Do not use it.

If you need to print to some buffer `b`, you must first define a formatter writing to `b`, using `let to_b = formatter_of_buffer b`; then use regular calls to `Format.fprintf` on formatter `to_b`.

```
val kprintf :
  (string -> 'a) -> ('b, unit, string, 'a) Pervasives.format4 -> 'b
```

Deprecated. An alias for `ksprintf`.

```
val set_all_formatter_output_functions :
  out:(string -> int -> int -> unit) ->
  flush:(unit -> unit) ->
  newline:(unit -> unit) -> spaces:(int -> unit) -> unit
```

Deprecated. Subsumed by `set_formatter_out_functions`.

```
val get_all_formatter_output_functions :
  unit ->
  (string -> int -> int -> unit) * (unit -> unit) * (unit -> unit) *
  (int -> unit)
```

Deprecated. Subsumed by `get_formatter_out_functions`.

```
val pp_set_all_formatter_output_functions :
  formatter ->
  out:(string -> int -> int -> unit) ->
  flush:(unit -> unit) ->
  newline:(unit -> unit) -> spaces:(int -> unit) -> unit
```

Deprecated. Subsumed by `pp_set_formatter_out_functions`.

```
val pp_get_all_formatter_output_functions :
  formatter ->
  unit ->
  (string -> int -> int -> unit) * (unit -> unit) * (unit -> unit) *
  (int -> unit)
```

Deprecated. Subsumed by `pp_get_formatter_out_functions`.

Tabulation boxes are deprecated.

```
val pp_open_tbox : formatter -> unit -> unit
```

Deprecated. since 4.03.0

```
val pp_close_tbox : formatter -> unit -> unit
```

Deprecated. since 4.03.0

```
val pp_print_tbreak : formatter -> int -> int -> unit
```

Deprecated. since 4.03.0

```
val pp_set_tab : formatter -> unit -> unit
```

Deprecated. since 4.03.0

```
val pp_print_tab : formatter -> unit -> unit
```

Deprecated. since 4.03.0

```
val open_tbox : unit -> unit
```

Deprecated. since 4.03.0

```
val close_tbox : unit -> unit
```

Deprecated. since 4.03.0

```
val print_tbreak : int -> int -> unit
```

Deprecated. since 4.03.0

```
val set_tab : unit -> unit
```

Deprecated. since 4.03.0

```
val print_tab : unit -> unit
```

Deprecated. since 4.03.0

21.12 Module `Gc` : Memory management control and statistics; finalised values.

```
type stat =
{  minor_words : float ;
```

Number of words allocated in the minor heap since the program was started. This number is accurate in byte-code programs, but only an approximation in programs compiled to native code.

```
  promoted_words : float ;
```

Number of words allocated in the minor heap that survived a minor collection and were moved to the major heap since the program was started.

```
  major_words : float ;
```

Number of words allocated in the major heap, including the promoted words, since the program was started.

```
  minor_collections : int ;
```

Number of minor collections since the program was started.

```
  major_collections : int ;
```

Number of major collection cycles completed since the program was started.

```
  heap_words : int ;
```

Total size of the major heap, in words.

```
  heap_chunks : int ;
```

Number of contiguous pieces of memory that make up the major heap.

```
  live_words : int ;
```

Number of words of live data in the major heap, including the header words.

```
  live_blocks : int ;
```

Number of live blocks in the major heap.

```
  free_words : int ;
```

Number of words in the free list.

`free_blocks : int ;`

Number of blocks in the free list.

`largest_free : int ;`

Size (in words) of the largest block in the free list.

`fragments : int ;`

Number of wasted words due to fragmentation. These are 1-words free blocks placed between two live blocks. They are not available for allocation.

`compactions : int ;`

Number of heap compactions since the program was started.

`top_heap_words : int ;`

Maximum size reached by the major heap, in words.

`stack_size : int ;`

Current size of the stack, in words.

Since: 3.12.0

`}`

The memory management counters are returned in a `stat` record.

The total amount of memory allocated by the program since it was started is (in words) `minor_words + major_words - promoted_words`. Multiply by the word size (4 on a 32-bit machine, 8 on a 64-bit machine) to get the number of bytes.

```
type control =
{  mutable minor_heap_size : int ;
```

The size (in words) of the minor heap. Changing this parameter will trigger a minor collection. Default: 256k.

`mutable major_heap_increment : int ;`

How much to add to the major heap when increasing it. If this number is less than or equal to 1000, it is a percentage of the current heap size (i.e. setting it to 100 will double the heap size at each increase). If it is more than 1000, it is a fixed number of words that will be added to the heap. Default: 15.

`mutable space_overhead : int ;`

The major GC speed is computed from this parameter. This is the memory that will be "wasted" because the GC does not immediatly collect unreachable blocks. It is expressed as a percentage of the memory used for live data. The GC will work more (use more CPU time and collect blocks more eagerly) if `space_overhead` is smaller. Default: 80.

`mutable verbose : int ;`

This value controls the GC messages on standard error output. It is a sum of some of the following flags, to print messages on the corresponding events:

- `0x001` Start of major GC cycle.
- `0x002` Minor collection and major GC slice.
- `0x004` Growing and shrinking of the heap.
- `0x008` Resizing of stacks and memory manager tables.
- `0x010` Heap compaction.
- `0x020` Change of GC parameters.
- `0x040` Computation of major GC slice size.
- `0x080` Calling of finalisation functions.
- `0x100` Bytecode executable and shared library search at start-up.
- `0x200` Computation of compaction-triggering condition.
- `0x400` Output GC statistics at program exit. Default: 0.

`mutable max_overhead : int ;`

Heap compaction is triggered when the estimated amount of "wasted" memory is more than `max_overhead` percent of the amount of live data. If `max_overhead` is set to 0, heap compaction is triggered at the end of each major GC cycle (this setting is intended for testing purposes only). If `max_overhead >= 1000000`, compaction is never triggered. If compaction is permanently disabled, it is strongly suggested to set `allocation_policy` to 1. Default: 500.

`mutable stack_limit : int ;`

The maximum size of the stack (in words). This is only relevant to the byte-code runtime, as the native code runtime uses the operating system's stack. Default: 1024k.

`mutable allocation_policy : int ;`

The policy used for allocating in the heap. Possible values are 0 and 1. 0 is the next-fit policy, which is quite fast but can result in fragmentation. 1 is the first-fit policy, which can be slower in some cases but can be better for programs with fragmentation problems. Default: 0.

Since: 3.11.0

`window_size : int ;`

The size of the window used by the major GC for smoothing out variations in its workload. This is an integer between 1 and 50. Default: 1.

Since: 4.03.0

`}`

The GC parameters are given as a `control` record. Note that these parameters can also be initialised by setting the OCAMLRUNPARAM environment variable. See the documentation of `ocamlrun`.

`val stat : unit -> stat`

Return the current values of the memory management counters in a `stat` record. This function examines every heap block to get the statistics.

`val quick_stat : unit -> stat`

Same as `stat` except that `live_words`, `live_blocks`, `free_words`, `free_blocks`, `largest_free`, and `fragments` are set to 0. This function is much faster than `stat` because it does not need to go through the heap.

`val counters : unit -> float * float * float`

Return `(minor_words, promoted_words, major_words)`. This function is as fast as `quick_stat`.

`val minor_words : unit -> float`

Number of words allocated in the minor heap since the program was started. This number is accurate in byte-code programs, but only an approximation in programs compiled to native code.

In native code this function does not allocate.

Since: 4.04

`val get : unit -> control`

Return the current values of the GC parameters in a `control` record.

`val set : control -> unit`

`set r` changes the GC parameters according to the `control` record `r`. The normal usage is: `Gc.set { (Gc.get()) with Gc.verbose = 0x00d }`

`val minor : unit -> unit`

Trigger a minor collection.

`val major_slice : int -> int`

`major_slice n` Do a minor collection and a slice of major collection. `n` is the size of the slice: the GC will do enough work to free (on average) `n` words of memory. If `n` = 0, the GC will try to do enough work to ensure that the next automatic slice has no work to do. This function returns an unspecified integer (currently: 0).

`val major : unit -> unit`

Do a minor collection and finish the current major collection cycle.

`val full_major : unit -> unit`

Do a minor collection, finish the current major collection cycle, and perform a complete new cycle. This will collect all currently unreachable blocks.

`val compact : unit -> unit`

Perform a full major collection and compact the heap. Note that heap compaction is a lengthy operation.

`val print_stat : Pervasives.out_channel -> unit`

Print the current values of the memory management counters (in human-readable form) into the channel argument.

`val allocated_bytes : unit -> float`

Return the total number of bytes allocated since the program was started. It is returned as a `float` to avoid overflow problems with `int` on 32-bit machines.

`val get_minor_free : unit -> int`

Return the current size of the free space inside the minor heap.

Since: 4.03.0

`val get_bucket : int -> int`

`get_bucket n` returns the current size of the `n`-th future bucket of the GC smoothing system. The unit is one millionth of a full GC. Raise `Invalid_argument` if `n` is negative, return 0 if n is larger than the smoothing window.

Since: 4.03.0

`val get_credit : unit -> int`

`get_credit ()` returns the current size of the "work done in advance" counter of the GC smoothing system. The unit is one millionth of a full GC.

Since: 4.03.0

`val huge_fallback_count : unit -> int`

Return the number of times we tried to map huge pages and had to fall back to small pages. This is always 0 if `OCAMLRUNPARAM` contains `H=1`.

Since: 4.03.0

`val finalise : ('a -> unit) -> 'a -> unit`

`finalise f v` registers `f` as a finalisation function for `v`. `v` must be heap-allocated. `f` will be called with `v` as argument at some point between the first time `v` becomes unreachable (including through weak pointers) and the time `v` is collected by the GC. Several functions can be registered for the same value, or even several instances of the same function. Each instance will be called once (or never, if the program terminates before `v` becomes unreachable).

The GC will call the finalisation functions in the order of deallocation. When several values become unreachable at the same time (i.e. during the same GC cycle), the finalisation functions will be called in the reverse order of the corresponding calls to `finalise`. If `finalise` is called in the same order as the values are allocated, that means each value is

finalised before the values it depends upon. Of course, this becomes false if additional dependencies are introduced by assignments.

In the presence of multiple OCaml threads it should be assumed that any particular finaliser may be executed in any of the threads.

Anything reachable from the closure of finalisation functions is considered reachable, so the following code will not work as expected:

- `let v = ...  in Gc.finalise (fun _ -> ...v...)  v`

Instead you should make sure that `v` is not in the closure of the finalisation function by writing:

- `let f = fun x -> ...  let v = ...  in Gc.finalise f v`

The `f` function can use all features of OCaml, including assignments that make the value reachable again. It can also loop forever (in this case, the other finalisation functions will not be called during the execution of f, unless it calls `finalise_release`). It can call `finalise` on `v` or other values to register other functions or even itself. It can raise an exception; in this case the exception will interrupt whatever the program was doing when the function was called.

`finalise` will raise `Invalid_argument` if `v` is not guaranteed to be heap-allocated. Some examples of values that are not heap-allocated are integers, constant constructors, booleans, the empty array, the empty list, the unit value. The exact list of what is heap-allocated or not is implementation-dependent. Some constant values can be heap-allocated but never deallocated during the lifetime of the program, for example a list of integer constants; this is also implementation-dependent. Note that values of types `float` are sometimes allocated and sometimes not, so finalising them is unsafe, and `finalise` will also raise `Invalid_argument` for them. Values of type `'a Lazy.t` (for any `'a`) are like `float` in this respect, except that the compiler sometimes optimizes them in a way that prevents `finalise` from detecting them. In this case, it will not raise `Invalid_argument`, but you should still avoid calling `finalise` on lazy values.

The results of calling `String.make`[21.37], `Bytes.make`[21.4], `Bytes.create`[21.4], `Array.make`[21.2], and `Pervasives.ref`[20.2] are guaranteed to be heap-allocated and non-constant except when the length argument is `0`.

`val finalise_last : (unit -> unit) -> 'a -> unit`

same as `Gc.finalise`[21.12] except the value is not given as argument. So you can't use the given value for the computation of the finalisation function. The benefit is that the function is called after the value is unreachable for the last time instead of the first time. So contrary to `Gc.finalise`[21.12] the value will never be reachable again or used again. In particular every weak pointer and ephemeron that contained this value as key or data is unset before running the finalisation function. Moreover the finalisation function attached with 'GC.finalise' are always called before the finalisation function attached with 'GC.finalise_last'.

Since: 4.04

`val finalise_release : unit -> unit`

A finalisation function may call `finalise_release` to tell the GC that it can launch the next finalisation function without waiting for the current one to return.

`type alarm`

An alarm is a piece of data that calls a user function at the end of each major GC cycle. The following functions are provided to create and delete alarms.

`val create_alarm : (unit -> unit) -> alarm`

`create_alarm f` will arrange for `f` to be called at the end of each major GC cycle, starting with the current cycle or the next one. A value of type `alarm` is returned that you can use to call `delete_alarm`.

`val delete_alarm : alarm -> unit`

`delete_alarm a` will stop the calls to the function associated to `a`. Calling `delete_alarm a` again has no effect.

21.13 Module `Genlex` : A generic lexical analyzer.

This module implements a simple 'standard' lexical analyzer, presented as a function from character streams to token streams. It implements roughly the lexical conventions of OCaml, but is parameterized by the set of keywords of your language.

Example: a lexer suitable for a desk calculator is obtained by

```
let lexer = make_lexer ["+";"-";"*";"/";"let";"="; "("; ")"]
```

The associated parser would be a function from `token stream` to, for instance, `int`, and would have rules such as:

```
let rec parse_expr = parser
  | [< n1 = parse_atom; n2 = parse_remainder n1 >] -> n2
and parse_atom = parser
  | [< 'Int n >] -> n
  | [< 'Kwd "("; n = parse_expr; 'Kwd ")" >] -> n
and parse_remainder n1 = parser
  | [< 'Kwd "+"; n2 = parse_expr >] -> n1+n2
  | [< >] -> n1
```

One should notice that the use of the `parser` keyword and associated notation for streams are only available through camlp4 extensions. This means that one has to preprocess its sources *e. g.* by using the `"-pp"` command-line switch of the compilers.

```
type token =
  | Kwd of string
  | Ident of string
```

```
  | Int of int
  | Float of float
  | String of string
  | Char of char
```

The type of tokens. The lexical classes are: `Int` and `Float` for integer and floating-point numbers; `String` for string literals, enclosed in double quotes; `Char` for character literals, enclosed in single quotes; `Ident` for identifiers (either sequences of letters, digits, underscores and quotes, or sequences of 'operator characters' such as `+`, `*`, etc); and `Kwd` for keywords (either identifiers or single 'special characters' such as `(`, `}`, etc).

```
val make_lexer : string list -> char Stream.t -> token Stream.t
```

Construct the lexer function. The first argument is the list of keywords. An identifier `s` is returned as `Kwd s` if `s` belongs to this list, and as `Ident s` otherwise. A special character `s` is returned as `Kwd s` if `s` belongs to this list, and cause a lexical error (exception `Stream.Error` with the offending lexeme as its parameter) otherwise. Blanks and newlines are skipped. Comments delimited by `(*` and `*)` are skipped as well, and can be nested. A `Stream.Failure` exception is raised if end of stream is unexpectedly reached.

21.14 Module `Hashtbl` : Hash tables and hash functions.

Hash tables are hashed association tables, with in-place modification.

Generic interface

```
type ('a, 'b) t
```

The type of hash tables from type `'a` to type `'b`.

```
val create : ?random:bool -> int -> ('a, 'b) t
```

`Hashtbl.create n` creates a new, empty hash table, with initial size `n`. For best results, `n` should be on the order of the expected number of elements that will be in the table. The table grows as needed, so `n` is just an initial guess.

The optional `random` parameter (a boolean) controls whether the internal organization of the hash table is randomized at each execution of `Hashtbl.create` or deterministic over all executions.

A hash table that is created with `~random:false` uses a fixed hash function (`Hashtbl.hash`[21.14]) to distribute keys among buckets. As a consequence, collisions between keys happen deterministically. In Web-facing applications or other security-sensitive applications, the deterministic collision patterns can be exploited by a malicious user to create a denial-of-service attack: the attacker sends input crafted to create many collisions in the table, slowing the application down.

A hash table that is created with `~random:true` uses the seeded hash function `Hashtbl.seeded_hash`[21.14] with a seed that is randomly chosen at hash table creation

time. In effect, the hash function used is randomly selected among `2^{30}` different hash functions. All these hash functions have different collision patterns, rendering ineffective the denial-of-service attack described above. However, because of randomization, enumerating all elements of the hash table using `Hashtbl.fold`[21.14] or `Hashtbl.iter`[21.14] is no longer deterministic: elements are enumerated in different orders at different runs of the program.

If no `~random` parameter is given, hash tables are created in non-random mode by default. This default can be changed either programmatically by calling `Hashtbl.randomize`[21.14] or by setting the `R` flag in the `OCAMLRUNPARAM` environment variable.

Before 4.00.0 the `random` parameter was not present and all hash tables were created in non-randomized mode.

`val clear : ('a, 'b) t -> unit`

Empty a hash table. Use `reset` instead of `clear` to shrink the size of the bucket table to its initial size.

`val reset : ('a, 'b) t -> unit`

Empty a hash table and shrink the size of the bucket table to its initial size.

Since: 4.00.0

`val copy : ('a, 'b) t -> ('a, 'b) t`

Return a copy of the given hashtable.

`val add : ('a, 'b) t -> 'a -> 'b -> unit`

`Hashtbl.add tbl x y` adds a binding of `x` to `y` in table `tbl`. Previous bindings for `x` are not removed, but simply hidden. That is, after performing `Hashtbl.remove`[21.14] `tbl x`, the previous binding for `x`, if any, is restored. (Same behavior as with association lists.)

`val find : ('a, 'b) t -> 'a -> 'b`

`Hashtbl.find tbl x` returns the current binding of `x` in `tbl`, or raises `Not_found` if no such binding exists.

`val find_all : ('a, 'b) t -> 'a -> 'b list`

`Hashtbl.find_all tbl x` returns the list of all data associated with `x` in `tbl`. The current binding is returned first, then the previous bindings, in reverse order of introduction in the table.

`val mem : ('a, 'b) t -> 'a -> bool`

`Hashtbl.mem tbl x` checks if `x` is bound in `tbl`.

`val remove : ('a, 'b) t -> 'a -> unit`

`Hashtbl.remove tbl x` removes the current binding of `x` in `tbl`, restoring the previous binding if it exists. It does nothing if `x` is not bound in `tbl`.

`val replace : ('a, 'b) t -> 'a -> 'b -> unit`

`Hashtbl.replace tbl x y` replaces the current binding of `x` in `tbl` by a binding of `x` to `y`. If `x` is unbound in `tbl`, a binding of `x` to `y` is added to `tbl`. This is functionally equivalent to `Hashtbl.remove`[21.14] `tbl x` followed by `Hashtbl.add`[21.14] `tbl x y`.

`val iter : ('a -> 'b -> unit) -> ('a, 'b) t -> unit`

`Hashtbl.iter f tbl` applies `f` to all bindings in table `tbl`. `f` receives the key as first argument, and the associated value as second argument. Each binding is presented exactly once to `f`.

The order in which the bindings are passed to `f` is unspecified. However, if the table contains several bindings for the same key, they are passed to `f` in reverse order of introduction, that is, the most recent binding is passed first.

If the hash table was created in non-randomized mode, the order in which the bindings are enumerated is reproducible between successive runs of the program, and even between minor versions of OCaml. For randomized hash tables, the order of enumeration is entirely random.

The behavior is not defined if the hash table is modified by `f` during the iteration.

`val filter_map_inplace : ('a -> 'b -> 'b option) -> ('a, 'b) t -> unit`

`Hashtbl.filter_map_inplace f tbl` applies `f` to all bindings in table `tbl` and update each binding depending on the result of `f`. If `f` returns `None`, the binding is discarded. If it returns `Some new_val`, the binding is update to associate the key to `new_val`.

Other comments for `Hashtbl.iter`[21.14] apply as well.

Since: 4.03.0

`val fold : ('a -> 'b -> 'c -> 'c) -> ('a, 'b) t -> 'c -> 'c`

`Hashtbl.fold f tbl init` computes `(f kN dN ... (f k1 d1 init)...)`, where `k1 ... kN` are the keys of all bindings in `tbl`, and `d1 ... dN` are the associated values. Each binding is presented exactly once to `f`.

The order in which the bindings are passed to `f` is unspecified. However, if the table contains several bindings for the same key, they are passed to `f` in reverse order of introduction, that is, the most recent binding is passed first.

If the hash table was created in non-randomized mode, the order in which the bindings are enumerated is reproducible between successive runs of the program, and even between minor versions of OCaml. For randomized hash tables, the order of enumeration is entirely random.

The behavior is not defined if the hash table is modified by `f` during the iteration.

`val length : ('a, 'b) t -> int`

`Hashtbl.length tbl` returns the number of bindings in `tbl`. It takes constant time. Multiple bindings are counted once each, so `Hashtbl.length` gives the number of times `Hashtbl.iter` calls its first argument.

```
val randomize : unit -> unit
```

After a call to `Hashtbl.randomize()`, hash tables are created in randomized mode by default: `Hashtbl.create`[21.14] returns randomized hash tables, unless the `~random:false` optional parameter is given. The same effect can be achieved by setting the `R` parameter in the `OCAMLRUNPARAM` environment variable.

It is recommended that applications or Web frameworks that need to protect themselves against the denial-of-service attack described in `Hashtbl.create`[21.14] call `Hashtbl.randomize()` at initialization time.

Note that once `Hashtbl.randomize()` was called, there is no way to revert to the non-randomized default behavior of `Hashtbl.create`[21.14]. This is intentional. Non-randomized hash tables can still be created using `Hashtbl.create ~random:false`.

Since: 4.00.0

```
val is_randomized : unit -> bool
```

return if the tables are currently created in randomized mode by default

Since: 4.02.0

```
type statistics =
{  num_bindings : int ;
```

Number of bindings present in the table. Same value as returned by `Hashtbl.length`[21.14].

```
  num_buckets : int ;
```

Number of buckets in the table.

```
  max_bucket_length : int ;
```

Maximal number of bindings per bucket.

```
  bucket_histogram : int array ;
```

Histogram of bucket sizes. This array `histo` has length `max_bucket_length + 1`. The value of `histo.(i)` is the number of buckets whose size is `i`.

```
}
val stats : ('a, 'b) t -> statistics
```

`Hashtbl.stats tbl` returns statistics about the table `tbl`: number of buckets, size of the biggest bucket, distribution of buckets by size.

Since: 4.00.0

Functorial interface

The functorial interface allows the use of specific comparison and hash functions, either for performance/security concerns, or because keys are not hashable/comparable with the polymorphic builtins.

For instance, one might want to specialize a table for integer keys:

```
module IntHash =
  struct
    type t = int
    let equal i j = i=j
    let hash i = i land max_int
  end

module IntHashtbl = Hashtbl.Make(IntHash)

let h = IntHashtbl.create 17 in
IntHashtbl.add h 12 "hello"
```

This creates a new module `IntHashtbl`, with a new type `'a IntHashtbl.t` of tables from `int` to `'a`. In this example, `h` contains `string` values so its type is `string IntHashtbl.t`.

Note that the new type `'a IntHashtbl.t` is not compatible with the type `('a,'b) Hashtbl.t` of the generic interface. For example, `Hashtbl.length h` would not type-check, you must use `IntHashtbl.length`.

```
module type HashedType =
  sig
```

`type t`

The type of the hashtable keys.

`val equal : t -> t -> bool`

The equality predicate used to compare keys.

`val hash : t -> int`

A hashing function on keys. It must be such that if two keys are equal according to `equal`, then they have identical hash values as computed by `hash`. Examples: suitable (`equal`, `hash`) pairs for arbitrary key types include

- (`(=)`, `Hashtbl.hash`[21.14]) for comparing objects by structure (provided objects do not contain floats)
- (`(fun x y -> compare x y = 0)`, `Hashtbl.hash`[21.14]) for comparing objects by structure and handling `Pervasives.nan`[20.2] correctly
- (`(==)`, `Hashtbl.hash`[21.14]) for comparing objects by physical equality (e.g. for mutable or cyclic objects).

```
  end
```

The input signature of the functor `Hashtbl.Make`[21.14].

```
module type S =
  sig
```

```
    type key
    type 'a t
    val create : int -> 'a t
    val clear : 'a t -> unit
    val reset : 'a t -> unit
    val copy : 'a t -> 'a t
    val add : 'a t -> key -> 'a -> unit
    val remove : 'a t -> key -> unit
    val find : 'a t -> key -> 'a
    val find_all : 'a t -> key -> 'a list
    val replace : 'a t -> key -> 'a -> unit
    val mem : 'a t -> key -> bool
    val iter : (key -> 'a -> unit) -> 'a t -> unit
    val filter_map_inplace : (key -> 'a -> 'a option) -> 'a t -> unit
    val fold : (key -> 'a -> 'b -> 'b) -> 'a t -> 'b -> 'b
    val length : 'a t -> int
    val stats : 'a t -> Hashtbl.statistics
  end
```

The output signature of the functor `Hashtbl.Make`[21.14].

```
module Make :
   functor (H : HashedType) -> S  with type key = H.t
```

Functor building an implementation of the hashtable structure. The functor `Hashtbl.Make` returns a structure containing a type `key` of keys and a type `'a t` of hash tables associating data of type `'a` to keys of type `key`. The operations perform similarly to those of the generic interface, but use the hashing and equality functions specified in the functor argument `H` instead of generic equality and hashing. Since the hash function is not seeded, the `create` operation of the result structure always returns non-randomized hash tables.

```
module type SeededHashedType =
  sig
    type t
```

The type of the hashtable keys.

```
    val equal : t -> t -> bool
```

The equality predicate used to compare keys.

```
    val hash : int -> t -> int
```

A seeded hashing function on keys. The first argument is the seed. It must be the case that if `equal x y` is true, then `hash seed x = hash seed y` for any value of `seed`. A suitable choice for `hash` is the function `Hashtbl.seeded_hash`[21.14] below.

```
  end
```

The input signature of the functor `Hashtbl.MakeSeeded`[21.14].

Since: 4.00.0

```
module type SeededS =
  sig
    type key
    type 'a t
    val create : ?random:bool -> int -> 'a t
    val clear : 'a t -> unit
    val reset : 'a t -> unit
    val copy : 'a t -> 'a t
    val add : 'a t -> key -> 'a -> unit
    val remove : 'a t -> key -> unit
    val find : 'a t -> key -> 'a
    val find_all : 'a t -> key -> 'a list
    val replace : 'a t -> key -> 'a -> unit
    val mem : 'a t -> key -> bool
    val iter : (key -> 'a -> unit) -> 'a t -> unit
    val filter_map_inplace : (key -> 'a -> 'a option) -> 'a t -> unit
    val fold : (key -> 'a -> 'b -> 'b) -> 'a t -> 'b -> 'b
    val length : 'a t -> int
    val stats : 'a t -> Hashtbl.statistics
  end
```

The output signature of the functor `Hashtbl.MakeSeeded`[21.14].

Since: 4.00.0

```
module MakeSeeded :
   functor (H : SeededHashedType) -> SeededS  with type key = H.t
```

Functor building an implementation of the hashtable structure. The functor `Hashtbl.MakeSeeded` returns a structure containing a type `key` of keys and a type `'a t` of hash tables associating data of type `'a` to keys of type `key`. The operations perform similarly to those of the generic interface, but use the seeded hashing and equality functions specified in the functor argument `H` instead of generic equality and hashing. The `create` operation of the result structure supports the `~random` optional parameter and returns

randomized hash tables if `~random:true` is passed or if randomization is globally on (see `Hashtbl.randomize`[21.14]).

Since: 4.00.0

The polymorphic hash functions

`val hash : 'a -> int`

`Hashtbl.hash x` associates a nonnegative integer to any value of any type. It is guaranteed that if `x = y` or `Pervasives.compare x y = 0`, then `hash x = hash y`. Moreover, `hash` always terminates, even on cyclic structures.

`val seeded_hash : int -> 'a -> int`

A variant of `Hashtbl.hash`[21.14] that is further parameterized by an integer seed.

Since: 4.00.0

`val hash_param : int -> int -> 'a -> int`

`Hashtbl.hash_param meaningful total x` computes a hash value for `x`, with the same properties as for `hash`. The two extra integer parameters `meaningful` and `total` give more precise control over hashing. Hashing performs a breadth-first, left-to-right traversal of the structure `x`, stopping after `meaningful` meaningful nodes were encountered, or `total` nodes (meaningful or not) were encountered. If `total` as specified by the user exceeds a certain value, currently 256, then it is capped to that value. Meaningful nodes are: integers; floating-point numbers; strings; characters; booleans; and constant constructors. Larger values of `meaningful` and `total` means that more nodes are taken into account to compute the final hash value, and therefore collisions are less likely to happen. However, hashing takes longer. The parameters `meaningful` and `total` govern the tradeoff between accuracy and speed. As default choices, `Hashtbl.hash`[21.14] and `Hashtbl.seeded_hash`[21.14] take `meaningful = 10` and `total = 100`.

`val seeded_hash_param : int -> int -> int -> 'a -> int`

A variant of `Hashtbl.hash_param`[21.14] that is further parameterized by an integer seed. Usage: `Hashtbl.seeded_hash_param meaningful total seed x`.

Since: 4.00.0

21.15 Module `Int32` : 32-bit integers.

This module provides operations on the type `int32` of signed 32-bit integers. Unlike the built-in `int` type, the type `int32` is guaranteed to be exactly 32-bit wide on all platforms. All arithmetic operations over `int32` are taken modulo 2^{32}.

Performance notice: values of type `int32` occupy more memory space than values of type `int`, and arithmetic operations on `int32` are generally slower than those on `int`. Use `int32` only when the application requires exact 32-bit arithmetic.

`val zero : int32`
The 32-bit integer 0.

`val one : int32`
The 32-bit integer 1.

`val minus_one : int32`
The 32-bit integer -1.

`val neg : int32 -> int32`
Unary negation.

`val add : int32 -> int32 -> int32`
Addition.

`val sub : int32 -> int32 -> int32`
Subtraction.

`val mul : int32 -> int32 -> int32`
Multiplication.

`val div : int32 -> int32 -> int32`
Integer division. Raise `Division_by_zero` if the second argument is zero. This division rounds the real quotient of its arguments towards zero, as specified for `Pervasives.(/)`[20.2].

`val rem : int32 -> int32 -> int32`
Integer remainder. If `y` is not zero, the result of `Int32.rem x y` satisfies the following property: `x = Int32.add (Int32.mul (Int32.div x y) y) (Int32.rem x y)`. If `y = 0`, `Int32.rem x y` raises `Division_by_zero`.

`val succ : int32 -> int32`
Successor. `Int32.succ x` is `Int32.add x Int32.one`.

`val pred : int32 -> int32`
Predecessor. `Int32.pred x` is `Int32.sub x Int32.one`.

`val abs : int32 -> int32`
Return the absolute value of its argument.

`val max_int : int32`
The greatest representable 32-bit integer, 2^{31} - 1.

`val min_int : int32`

The smallest representable 32-bit integer, -2^{31}.

`val logand : int32 -> int32 -> int32`

Bitwise logical and.

`val logor : int32 -> int32 -> int32`

Bitwise logical or.

`val logxor : int32 -> int32 -> int32`

Bitwise logical exclusive or.

`val lognot : int32 -> int32`

Bitwise logical negation

`val shift_left : int32 -> int -> int32`

`Int32.shift_left x y` shifts `x` to the left by `y` bits. The result is unspecified if `y < 0` or `y >= 32`.

`val shift_right : int32 -> int -> int32`

`Int32.shift_right x y` shifts `x` to the right by `y` bits. This is an arithmetic shift: the sign bit of `x` is replicated and inserted in the vacated bits. The result is unspecified if `y < 0` or `y >= 32`.

`val shift_right_logical : int32 -> int -> int32`

`Int32.shift_right_logical x y` shifts `x` to the right by `y` bits. This is a logical shift: zeroes are inserted in the vacated bits regardless of the sign of `x`. The result is unspecified if `y < 0` or `y >= 32`.

`val of_int : int -> int32`

Convert the given integer (type `int`) to a 32-bit integer (type `int32`).

`val to_int : int32 -> int`

Convert the given 32-bit integer (type `int32`) to an integer (type `int`). On 32-bit platforms, the 32-bit integer is taken modulo 2^{31}, i.e. the high-order bit is lost during the conversion. On 64-bit platforms, the conversion is exact.

`val of_float : float -> int32`

Convert the given floating-point number to a 32-bit integer, discarding the fractional part (truncate towards 0). The result of the conversion is undefined if, after truncation, the number is outside the range [`Int32.min_int`[21.15], `Int32.max_int`[21.15]].

`val to_float : int32 -> float`

Convert the given 32-bit integer to a floating-point number.

`val of_string : string -> int32`

Convert the given string to a 32-bit integer. The string is read in decimal (by default) or in hexadecimal, octal or binary if the string begins with `0x`, `0o` or `0b` respectively. Raise `Failure "int_of_string"` if the given string is not a valid representation of an integer, or if the integer represented exceeds the range of integers representable in type `int32`.

`val to_string : int32 -> string`

Return the string representation of its argument, in signed decimal.

`val bits_of_float : float -> int32`

Return the internal representation of the given float according to the IEEE 754 floating-point 'single format' bit layout. Bit 31 of the result represents the sign of the float; bits 30 to 23 represent the (biased) exponent; bits 22 to 0 represent the mantissa.

`val float_of_bits : int32 -> float`

Return the floating-point number whose internal representation, according to the IEEE 754 floating-point 'single format' bit layout, is the given `int32`.

`type t = int32`

An alias for the type of 32-bit integers.

`val compare : t -> t -> int`

The comparison function for 32-bit integers, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `Int32` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

`val equal : t -> t -> bool`

The equal function for int32s.

Since: 4.03.0

21.16 Module `Int64` : 64-bit integers.

This module provides operations on the type `int64` of signed 64-bit integers. Unlike the built-in `int` type, the type `int64` is guaranteed to be exactly 64-bit wide on all platforms. All arithmetic operations over `int64` are taken modulo 2^{64}

Performance notice: values of type `int64` occupy more memory space than values of type `int`, and arithmetic operations on `int64` are generally slower than those on `int`. Use `int64` only when the application requires exact 64-bit arithmetic.

`val zero : int64`

The 64-bit integer 0.

`val one : int64`

The 64-bit integer 1.

`val minus_one : int64`
The 64-bit integer -1.

`val neg : int64 -> int64`
Unary negation.

`val add : int64 -> int64 -> int64`
Addition.

`val sub : int64 -> int64 -> int64`
Subtraction.

`val mul : int64 -> int64 -> int64`
Multiplication.

`val div : int64 -> int64 -> int64`
Integer division. Raise `Division_by_zero` if the second argument is zero. This division rounds the real quotient of its arguments towards zero, as specified for `Pervasives.(/)`[20.2].

`val rem : int64 -> int64 -> int64`
Integer remainder. If `y` is not zero, the result of `Int64.rem x y` satisfies the following property: `x = Int64.add (Int64.mul (Int64.div x y) y) (Int64.rem x y)`. If `y = 0`, `Int64.rem x y` raises `Division_by_zero`.

`val succ : int64 -> int64`
Successor. `Int64.succ x` is `Int64.add x Int64.one`.

`val pred : int64 -> int64`
Predecessor. `Int64.pred x` is `Int64.sub x Int64.one`.

`val abs : int64 -> int64`
Return the absolute value of its argument.

`val max_int : int64`
The greatest representable 64-bit integer, 2^{63} - 1.

`val min_int : int64`
The smallest representable 64-bit integer, -2^{63}.

`val logand : int64 -> int64 -> int64`
Bitwise logical and.

`val logor : int64 -> int64 -> int64`

Bitwise logical or.

`val logxor : int64 -> int64 -> int64`

Bitwise logical exclusive or.

`val lognot : int64 -> int64`

Bitwise logical negation

`val shift_left : int64 -> int -> int64`

`Int64.shift_left x y` shifts `x` to the left by `y` bits. The result is unspecified if `y < 0` or `y >= 64`.

`val shift_right : int64 -> int -> int64`

`Int64.shift_right x y` shifts `x` to the right by `y` bits. This is an arithmetic shift: the sign bit of `x` is replicated and inserted in the vacated bits. The result is unspecified if `y < 0` or `y >= 64`.

`val shift_right_logical : int64 -> int -> int64`

`Int64.shift_right_logical x y` shifts `x` to the right by `y` bits. This is a logical shift: zeroes are inserted in the vacated bits regardless of the sign of `x`. The result is unspecified if `y < 0` or `y >= 64`.

`val of_int : int -> int64`

Convert the given integer (type `int`) to a 64-bit integer (type `int64`).

`val to_int : int64 -> int`

Convert the given 64-bit integer (type `int64`) to an integer (type `int`). On 64-bit platforms, the 64-bit integer is taken modulo 2^{63}, i.e. the high-order bit is lost during the conversion. On 32-bit platforms, the 64-bit integer is taken modulo 2^{31}, i.e. the top 33 bits are lost during the conversion.

`val of_float : float -> int64`

Convert the given floating-point number to a 64-bit integer, discarding the fractional part (truncate towards 0). The result of the conversion is undefined if, after truncation, the number is outside the range [`Int64.min_int`[21.16], `Int64.max_int`[21.16]].

`val to_float : int64 -> float`

Convert the given 64-bit integer to a floating-point number.

`val of_int32 : int32 -> int64`

Convert the given 32-bit integer (type `int32`) to a 64-bit integer (type `int64`).

`val to_int32 : int64 -> int32`

Convert the given 64-bit integer (type `int64`) to a 32-bit integer (type `int32`). The 64-bit integer is taken modulo 2^{32}, i.e. the top 32 bits are lost during the conversion.

`val of_nativeint : nativeint -> int64`

Convert the given native integer (type `nativeint`) to a 64-bit integer (type `int64`).

`val to_nativeint : int64 -> nativeint`

Convert the given 64-bit integer (type `int64`) to a native integer. On 32-bit platforms, the 64-bit integer is taken modulo 2^{32}. On 64-bit platforms, the conversion is exact.

`val of_string : string -> int64`

Convert the given string to a 64-bit integer. The string is read in decimal (by default) or in hexadecimal, octal or binary if the string begins with `0x`, `0o` or `0b` respectively. Raise `Failure "int_of_string"` if the given string is not a valid representation of an integer, or if the integer represented exceeds the range of integers representable in type `int64`.

`val to_string : int64 -> string`

Return the string representation of its argument, in decimal.

`val bits_of_float : float -> int64`

Return the internal representation of the given float according to the IEEE 754 floating-point 'double format' bit layout. Bit 63 of the result represents the sign of the float; bits 62 to 52 represent the (biased) exponent; bits 51 to 0 represent the mantissa.

`val float_of_bits : int64 -> float`

Return the floating-point number whose internal representation, according to the IEEE 754 floating-point 'double format' bit layout, is the given `int64`.

`type t = int64`

An alias for the type of 64-bit integers.

`val compare : t -> t -> int`

The comparison function for 64-bit integers, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `Int64` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

`val equal : t -> t -> bool`

The equal function for int64s.

Since: 4.03.0

21.17 Module `Lazy` : Deferred computations.

`type 'a t = 'a lazy_t`

A value of type `'a Lazy.t` is a deferred computation, called a suspension, that has a result of type `'a`. The special expression syntax `lazy (expr)` makes a suspension of the computation of `expr`, without computing `expr` itself yet. "Forcing" the suspension will then compute `expr` and return its result.

Note: `lazy_t` is the built-in type constructor used by the compiler for the `lazy` keyword. You should not use it directly. Always use `Lazy.t` instead.

Note: `Lazy.force` is not thread-safe. If you use this module in a multi-threaded program, you will need to add some locks.

Note: if the program is compiled with the `-rectypes` option, ill-founded recursive definitions of the form `let rec x = lazy x` or `let rec x = lazy(lazy(...(lazy x)))` are accepted by the type-checker and lead, when forced, to ill-formed values that trigger infinite loops in the garbage collector and other parts of the run-time system. Without the `-rectypes` option, such ill-founded recursive definitions are rejected by the type-checker.

```
exception Undefined
```

```
val force : 'a t -> 'a
```

`force x` forces the suspension `x` and returns its result. If `x` has already been forced, `Lazy.force x` returns the same value again without recomputing it. If it raised an exception, the same exception is raised again. Raise `Undefined` if the forcing of `x` tries to force `x` itself recursively.

```
val force_val : 'a t -> 'a
```

`force_val x` forces the suspension `x` and returns its result. If `x` has already been forced, `force_val x` returns the same value again without recomputing it. Raise `Undefined` if the forcing of `x` tries to force `x` itself recursively. If the computation of `x` raises an exception, it is unspecified whether `force_val x` raises the same exception or `Undefined`.

```
val from_fun : (unit -> 'a) -> 'a t
```

`from_fun f` is the same as `lazy (f ())` but slightly more efficient.

`from_fun` should only be used if the function `f` is already defined. In particular it is always less efficient to write `from_fun (fun () -> expr)` than `lazy expr`.

Since: 4.00.0

```
val from_val : 'a -> 'a t
```

`from_val v` returns an already-forced suspension of `v`. This is for special purposes only and should not be confused with `lazy (v)`.

Since: 4.00.0

```
val is_val : 'a t -> bool
```

`is_val x` returns `true` if `x` has already been forced and did not raise an exception.

Since: 4.00.0

```
val lazy_from_fun : (unit -> 'a) -> 'a t
```

Deprecated. synonym for `from_fun`.

```
val lazy_from_val : 'a -> 'a t
```

Deprecated. synonym for `from_val`.

```
val lazy_is_val : 'a t -> bool
```

Deprecated. synonym for `is_val`.

21.18 Module `Lexing` : The run-time library for lexers generated by `ocamllex`.

Positions

```
type position =
{  pos_fname : string ;
  pos_lnum : int ;
  pos_bol : int ;
  pos_cnum : int ;
}
```

A value of type `position` describes a point in a source file. `pos_fname` is the file name; `pos_lnum` is the line number; `pos_bol` is the offset of the beginning of the line (number of characters between the beginning of the lexbuf and the beginning of the line); `pos_cnum` is the offset of the position (number of characters between the beginning of the lexbuf and the position). The difference between `pos_cnum` and `pos_bol` is the character offset within the line (i.e. the column number, assuming each character is one column wide).

See the documentation of type `lexbuf` for information about how the lexing engine will manage positions.

```
val dummy_pos : position
```

A value of type `position`, guaranteed to be different from any valid position.

Lexer buffers

```
type lexbuf =
{  refill_buff : lexbuf -> unit ;
  mutable lex_buffer : bytes ;
  mutable lex_buffer_len : int ;
  mutable lex_abs_pos : int ;
  mutable lex_start_pos : int ;
  mutable lex_curr_pos : int ;
  mutable lex_last_pos : int ;
  mutable lex_last_action : int ;
```

```
  mutable lex_eof_reached : bool ;
  mutable lex_mem : int array ;
  mutable lex_start_p : position ;
  mutable lex_curr_p : position ;
}
```

The type of lexer buffers. A lexer buffer is the argument passed to the scanning functions defined by the generated scanners. The lexer buffer holds the current state of the scanner, plus a function to refill the buffer from the input.

At each token, the lexing engine will copy `lex_curr_p` to `lex_start_p`, then change the `pos_cnum` field of `lex_curr_p` by updating it with the number of characters read since the start of the `lexbuf`. The other fields are left unchanged by the lexing engine. In order to keep them accurate, they must be initialised before the first use of the lexbuf, and updated by the relevant lexer actions (i.e. at each end of line – see also `new_line`).

`val from_channel : Pervasives.in_channel -> lexbuf`

Create a lexer buffer on the given input channel. `Lexing.from_channel inchan` returns a lexer buffer which reads from the input channel `inchan`, at the current reading position.

`val from_string : string -> lexbuf`

Create a lexer buffer which reads from the given string. Reading starts from the first character in the string. An end-of-input condition is generated when the end of the string is reached.

`val from_function : (bytes -> int -> int) -> lexbuf`

Create a lexer buffer with the given function as its reading method. When the scanner needs more characters, it will call the given function, giving it a byte sequence `s` and a byte count `n`. The function should put `n` bytes or fewer in `s`, starting at index 0, and return the number of bytes provided. A return value of 0 means end of input.

Functions for lexer semantic actions

The following functions can be called from the semantic actions of lexer definitions (the ML code enclosed in braces that computes the value returned by lexing functions). They give access to the character string matched by the regular expression associated with the semantic action. These functions must be applied to the argument `lexbuf`, which, in the code generated by `ocamllex`, is bound to the lexer buffer passed to the parsing function.

`val lexeme : lexbuf -> string`

`Lexing.lexeme lexbuf` returns the string matched by the regular expression.

`val lexeme_char : lexbuf -> int -> char`

`Lexing.lexeme_char lexbuf i` returns character number `i` in the matched string.

`val lexeme_start : lexbuf -> int`

`Lexing.lexeme_start lexbuf` returns the offset in the input stream of the first character of the matched string. The first character of the stream has offset 0.

`val lexeme_end : lexbuf -> int`

`Lexing.lexeme_end lexbuf` returns the offset in the input stream of the character following the last character of the matched string. The first character of the stream has offset 0.

`val lexeme_start_p : lexbuf -> position`

Like `lexeme_start`, but return a complete `position` instead of an offset.

`val lexeme_end_p : lexbuf -> position`

Like `lexeme_end`, but return a complete `position` instead of an offset.

`val new_line : lexbuf -> unit`

Update the `lex_curr_p` field of the lexbuf to reflect the start of a new line. You can call this function in the semantic action of the rule that matches the end-of-line character.

Since: 3.11.0

Miscellaneous functions

`val flush_input : lexbuf -> unit`

Discard the contents of the buffer and reset the current position to 0. The next use of the lexbuf will trigger a refill.

21.19 Module `List` : List operations.

Some functions are flagged as not tail-recursive. A tail-recursive function uses constant stack space, while a non-tail-recursive function uses stack space proportional to the length of its list argument, which can be a problem with very long lists. When the function takes several list arguments, an approximate formula giving stack usage (in some unspecified constant unit) is shown in parentheses.

The above considerations can usually be ignored if your lists are not longer than about 10000 elements.

`val length : 'a list -> int`

Return the length (number of elements) of the given list.

`val cons : 'a -> 'a list -> 'a list`

`cons x xs` is `x :: xs`

Since: 4.03.0

`val hd : 'a list -> 'a`

Return the first element of the given list. Raise `Failure "hd"` if the list is empty.

`val tl : 'a list -> 'a list`

Return the given list without its first element. Raise `Failure "tl"` if the list is empty.

`val nth : 'a list -> int -> 'a`

Return the `n`-th element of the given list. The first element (head of the list) is at position 0. Raise `Failure "nth"` if the list is too short. Raise `Invalid_argument "List.nth"` if `n` is negative.

`val rev : 'a list -> 'a list`

List reversal.

`val append : 'a list -> 'a list -> 'a list`

Concatenate two lists. Same as the infix operator `@`. Not tail-recursive (length of the first argument).

`val rev_append : 'a list -> 'a list -> 'a list`

`List.rev_append l1 l2` reverses `l1` and concatenates it to `l2`. This is equivalent to `List.rev`[21.19] `l1 @ l2`, but `rev_append` is tail-recursive and more efficient.

`val concat : 'a list list -> 'a list`

Concatenate a list of lists. The elements of the argument are all concatenated together (in the same order) to give the result. Not tail-recursive (length of the argument + length of the longest sub-list).

`val flatten : 'a list list -> 'a list`

An alias for `concat`.

Iterators

`val iter : ('a -> unit) -> 'a list -> unit`

`List.iter f [a1; ...; an]` applies function `f` in turn to `a1; ...; an`. It is equivalent to `begin f a1; f a2; ...; f an; () end`.

`val iteri : (int -> 'a -> unit) -> 'a list -> unit`

Same as `List.iter`[21.19], but the function is applied to the index of the element as first argument (counting from 0), and the element itself as second argument.

Since: 4.00.0

`val map : ('a -> 'b) -> 'a list -> 'b list`

`List.map f [a1; ...; an]` applies function `f` to `a1, ..., an`, and builds the list `[f a1; ...; f an]` with the results returned by `f`. Not tail-recursive.

`val mapi : (int -> 'a -> 'b) -> 'a list -> 'b list`

Same as `List.map`[21.19], but the function is applied to the index of the element as first argument (counting from 0), and the element itself as second argument. Not tail-recursive.

Since: 4.00.0

`val rev_map : ('a -> 'b) -> 'a list -> 'b list`

`List.rev_map f l` gives the same result as `List.rev`[21.19] `(List.map`[21.19] `f l)`, but is tail-recursive and more efficient.

`val fold_left : ('a -> 'b -> 'a) -> 'a -> 'b list -> 'a`

`List.fold_left f a [b1; ...; bn]` is `f (... (f (f a b1) b2) ...) bn`.

`val fold_right : ('a -> 'b -> 'b) -> 'a list -> 'b -> 'b`

`List.fold_right f [a1; ...; an] b` is `f a1 (f a2 (... (f an b) ...))`. Not tail-recursive.

Iterators on two lists

`val iter2 : ('a -> 'b -> unit) -> 'a list -> 'b list -> unit`

`List.iter2 f [a1; ...; an] [b1; ...; bn]` calls in turn `f a1 b1; ...; f an bn`. Raise `Invalid_argument` if the two lists are determined to have different lengths.

`val map2 : ('a -> 'b -> 'c) -> 'a list -> 'b list -> 'c list`

`List.map2 f [a1; ...; an] [b1; ...; bn]` is `[f a1 b1; ...; f an bn]`. Raise `Invalid_argument` if the two lists are determined to have different lengths. Not tail-recursive.

`val rev_map2 : ('a -> 'b -> 'c) -> 'a list -> 'b list -> 'c list`

`List.rev_map2 f l1 l2` gives the same result as `List.rev`[21.19] `(List.map2`[21.19] `f l1 l2)`, but is tail-recursive and more efficient.

`val fold_left2 : ('a -> 'b -> 'c -> 'a) -> 'a -> 'b list -> 'c list -> 'a`

`List.fold_left2 f a [b1; ...; bn] [c1; ...; cn]` is `f (... (f (f a b1 c1) b2 c2) ...) bn cn`. Raise `Invalid_argument` if the two lists are determined to have different lengths.

`val fold_right2 : ('a -> 'b -> 'c -> 'c) -> 'a list -> 'b list -> 'c -> 'c`

`List.fold_right2 f [a1; ...; an] [b1; ...; bn] c` is `f a1 b1 (f a2 b2 (... (f an bn c) ...))`. Raise `Invalid_argument` if the two lists are determined to have different lengths. Not tail-recursive.

List scanning

`val for_all : ('a -> bool) -> 'a list -> bool`

`for_all p [a1; ...; an]` checks if all elements of the list satisfy the predicate `p`. That is, it returns `(p a1) && (p a2) && ... && (p an)`.

`val exists : ('a -> bool) -> 'a list -> bool`

`exists p [a1; ...; an]` checks if at least one element of the list satisfies the predicate `p`. That is, it returns `(p a1) || (p a2) || ... || (p an)`.

`val for_all2 : ('a -> 'b -> bool) -> 'a list -> 'b list -> bool`

Same as `List.for_all`[21.19], but for a two-argument predicate. Raise `Invalid_argument` if the two lists are determined to have different lengths.

`val exists2 : ('a -> 'b -> bool) -> 'a list -> 'b list -> bool`

Same as `List.exists`[21.19], but for a two-argument predicate. Raise `Invalid_argument` if the two lists are determined to have different lengths.

`val mem : 'a -> 'a list -> bool`

`mem a l` is true if and only if `a` is equal to an element of `l`.

`val memq : 'a -> 'a list -> bool`

Same as `List.mem`[21.19], but uses physical equality instead of structural equality to compare list elements.

List searching

`val find : ('a -> bool) -> 'a list -> 'a`

`find p l` returns the first element of the list `l` that satisfies the predicate `p`. Raise `Not_found` if there is no value that satisfies `p` in the list `l`.

`val filter : ('a -> bool) -> 'a list -> 'a list`

`filter p l` returns all the elements of the list `l` that satisfy the predicate `p`. The order of the elements in the input list is preserved.

`val find_all : ('a -> bool) -> 'a list -> 'a list`

`find_all` is another name for `List.filter`[21.19].

`val partition : ('a -> bool) -> 'a list -> 'a list * 'a list`

`partition p l` returns a pair of lists `(l1, l2)`, where `l1` is the list of all the elements of `l` that satisfy the predicate `p`, and `l2` is the list of all the elements of `l` that do not satisfy `p`. The order of the elements in the input list is preserved.

Association lists

`val assoc : 'a -> ('a * 'b) list -> 'b`

`assoc a l` returns the value associated with key `a` in the list of pairs `l`. That is, `assoc a [ ...; (a,b); ...] = b` if `(a,b)` is the leftmost binding of `a` in list `l`. Raise `Not_found` if there is no value associated with `a` in the list `l`.

`val assq : 'a -> ('a * 'b) list -> 'b`

Same as `List.assoc`[21.19], but uses physical equality instead of structural equality to compare keys.

`val mem_assoc : 'a -> ('a * 'b) list -> bool`

Same as `List.assoc`[21.19], but simply return true if a binding exists, and false if no bindings exist for the given key.

`val mem_assq : 'a -> ('a * 'b) list -> bool`

Same as `List.mem_assoc`[21.19], but uses physical equality instead of structural equality to compare keys.

`val remove_assoc : 'a -> ('a * 'b) list -> ('a * 'b) list`

`remove_assoc a l` returns the list of pairs `l` without the first pair with key `a`, if any. Not tail-recursive.

`val remove_assq : 'a -> ('a * 'b) list -> ('a * 'b) list`

Same as `List.remove_assoc`[21.19], but uses physical equality instead of structural equality to compare keys. Not tail-recursive.

Lists of pairs

`val split : ('a * 'b) list -> 'a list * 'b list`

Transform a list of pairs into a pair of lists: `split [(a1,b1); ...; (an,bn)]` is `([a1; ...; an], [b1; ...; bn])`. Not tail-recursive.

`val combine : 'a list -> 'b list -> ('a * 'b) list`

Transform a pair of lists into a list of pairs: `combine [a1; ...; an] [b1; ...; bn]` is `[(a1,b1); ...; (an,bn)]`. Raise `Invalid_argument` if the two lists have different lengths. Not tail-recursive.

Sorting

`val sort : ('a -> 'a -> int) -> 'a list -> 'a list`

Sort a list in increasing order according to a comparison function. The comparison function must return 0 if its arguments compare as equal, a positive integer if the first is greater, and a negative integer if the first is smaller (see Array.sort for a complete specification). For example, `Pervasives.compare`[20.2] is a suitable comparison function. The resulting list is sorted in increasing order. `List.sort` is guaranteed to run in constant heap space (in addition to the size of the result list) and logarithmic stack space.

The current implementation uses Merge Sort. It runs in constant heap space and logarithmic stack space.

`val stable_sort : ('a -> 'a -> int) -> 'a list -> 'a list`

Same as `List.sort`[21.19], but the sorting algorithm is guaranteed to be stable (i.e. elements that compare equal are kept in their original order) .

The current implementation uses Merge Sort. It runs in constant heap space and logarithmic stack space.

`val fast_sort : ('a -> 'a -> int) -> 'a list -> 'a list`

Same as `List.sort`[21.19] or `List.stable_sort`[21.19], whichever is faster on typical input.

`val sort_uniq : ('a -> 'a -> int) -> 'a list -> 'a list`

Same as `List.sort`[21.19], but also remove duplicates.

Since: 4.02.0

`val merge : ('a -> 'a -> int) -> 'a list -> 'a list -> 'a list`

Merge two lists: Assuming that `l1` and `l2` are sorted according to the comparison function `cmp`, `merge cmp l1 l2` will return a sorted list containting all the elements of `l1` and `l2`. If several elements compare equal, the elements of `l1` will be before the elements of `l2`. Not tail-recursive (sum of the lengths of the arguments).

21.20 Module `Map` : Association tables over ordered types.

This module implements applicative association tables, also known as finite maps or dictionaries, given a total ordering function over the keys. All operations over maps are purely applicative (no side-effects). The implementation uses balanced binary trees, and therefore searching and insertion take time logarithmic in the size of the map.

For instance:

```
module IntPairs =
  struct
    type t = int * int
    let compare (x0,y0) (x1,y1) =
      match Pervasives.compare x0 x1 with
          0 -> Pervasives.compare y0 y1
        | c -> c
```

```
  end

module PairsMap = Map.Make(IntPairs)

let m = PairsMap.(empty |> add (0,1) "hello" |> add (1,0) "world")
```

This creates a new module `PairsMap`, with a new type `'a PairsMap.t` of maps from `int * int` to `'a`. In this example, `m` contains `string` values so its type is `string PairsMap.t`.

```
module type OrderedType =
  sig
```

`type t`

The type of the map keys.

`val compare : t -> t -> int`

A total ordering function over the keys. This is a two-argument function `f` such that `f e1 e2` is zero if the keys `e1` and `e2` are equal, `f e1 e2` is strictly negative if `e1` is smaller than `e2`, and `f e1 e2` is strictly positive if `e1` is greater than `e2`. Example: a suitable ordering function is the generic structural comparison function `Pervasives.compare`[20.2].

```
  end
```

Input signature of the functor `Map.Make`[21.20].

```
module type S =
  sig
```

`type key`

The type of the map keys.

`type +'a t`

The type of maps from type `key` to type `'a`.

`val empty : 'a t`

The empty map.

`val is_empty : 'a t -> bool`

Test whether a map is empty or not.

`val mem : key -> 'a t -> bool`

`mem x m` returns `true` if `m` contains a binding for `x`, and `false` otherwise.

```
val add : key -> 'a -> 'a t -> 'a t
```

`add x y m` returns a map containing the same bindings as `m`, plus a binding of `x` to `y`. If `x` was already bound in `m` to a value that is physically equal to `y`, `m` is returned unchanged (the result of the function is then physically equal to `m`). Otherwise, the previous binding of `x` in `m` disappears.

Before 4.03 Physical equality was not ensured.

```
val singleton : key -> 'a -> 'a t
```

`singleton x y` returns the one-element map that contains a binding `y` for `x`.

Since: 3.12.0

```
val remove : key -> 'a t -> 'a t
```

`remove x m` returns a map containing the same bindings as `m`, except for `x` which is unbound in the returned map. If `x` was not in `m`, `m` is returned unchanged (the result of the function is then physically equal to `m`).

Before 4.03 Physical equality was not ensured.

```
val merge :
  (key -> 'a option -> 'b option -> 'c option) ->
  'a t -> 'b t -> 'c t
```

`merge f m1 m2` computes a map whose keys is a subset of keys of `m1` and of `m2`. The presence of each such binding, and the corresponding value, is determined with the function `f`.

Since: 3.12.0

```
val union : (key -> 'a -> 'a -> 'a option) ->
  'a t -> 'a t -> 'a t
```

`union f m1 m2` computes a map whose keys is the union of keys of `m1` and of `m2`. When the same binding is defined in both arguments, the function `f` is used to combine them.

Since: 4.03.0

```
val compare : ('a -> 'a -> int) -> 'a t -> 'a t -> int
```

Total ordering between maps. The first argument is a total ordering used to compare data associated with equal keys in the two maps.

```
val equal : ('a -> 'a -> bool) -> 'a t -> 'a t -> bool
```

`equal cmp m1 m2` tests whether the maps `m1` and `m2` are equal, that is, contain equal keys and associate them with equal data. `cmp` is the equality predicate used to compare the data associated with the keys.

```
val iter : (key -> 'a -> unit) -> 'a t -> unit
```

`iter f m` applies `f` to all bindings in map `m`. `f` receives the key as first argument, and the associated value as second argument. The bindings are passed to `f` in increasing order with respect to the ordering over the type of the keys.

```
val fold : (key -> 'a -> 'b -> 'b) -> 'a t -> 'b -> 'b
```

`fold f m a` computes `(f kN dN ... (f k1 d1 a)...)`, where `k1 ... kN` are the keys of all bindings in `m` (in increasing order), and `d1 ... dN` are the associated data.

```
val for_all : (key -> 'a -> bool) -> 'a t -> bool
```

`for_all p m` checks if all the bindings of the map satisfy the predicate `p`.

Since: 3.12.0

```
val exists : (key -> 'a -> bool) -> 'a t -> bool
```

`exists p m` checks if at least one binding of the map satisfy the predicate `p`.

Since: 3.12.0

```
val filter : (key -> 'a -> bool) -> 'a t -> 'a t
```

`filter p m` returns the map with all the bindings in `m` that satisfy predicate `p`. If `p` satisfies every binding in `m`, `m` is returned unchanged (the result of the function is then physically equal to `m`)

Before 4.03 Physical equality was not ensured.

Since: 3.12.0

```
val partition : (key -> 'a -> bool) -> 'a t -> 'a t * 'a t
```

`partition p m` returns a pair of maps `(m1, m2)`, where `m1` contains all the bindings of `s` that satisfy the predicate `p`, and `m2` is the map with all the bindings of `s` that do not satisfy `p`.

Since: 3.12.0

```
val cardinal : 'a t -> int
```

Return the number of bindings of a map.

Since: 3.12.0

```
val bindings : 'a t -> (key * 'a) list
```

Return the list of all bindings of the given map. The returned list is sorted in increasing order with respect to the ordering `Ord.compare`, where `Ord` is the argument given to `Map.Make`[21.20].

Since: 3.12.0

```
val min_binding : 'a t -> key * 'a
```

Return the smallest binding of the given map (with respect to the `Ord.compare` ordering), or raise `Not_found` if the map is empty.

Since: 3.12.0

```
val max_binding : 'a t -> key * 'a
```

Same as `Map.S.min_binding`[21.20], but returns the largest binding of the given map.

Since: 3.12.0

```
val choose : 'a t -> key * 'a
```

Return one binding of the given map, or raise `Not_found` if the map is empty. Which binding is chosen is unspecified, but equal bindings will be chosen for equal maps.

Since: 3.12.0

```
val split : key -> 'a t -> 'a t * 'a option * 'a t
```

`split x m` returns a triple `(l, data, r)`, where `l` is the map with all the bindings of `m` whose key is strictly less than `x`; `r` is the map with all the bindings of `m` whose key is strictly greater than `x`; `data` is `None` if `m` contains no binding for `x`, or `Some v` if `m` binds `v` to `x`.

Since: 3.12.0

```
val find : key -> 'a t -> 'a
```

`find x m` returns the current binding of `x` in `m`, or raises `Not_found` if no such binding exists.

```
val map : ('a -> 'b) -> 'a t -> 'b t
```

`map f m` returns a map with same domain as `m`, where the associated value `a` of all bindings of `m` has been replaced by the result of the application of `f` to `a`. The bindings are passed to `f` in increasing order with respect to the ordering over the type of the keys.

```
val mapi : (key -> 'a -> 'b) -> 'a t -> 'b t
```

Same as `Map.S.map`[21.20], but the function receives as arguments both the key and the associated value for each binding of the map.

```
end
```

Output signature of the functor `Map.Make`[21.20].

```
module Make :
  functor (Ord :  OrderedType) -> S  with type key = Ord.t
```

Functor building an implementation of the map structure given a totally ordered type.

21.21 Module `Marshal` : Marshaling of data structures.

This module provides functions to encode arbitrary data structures as sequences of bytes, which can then be written on a file or sent over a pipe or network connection. The bytes can then be read back later, possibly in another process, and decoded back into a data structure. The format for the byte sequences is compatible across all machines for a given version of OCaml.

Warning: marshaling is currently not type-safe. The type of marshaled data is not transmitted along the value of the data, making it impossible to check that the data read back possesses the type expected by the context. In particular, the result type of the `Marshal.from_*` functions is given as `'a`, but this is misleading: the returned OCaml value does not possess type `'a` for all `'a`; it has one, unique type which cannot be determined at compile-type. The programmer should explicitly give the expected type of the returned value, using the following syntax:

- `(Marshal.from_channel chan : type)`. Anything can happen at run-time if the object in the file does not belong to the given type.

Values of extensible variant types, for example exceptions (of extensible type `exn`), returned by the unmarhsaller should not be pattern-matched over through `match ... with` or `try ... with`, because unmarshalling does not preserve the information required for matching their constructors. Structural equalities with other extensible variant values does not work either. Most other uses such as Printexc.to_string, will still work as expected.

The representation of marshaled values is not human-readable, and uses bytes that are not printable characters. Therefore, input and output channels used in conjunction with `Marshal.to_channel` and `Marshal.from_channel` must be opened in binary mode, using e.g. `open_out_bin` or `open_in_bin`; channels opened in text mode will cause unmarshaling errors on platforms where text channels behave differently than binary channels, e.g. Windows.

`type extern_flags =`

— No_sharing
: Don't preserve sharing

— Closures
: Send function closures

— Compat_32
: Ensure 32-bit compatibility

The flags to the `Marshal.to_*` functions below.

`val to_channel : Pervasives.out_channel -> 'a -> extern_flags list -> unit`

`Marshal.to_channel chan v flags` writes the representation of `v` on channel `chan`. The `flags` argument is a possibly empty list of flags that governs the marshaling behavior with respect to sharing, functional values, and compatibility between 32- and 64-bit platforms.

If `flags` does not contain `Marshal.No_sharing`, circularities and sharing inside the value `v` are detected and preserved in the sequence of bytes produced. In particular, this guarantees that marshaling always terminates. Sharing between values marshaled by successive calls to `Marshal.to_channel` is neither detected nor preserved, though. If `flags` contains `Marshal.No_sharing`, sharing is ignored. This results in faster marshaling if `v` contains no

shared substructures, but may cause slower marshaling and larger byte representations if `v` actually contains sharing, or even non-termination if `v` contains cycles.

If `flags` does not contain `Marshal.Closures`, marshaling fails when it encounters a functional value inside `v`: only 'pure' data structures, containing neither functions nor objects, can safely be transmitted between different programs. If `flags` contains `Marshal.Closures`, functional values will be marshaled as a the position in the code of the program together with the values corresponding to the free variables captured in the closure. In this case, the output of marshaling can only be read back in processes that run exactly the same program, with exactly the same compiled code. (This is checked at un-marshaling time, using an MD5 digest of the code transmitted along with the code position.)

The exact definition of which free variables are captured in a closure is not specified and can very between bytecode and native code (and according to optimization flags). In particular, a function value accessing a global reference may or may not include the reference in its closure. If it does, unmarshaling the corresponding closure will create a new reference, different from the global one.

If `flags` contains `Marshal.Compat_32`, marshaling fails when it encounters an integer value outside the range `[-2{^30}, 2{^30}-1]` of integers that are representable on a 32-bit platform. This ensures that marshaled data generated on a 64-bit platform can be safely read back on a 32-bit platform. If `flags` does not contain `Marshal.Compat_32`, integer values outside the range `[-2{^30}, 2{^30}-1]` are marshaled, and can be read back on a 64-bit platform, but will cause an error at un-marshaling time when read back on a 32-bit platform. The `Mashal.Compat_32` flag only matters when marshaling is performed on a 64-bit platform; it has no effect if marshaling is performed on a 32-bit platform.

`val to_bytes : 'a -> extern_flags list -> bytes`

`Marshal.to_bytes v flags` returns a byte sequence containing the representation of `v`. The `flags` argument has the same meaning as for `Marshal.to_channel`[21.21].

Since: 4.02.0

`val to_string : 'a -> extern_flags list -> string`

Same as `to_bytes` but return the result as a string instead of a byte sequence.

`val to_buffer : bytes -> int -> int -> 'a -> extern_flags list -> int`

`Marshal.to_buffer buff ofs len v flags` marshals the value `v`, storing its byte representation in the sequence `buff`, starting at index `ofs`, and writing at most `len` bytes. It returns the number of bytes actually written to the sequence. If the byte representation of `v` does not fit in `len` characters, the exception `Failure` is raised.

`val from_channel : Pervasives.in_channel -> 'a`

`Marshal.from_channel chan` reads from channel `chan` the byte representation of a structured value, as produced by one of the `Marshal.to_*` functions, and reconstructs and returns the corresponding value.

It raises `End_of_file` if the function has already reached the end of file when starting to read from the channel, and raises `Failure "input_value: truncated object"` if it reaches the end of file later during the unmarshalling.

`val from_bytes : bytes -> int -> 'a`

`Marshal.from_bytes buff ofs` unmarshals a structured value like `Marshal.from_channel`[21.21] does, except that the byte representation is not read from a channel, but taken from the byte sequence `buff`, starting at position `ofs`. The byte sequence is not mutated.

Since: 4.02.0

`val from_string : string -> int -> 'a`

Same as `from_bytes` but take a string as argument instead of a byte sequence.

`val header_size : int`

The bytes representing a marshaled value are composed of a fixed-size header and a variable-sized data part, whose size can be determined from the header. `Marshal.header_size`[21.21] is the size, in bytes, of the header. `Marshal.data_size`[21.21] `buff ofs` is the size, in bytes, of the data part, assuming a valid header is stored in `buff` starting at position `ofs`. Finally, `Marshal.total_size`[21.21] `buff ofs` is the total size, in bytes, of the marshaled value. Both `Marshal.data_size`[21.21] and `Marshal.total_size`[21.21] raise `Failure` if `buff`, `ofs` does not contain a valid header.

To read the byte representation of a marshaled value into a byte sequence, the program needs to read first `Marshal.header_size`[21.21] bytes into the sequence, then determine the length of the remainder of the representation using `Marshal.data_size`[21.21], make sure the sequence is large enough to hold the remaining data, then read it, and finally call `Marshal.from_bytes`[21.21] to unmarshal the value.

`val data_size : bytes -> int -> int`

See `Marshal.header_size`[21.21].

`val total_size : bytes -> int -> int`

See `Marshal.header_size`[21.21].

21.22 Module `MoreLabels` : Extra labeled libraries.

This meta-module provides labelized version of the `Hashtbl`[21.14], `Map`[21.20] and `Set`[21.31] modules.

They only differ by their labels. They are provided to help porting from previous versions of OCaml. The contents of this module are subject to change.

```
module Hashtbl :
  sig
    type ('a, 'b) t = ('a, 'b) Hashtbl.t
    val create : ?random:bool -> int -> ('a, 'b) t
    val clear : ('a, 'b) t -> unit
```

```
val reset : ('a, 'b) t -> unit
val copy : ('a, 'b) t -> ('a, 'b) t
val add : ('a, 'b) t -> key:'a -> data:'b -> unit
val find : ('a, 'b) t -> 'a -> 'b
val find_all : ('a, 'b) t -> 'a -> 'b list
val mem : ('a, 'b) t -> 'a -> bool
val remove : ('a, 'b) t -> 'a -> unit
val replace : ('a, 'b) t -> key:'a -> data:'b -> unit
val iter : f:(key:'a -> data:'b -> unit) -> ('a, 'b) t -> unit
val filter_map_inplace :
  f:(key:'a -> data:'b -> 'b option) -> ('a, 'b) t -> unit
val fold : f:(key:'a -> data:'b -> 'c -> 'c) ->
  ('a, 'b) t -> init:'c -> 'c
val length : ('a, 'b) t -> int
val randomize : unit -> unit
type statistics = Hashtbl.statistics
val stats : ('a, 'b) t -> statistics
module type HashedType =
Hashtbl.HashedType
module type SeededHashedType =
Hashtbl.SeededHashedType
module type S =
  sig
    type key
    type 'a t
    val create : int -> 'a t
    val clear : 'a t -> unit
    val reset : 'a t -> unit
    val copy : 'a t -> 'a t
    val add : 'a t -> key:key -> data:'a -> unit
    val remove : 'a t -> key -> unit
    val find : 'a t -> key -> 'a
    val find_all : 'a t -> key -> 'a list
    val replace : 'a t -> key:key -> data:'a -> unit
    val mem : 'a t -> key -> bool
    val iter : f:(key:key -> data:'a -> unit) ->
      'a t -> unit
```

```
    val filter_map_inplace :
      f:(key:key -> data:'a -> 'a option) ->
      'a t -> unit
    val fold : f:(key:key -> data:'a -> 'b -> 'b) ->
      'a t -> init:'b -> 'b
    val length : 'a t -> int
    val stats : 'a t -> MoreLabels.Hashtbl.statistics
  end
module type SeededS =
  sig
    type key
    type 'a t
    val create : ?random:bool -> int -> 'a t
    val clear : 'a t -> unit
    val reset : 'a t -> unit
    val copy : 'a t -> 'a t
    val add : 'a t ->
      key:key -> data:'a -> unit
    val remove : 'a t -> key -> unit
    val find : 'a t -> key -> 'a
    val find_all : 'a t -> key -> 'a list
    val replace : 'a t ->
      key:key -> data:'a -> unit
    val mem : 'a t -> key -> bool
    val iter : f:(key:key -> data:'a -> unit) ->
      'a t -> unit
    val filter_map_inplace :
      f:(key:key -> data:'a -> 'a option) ->
      'a t -> unit
    val fold : f:(key:key -> data:'a -> 'b -> 'b) ->
      'a t -> init:'b -> 'b
    val length : 'a t -> int
    val stats : 'a t -> MoreLabels.Hashtbl.statistics
  end
module Make :
functor (H : HashedType) -> S  with type key = H.t
module MakeSeeded :
functor (H : SeededHashedType) -> SeededS  with type key = H.t
```

```
    val hash : 'a -> int
    val seeded_hash : int -> 'a -> int
    val hash_param : int -> int -> 'a -> int
    val seeded_hash_param : int -> int -> int -> 'a -> int
  end
module Map :
  sig
    module type OrderedType =
    Map.OrderedType
    module type S =
      sig
        type key
        type +'a t
        val empty : 'a t
        val is_empty : 'a t -> bool
        val mem : key -> 'a t -> bool
        val add : key:key ->
          data:'a -> 'a t -> 'a t
        val singleton : key -> 'a -> 'a t
        val remove : key -> 'a t -> 'a t
        val merge :
          f:(key -> 'a option -> 'b option -> 'c option) ->
          'a t -> 'b t -> 'c t
        val union : f:(key -> 'a -> 'a -> 'a option) ->
          'a t -> 'a t -> 'a t
        val compare : cmp:('a -> 'a -> int) ->
          'a t -> 'a t -> int
        val equal : cmp:('a -> 'a -> bool) ->
          'a t -> 'a t -> bool
        val iter : f:(key:key -> data:'a -> unit) ->
          'a t -> unit
        val fold : f:(key:key -> data:'a -> 'b -> 'b) ->
          'a t -> init:'b -> 'b
        val for_all : f:(key -> 'a -> bool) -> 'a t -> bool
        val exists : f:(key -> 'a -> bool) -> 'a t -> bool
        val filter : f:(key -> 'a -> bool) ->
          'a t -> 'a t
        val partition : f:(key -> 'a -> bool) ->
```

```
          'a t -> 'a t * 'a t
        val cardinal : 'a t -> int
        val bindings : 'a t -> (key * 'a) list
        val min_binding : 'a t -> key * 'a
        val max_binding : 'a t -> key * 'a
        val choose : 'a t -> key * 'a
        val split : key ->
          'a t ->
          'a t * 'a option * 'a t
        val find : key -> 'a t -> 'a
        val map : f:('a -> 'b) -> 'a t -> 'b t
        val mapi : f:(key -> 'a -> 'b) ->
          'a t -> 'b t
      end
    module Make :
    functor (Ord :  OrderedType) -> S  with type key = Ord.t
  end
module Set :
  sig
    module type OrderedType =
    Set.OrderedType
    module type S =
      sig
        type elt
        type t
        val empty : t
        val is_empty : t -> bool
        val mem : elt -> t -> bool
        val add : elt -> t -> t
        val singleton : elt -> t
        val remove : elt -> t -> t
        val union : t -> t -> t
        val inter : t -> t -> t
        val diff : t -> t -> t
        val compare : t -> t -> int
        val equal : t -> t -> bool
```

```
        val subset : t -> t -> bool
        val iter : f:(elt -> unit) -> t -> unit
        val map : f:(elt -> elt) ->
          t -> t
        val fold : f:(elt -> 'a -> 'a) -> t -> init:'a -> 'a
        val for_all : f:(elt -> bool) -> t -> bool
        val exists : f:(elt -> bool) -> t -> bool
        val filter : f:(elt -> bool) -> t -> t
        val partition : f:(elt -> bool) ->
          t -> t * t
        val cardinal : t -> int
        val elements : t -> elt list
        val min_elt : t -> elt
        val max_elt : t -> elt
        val choose : t -> elt
        val split : elt ->
          t -> t * bool * t
        val find : elt -> t -> elt
        val of_list : elt list -> t
      end

    module Make :
    functor (Ord :  OrderedType) -> S  with type elt = Ord.t
  end
```

21.23 Module `Nativeint` : Processor-native integers.

This module provides operations on the type `nativeint` of signed 32-bit integers (on 32-bit platforms) or signed 64-bit integers (on 64-bit platforms). This integer type has exactly the same width as that of a pointer type in the C compiler. All arithmetic operations over `nativeint` are taken modulo 2^{32} or 2^{64} depending on the word size of the architecture.

Performance notice: values of type `nativeint` occupy more memory space than values of type `int`, and arithmetic operations on `nativeint` are generally slower than those on `int`. Use `nativeint` only when the application requires the extra bit of precision over the `int` type.

`val zero : nativeint`

The native integer 0.

`val one : nativeint`

The native integer 1.

`val minus_one : nativeint`

The native integer -1.

`val neg : nativeint -> nativeint`

Unary negation.

`val add : nativeint -> nativeint -> nativeint`

Addition.

`val sub : nativeint -> nativeint -> nativeint`

Subtraction.

`val mul : nativeint -> nativeint -> nativeint`

Multiplication.

`val div : nativeint -> nativeint -> nativeint`

Integer division. Raise `Division_by_zero` if the second argument is zero. This division rounds the real quotient of its arguments towards zero, as specified for `Pervasives.(/)`[20.2].

`val rem : nativeint -> nativeint -> nativeint`

Integer remainder. If `y` is not zero, the result of `Nativeint.rem x y` satisfies the following properties: `Nativeint.zero <= Nativeint.rem x y < Nativeint.abs y` and `x = Nativeint.add (Nativeint.mul (Nativeint.div x y) y) (Nativeint.rem x y)`. If `y = 0`, `Nativeint.rem x y` raises `Division_by_zero`.

`val succ : nativeint -> nativeint`

Successor. `Nativeint.succ x` is `Nativeint.add x Nativeint.one`.

`val pred : nativeint -> nativeint`

Predecessor. `Nativeint.pred x` is `Nativeint.sub x Nativeint.one`.

`val abs : nativeint -> nativeint`

Return the absolute value of its argument.

`val size : int`

The size in bits of a native integer. This is equal to `32` on a 32-bit platform and to `64` on a 64-bit platform.

`val max_int : nativeint`

The greatest representable native integer, either 2^{31} - 1 on a 32-bit platform, or 2^{63} - 1 on a 64-bit platform.

`val min_int : nativeint`

The greatest representable native integer, either -2^{31} on a 32-bit platform, or -2^{63} on a 64-bit platform.

`val logand : nativeint -> nativeint -> nativeint`

Bitwise logical and.

`val logor : nativeint -> nativeint -> nativeint`

Bitwise logical or.

`val logxor : nativeint -> nativeint -> nativeint`

Bitwise logical exclusive or.

`val lognot : nativeint -> nativeint`

Bitwise logical negation

`val shift_left : nativeint -> int -> nativeint`

`Nativeint.shift_left x y` shifts `x` to the left by `y` bits. The result is unspecified if `y < 0` or `y >= bitsize`, where `bitsize` is `32` on a 32-bit platform and `64` on a 64-bit platform.

`val shift_right : nativeint -> int -> nativeint`

`Nativeint.shift_right x y` shifts `x` to the right by `y` bits. This is an arithmetic shift: the sign bit of `x` is replicated and inserted in the vacated bits. The result is unspecified if `y < 0` or `y >= bitsize`.

`val shift_right_logical : nativeint -> int -> nativeint`

`Nativeint.shift_right_logical x y` shifts `x` to the right by `y` bits. This is a logical shift: zeroes are inserted in the vacated bits regardless of the sign of `x`. The result is unspecified if `y < 0` or `y >= bitsize`.

`val of_int : int -> nativeint`

Convert the given integer (type `int`) to a native integer (type `nativeint`).

`val to_int : nativeint -> int`

Convert the given native integer (type `nativeint`) to an integer (type `int`). The high-order bit is lost during the conversion.

`val of_float : float -> nativeint`

Convert the given floating-point number to a native integer, discarding the fractional part (truncate towards 0). The result of the conversion is undefined if, after truncation, the number is outside the range [`Nativeint.min_int`[21.23], `Nativeint.max_int`[21.23]].

`val to_float : nativeint -> float`

Convert the given native integer to a floating-point number.

`val of_int32 : int32 -> nativeint`

Convert the given 32-bit integer (type `int32`) to a native integer.

`val to_int32 : nativeint -> int32`

Convert the given native integer to a 32-bit integer (type `int32`). On 64-bit platforms, the 64-bit native integer is taken modulo 2^{32}, i.e. the top 32 bits are lost. On 32-bit platforms, the conversion is exact.

`val of_string : string -> nativeint`

Convert the given string to a native integer. The string is read in decimal (by default) or in hexadecimal, octal or binary if the string begins with `0x`, `0o` or `0b` respectively. Raise `Failure "int_of_string"` if the given string is not a valid representation of an integer, or if the integer represented exceeds the range of integers representable in type `nativeint`.

`val to_string : nativeint -> string`

Return the string representation of its argument, in decimal.

`type t = nativeint`

An alias for the type of native integers.

`val compare : t -> t -> int`

The comparison function for native integers, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `Nativeint` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

`val equal : t -> t -> bool`

The equal function for natives ints.

Since: 4.03.0

21.24 Module `Oo` : Operations on objects

`val copy : (< .. > as 'a) -> 'a`

`Oo.copy o` returns a copy of object `o`, that is a fresh object with the same methods and instance variables as `o`.

`val id : < .. > -> int`

Return an integer identifying this object, unique for the current execution of the program. The generic comparison and hashing functions are based on this integer. When an object is obtained by unmarshaling, the id is refreshed, and thus different from the original object. As a consequence, the internal invariants of data structures such as hash table or sets containing objects are broken after unmarshaling the data structures.

21.25 Module Parsing : The run-time library for parsers generated by ocamlyacc.

```
val symbol_start : unit -> int
```

symbol_start and Parsing.symbol_end[21.25] are to be called in the action part of a grammar rule only. They return the offset of the string that matches the left-hand side of the rule: symbol_start() returns the offset of the first character; symbol_end() returns the offset after the last character. The first character in a file is at offset 0.

```
val symbol_end : unit -> int
```

See Parsing.symbol_start[21.25].

```
val rhs_start : int -> int
```

Same as Parsing.symbol_start[21.25] and Parsing.symbol_end[21.25], but return the offset of the string matching the nth item on the right-hand side of the rule, where n is the integer parameter to rhs_start and rhs_end. n is 1 for the leftmost item.

```
val rhs_end : int -> int
```

See Parsing.rhs_start[21.25].

```
val symbol_start_pos : unit -> Lexing.position
```

Same as symbol_start, but return a position instead of an offset.

```
val symbol_end_pos : unit -> Lexing.position
```

Same as symbol_end, but return a position instead of an offset.

```
val rhs_start_pos : int -> Lexing.position
```

Same as rhs_start, but return a position instead of an offset.

```
val rhs_end_pos : int -> Lexing.position
```

Same as rhs_end, but return a position instead of an offset.

```
val clear_parser : unit -> unit
```

Empty the parser stack. Call it just after a parsing function has returned, to remove all pointers from the parser stack to structures that were built by semantic actions during parsing. This is optional, but lowers the memory requirements of the programs.

```
exception Parse_error
```

Raised when a parser encounters a syntax error. Can also be raised from the action part of a grammar rule, to initiate error recovery.

```
val set_trace : bool -> bool
```

Control debugging support for `ocamlyacc`-generated parsers. After `Parsing.set_trace true`, the pushdown automaton that executes the parsers prints a trace of its actions (reading a token, shifting a state, reducing by a rule) on standard output. `Parsing.set_trace false` turns this debugging trace off. The boolean returned is the previous state of the trace flag.

Since: 3.11.0

21.26 Module `Printexc` : Facilities for printing exceptions and inspecting current call stack.

`val to_string : exn -> string`

`Printexc.to_string e` returns a string representation of the exception `e`.

`val print : ('a -> 'b) -> 'a -> 'b`

`Printexc.print fn x` applies `fn` to `x` and returns the result. If the evaluation of `fn x` raises any exception, the name of the exception is printed on standard error output, and the exception is raised again. The typical use is to catch and report exceptions that escape a function application.

`val catch : ('a -> 'b) -> 'a -> 'b`

`Printexc.catch fn x` is similar to `Printexc.print`[21.26], but aborts the program with exit code 2 after printing the uncaught exception. This function is deprecated: the runtime system is now able to print uncaught exceptions as precisely as `Printexc.catch` does. Moreover, calling `Printexc.catch` makes it harder to track the location of the exception using the debugger or the stack backtrace facility. So, do not use `Printexc.catch` in new code.

`val print_backtrace : Pervasives.out_channel -> unit`

`Printexc.print_backtrace oc` prints an exception backtrace on the output channel `oc`. The backtrace lists the program locations where the most-recently raised exception was raised and where it was propagated through function calls.

Since: 3.11.0

`val get_backtrace : unit -> string`

`Printexc.get_backtrace ()` returns a string containing the same exception backtrace that `Printexc.print_backtrace` would print.

Since: 3.11.0

`val record_backtrace : bool -> unit`

`Printexc.record_backtrace b` turns recording of exception backtraces on (if `b = true`) or off (if `b = false`). Initially, backtraces are not recorded, unless the `b` flag is given to the program through the `OCAMLRUNPARAM` variable.

Since: 3.11.0

`val backtrace_status : unit -> bool`

`Printexc.backtrace_status()` returns `true` if exception backtraces are currently recorded, `false` if not.

Since: 3.11.0

`val register_printer : (exn -> string option) -> unit`

`Printexc.register_printer fn` registers `fn` as an exception printer. The printer should return `None` or raise an exception if it does not know how to convert the passed exception, and `Some s` with `s` the resulting string if it can convert the passed exception. Exceptions raised by the printer are ignored.

When converting an exception into a string, the printers will be invoked in the reverse order of their registrations, until a printer returns a `Some s` value (if no such printer exists, the runtime will use a generic printer).

When using this mechanism, one should be aware that an exception backtrace is attached to the thread that saw it raised, rather than to the exception itself. Practically, it means that the code related to `fn` should not use the backtrace if it has itself raised an exception before.

Since: 3.11.2

Raw backtraces

`type raw_backtrace`

The abstract type `raw_backtrace` stores a backtrace in a low-level format, instead of directly exposing them as string as the `get_backtrace()` function does.

This allows delaying the formatting of backtraces to when they are actually printed, which may be useful if you record more backtraces than you print.

Raw backtraces cannot be marshalled. If you need marshalling, you should use the array returned by the `backtrace_slots` function of the next section.

Since: 4.01.0

`val get_raw_backtrace : unit -> raw_backtrace`

`Printexc.get_raw_backtrace ()` returns the same exception backtrace that `Printexc.print_backtrace` would print, but in a raw format.

Since: 4.01.0

`val print_raw_backtrace : Pervasives.out_channel -> raw_backtrace -> unit`

Print a raw backtrace in the same format `Printexc.print_backtrace` uses.

Since: 4.01.0

`val raw_backtrace_to_string : raw_backtrace -> string`

Return a string from a raw backtrace, in the same format `Printexc.get_backtrace` uses.

Since: 4.01.0

Current call stack

`val get_callstack : int -> raw_backtrace`

`Printexc.get_callstack n` returns a description of the top of the call stack on the current program point (for the current thread), with at most `n` entries. (Note: this function is not related to exceptions at all, despite being part of the `Printexc` module.)

Since: 4.01.0

Uncaught exceptions

`val set_uncaught_exception_handler : (exn -> raw_backtrace -> unit) -> unit`

`Printexc.set_uncaught_exception_handler fn` registers `fn` as the handler for uncaught exceptions. The default handler prints the exception and backtrace on standard error output.

Note that when `fn` is called all the functions registered with `Pervasives.at_exit`[20.2] have already been called. Because of this you must make sure any output channel `fn` writes on is flushed.

Also note that exceptions raised by user code in the interactive toplevel are not passed to this function as they are caught by the toplevel itself.

If `fn` raises an exception, both the exceptions passed to `fn` and raised by `fn` will be printed with their respective backtrace.

Since: 4.02.0

Manipulation of backtrace information

These functions are used to traverse the slots of a raw backtrace and extract information from them in a programmer-friendly format.

`type backtrace_slot`

The abstract type `backtrace_slot` represents a single slot of a backtrace.

Since: 4.02

`val backtrace_slots : raw_backtrace -> backtrace_slot array option`

Returns the slots of a raw backtrace, or `None` if none of them contain useful information.

In the return array, the slot at index `0` corresponds to the most recent function call, raise, or primitive `get_backtrace` call in the trace.

Some possible reasons for returning `None` are as follow:

- none of the slots in the trace come from modules compiled with debug information (`-g`)
- the program is a bytecode program that has not been linked with debug information enabled (`ocamlc -g`)

Since: 4.02.0

```
type location =
{  filename : string ;
  line_number : int ;
  start_char : int ;
  end_char : int ;
}
```

The type of location information found in backtraces. `start_char` and `end_char` are positions relative to the beginning of the line.

Since: 4.02

```
module Slot :
  sig
```

```
type t = Printexc.backtrace_slot
```

```
val is_raise : t -> bool
```

`is_raise slot` is `true` when `slot` refers to a raising point in the code, and `false` when it comes from a simple function call.

Since: 4.02

```
val is_inline : t -> bool
```

`is_inline slot` is `true` when `slot` refers to a call that got inlined by the compiler, and `false` when it comes from any other context.

Since: 4.04.0

```
val location : t -> Printexc.location option
```

`location slot` returns the location information of the slot, if available, and `None` otherwise.

Some possible reasons for failing to return a location are as follow:

- the slot corresponds to a compiler-inserted raise
- the slot corresponds to a part of the program that has not been compiled with debug information (`-g`)

Since: 4.02

```
val format : int -> t -> string option
```

`format pos slot` returns the string representation of `slot` as `raw_backtrace_to_string` would format it, assuming it is the `pos`-th element of the backtrace: the `0`-th element is pretty-printed differently than the others.

Whole-backtrace printing functions also skip some uninformative slots; in that case, `format pos slot` returns `None`.

Since: 4.02

```
end
```

Raw backtrace slots

```
type raw_backtrace_slot
```

This type allows direct access to raw backtrace slots, without any conversion in an OCaml-usable data-structure. Being process-specific, they must absolutely not be marshalled, and are unsafe to use for this reason (marshalling them may not fail, but un-marshalling and using the result will result in undefined behavior).

Elements of this type can still be compared and hashed: when two elements are equal, then they represent the same source location (the converse is not necessarily true in presence of inlining, for example).

Since: 4.02.0

```
val raw_backtrace_length : raw_backtrace -> int
```

`raw_backtrace_length bckt` returns the number of slots in the backtrace `bckt`.

Since: 4.02

```
val get_raw_backtrace_slot : raw_backtrace -> int -> raw_backtrace_slot
```

`get_slot bckt pos` returns the slot in position `pos` in the backtrace `bckt`.

Since: 4.02

```
val convert_raw_backtrace_slot : raw_backtrace_slot -> backtrace_slot
```

Extracts the user-friendly `backtrace_slot` from a low-level `raw_backtrace_slot`.

Since: 4.02

```
val get_raw_backtrace_next_slot :
  raw_backtrace_slot -> raw_backtrace_slot option
```

`get_raw_backtrace_next_slot slot` returns the next slot inlined, if any.

Since: 4.04.0

Exception slots

```
val exn_slot_id : exn -> int
```

`Printexc.exn_slot_id` returns an integer which uniquely identifies the constructor used to create the exception value `exn` (in the current runtime).

Since: 4.02.0

```
val exn_slot_name : exn -> string
```

`Printexc.exn_slot_id exn` returns the internal name of the constructor used to create the exception value `exn`.

Since: 4.02.0

21.27 Module `Printf` : Formatted output functions.

```
val fprintf :
  Pervasives.out_channel ->
  ('a, Pervasives.out_channel, unit) Pervasives.format -> 'a
```

`fprintf outchan format arg1 ... argN` formats the arguments `arg1` to `argN` according to the format string `format`, and outputs the resulting string on the channel `outchan`.

The format string is a character string which contains two types of objects: plain characters, which are simply copied to the output channel, and conversion specifications, each of which causes conversion and printing of arguments.

Conversion specifications have the following form:

`% [flags] [width] [.precision] type`

In short, a conversion specification consists in the `%` character, followed by optional modifiers and a type which is made of one or two characters.

The types and their meanings are:

- `d`, `i`: convert an integer argument to signed decimal.
- `u`, `n`, `l`, `L`, or `N`: convert an integer argument to unsigned decimal. Warning: `n`, `l`, `L`, and `N` are used for `scanf`, and should not be used for `printf`.
- `x`: convert an integer argument to unsigned hexadecimal, using lowercase letters.
- `X`: convert an integer argument to unsigned hexadecimal, using uppercase letters.
- `o`: convert an integer argument to unsigned octal.
- `s`: insert a string argument.
- `S`: convert a string argument to OCaml syntax (double quotes, escapes).
- `c`: insert a character argument.
- `C`: convert a character argument to OCaml syntax (single quotes, escapes).

- `f`: convert a floating-point argument to decimal notation, in the style `dddd.ddd`.
- `F`: convert a floating-point argument to OCaml syntax (`dddd.` or `dddd.ddd` or `d.ddd e+-dd`).
- `e` or `E`: convert a floating-point argument to decimal notation, in the style `d.ddd e+-dd` (mantissa and exponent).
- `g` or `G`: convert a floating-point argument to decimal notation, in style `f` or `e`, `E` (whichever is more compact).
- `h` or `H`: convert a floating-point argument to hexadecimal notation, in the style `0xh.hhhh e+-dd` (hexadecimal mantissa, exponent in decimal and denotes a power of 2).
- `B`: convert a boolean argument to the string `true` or `false`
- `b`: convert a boolean argument (deprecated; do not use in new programs).
- `ld`, `li`, `lu`, `lx`, `lX`, `lo`: convert an `int32` argument to the format specified by the second letter (decimal, hexadecimal, etc).
- `nd`, `ni`, `nu`, `nx`, `nX`, `no`: convert a `nativeint` argument to the format specified by the second letter.
- `Ld`, `Li`, `Lu`, `Lx`, `LX`, `Lo`: convert an `int64` argument to the format specified by the second letter.
- `a`: user-defined printer. Take two arguments and apply the first one to `outchan` (the current output channel) and to the second argument. The first argument must therefore have type `out_channel -> 'b -> unit` and the second `'b`. The output produced by the function is inserted in the output of `fprintf` at the current point.
- `t`: same as `%a`, but take only one argument (with type `out_channel -> unit`) and apply it to `outchan`.
- `{ fmt %}`: convert a format string argument to its type digest. The argument must have the same type as the internal format string `fmt`.
- `( fmt %)`: format string substitution. Take a format string argument and substitute it to the internal format string `fmt` to print following arguments. The argument must have the same type as the internal format string `fmt`.
- `!`: take no argument and flush the output.
- `%`: take no argument and output one `%` character.
- `@`: take no argument and output one `@` character.
- `,`: take no argument and output nothing: a no-op delimiter for conversion specifications.

The optional `flags` are:

- `-`: left-justify the output (default is right justification).
- `0`: for numerical conversions, pad with zeroes instead of spaces.
- `+`: for signed numerical conversions, prefix number with a `+` sign if positive.

- space: for signed numerical conversions, prefix number with a space if positive.
- `#`: request an alternate formatting style for the hexadecimal and octal integer types (`x`, `X`, `o`, `lx`, `lX`, `lo`, `Lx`, `LX`, `Lo`).

The optional `width` is an integer indicating the minimal width of the result. For instance, `%6d` prints an integer, prefixing it with spaces to fill at least 6 characters.

The optional `precision` is a dot `.` followed by an integer indicating how many digits follow the decimal point in the `%f`, `%e`, and `%E` conversions. For instance, `%.4f` prints a `float` with 4 fractional digits.

The integer in a `width` or `precision` can also be specified as `*`, in which case an extra integer argument is taken to specify the corresponding `width` or `precision`. This integer argument precedes immediately the argument to print. For instance, `%.*f` prints a `float` with as many fractional digits as the value of the argument given before the float.

```
val printf : ('a, Pervasives.out_channel, unit) Pervasives.format -> 'a
```

Same as `Printf.fprintf`[21.27], but output on `stdout`.

```
val eprintf : ('a, Pervasives.out_channel, unit) Pervasives.format -> 'a
```

Same as `Printf.fprintf`[21.27], but output on `stderr`.

```
val sprintf : ('a, unit, string) Pervasives.format -> 'a
```

Same as `Printf.fprintf`[21.27], but instead of printing on an output channel, return a string containing the result of formatting the arguments.

```
val bprintf : Buffer.t -> ('a, Buffer.t, unit) Pervasives.format -> 'a
```

Same as `Printf.fprintf`[21.27], but instead of printing on an output channel, append the formatted arguments to the given extensible buffer (see module `Buffer`[21.3]).

```
val ifprintf : 'b -> ('a, 'b, 'c, unit) Pervasives.format4 -> 'a
```

Same as `Printf.fprintf`[21.27], but does not print anything. Useful to ignore some material when conditionally printing.

Since: 3.10.0

Formatted output functions with continuations.

```
val kfprintf :
  (Pervasives.out_channel -> 'd) ->
  Pervasives.out_channel ->
  ('a, Pervasives.out_channel, unit, 'd) Pervasives.format4 -> 'a
```

Same as `fprintf`, but instead of returning immediately, passes the out channel to its first argument at the end of printing.

Since: 3.09.0

```
val ikfprintf : ('b -> 'd) -> 'b -> ('a, 'b, 'c, 'd) Pervasives.format4 -> 'a
```

Same as `kfprintf` above, but does not print anything. Useful to ignore some material when conditionally printing.

Since: 4.0

```
val ksprintf :
  (string -> 'd) -> ('a, unit, string, 'd) Pervasives.format4 -> 'a
```

Same as `sprintf` above, but instead of returning the string, passes it to the first argument.

Since: 3.09.0

```
val kbprintf :
  (Buffer.t -> 'd) ->
  Buffer.t -> ('a, Buffer.t, unit, 'd) Pervasives.format4 -> 'a
```

Same as `bprintf`, but instead of returning immediately, passes the buffer to its first argument at the end of printing.

Since: 3.10.0

Deprecated

```
val kprintf :
  (string -> 'b) -> ('a, unit, string, 'b) Pervasives.format4 -> 'a
```

A deprecated synonym for `ksprintf`.

21.28 Module `Queue` : First-in first-out queues.

This module implements queues (FIFOs), with in-place modification.

Warning This module is not thread-safe: each `Queue.t`[21.28] value must be protected from concurrent access (e.g. with a `Mutex.t`). Failure to do so can lead to a crash.

```
type 'a t
```

The type of queues containing elements of type `'a`.

```
exception Empty
```

Raised when `Queue.take`[21.28] or `Queue.peek`[21.28] is applied to an empty queue.

```
val create : unit -> 'a t
```

Return a new queue, initially empty.

```
val add : 'a -> 'a t -> unit
```

`add x q` adds the element `x` at the end of the queue `q`.

```
val push : 'a -> 'a t -> unit
```

`push` is a synonym for `add`.

```
val take : 'a t -> 'a
```

`take q` removes and returns the first element in queue `q`, or raises `Empty` if the queue is empty.

`val pop : 'a t -> 'a`

`pop` is a synonym for `take`.

`val peek : 'a t -> 'a`

`peek q` returns the first element in queue `q`, without removing it from the queue, or raises `Empty` if the queue is empty.

`val top : 'a t -> 'a`

`top` is a synonym for `peek`.

`val clear : 'a t -> unit`

Discard all elements from a queue.

`val copy : 'a t -> 'a t`

Return a copy of the given queue.

`val is_empty : 'a t -> bool`

Return `true` if the given queue is empty, `false` otherwise.

`val length : 'a t -> int`

Return the number of elements in a queue.

`val iter : ('a -> unit) -> 'a t -> unit`

`iter f q` applies `f` in turn to all elements of `q`, from the least recently entered to the most recently entered. The queue itself is unchanged.

`val fold : ('b -> 'a -> 'b) -> 'b -> 'a t -> 'b`

`fold f accu q` is equivalent to `List.fold_left f accu l`, where `l` is the list of `q`'s elements. The queue remains unchanged.

`val transfer : 'a t -> 'a t -> unit`

`transfer q1 q2` adds all of `q1`'s elements at the end of the queue `q2`, then clears `q1`. It is equivalent to the sequence `iter (fun x -> add x q2) q1; clear q1`, but runs in constant time.

21.29 Module `Random` : Pseudo-random number generators (PRNG).

Basic functions

`val init : int -> unit`

Initialize the generator, using the argument as a seed. The same seed will always yield the same sequence of numbers.

`val full_init : int array -> unit`

Same as `Random.init`[21.29] but takes more data as seed.

`val self_init : unit -> unit`

Initialize the generator with a random seed chosen in a system-dependent way. If `/dev/urandom` is available on the host machine, it is used to provide a highly random initial seed. Otherwise, a less random seed is computed from system parameters (current time, process IDs).

`val bits : unit -> int`

Return 30 random bits in a nonnegative integer.

Before 3.12.0 used a different algorithm (affects all the following functions)

`val int : int -> int`

`Random.int bound` returns a random integer between 0 (inclusive) and `bound` (exclusive). `bound` must be greater than 0 and less than 2^{30}.

`val int32 : Int32.t -> Int32.t`

`Random.int32 bound` returns a random integer between 0 (inclusive) and `bound` (exclusive). `bound` must be greater than 0.

`val nativeint : Nativeint.t -> Nativeint.t`

`Random.nativeint bound` returns a random integer between 0 (inclusive) and `bound` (exclusive). `bound` must be greater than 0.

`val int64 : Int64.t -> Int64.t`

`Random.int64 bound` returns a random integer between 0 (inclusive) and `bound` (exclusive). `bound` must be greater than 0.

`val float : float -> float`

`Random.float bound` returns a random floating-point number between 0 and `bound` (inclusive). If `bound` is negative, the result is negative or zero. If `bound` is 0, the result is 0.

`val bool : unit -> bool`

`Random.bool ()` returns `true` or `false` with probability 0.5 each.

Advanced functions

The functions from module `State` manipulate the current state of the random generator explicitly. This allows using one or several deterministic PRNGs, even in a multi-threaded program, without interference from other parts of the program.

```
module State :
  sig
```

`type t`

The type of PRNG states.

`val make : int array -> t`

Create a new state and initialize it with the given seed.

`val make_self_init : unit -> t`

Create a new state and initialize it with a system-dependent low-entropy seed.

`val copy : t -> t`

Return a copy of the given state.

```
val bits : t -> int
val int : t -> int -> int
val int32 : t -> Int32.t -> Int32.t
val nativeint : t -> Nativeint.t -> Nativeint.t
val int64 : t -> Int64.t -> Int64.t
val float : t -> float -> float
val bool : t -> bool
```

These functions are the same as the basic functions, except that they use (and update) the given PRNG state instead of the default one.

```
  end
```

`val get_state : unit -> State.t`

Return the current state of the generator used by the basic functions.

`val set_state : State.t -> unit`

Set the state of the generator used by the basic functions.

21.30 Module `Scanf` : Formatted input functions.

Introduction

Functional input with format strings

The module `Scanf` provides formatted input functions or *scanners*.

The formatted input functions can read from any kind of input, including strings, files, or anything that can return characters. The more general source of characters is named a *formatted input channel* (or *scanning buffer*) and has type `Scanf.Scanning.in_channel`[21.30]. The more general formatted input function reads from any scanning buffer and is named `bscanf`.

Generally speaking, the formatted input functions have 3 arguments:

- the first argument is a source of characters for the input,
- the second argument is a format string that specifies the values to read,
- the third argument is a *receiver function* that is applied to the values read.

Hence, a typical call to the formatted input function `Scanf.bscanf`[21.30] is `bscanf ic fmt f`, where:

- `ic` is a source of characters (typically a *formatted input channel* with type `Scanf.Scanning.in_channel`[21.30]),
- `fmt` is a format string (the same format strings as those used to print material with module `Printf`[21.27] or `Format`[21.11]),
- `f` is a function that has as many arguments as the number of values to read in the input according to `fmt`.

A simple example

As suggested above, the expression `bscanf ic "%d" f` reads a decimal integer `n` from the source of characters `ic` and returns `f n`.

For instance,

- if we use `stdin` as the source of characters (`Scanf.Scanning.stdin`[21.30] is the predefined formatted input channel that reads from standard input),
- if we define the receiver `f` as `let f x = x + 1`,

then `bscanf Scanning.stdin "%d" f` reads an integer `n` from the standard input and returns `f n` (that is `n + 1`). Thus, if we evaluate `bscanf stdin "%d" f`, and then enter `41` at the keyboard, the result we get is `42`.

Formatted input as a functional feature

The OCaml scanning facility is reminiscent of the corresponding C feature. However, it is also largely different, simpler, and yet more powerful: the formatted input functions are higher-order functionals and the parameter passing mechanism is just the regular function application not the variable assignment based mechanism which is typical for formatted input in imperative languages; the OCaml format strings also feature useful additions to easily define complex tokens; as expected within a functional programming language, the formatted input functions also support polymorphism, in particular arbitrary interaction with polymorphic user-defined scanners. Furthermore, the OCaml formatted input facility is fully type-checked at compile time.

Formatted input channel

```
module Scanning :
  sig
```

```
    type in_channel
```

The notion of input channel for the `Scanf` module: those channels provide all the machinery necessary to read from any source of characters, including a `!Pervasives.in_channel` value. A `Scanf.Scanning.in_channel` value is also called a *formatted input channel* or equivalently a *scanning buffer*. The type `Scanning.scanbuf` below is an alias for `Scanning.in_channel`.

Since: 3.12.0

```
    type scanbuf = in_channel
```

The type of scanning buffers. A scanning buffer is the source from which a formatted input function gets characters. The scanning buffer holds the current state of the scan, plus a function to get the next char from the input, and a token buffer to store the string matched so far.

Note: a scanning action may often require to examine one character in advance; when this 'lookahead' character does not belong to the token read, it is stored back in the scanning buffer and becomes the next character yet to be read.

```
    val stdin : in_channel
```

The standard input notion for the `Scanf` module. `Scanning.stdin` is the `Scanning.in_channel` formatted input channel attached to `!Pervasives.stdin`.

Note: in the interactive system, when input is read from `!Pervasives.stdin`, the newline character that triggers evaluation is part of the input; thus, the scanning specifications must properly skip this additional newline character (for instance, simply add a `'\n'` as the last character of the format string).

Since: 3.12.0

```
    type file_name = string
```

A convenient alias to designate a file name.

Since: 4.00.0

`val open_in : file_name -> in_channel`

`Scanning.open_in fname` returns a `!Scanning.in_channel` formatted input channel for bufferized reading in text mode from file `fname`.

Note: `open_in` returns a formatted input channel that efficiently reads characters in large chunks; in contrast, `from_channel` below returns formatted input channels that must read one character at a time, leading to a much slower scanning rate.

Since: 3.12.0

`val open_in_bin : file_name -> in_channel`

`Scanning.open_in_bin fname` returns a `!Scanning.in_channel` formatted input channel for bufferized reading in binary mode from file `fname`.

Since: 3.12.0

`val close_in : in_channel -> unit`

Closes the `!Pervasives.in_channel` associated with the given `!Scanning.in_channel` formatted input channel.

Since: 3.12.0

`val from_file : file_name -> in_channel`

An alias for `!Scanning.open_in` above.

`val from_file_bin : string -> in_channel`

An alias for `!Scanning.open_in_bin` above.

`val from_string : string -> in_channel`

`Scanning.from_string s` returns a `!Scanning.in_channel` formatted input channel which reads from the given string. Reading starts from the first character in the string. The end-of-input condition is set when the end of the string is reached.

`val from_function : (unit -> char) -> in_channel`

`Scanning.from_function f` returns a `!Scanning.in_channel` formatted input channel with the given function as its reading method.

When scanning needs one more character, the given function is called.

When the function has no more character to provide, it *must* signal an end-of-input condition by raising the exception `End_of_file`.

`val from_channel : Pervasives.in_channel -> in_channel`

`Scanning.from_channel ic` returns a `!Scanning.in_channel` formatted input channel which reads from the regular `!Pervasives.in_channel` input channel `ic` argument. Reading starts at current reading position of `ic`.

```
val end_of_input : in_channel -> bool
```

Scanning.end_of_input ic tests the end-of-input condition of the given !Scanning.in_channel formatted input channel.

```
val beginning_of_input : in_channel -> bool
```

Scanning.beginning_of_input ic tests the beginning of input condition of the given !Scanning.in_channel formatted input channel.

```
val name_of_input : in_channel -> string
```

Scanning.name_of_input ic returns the name of the character source for the given !Scanning.in_channel formatted input channel.

Since: 3.09.0

```
val stdib : in_channel
```

A deprecated alias for !Scanning.stdin, the scanning buffer reading from !Pervasives.stdin.

```
end
```

Type of formatted input functions

```
type ('a, 'b, 'c, 'd) scanner = ('a, Scanning.in_channel, 'b, 'c, 'a -> 'd, 'd) Pervasives.form
  'c
```

The type of formatted input scanners: ('a, 'b, 'c, 'd) scanner is the type of a formatted input function that reads from some formatted input channel according to some format string; more precisely, if scan is some formatted input function, then scan ic fmt f applies f to all the arguments specified by format string fmt, when scan has read those arguments from the !Scanning.in_channel formatted input channel ic.

For instance, the !Scanf.scanf function below has type ('a, 'b, 'c, 'd) scanner, since it is a formatted input function that reads from !Scanning.stdin: scanf fmt f applies f to the arguments specified by fmt, reading those arguments from !Pervasives.stdin as expected.

If the format fmt has some %r indications, the corresponding formatted input functions must be provided *before* receiver function f. For instance, if read_elem is an input function for values of type t, then bscanf ic "%r;" read_elem f reads a value v of type t followed by a ';' character, and returns f v.

Since: 3.10.0

```
exception Scan_failure of string
```

When the input can not be read according to the format string specification, formatted input functions typically raise exception Scan_failure.

The general formatted input function

```
val bscanf : Scanning.in_channel -> ('a, 'b, 'c, 'd) scanner
```

`bscanf ic fmt r1 ... rN f` reads characters from the `!Scanning.in_channel` formatted input channel `ic` and converts them to values according to format string `fmt`. As a final step, receiver function `f` is applied to the values read and gives the result of the `bscanf` call.

For instance, if `f` is the function `fun s i -> i + 1`, then `Scanf.sscanf "x= 1" "%s = %i" f` returns `2`.

Arguments `r1` to `rN` are user-defined input functions that read the argument corresponding to the `%r` conversions specified in the format string.

Format string description

The format string is a character string which contains three types of objects:

- plain characters, which are simply matched with the characters of the input (with a special case for space and line feed, see [21.30]),
- conversion specifications, each of which causes reading and conversion of one argument for the function `f` (see [21.30]),
- scanning indications to specify boundaries of tokens (see scanning [21.30]).

The space character in format strings

As mentioned above, a plain character in the format string is just matched with the next character of the input; however, two characters are special exceptions to this rule: the space character (`' '` or ASCII code 32) and the line feed character (`'\n'` or ASCII code 10). A space does not match a single space character, but any amount of 'whitespace' in the input. More precisely, a space inside the format string matches *any number* of tab, space, line feed and carriage return characters. Similarly, a line feed character in the format string matches either a single line feed or a carriage return followed by a line feed.

Matching *any* amount of whitespace, a space in the format string also matches no amount of whitespace at all; hence, the call `bscanf ib "Price = %d $" (fun p -> p)` succeeds and returns `1` when reading an input with various whitespace in it, such as `Price = 1 $`, `Price = 1 $`, or even `Price=1$`.

Conversion specifications in format strings

Conversion specifications consist in the `%` character, followed by an optional flag, an optional field width, and followed by one or two conversion characters.

The conversion characters and their meanings are:

- `d`: reads an optionally signed decimal integer (`0-9+`).
- `i`: reads an optionally signed integer (usual input conventions for decimal (`0-9+`), hexadecimal (`0x[0-9a-f]+` and `0X[0-9A-F]+`), octal (`0o[0-7]+`), and binary (`0b[0-1]+`) notations are understood).

- `u`: reads an unsigned decimal integer.
- `x` or `X`: reads an unsigned hexadecimal integer (`[0-9a-fA-F]+`).
- `o`: reads an unsigned octal integer (`[0-7]+`).
- `s`: reads a string argument that spreads as much as possible, until the following bounding condition holds:
  - a whitespace has been found (see [21.30]),
  - a scanning indication (see scanning [21.30]) has been encountered,
  - the end-of-input has been reached.

  Hence, this conversion always succeeds: it returns an empty string if the bounding condition holds when the scan begins.
- `S`: reads a delimited string argument (delimiters and special escaped characters follow the lexical conventions of OCaml).
- `c`: reads a single character. To test the current input character without reading it, specify a null field width, i.e. use specification `%0c`. Raise `Invalid_argument`, if the field width specification is greater than 1.
- `C`: reads a single delimited character (delimiters and special escaped characters follow the lexical conventions of OCaml).
- `f`, `e`, `E`, `g`, `G`: reads an optionally signed floating-point number in decimal notation, in the style `dddd.ddd e/E+-dd`.
- `h`, `H`: reads an optionally signed floating-point number in hexadecimal notation.
- `F`: reads a floating point number according to the lexical conventions of OCaml (hence the decimal point is mandatory if the exponent part is not mentioned).
- `B`: reads a boolean argument (`true` or `false`).
- `b`: reads a boolean argument (for backward compatibility; do not use in new programs).
- `ld`, `li`, `lu`, `lx`, `lX`, `lo`: reads an `int32` argument to the format specified by the second letter for regular integers.
- `nd`, `ni`, `nu`, `nx`, `nX`, `no`: reads a `nativeint` argument to the format specified by the second letter for regular integers.
- `Ld`, `Li`, `Lu`, `Lx`, `LX`, `Lo`: reads an `int64` argument to the format specified by the second letter for regular integers.
- `[ range ]`: reads characters that matches one of the characters mentioned in the range of characters `range` (or not mentioned in it, if the range starts with `^`). Reads a `string` that can be empty, if the next input character does not match the range. The set of characters from `c1` to `c2` (inclusively) is denoted by `c1-c2`. Hence, `%[0-9]` returns a string representing a

decimal number or an empty string if no decimal digit is found; similarly, `%[0-9a-f]` returns a string of hexadecimal digits. If a closing bracket appears in a range, it must occur as the first character of the range (or just after the `^` in case of range negation); hence `[]]` matches a `]` character and `[^]]` matches any character that is not `]`. Use `%%` and `%@` to include a `%` or a `@` in a range.

- `r`: user-defined reader. Takes the next `ri` formatted input function and applies it to the scanning buffer `ib` to read the next argument. The input function `ri` must therefore have type `Scanning.in_channel -> 'a` and the argument read has type `'a`.
- `{ fmt %}`: reads a format string argument. The format string read must have the same type as the format string specification `fmt`. For instance, `"%{ %i %}"` reads any format string that can read a value of type `int`; hence, if `s` is the string `"fmt:\"number is %u\""`, then `Scanf.sscanf s "fmt:  %{%i%}"` succeeds and returns the format string `"number is %u"`.
- `( fmt %)`: scanning sub-format substitution. Reads a format string `rf` in the input, then goes on scanning with `rf` instead of scanning with `fmt`. The format string `rf` must have the same type as the format string specification `fmt` that it replaces. For instance, `"%( %i %)"` reads any format string that can read a value of type `int`. The conversion returns the format string read `rf`, and then a value read using `rf`. Hence, if `s` is the string `"\"%4d\"1234.00"`, then `Scanf.sscanf s "%(%i%)" (fun fmt i -> fmt, i)` evaluates to `("%4d", 1234)`. This behaviour is not mere format substitution, since the conversion returns the format string read as additional argument. If you need pure format substitution, use special flag `_` to discard the extraneous argument: conversion `%_( fmt %)` reads a format string `rf` and then behaves the same as format string `rf`. Hence, if `s` is the string `"\"%4d\"1234.00"`, then `Scanf.sscanf s "%_(%i%)"` is simply equivalent to `Scanf.sscanf "1234.00" "%4d"`.
- `l`: returns the number of lines read so far.
- `n`: returns the number of characters read so far.
- `N` or `L`: returns the number of tokens read so far.
- `!`: matches the end of input condition.
- `%`: matches one `%` character in the input.
- `@`: matches one `@` character in the input.
- `,`: does nothing.

Following the `%` character that introduces a conversion, there may be the special flag `_`: the conversion that follows occurs as usual, but the resulting value is discarded. For instance, if `f` is the function `fun i -> i + 1`, and `s` is the string `"x = 1"`, then `Scanf.sscanf s "%_s = %i" f` returns `2`.

The field width is composed of an optional integer literal indicating the maximal width of the token to read. For instance, `%6d` reads an integer, having at most 6 decimal digits; `%4f` reads a float with at most 4 characters; and `%8[\000-\255]` returns the next 8 characters (or all the characters still available, if fewer than 8 characters are available in the input).

Notes:

- as mentioned above, a `%s` conversion always succeeds, even if there is nothing to read in the input: in this case, it simply returns `""`.
- in addition to the relevant digits, `'_'` characters may appear inside numbers (this is reminiscent to the usual OCaml lexical conventions). If stricter scanning is desired, use the range conversion facility instead of the number conversions.
- the `scanf` facility is not intended for heavy duty lexical analysis and parsing. If it appears not expressive enough for your needs, several alternative exists: regular expressions (module `Str`), stream parsers, `ocamllex`-generated lexers, `ocamlyacc`-generated parsers.

Scanning indications in format strings

Scanning indications appear just after the string conversions `%s` and `%[ range ]` to delimit the end of the token. A scanning indication is introduced by a `@` character, followed by some plain character `c`. It means that the string token should end just before the next matching `c` (which is skipped). If no `c` character is encountered, the string token spreads as much as possible. For instance, `"%s@\t"` reads a string up to the next tab character or to the end of input. If a `@` character appears anywhere else in the format string, it is treated as a plain character.

Note:

- As usual in format strings, `%` and `@` characters must be escaped using `%%` and `%@`; this rule still holds within range specifications and scanning indications. For instance, format `"%s@%%"` reads a string up to the next `%` character, and format `"%s@%@"` reads a string up to the next `@`.
- The scanning indications introduce slight differences in the syntax of `Scanf` format strings, compared to those used for the `Printf` module. However, the scanning indications are similar to those used in the `Format` module; hence, when producing formatted text to be scanned by `!Scanf.bscanf`, it is wise to use printing functions from the `Format` module (or, if you need to use functions from `Printf`, banish or carefully double check the format strings that contain `'@'` characters).

Exceptions during scanning

Scanners may raise the following exceptions when the input cannot be read according to the format string:

- Raise `Scanf.Scan_failure` if the input does not match the format.
- Raise `Failure` if a conversion to a number is not possible.
- Raise `End_of_file` if the end of input is encountered while some more characters are needed to read the current conversion specification.
- Raise `Invalid_argument` if the format string is invalid.

Note:

- as a consequence, scanning a `%s` conversion never raises exception `End_of_file`: if the end of input is reached the conversion succeeds and simply returns the characters read so far, or `""` if none were ever read.

Specialised formatted input functions

```
val sscanf : string -> ('a, 'b, 'c, 'd) scanner
```

Same as `Scanf.bscanf`[21.30], but reads from the given string.

```
val scanf : ('a, 'b, 'c, 'd) scanner
```

Same as `Scanf.bscanf`[21.30], but reads from the predefined formatted input channel `Scanf.Scanning.stdin`[21.30] that is connected to `!Pervasives.stdin`.

```
val kscanf :
  Scanning.in_channel ->
  (Scanning.in_channel -> exn -> 'd) -> ('a, 'b, 'c, 'd) scanner
```

Same as `Scanf.bscanf`[21.30], but takes an additional function argument `ef` that is called in case of error: if the scanning process or some conversion fails, the scanning function aborts and calls the error handling function `ef` with the formatted input channel and the exception that aborted the scanning process as arguments.

```
val ksscanf :
  string ->
  (Scanning.in_channel -> exn -> 'd) -> ('a, 'b, 'c, 'd) scanner
```

Same as `Scanf.kscanf`[21.30] but reads from the given string.

Since: 4.02.0

Reading format strings from input

```
val bscanf_format :
  Scanning.in_channel ->
  ('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6 ->
  (('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6 -> 'g) -> 'g
```

`bscanf_format ic fmt f` reads a format string token from the formatted input channel `ic`, according to the given format string `fmt`, and applies `f` to the resulting format string value. Raise `Scan_failure` if the format string value read does not have the same type as `fmt`.

Since: 3.09.0

```
val sscanf_format :
  string ->
  ('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6 ->
  (('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6 -> 'g) -> 'g
```

Same as `Scanf.bscanf_format`[21.30], but reads from the given string.

Since: 3.09.0

```
val format_from_string :
  string ->
  ('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6 ->
  ('a, 'b, 'c, 'd, 'e, 'f) Pervasives.format6
```

format_from_string s fmt converts a string argument to a format string, according to the given format string fmt. Raise Scan_failure if s, considered as a format string, does not have the same type as fmt.

Since: 3.10.0

```
val unescaped : string -> string
```

unescaped s return a copy of s with escape sequences (according to the lexical conventions of OCaml) replaced by their corresponding special characters. More precisely, Scanf.unescaped has the following property: for all string s, Scanf.unescaped (String.escaped s) = s.

Always return a copy of the argument, even if there is no escape sequence in the argument. Raise Scan_failure if s is not properly escaped (i.e. s has invalid escape sequences or special characters that are not properly escaped). For instance, String.unescaped "\"" will fail.

Since: 4.00.0

Deprecated

```
val fscanf : Pervasives.in_channel -> ('a, 'b, 'c, 'd) scanner
```

Deprecated. Scanf.fscanf is error prone and deprecated since 4.03.0.

This function violates the following invariant of the Scanf module: To preserve scanning semantics, all scanning functions defined in Scanf must read from a user defined Scanning.in_channel formatted input channel.

If you need to read from a !Pervasives.in_channel input channel ic, simply define a !Scanning.in_channel formatted input channel as in let ib = Scanning.from_channel ic, then use !Scanf.bscanf ib as usual.

```
val kfscanf :
  Pervasives.in_channel ->
  (Scanning.in_channel -> exn -> 'd) -> ('a, 'b, 'c, 'd) scanner
```

Deprecated. Scanf.kfscanf is error prone and deprecated since 4.03.0.

21.31 Module Set : Sets over ordered types.

This module implements the set data structure, given a total ordering function over the set elements. All operations over sets are purely applicative (no side-effects). The implementation uses balanced binary trees, and is therefore reasonably efficient: insertion and membership take time logarithmic in the size of the set, for instance.

The `Make` functor constructs implementations for any type, given a `compare` function. For instance:

```
module IntPairs =
  struct
    type t = int * int
    let compare (x0,y0) (x1,y1) =
      match Pervasives.compare x0 x1 with
          0 -> Pervasives.compare y0 y1
        | c -> c
  end

module PairsSet = Set.Make(IntPairs)

let m = PairsSet.(empty |> add (2,3) |> add (5,7) |> add (11,13))
```

This creates a new module `PairsSet`, with a new type `PairsSet.t` of sets of `int * int`.

```
module type OrderedType =
  sig
```

`type t`

The type of the set elements.

`val compare : t -> t -> int`

A total ordering function over the set elements. This is a two-argument function `f` such that `f e1 e2` is zero if the elements `e1` and `e2` are equal, `f e1 e2` is strictly negative if `e1` is smaller than `e2`, and `f e1 e2` is strictly positive if `e1` is greater than `e2`.
Example: a suitable ordering function is the generic structural comparison function `Pervasives.compare`[20.2].

```
  end
```

Input signature of the functor `Set.Make`[21.31].

```
module type S =
  sig
```

`type elt`

The type of the set elements.

`type t`

The type of sets.

`val empty : t`

The empty set.

```
val is_empty : t -> bool
```

Test whether a set is empty or not.

```
val mem : elt -> t -> bool
```

`mem x s` tests whether `x` belongs to the set `s`.

```
val add : elt -> t -> t
```

`add x s` returns a set containing all elements of `s`, plus `x`. If `x` was already in `s`, `s` is returned unchanged (the result of the function is then physically equal to `s`).
Before 4.03 Physical equality was not ensured.

```
val singleton : elt -> t
```

`singleton x` returns the one-element set containing only `x`.

```
val remove : elt -> t -> t
```

`remove x s` returns a set containing all elements of `s`, except `x`. If `x` was not in `s`, `s` is returned unchanged (the result of the function is then physically equal to `s`).
Before 4.03 Physical equality was not ensured.

```
val union : t -> t -> t
```

Set union.

```
val inter : t -> t -> t
```

Set intersection.

```
val diff : t -> t -> t
```

Set difference.

```
val compare : t -> t -> int
```

Total ordering between sets. Can be used as the ordering function for doing sets of sets.

```
val equal : t -> t -> bool
```

`equal s1 s2` tests whether the sets `s1` and `s2` are equal, that is, contain equal elements.

```
val subset : t -> t -> bool
```

`subset s1 s2` tests whether the set `s1` is a subset of the set `s2`.

```
val iter : (elt -> unit) -> t -> unit
```

`iter f s` applies `f` in turn to all elements of `s`. The elements of `s` are presented to `f` in increasing order with respect to the ordering over the type of the elements.

```
val map : (elt -> elt) -> t -> t
```

`map f s` is the set whose elements are `f a0`,`f a1`... `f aN`, where `a0`,`a1`...`aN` are the elements of `s`.

The elements are passed to `f` in increasing order with respect to the ordering over the type of the elements.

If no element of `s` is changed by `f`, `s` is returned unchanged. (If each output of `f` is physically equal to its input, the returned set is physically equal to `s`.)

```
val fold : (elt -> 'a -> 'a) -> t -> 'a -> 'a
```

`fold f s a` computes `(f xN ... (f x2 (f x1 a))...)`, where `x1 ... xN` are the elements of `s`, in increasing order.

```
val for_all : (elt -> bool) -> t -> bool
```

`for_all p s` checks if all elements of the set satisfy the predicate `p`.

```
val exists : (elt -> bool) -> t -> bool
```

`exists p s` checks if at least one element of the set satisfies the predicate `p`.

```
val filter : (elt -> bool) -> t -> t
```

`filter p s` returns the set of all elements in `s` that satisfy predicate `p`. If `p` satisfies every element in `s`, `s` is returned unchanged (the result of the function is then physically equal to `s`).

Before 4.03 Physical equality was not ensured.

```
val partition : (elt -> bool) -> t -> t * t
```

`partition p s` returns a pair of sets `(s1, s2)`, where `s1` is the set of all the elements of `s` that satisfy the predicate `p`, and `s2` is the set of all the elements of `s` that do not satisfy `p`.

```
val cardinal : t -> int
```

Return the number of elements of a set.

```
val elements : t -> elt list
```

Return the list of all elements of the given set. The returned list is sorted in increasing order with respect to the ordering `Ord.compare`, where `Ord` is the argument given to `Set.Make`[21.31].

```
val min_elt : t -> elt
```

Return the smallest element of the given set (with respect to the `Ord.compare` ordering), or raise `Not_found` if the set is empty.

```
val max_elt : t -> elt
```

Same as `Set.S.min_elt`[21.31], but returns the largest element of the given set.

```
val choose : t -> elt
```

Return one element of the given set, or raise `Not_found` if the set is empty. Which element is chosen is unspecified, but equal elements will be chosen for equal sets.

```
val split : elt -> t -> t * bool * t
```

`split x s` returns a triple `(l, present, r)`, where `l` is the set of elements of `s` that are strictly less than `x`; `r` is the set of elements of `s` that are strictly greater than `x`; `present` is `false` if `s` contains no element equal to `x`, or `true` if `s` contains an element equal to `x`.

```
val find : elt -> t -> elt
```

`find x s` returns the element of `s` equal to `x` (according to `Ord.compare`), or raise `Not_found` if no such element exists.

Since: 4.01.0

```
val of_list : elt list -> t
```

`of_list l` creates a set from a list of elements. This is usually more efficient than folding `add` over the list, except perhaps for lists with many duplicated elements.

Since: 4.02.0

```
end
```

Output signature of the functor `Set.Make`[21.31].

```
module Make :
   functor (Ord :  OrderedType) -> S  with type elt = Ord.t
```

Functor building an implementation of the set structure given a totally ordered type.

21.32 Module `Sort` : Sorting and merging lists.

This module is obsolete and exists only for backward compatibility. The sorting functions in `Array`[21.2] and `List`[21.19] should be used instead. The new functions are faster and use less memory.Sorting and merging lists.

```
val list : ('a -> 'a -> bool) -> 'a list -> 'a list
```

Sort a list in increasing order according to an ordering predicate. The predicate should return `true` if its first argument is less than or equal to its second argument.

`val array : ('a -> 'a -> bool) -> 'a array -> unit`

Sort an array in increasing order according to an ordering predicate. The predicate should return `true` if its first argument is less than or equal to its second argument. The array is sorted in place.

`val merge : ('a -> 'a -> bool) -> 'a list -> 'a list -> 'a list`

Merge two lists according to the given predicate. Assuming the two argument lists are sorted according to the predicate, `merge` returns a sorted list containing the elements from the two lists. The behavior is undefined if the two argument lists were not sorted.

21.33 Module `Spacetime` : Profiling of a program's space behaviour over time.

Currently only supported on x86-64 platforms running 64-bit code.

To use the functions in this module you must:

- configure the compiler with "-spacetime";
- compile to native code. Without these conditions being satisfied the functions in this module will have no effect.

Instead of manually taking profiling heap snapshots with this module it is possible to use an automatic snapshot facility that writes profiling information at fixed intervals to a file. To enable this, all that needs to be done is to build the relevant program using a compiler configured with -spacetime; and set the environment variable OCAML_SPACETIME_INTERVAL to an integer number of milliseconds giving the interval between profiling heap snapshots. This interval should not be made excessively small relative to the running time of the program. A typical interval to start with might be 1/100 of the running time of the program. The program must exit "normally" (i.e. by calling `exit`, with whatever exit code, rather than being abnormally terminated by a signal) so that the snapshot file is correctly completed.

When using the automatic snapshot mode the profiling output is written to a file called "spacetime-<pid>" where <pid> is the process ID of the program. (If the program forks and continues executing then multiple files may be produced with different pid numbers.) The profiling output is by default written to the current working directory when the program starts. This may be customised by setting the OCAML_SPACETIME_SNAPSHOT_DIR environment variable to the name of the desired directory.

If using automatic snapshots the presence of the `save_event_for_automatic_snapshots` function, below, should be noted.

The functions in this module are thread safe.

For functions to decode the information recorded by the profiler, see the Spacetime offline library in otherlibs/.

```
module Series :
  sig
```

```
    type t
```

Type representing a file that will hold a series of heap snapshots together with additional information required to interpret those snapshots.

```
    val create : path:string -> t
```

`create ~path` creates a series file at `path`.

```
    val save_event : ?time:float -> t -> event_name:string -> unit
```

`save_event` writes an event, which is an arbitrary string, into the given series file. This may be used for identifying particular points during program execution when analysing the profile. The optional `time` parameter is as for `Snapshot.take`.

```
    val save_and_close : ?time:float -> t -> unit
```

`save_and_close series` writes information into `series` required for interpeting the snapshots that `series` contains and then closes the `series` file. This function must be called to produce a valid series file. The optional `time` parameter is as for `Snapshot.take`.

```
  end
```

```
module Snapshot :
  sig
```

```
    val take : ?time:float -> Spacetime.Series.t -> unit
```

`take series` takes a snapshot of the profiling annotations on the values in the minor and major heaps, together with GC stats, and write the result to the `series` file. This function triggers a minor GC but does not allocate any memory itself. If the optional `time` is specified, it will be used instead of the result of `Sys.time` as the timestamp of the snapshot. Such `time`s should start from zero and be monotonically increasing. This parameter is intended to be used so that snapshots can be correlated against wall clock time (which is not supported in the standard library) rather than elapsed CPU time.

```
  end
```

```
val save_event_for_automatic_snapshots : event_name:string -> unit
```

Like `Series.save_event`, but writes to the automatic snapshot file. This function is a no-op if OCAML_SPACETIME_INTERVAL was not set.

21.34 Module `Stack` : Last-in first-out stacks.

This module implements stacks (LIFOs), with in-place modification.

`type 'a t`
: The type of stacks containing elements of type `'a`.

`exception Empty`
: Raised when `Stack.pop`[21.34] or `Stack.top`[21.34] is applied to an empty stack.

`val create : unit -> 'a t`
: Return a new stack, initially empty.

`val push : 'a -> 'a t -> unit`
: `push x s` adds the element `x` at the top of stack `s`.

`val pop : 'a t -> 'a`
: `pop s` removes and returns the topmost element in stack `s`, or raises `Empty` if the stack is empty.

`val top : 'a t -> 'a`
: `top s` returns the topmost element in stack `s`, or raises `Empty` if the stack is empty.

`val clear : 'a t -> unit`
: Discard all elements from a stack.

`val copy : 'a t -> 'a t`
: Return a copy of the given stack.

`val is_empty : 'a t -> bool`
: Return `true` if the given stack is empty, `false` otherwise.

`val length : 'a t -> int`
: Return the number of elements in a stack. Time complexity O(1)

`val iter : ('a -> unit) -> 'a t -> unit`
: `iter f s` applies `f` in turn to all elements of `s`, from the element at the top of the stack to the element at the bottom of the stack. The stack itself is unchanged.

`val fold : ('b -> 'a -> 'b) -> 'b -> 'a t -> 'b`
: `fold f accu s` is `(f (... (f (f accu x1) x2) ...) xn)` where `x1` is the top of the stack, `x2` the second element, and `xn` the bottom element. The stack is unchanged.

  Since: 4.03

21.35 Module StdLabels : Standard labeled libraries.

This meta-module provides labelized version of the Array[21.2], Bytes[21.4], List[21.19] and String[21.37] modules.

They only differ by their labels. Detailed interfaces can be found in arrayLabels.mli, bytesLabels.mli, listLabels.mli and stringLabels.mli.

```
module Array :
   ArrayLabels
module Bytes :
   BytesLabels
module List :
   ListLabels
module String :
   StringLabels
```

21.36 Module Stream : Streams and parsers.

```
type 'a t
```

The type of streams holding values of type 'a.

```
exception Failure
```

Raised by parsers when none of the first components of the stream patterns is accepted.

```
exception Error of string
```

Raised by parsers when the first component of a stream pattern is accepted, but one of the following components is rejected.

Stream builders

```
val from : (int -> 'a option) -> 'a t
```

Stream.from f returns a stream built from the function f. To create a new stream element, the function f is called with the current stream count. The user function f must return either Some <value> for a value or None to specify the end of the stream.

Do note that the indices passed to f may not start at 0 in the general case. For example, [< '0; '1; Stream.from f >] would call f the first time with count 2.

```
val of_list : 'a list -> 'a t
```

Return the stream holding the elements of the list in the same order.

```
val of_string : string -> char t
```

Return the stream of the characters of the string parameter.

`val of_bytes : bytes -> char t`

Return the stream of the characters of the bytes parameter.

Since: 4.02.0

`val of_channel : Pervasives.in_channel -> char t`

Return the stream of the characters read from the input channel.

Stream iterator

`val iter : ('a -> unit) -> 'a t -> unit`

`Stream.iter f s` scans the whole stream s, applying function `f` in turn to each stream element encountered.

Predefined parsers

`val next : 'a t -> 'a`

Return the first element of the stream and remove it from the stream. Raise Stream.Failure if the stream is empty.

`val empty : 'a t -> unit`

Return `()` if the stream is empty, else raise `Stream.Failure`.

Useful functions

`val peek : 'a t -> 'a option`

Return `Some` of "the first element" of the stream, or `None` if the stream is empty.

`val junk : 'a t -> unit`

Remove the first element of the stream, possibly unfreezing it before.

`val count : 'a t -> int`

Return the current count of the stream elements, i.e. the number of the stream elements discarded.

`val npeek : int -> 'a t -> 'a list`

`npeek n` returns the list of the `n` first elements of the stream, or all its remaining elements if less than `n` elements are available.

21.37 Module String : String operations.

A string is an immutable data structure that contains a fixed-length sequence of (single-byte) characters. Each character can be accessed in constant time through its index.

Given a string s of length l, we can access each of the l characters of s via its index in the sequence. Indexes start at 0, and we will call an index valid in s if it falls within the range [0...l-1] (inclusive). A position is the point between two characters or at the beginning or end of the string. We call a position valid in s if it falls within the range [0...l] (inclusive). Note that the character at index n is between positions n and n+1.

Two parameters start and len are said to designate a valid substring of s if len >= 0 and start and start+len are valid positions in s.

OCaml strings used to be modifiable in place, for instance via the String.set[21.37] and String.blit[21.37] functions described below. This usage is deprecated and only possible when the compiler is put in "unsafe-string" mode by giving the -unsafe-string command-line option (which is currently the default for reasons of backward compatibility). This is done by making the types string and bytes (see module Bytes[21.4]) interchangeable so that functions expecting byte sequences can also accept strings as arguments and modify them.

All new code should avoid this feature and be compiled with the -safe-string command-line option to enforce the separation between the types string and bytes.

```
val length : string -> int
```

Return the length (number of characters) of the given string.

```
val get : string -> int -> char
```

String.get s n returns the character at index n in string s. You can also write s.[n] instead of String.get s n.

Raise Invalid_argument if n not a valid index in s.

```
val set : bytes -> int -> char -> unit
```

Deprecated. This is a deprecated alias of Bytes.set[21.4]. String.set s n c modifies byte sequence s in place, replacing the byte at index n with c. You can also write s.[n] <- c instead of String.set s n c.

Raise Invalid_argument if n is not a valid index in s.

```
val create : int -> bytes
```

Deprecated. This is a deprecated alias of Bytes.create[21.4]. String.create n returns a fresh byte sequence of length n. The sequence is uninitialized and contains arbitrary bytes.

Raise Invalid_argument if n < 0 or n > Sys.max_string_length[21.38].

```
val make : int -> char -> string
```

String.make n c returns a fresh string of length n, filled with the character c.

Raise Invalid_argument if n < 0 or n > Sys.max_string_length[21.38].

```
val init : int -> (int -> char) -> string
```

`String.init n f` returns a string of length `n`, with character `i` initialized to the result of `f i` (called in increasing index order).

Raise `Invalid_argument` if `n < 0` or `n > Sys.max_string_length`[21.38].

Since: 4.02.0

`val copy : string -> string`

Deprecated. Because strings are immutable, it doesn't make much sense to make identical copies of them.Return a copy of the given string.

`val sub : string -> int -> int -> string`

`String.sub s start len` returns a fresh string of length `len`, containing the substring of `s` that starts at position `start` and has length `len`.

Raise `Invalid_argument` if `start` and `len` do not designate a valid substring of `s`.

`val fill : bytes -> int -> int -> char -> unit`

Deprecated. This is a deprecated alias of `Bytes.fill`[21.4]. `String.fill s start len c` modifies byte sequence `s` in place, replacing `len` bytes with `c`, starting at `start`.

Raise `Invalid_argument` if `start` and `len` do not designate a valid range of `s`.

`val blit : string -> int -> bytes -> int -> int -> unit`

Same as `Bytes.blit_string`[21.4].

`val concat : string -> string list -> string`

`String.concat sep sl` concatenates the list of strings `sl`, inserting the separator string `sep` between each.

Raise `Invalid_argument` if the result is longer than `Sys.max_string_length`[21.38] bytes.

`val iter : (char -> unit) -> string -> unit`

`String.iter f s` applies function `f` in turn to all the characters of `s`. It is equivalent to `f s.[0]; f s.[1]; ...; f s.[String.length s - 1]; ()`.

`val iteri : (int -> char -> unit) -> string -> unit`

Same as `String.iter`[21.37], but the function is applied to the index of the element as first argument (counting from 0), and the character itself as second argument.

Since: 4.00.0

`val map : (char -> char) -> string -> string`

`String.map f s` applies function `f` in turn to all the characters of `s` (in increasing index order) and stores the results in a new string that is returned.

Since: 4.00.0

`val mapi : (int -> char -> char) -> string -> string`

`String.mapi f s` calls `f` with each character of `s` and its index (in increasing index order) and stores the results in a new string that is returned.

Since: 4.02.0

`val trim : string -> string`

Return a copy of the argument, without leading and trailing whitespace. The characters regarded as whitespace are: `' '`, `'\012'`, `'\n'`, `'\r'`, and `'\t'`. If there is neither leading nor trailing whitespace character in the argument, return the original string itself, not a copy.

Since: 4.00.0

`val escaped : string -> string`

Return a copy of the argument, with special characters represented by escape sequences, following the lexical conventions of OCaml. All characters outside the ASCII printable range (32..126) are escaped, as well as backslash and double-quote.

If there is no special character in the argument that needs escaping, return the original string itself, not a copy.

Raise `Invalid_argument` if the result is longer than `Sys.max_string_length`[21.38] bytes.

The function `Scanf.unescaped`[21.30] is a left inverse of `escaped`, i.e. `Scanf.unescaped (escaped s) = s` for any string `s` (unless `escape s` fails).

`val index : string -> char -> int`

`String.index s c` returns the index of the first occurrence of character `c` in string `s`.

Raise `Not_found` if `c` does not occur in `s`.

`val rindex : string -> char -> int`

`String.rindex s c` returns the index of the last occurrence of character `c` in string `s`.

Raise `Not_found` if `c` does not occur in `s`.

`val index_from : string -> int -> char -> int`

`String.index_from s i c` returns the index of the first occurrence of character `c` in string `s` after position `i`. `String.index s c` is equivalent to `String.index_from s 0 c`.

Raise `Invalid_argument` if `i` is not a valid position in `s`. Raise `Not_found` if `c` does not occur in `s` after position `i`.

`val rindex_from : string -> int -> char -> int`

`String.rindex_from s i c` returns the index of the last occurrence of character `c` in string `s` before position `i+1`. `String.rindex s c` is equivalent to `String.rindex_from s (String.length s - 1) c`.

Raise `Invalid_argument` if `i+1` is not a valid position in `s`. Raise `Not_found` if `c` does not occur in `s` before position `i+1`.

`val contains : string -> char -> bool`

`String.contains s c` tests if character `c` appears in the string `s`.

`val contains_from : string -> int -> char -> bool`

`String.contains_from s start c` tests if character `c` appears in `s` after position `start`. `String.contains s c` is equivalent to `String.contains_from s 0 c`.

Raise `Invalid_argument` if `start` is not a valid position in `s`.

`val rcontains_from : string -> int -> char -> bool`

`String.rcontains_from s stop c` tests if character `c` appears in `s` before position `stop+1`.

Raise `Invalid_argument` if `stop < 0` or `stop+1` is not a valid position in `s`.

`val uppercase : string -> string`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with all lowercase letters translated to uppercase, including accented letters of the ISO Latin-1 (8859-1) character set.

`val lowercase : string -> string`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with all uppercase letters translated to lowercase, including accented letters of the ISO Latin-1 (8859-1) character set.

`val capitalize : string -> string`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with the first character set to uppercase, using the ISO Latin-1 (8859-1) character set..

`val uncapitalize : string -> string`

Deprecated. Functions operating on Latin-1 character set are deprecated.Return a copy of the argument, with the first character set to lowercase, using the ISO Latin-1 (8859-1) character set..

`val uppercase_ascii : string -> string`

Return a copy of the argument, with all lowercase letters translated to uppercase, using the US-ASCII character set.

Since: 4.03.0

`val lowercase_ascii : string -> string`

Return a copy of the argument, with all uppercase letters translated to lowercase, using the US-ASCII character set.

Since: 4.03.0

`val capitalize_ascii : string -> string`

Return a copy of the argument, with the first character set to uppercase, using the US-ASCII character set.

Since: 4.03.0

`val uncapitalize_ascii : string -> string`

Return a copy of the argument, with the first character set to lowercase, using the US-ASCII character set.

Since: 4.03.0

`type t = string`

An alias for the type of strings.

`val compare : t -> t -> int`

The comparison function for strings, with the same specification as `Pervasives.compare`[20.2]. Along with the type `t`, this function `compare` allows the module `String` to be passed as argument to the functors `Set.Make`[21.31] and `Map.Make`[21.20].

`val equal : t -> t -> bool`

The equal function for strings.

Since: 4.03.0

`val split_on_char : char -> string -> string list`

`String.split_on_char sep s` returns the list of all (possibly empty) substrings of `s` that are delimited by the `sep` character.

The function's output is specified by the following invariants:

- The list is not empty.
- Concatenating its elements using `sep` as a separator returns a string equal to the input (`String.concat (String.make 1 sep) (String.split_on_char sep s) = s`).
- No string in the result contains the `sep` character.

Since: 4.04.0

21.38 Module `Sys` : System interface.

Every function in this module raises `Sys_error` with an informative message when the underlying system call signal an error.

`val argv : string array`

The command line arguments given to the process. The first element is the command name used to invoke the program. The following elements are the command-line arguments given to the program.

`val executable_name : string`

The name of the file containing the executable currently running.

`val file_exists : string -> bool`

Test if a file with the given name exists.

`val is_directory : string -> bool`

Returns `true` if the given name refers to a directory, `false` if it refers to another kind of file. Raise `Sys_error` if no file exists with the given name.

Since: 3.10.0

`val remove : string -> unit`

Remove the given file name from the file system.

`val rename : string -> string -> unit`

Rename a file. The first argument is the old name and the second is the new name. If there is already another file under the new name, `rename` may replace it, or raise an exception, depending on your operating system.

`val getenv : string -> string`

Return the value associated to a variable in the process environment. Raise `Not_found` if the variable is unbound.

`val command : string -> int`

Execute the given shell command and return its exit code.

`val time : unit -> float`

Return the processor time, in seconds, used by the program since the beginning of execution.

`val chdir : string -> unit`

Change the current working directory of the process.

`val getcwd : unit -> string`

Return the current working directory of the process.

`val readdir : string -> string array`

Return the names of all files present in the given directory. Names denoting the current directory and the parent directory (`"."` and `".."` in Unix) are not returned. Each string in the result is a file name rather than a complete path. There is no guarantee that the name strings in the resulting array will appear in any specific order; they are not, in particular, guaranteed to appear in alphabetical order.

`val interactive : bool Pervasives.ref`

This reference is initially set to `false` in standalone programs and to `true` if the code is being executed under the interactive toplevel system `ocaml`.

`val os_type : string`

Operating system currently executing the OCaml program. One of

- `"Unix"` (for all Unix versions, including Linux and Mac OS X),
- `"Win32"` (for MS-Windows, OCaml compiled with MSVC++ or Mingw),
- `"Cygwin"` (for MS-Windows, OCaml compiled with Cygwin).

```
type backend_type =
  | Native  | Bytecode  | Other of string
```

Currently, the official distribution only supports `Native` and `Bytecode`, but it can be other backends with alternative compilers, for example, javascript.

Since: 4.04.0

`val backend_type : backend_type`

Backend type currently executing the OCaml program. @ since 4.04.0

`val unix : bool`

True if `Sys.os_type = "Unix"`.

Since: 4.01.0

`val win32 : bool`

True if `Sys.os_type = "Win32"`.

Since: 4.01.0

`val cygwin : bool`

True if `Sys.os_type = "Cygwin"`.

Since: 4.01.0

`val word_size : int`

Size of one word on the machine currently executing the OCaml program, in bits: 32 or 64.

`val int_size : int`

Size of an int. It is 31 bits (resp. 63 bits) when using the OCaml compiler on a 32 bits (resp. 64 bits) platform. It may differ for other compilers, e.g. it is 32 bits when compiling to JavaScript.

Since: 4.03.0

`val big_endian : bool`

Whether the machine currently executing the Caml program is big-endian.

Since: 4.00.0

`val max_string_length : int`

Maximum length of strings and byte sequences.

`val max_array_length : int`

Maximum length of a normal array. The maximum length of a float array is `max_array_length/2` on 32-bit machines and `max_array_length` on 64-bit machines.

`val runtime_variant : unit -> string`

Return the name of the runtime variant the program is running on. This is normally the argument given to `-runtime-variant` at compile time, but for byte-code it can be changed after compilation.

Since: 4.03.0

`val runtime_parameters : unit -> string`

Return the value of the runtime parameters, in the same format as the contents of the `OCAMLRUNPARAM` environment variable.

Since: 4.03.0

Signal handling

```
type signal_behavior =
  | Signal_default  | Signal_ignore  | Signal_handle of (int -> unit)
```

What to do when receiving a signal:

- `Signal_default`: take the default behavior (usually: abort the program)
- `Signal_ignore`: ignore the signal
- `Signal_handle f`: call function `f`, giving it the signal number as argument.

`val signal : int -> signal_behavior -> signal_behavior`

Set the behavior of the system on receipt of a given signal. The first argument is the signal number. Return the behavior previously associated with the signal. If the signal number is invalid (or not available on your system), an `Invalid_argument` exception is raised.

`val set_signal : int -> signal_behavior -> unit`

Same as `Sys.signal`[21.38] but return value is ignored.

Signal numbers for the standard POSIX signals.

`val sigabrt : int`
: Abnormal termination

`val sigalrm : int`
: Timeout

`val sigfpe : int`
: Arithmetic exception

`val sighup : int`
: Hangup on controlling terminal

`val sigill : int`
: Invalid hardware instruction

`val sigint : int`
: Interactive interrupt (ctrl-C)

`val sigkill : int`
: Termination (cannot be ignored)

`val sigpipe : int`
: Broken pipe

`val sigquit : int`
: Interactive termination

`val sigsegv : int`
: Invalid memory reference

`val sigterm : int`
: Termination

`val sigusr1 : int`
: Application-defined signal 1

`val sigusr2 : int`
: Application-defined signal 2

`val sigchld : int`
: Child process terminated

`val sigcont : int`

Continue

`val sigstop : int`
Stop

`val sigtstp : int`
Interactive stop

`val sigttin : int`
Terminal read from background process

`val sigttou : int`
Terminal write from background process

`val sigvtalrm : int`
Timeout in virtual time

`val sigprof : int`
Profiling interrupt

`val sigbus : int`
Bus error
Since: 4.03

`val sigpoll : int`
Pollable event
Since: 4.03

`val sigsys : int`
Bad argument to routine
Since: 4.03

`val sigtrap : int`
Trace/breakpoint trap
Since: 4.03

`val sigurg : int`
Urgent condition on socket
Since: 4.03

`val sigxcpu : int`
Timeout in cpu time
Since: 4.03

`val sigxfsz : int`

File size limit exceeded

Since: 4.03

`exception Break`

Exception raised on interactive interrupt if `Sys.catch_break`[21.38] is on.

`val catch_break : bool -> unit`

`catch_break` governs whether interactive interrupt (ctrl-C) terminates the program or raises the `Break` exception. Call `catch_break true` to enable raising `Break`, and `catch_break false` to let the system terminate the program on user interrupt.

`val ocaml_version : string`

`ocaml_version` is the version of OCaml. It is a string of the form `"major.minor[.patchlevel][+additional-info]"`, where `major`, `minor`, and `patchlevel` are integers, and `additional-info` is an arbitrary string. The `[.patchlevel]` and `[+additional-info]` parts may be absent.

`val enable_runtime_warnings : bool -> unit`

Control whether the OCaml runtime system can emit warnings on stderr. Currently, the only supported warning is triggered when a channel created by `open_*` functions is finalized without being closed. Runtime warnings are enabled by default.

Since: 4.03.0

`val runtime_warnings_enabled : unit -> bool`

Return whether runtime warnings are currently enabled.

Since: 4.03.0

Optimization

`val opaque_identity : 'a -> 'a`

For the purposes of optimization, `opaque_identity` behaves like an unknown (and thus possibly side-effecting) function.

At runtime, `opaque_identity` disappears altogether.

A typical use of this function is to prevent pure computations from being optimized away in benchmarking loops. For example:

```
for _round = 1 to 100_000 do
  ignore (Sys.opaque_identity (my_pure_computation ()))
done
```

Since: 4.03.0

21.39 Module `Uchar` : Unicode characters.

Since: 4.03

`type t`

The type for Unicode characters.

A value of this type represents an Unicode scalar value[`http://unicode.org/glossary/#unicode_scalar_value`] which is an integer in the ranges `0x0000`...`0xD7FF` or `0xE000`...`0x10FFFF`.

`val min : t`

`min` is U+0000.

`val max : t`

`max` is U+10FFFF.

`val succ : t -> t`

`succ u` is the scalar value after `u` in the set of Unicode scalar values.

Raises `Invalid_argument` if `u` is `Uchar.max`[21.39].

`val pred : t -> t`

`pred u` is the scalar value before `u` in the set of Unicode scalar values.

Raises `Invalid_argument` if `u` is `Uchar.min`[21.39].

`val is_valid : int -> bool`

`is_valid n` is `true` iff `n` is an Unicode scalar value (i.e. in the ranges `0x0000`...`0xD7FF` or `0xE000`...`0x10FFFF`).

`val of_int : int -> t`

`of_int i` is `i` as an Unicode character.

Raises `Invalid_argument` if `i` does not satisfy `Uchar.is_valid`[21.39].

`val to_int : t -> int`

`to_int u` is `u` as an integer.

`val is_char : t -> bool`

`is_char u` is `true` iff `u` is a latin1 OCaml character.

`val of_char : char -> t`

`of_char c` is `c` as an Unicode character.

`val to_char : t -> char`

`to_char u` is `u` as an OCaml latin1 character.

Raises `Invalid_argument` if `u` does not satisfy `Uchar.is_char`[21.39].

`val equal : t -> t -> bool`

`equal u u'` is `u = u'`.

`val compare : t -> t -> int`

`compare u u'` is `Pervasives.compare u u'`.

`val hash : t -> int`

`hash u` associates a non-negative integer to `u`.

`val dump : Format.formatter -> t -> unit`

`dump ppf u` prints a representation of `u` on `ppf` using only US-ASCII encoded characters according to the Unicode notational convention for code points[`http://www.unicode.org/versions/latest/appA.pdf`].

21.40 Module `Weak` : Arrays of weak pointers and hash sets of weak pointers.

Low-level functions

`type 'a t`

The type of arrays of weak pointers (weak arrays). A weak pointer is a value that the garbage collector may erase whenever the value is not used any more (through normal pointers) by the program. Note that finalisation functions are run after the weak pointers are erased.

A weak pointer is said to be full if it points to a value, empty if the value was erased by the GC.

Notes:

- Integers are not allocated and cannot be stored in weak arrays.
- Weak arrays cannot be marshaled using `Pervasives.output_value`[20.2] nor the functions of the `Marshal`[21.21] module.

`val create : int -> 'a t`

`Weak.create n` returns a new weak array of length `n`. All the pointers are initially empty. Raise `Invalid_argument` if `n` is negative or greater than `Sys.max_array_length`[21.38]`-1`.

`val length : 'a t -> int`

`Weak.length ar` returns the length (number of elements) of `ar`.

`val set : 'a t -> int -> 'a option -> unit`

`Weak.set ar n (Some el)` sets the `n`th cell of `ar` to be a (full) pointer to `el`; `Weak.set ar n None` sets the `n`th cell of `ar` to empty. Raise `Invalid_argument "Weak.set"` if `n` is not in the range 0 to `Weak.length`[21.40] `a - 1`.

`val get : 'a t -> int -> 'a option`

`Weak.get ar n` returns None if the `n`th cell of `ar` is empty, `Some x` (where `x` is the value) if it is full. Raise `Invalid_argument "Weak.get"` if `n` is not in the range 0 to `Weak.length`[21.40] `a - 1`.

`val get_copy : 'a t -> int -> 'a option`

`Weak.get_copy ar n` returns None if the `n`th cell of `ar` is empty, `Some x` (where `x` is a (shallow) copy of the value) if it is full. In addition to pitfalls with mutable values, the interesting difference with `get` is that `get_copy` does not prevent the incremental GC from erasing the value in its current cycle (`get` may delay the erasure to the next GC cycle). Raise `Invalid_argument "Weak.get"` if `n` is not in the range 0 to `Weak.length`[21.40] `a - 1`.

`val check : 'a t -> int -> bool`

`Weak.check ar n` returns `true` if the `n`th cell of `ar` is full, `false` if it is empty. Note that even if `Weak.check ar n` returns `true`, a subsequent `Weak.get`[21.40] `ar n` can return `None`.

`val fill : 'a t -> int -> int -> 'a option -> unit`

`Weak.fill ar ofs len el` sets to `el` all pointers of `ar` from `ofs` to `ofs + len - 1`. Raise `Invalid_argument "Weak.fill"` if `ofs` and `len` do not designate a valid subarray of `a`.

`val blit : 'a t -> int -> 'a t -> int -> int -> unit`

`Weak.blit ar1 off1 ar2 off2 len` copies `len` weak pointers from `ar1` (starting at `off1`) to `ar2` (starting at `off2`). It works correctly even if `ar1` and `ar2` are the same. Raise `Invalid_argument "Weak.blit"` if `off1` and `len` do not designate a valid subarray of `ar1`, or if `off2` and `len` do not designate a valid subarray of `ar2`.

Weak hash sets

A weak hash set is a hashed set of values. Each value may magically disappear from the set when it is not used by the rest of the program any more. This is normally used to share data structures without inducing memory leaks. Weak hash sets are defined on values from a `Hashtbl.HashedType`[21.14] module; the `equal` relation and `hash` function are taken from that module. We will say that `v` is an instance of `x` if `equal x v` is `true`.

The `equal` relation must be able to work on a shallow copy of the values and give the same result as with the values themselves.

```
module type S =
  sig
```

`type data`

The type of the elements stored in the table.

`type t`

The type of tables that contain elements of type `data`. Note that weak hash sets cannot be marshaled using `Pervasives.output_value`[20.2] or the functions of the `Marshal`[21.21] module.

`val create : int -> t`

`create n` creates a new empty weak hash set, of initial size `n`. The table will grow as needed.

`val clear : t -> unit`

Remove all elements from the table.

`val merge : t -> data -> data`

`merge t x` returns an instance of `x` found in `t` if any, or else adds `x` to `t` and return `x`.

`val add : t -> data -> unit`

`add t x` adds `x` to `t`. If there is already an instance of `x` in `t`, it is unspecified which one will be returned by subsequent calls to `find` and `merge`.

`val remove : t -> data -> unit`

`remove t x` removes from `t` one instance of `x`. Does nothing if there is no instance of `x` in `t`.

`val find : t -> data -> data`

`find t x` returns an instance of `x` found in `t`. Raise `Not_found` if there is no such element.

`val find_all : t -> data -> data list`

`find_all t x` returns a list of all the instances of `x` found in `t`.

`val mem : t -> data -> bool`

`mem t x` returns `true` if there is at least one instance of `x` in `t`, false otherwise.

`val iter : (data -> unit) -> t -> unit`

`iter f t` calls `f` on each element of `t`, in some unspecified order. It is not specified what happens if `f` tries to change `t` itself.

`val fold : (data -> 'a -> 'a) -> t -> 'a -> 'a`

`fold f t init` computes `(f d1 (... (f dN init)))` where `d1 ... dN` are the elements of `t` in some unspecified order. It is not specified what happens if `f` tries to change `t` itself.

`val count : t -> int`

Count the number of elements in the table. `count t` gives the same result as `fold (fun _ n -> n+1) t 0` but does not delay the deallocation of the dead elements.

`val stats : t -> int * int * int * int * int * int`

Return statistics on the table. The numbers are, in order: table length, number of entries, sum of bucket lengths, smallest bucket length, median bucket length, biggest bucket length.

`end`

The output signature of the functor `Weak.Make`[21.40].

`module Make :`
`functor (H : Hashtbl.HashedType) -> S with type data = H.t`

Functor building an implementation of the weak hash set structure. `H.equal` can't be the physical equality, since only shallow copies of the elements in the set are given to it.

Chapter 22

The compiler front-end

This chapter describes the OCaml front-end, which declares the abstract syntax tree used by the compiler, provides a way to parse, print and pretty-print OCaml code, and ultimately allows to write abstract syntax tree preprocessors invoked via the `-ppx` flag (see chapters 8 and 11).

It is important to note that the exported front-end interface follows the evolution of the OCaml language and implementation, and thus does not provide **any** backwards compatibility guarantees.

The front-end is a part of `compiler-libs` library. Programs that use the `compiler-libs` library should be built as follows:

```
ocamlfind ocamlc other options -package compiler-libs.common other files
ocamlfind ocamlopt other options -package compiler-libs.common other files
```

Use of the `ocamlfind` utility is recommended. However, if this is not possible, an alternative method may be used:

```
ocamlc other options -I +compiler-libs ocamlcommon.cma other files
ocamlopt other options -I +compiler-libs ocamlcommon.cmxa other files
```

For interactive use of the `compiler-libs` library, start `ocaml` and type
`#load "compiler-libs/ocamlcommon.cma";;`.

22.1 Module `Ast_mapper` : The interface of a -ppx rewriter

A -ppx rewriter is a program that accepts a serialized abstract syntax tree and outputs another, possibly modified, abstract syntax tree. This module encapsulates the interface between the compiler and the -ppx rewriters, handling such details as the serialization format, forwarding of command-line flags, and storing state.

`Ast_mapper.mapper`[22.1.1] allows to implement AST rewriting using open recursion. A typical mapper would be based on `Ast_mapper.default_mapper`[22.1.1], a deep identity mapper, and will fall back on it for handling the syntax it does not modify. For example:

```
open Asttypes
open Parsetree
open Ast_mapper
```

```
let test_mapper argv =
  { default_mapper with
    expr = fun mapper expr ->
      match expr with
      | { pexp_desc = Pexp_extension ({ txt = "test" }, PStr [])} ->
        Ast_helper.Exp.constant (Const_int 42)
      | other -> default_mapper.expr mapper other; }

let () =
  register "ppx_test" test_mapper
```

This -ppx rewriter, which replaces `[%test]` in expressions with the constant `42`, can be compiled using `ocamlc -o ppx_test -I +compiler-libs ocamlcommon.cma ppx_test.ml`.

22.1.1 A generic Parsetree mapper

```
type mapper =
{  attribute : mapper -> Parsetree.attribute -> Parsetree.attribute ;
  attributes : mapper -> Parsetree.attribute list -> Parsetree.attribute list ;
  case : mapper -> Parsetree.case -> Parsetree.case ;
  cases : mapper -> Parsetree.case list -> Parsetree.case list ;
  class_declaration : mapper ->
  Parsetree.class_declaration -> Parsetree.class_declaration ;
  class_description : mapper ->
  Parsetree.class_description -> Parsetree.class_description ;
  class_expr : mapper -> Parsetree.class_expr -> Parsetree.class_expr ;
  class_field : mapper -> Parsetree.class_field -> Parsetree.class_field ;
  class_signature : mapper -> Parsetree.class_signature -> Parsetree.class_signature ;
  class_structure : mapper -> Parsetree.class_structure -> Parsetree.class_structure ;
  class_type : mapper -> Parsetree.class_type -> Parsetree.class_type ;
  class_type_declaration : mapper ->
  Parsetree.class_type_declaration -> Parsetree.class_type_declaration ;
  class_type_field : mapper -> Parsetree.class_type_field -> Parsetree.class_type_field ;
  constructor_declaration : mapper ->
  Parsetree.constructor_declaration -> Parsetree.constructor_declaration ;
  expr : mapper -> Parsetree.expression -> Parsetree.expression ;
  extension : mapper -> Parsetree.extension -> Parsetree.extension ;
  extension_constructor : mapper ->
  Parsetree.extension_constructor -> Parsetree.extension_constructor ;
  include_declaration : mapper ->
  Parsetree.include_declaration -> Parsetree.include_declaration ;
  include_description : mapper ->
  Parsetree.include_description -> Parsetree.include_description ;
  label_declaration : mapper ->
```

```
  Parsetree.label_declaration -> Parsetree.label_declaration ;
  location : mapper -> Location.t -> Location.t ;
  module_binding : mapper -> Parsetree.module_binding -> Parsetree.module_binding ;
  module_declaration : mapper ->
  Parsetree.module_declaration -> Parsetree.module_declaration ;
  module_expr : mapper -> Parsetree.module_expr -> Parsetree.module_expr ;
  module_type : mapper -> Parsetree.module_type -> Parsetree.module_type ;
  module_type_declaration : mapper ->
  Parsetree.module_type_declaration -> Parsetree.module_type_declaration ;
  open_description : mapper -> Parsetree.open_description -> Parsetree.open_description ;
  pat : mapper -> Parsetree.pattern -> Parsetree.pattern ;
  payload : mapper -> Parsetree.payload -> Parsetree.payload ;
  signature : mapper -> Parsetree.signature -> Parsetree.signature ;
  signature_item : mapper -> Parsetree.signature_item -> Parsetree.signature_item ;
  structure : mapper -> Parsetree.structure -> Parsetree.structure ;
  structure_item : mapper -> Parsetree.structure_item -> Parsetree.structure_item ;
  typ : mapper -> Parsetree.core_type -> Parsetree.core_type ;
  type_declaration : mapper -> Parsetree.type_declaration -> Parsetree.type_declaration ;
  type_extension : mapper -> Parsetree.type_extension -> Parsetree.type_extension ;
  type_kind : mapper -> Parsetree.type_kind -> Parsetree.type_kind ;
  value_binding : mapper -> Parsetree.value_binding -> Parsetree.value_binding ;
  value_description : mapper ->
  Parsetree.value_description -> Parsetree.value_description ;
  with_constraint : mapper -> Parsetree.with_constraint -> Parsetree.with_constraint ;
}
```

A mapper record implements one "method" per syntactic category, using an open recursion style: each method takes as its first argument the mapper to be applied to children in the syntax tree.

`val default_mapper : mapper`

A default mapper, which implements a "deep identity" mapping.

22.1.2 Apply mappers to compilation units

`val tool_name : unit -> string`

Can be used within a ppx preprocessor to know which tool is calling it `"ocamlc"`, `"ocamlopt"`, `"ocamldoc"`, `"ocamldep"`, `"ocaml"`, ... Some global variables that reflect command-line options are automatically synchronized between the calling tool and the ppx preprocessor: `Clflags.include_dirs`, `Config.load_path`, `Clflags.open_modules`, `Clflags.for_package`, `Clflags.debug`.

`val apply : source:string -> target:string -> mapper -> unit`

Apply a mapper (parametrized by the unit name) to a dumped parsetree found in the `source` file and put the result in the `target` file. The `structure` or `signature` field of the mapper is applied to the implementation or interface.

```
val run_main : (string list -> mapper) -> unit
```

Entry point to call to implement a standalone -ppx rewriter from a mapper, parametrized by the command line arguments. The current unit name can be obtained from `Location.input_name`. This function implements proper error reporting for uncaught exceptions.

22.1.3 Registration API

```
val register_function :
  (string -> (string list -> mapper) -> unit) Pervasives.ref
```

```
val register : string -> (string list -> mapper) -> unit
```

Apply the `register_function`. The default behavior is to run the mapper immediately, taking arguments from the process command line. This is to support a scenario where a mapper is linked as a stand-alone executable.

It is possible to overwrite the `register_function` to define "-ppx drivers", which combine several mappers in a single process. Typically, a driver starts by defining `register_function` to a custom implementation, then lets ppx rewriters (linked statically or dynamically) register themselves, and then run all or some of them. It is also possible to have -ppx drivers apply rewriters to only specific parts of an AST.

The first argument to `register` is a symbolic name to be used by the ppx driver.

22.1.4 Convenience functions to write mappers

```
val map_opt : ('a -> 'b) -> 'a option -> 'b option
```

```
val extension_of_error : Location.error -> Parsetree.extension
```

Encode an error into an 'ocaml.error' extension node which can be inserted in a generated Parsetree. The compiler will be responsible for reporting the error.

```
val attribute_of_warning : Location.t -> string -> Parsetree.attribute
```

Encode a warning message into an 'ocaml.ppwarning' attribute which can be inserted in a generated Parsetree. The compiler will be responsible for reporting the warning.

22.1.5 Helper functions to call external mappers

```
val add_ppx_context_str :
  tool_name:string -> Parsetree.structure -> Parsetree.structure
```

Extract information from the current environment and encode it into an attribute which is prepended to the list of structure items in order to pass the information to an external processor.

```
val add_ppx_context_sig :
  tool_name:string -> Parsetree.signature -> Parsetree.signature
```

Same as `add_ppx_context_str`, but for signatures.

```
val drop_ppx_context_str :
  restore:bool -> Parsetree.structure -> Parsetree.structure
```

Drop the ocaml.ppx.context attribute from a structure. If `restore` is true, also restore the associated data in the current process.

```
val drop_ppx_context_sig :
  restore:bool -> Parsetree.signature -> Parsetree.signature
```

Same as `drop_ppx_context_str`, but for signatures.

22.1.6 Cookies

Cookies are used to pass information from a ppx processor to a further invocation of itself, when called from the OCaml toplevel (or other tools that support cookies).

```
val set_cookie : string -> Parsetree.expression -> unit
val get_cookie : string -> Parsetree.expression option
```

22.2 Module `Asttypes` : Auxiliary AST types used by parsetree and typedtree.

```
type constant =
  | Const_int of int
  | Const_char of char
  | Const_string of string * string option
  | Const_float of string
  | Const_int32 of int32
  | Const_int64 of int64
  | Const_nativeint of nativeint
type rec_flag =
type direction_flag =
type private_flag =
type mutable_flag =
type virtual_flag =
type override_flag =
type closed_flag =
type label = string
type arg_label =
  | Nolabel  | Labelled of string
  | Optional of string
```

```
type 'a loc = 'a Location.loc =
{  txt : 'a ;
  loc : Location.t ;
}
type variance =
```

22.3 Module `Location` : Source code locations (ranges of positions), used in parsetree.

```
type t =
{  loc_start : Lexing.position ;
  loc_end : Lexing.position ;
  loc_ghost : bool ;
}
```

Note on the use of Lexing.position in this module. If `pos_fname = ""`, then use `!input_name` instead. If `pos_lnum = -1`, then `pos_bol = 0`. Use `pos_cnum` and re-parse the file to get the line and character numbers. Else all fields are correct.

`val none : t`

An arbitrary value of type `t`; describes an empty ghost range.

`val in_file : string -> t`

Return an empty ghost range located in a given file.

`val init : Lexing.lexbuf -> string -> unit`

Set the file name and line number of the `lexbuf` to be the start of the named file.

`val curr : Lexing.lexbuf -> t`

Get the location of the current token from the `lexbuf`.

`val symbol_rloc : unit -> t`

`val symbol_gloc : unit -> t`

`val rhs_loc : int -> t`

`rhs_loc n` returns the location of the symbol at position `n`, starting at 1, in the current parser rule.

`val input_name : string Pervasives.ref`

`val input_lexbuf : Lexing.lexbuf option Pervasives.ref`

`val get_pos_info : Lexing.position -> string * int * int`

`val print_loc : Format.formatter -> t -> unit`

`val print_error : Format.formatter -> t -> unit`

`val print_error_cur_file : Format.formatter -> unit -> unit`

```
val print_warning : t -> Format.formatter -> Warnings.t -> unit
val formatter_for_warnings : Format.formatter Pervasives.ref
val prerr_warning : t -> Warnings.t -> unit
val echo_eof : unit -> unit
val reset : unit -> unit
val warning_printer :
  (t -> Format.formatter -> Warnings.t -> unit) Pervasives.ref
```

Hook for intercepting warnings.

```
val default_warning_printer : t -> Format.formatter -> Warnings.t -> unit
```

Original warning printer for use in hooks.

```
val highlight_locations : Format.formatter -> t list -> bool
type 'a loc =
{  txt : 'a ;
  loc : t ;
}
val mknoloc : 'a -> 'a loc
val mkloc : 'a -> t -> 'a loc
val print : Format.formatter -> t -> unit
val print_compact : Format.formatter -> t -> unit
val print_filename : Format.formatter -> string -> unit
val absolute_path : string -> string
val show_filename : string -> string
```

In -absname mode, return the absolute path for this filename. Otherwise, returns the filename unchanged.

```
val absname : bool Pervasives.ref
type error =
{  loc : t ;
  msg : string ;
  sub : error list ;
  if_highlight : string ;
}
exception Error of error

val print_error_prefix : Format.formatter -> unit -> unit
val error :
  ?loc:t ->
  ?sub:error list -> ?if_highlight:string -> string -> error
val errorf :
```

```
  ?loc:t ->
  ?sub:error list ->
  ?if_highlight:string ->
  ('a, Format.formatter, unit, error) Pervasives.format4 -> 'a
val raise_errorf :
  ?loc:t ->
  ?sub:error list ->
  ?if_highlight:string ->
  ('a, Format.formatter, unit, 'b) Pervasives.format4 -> 'a
val error_of_printer : t -> (Format.formatter -> 'a -> unit) -> 'a -> error
val error_of_printer_file : (Format.formatter -> 'a -> unit) -> 'a -> error
val error_of_exn : exn -> error option
val register_error_of_exn : (exn -> error option) -> unit
val report_error : Format.formatter -> error -> unit
val error_reporter : (Format.formatter -> error -> unit) Pervasives.ref
```

Hook for intercepting error reports.

```
val default_error_reporter : Format.formatter -> error -> unit
```

Original error reporter for use in hooks.

```
val report_exception : Format.formatter -> exn -> unit
```

22.4 Module Longident : Long identifiers, used in parsetree.

```
type t =
  | Lident of string
  | Ldot of t * string
  | Lapply of t * t
val flatten : t -> string list
val last : t -> string
val parse : string -> t
```

22.5 Module Parse : Entry points in the parser

```
val implementation : Lexing.lexbuf -> Parsetree.structure
val interface : Lexing.lexbuf -> Parsetree.signature
val toplevel_phrase : Lexing.lexbuf -> Parsetree.toplevel_phrase
val use_file : Lexing.lexbuf -> Parsetree.toplevel_phrase list
val core_type : Lexing.lexbuf -> Parsetree.core_type
```

```
val expression : Lexing.lexbuf -> Parsetree.expression
val pattern : Lexing.lexbuf -> Parsetree.pattern
```

22.6 Module Parsetree : Abstract syntax tree produced by parsing

```
type constant =
  | Pconst_integer of string * char option
  | Pconst_char of char
  | Pconst_string of string * string option
  | Pconst_float of string * char option
```

22.6.1 Extension points

```
type attribute = string Asttypes.loc * payload
type extension = string Asttypes.loc * payload
type attributes = attribute list
type payload =
  | PStr of structure
  | PSig of signature
  | PTyp of core_type
  | PPat of pattern * expression option
```

22.6.2 Core language

```
type core_type =
{  ptyp_desc : core_type_desc ;
  ptyp_loc : Location.t ;
  ptyp_attributes : attributes ;
}
type core_type_desc =
  | Ptyp_any  | Ptyp_var of string
  | Ptyp_arrow of Asttypes.arg_label * core_type * core_type
  | Ptyp_tuple of core_type list
  | Ptyp_constr of Longident.t Asttypes.loc * core_type list
  | Ptyp_object of (string * attributes * core_type) list
   * Asttypes.closed_flag
  | Ptyp_class of Longident.t Asttypes.loc * core_type list
  | Ptyp_alias of core_type * string
  | Ptyp_variant of row_field list * Asttypes.closed_flag * Asttypes.label list option
  | Ptyp_poly of string list * core_type
  | Ptyp_package of package_type
```

```
  | Ptyp_extension of extension
type package_type = Longident.t Asttypes.loc *
  (Longident.t Asttypes.loc * core_type) list
type row_field =
  | Rtag of Asttypes.label * attributes * bool * core_type list
  | Rinherit of core_type
type pattern =
{  ppat_desc : pattern_desc ;
  ppat_loc : Location.t ;
  ppat_attributes : attributes ;
}
type pattern_desc =
  | Ppat_any  | Ppat_var of string Asttypes.loc
  | Ppat_alias of pattern * string Asttypes.loc
  | Ppat_constant of constant
  | Ppat_interval of constant * constant
  | Ppat_tuple of pattern list
  | Ppat_construct of Longident.t Asttypes.loc * pattern option
  | Ppat_variant of Asttypes.label * pattern option
  | Ppat_record of (Longident.t Asttypes.loc * pattern) list * Asttypes.closed_flag
  | Ppat_array of pattern list
  | Ppat_or of pattern * pattern
  | Ppat_constraint of pattern * core_type
  | Ppat_type of Longident.t Asttypes.loc
  | Ppat_lazy of pattern
  | Ppat_unpack of string Asttypes.loc
  | Ppat_exception of pattern
  | Ppat_extension of extension
  | Ppat_open of Longident.t Asttypes.loc * pattern
type expression =
{  pexp_desc : expression_desc ;
  pexp_loc : Location.t ;
  pexp_attributes : attributes ;
}
type expression_desc =
  | Pexp_ident of Longident.t Asttypes.loc
  | Pexp_constant of constant
  | Pexp_let of Asttypes.rec_flag * value_binding list * expression
  | Pexp_function of case list
  | Pexp_fun of Asttypes.arg_label * expression option * pattern
   * expression
  | Pexp_apply of expression * (Asttypes.arg_label * expression) list
  | Pexp_match of expression * case list
  | Pexp_try of expression * case list
```

```
  | Pexp_tuple of expression list
  | Pexp_construct of Longident.t Asttypes.loc * expression option
  | Pexp_variant of Asttypes.label * expression option
  | Pexp_record of (Longident.t Asttypes.loc * expression) list
   * expression option
  | Pexp_field of expression * Longident.t Asttypes.loc
  | Pexp_setfield of expression * Longident.t Asttypes.loc * expression
  | Pexp_array of expression list
  | Pexp_ifthenelse of expression * expression * expression option
  | Pexp_sequence of expression * expression
  | Pexp_while of expression * expression
  | Pexp_for of pattern * expression * expression
   * Asttypes.direction_flag * expression
  | Pexp_constraint of expression * core_type
  | Pexp_coerce of expression * core_type option * core_type
  | Pexp_send of expression * string
  | Pexp_new of Longident.t Asttypes.loc
  | Pexp_setinstvar of string Asttypes.loc * expression
  | Pexp_override of (string Asttypes.loc * expression) list
  | Pexp_letmodule of string Asttypes.loc * module_expr * expression
  | Pexp_letexception of extension_constructor * expression
  | Pexp_assert of expression
  | Pexp_lazy of expression
  | Pexp_poly of expression * core_type option
  | Pexp_object of class_structure
  | Pexp_newtype of string * expression
  | Pexp_pack of module_expr
  | Pexp_open of Asttypes.override_flag * Longident.t Asttypes.loc * expression
  | Pexp_extension of extension
type case =
{  pc_lhs : pattern ;
  pc_guard : expression option ;
  pc_rhs : expression ;
}
type value_description =
{  pval_name : string Asttypes.loc ;
  pval_type : core_type ;
  pval_prim : string list ;
  pval_attributes : attributes ;
  pval_loc : Location.t ;
}
type type_declaration =
{  ptype_name : string Asttypes.loc ;
  ptype_params : (core_type * Asttypes.variance) list ;
```

```
  ptype_cstrs : (core_type * core_type * Location.t) list ;
  ptype_kind : type_kind ;
  ptype_private : Asttypes.private_flag ;
  ptype_manifest : core_type option ;
  ptype_attributes : attributes ;
  ptype_loc : Location.t ;
}
type type_kind =
  | Ptype_abstract  | Ptype_variant of constructor_declaration list
  | Ptype_record of label_declaration list
type label_declaration =
{  pld_name : string Asttypes.loc ;
  pld_mutable : Asttypes.mutable_flag ;
  pld_type : core_type ;
  pld_loc : Location.t ;
  pld_attributes : attributes ;
}
type constructor_declaration =
{  pcd_name : string Asttypes.loc ;
  pcd_args : constructor_arguments ;
  pcd_res : core_type option ;
  pcd_loc : Location.t ;
  pcd_attributes : attributes ;
}
type constructor_arguments =
  | Pcstr_tuple of core_type list
  | Pcstr_record of label_declaration list
type type_extension =
{  ptyext_path : Longident.t Asttypes.loc ;
  ptyext_params : (core_type * Asttypes.variance) list ;
  ptyext_constructors : extension_constructor list ;
  ptyext_private : Asttypes.private_flag ;
  ptyext_attributes : attributes ;
}
type extension_constructor =
{  pext_name : string Asttypes.loc ;
  pext_kind : extension_constructor_kind ;
  pext_loc : Location.t ;
  pext_attributes : attributes ;
}
type extension_constructor_kind =
  | Pext_decl of constructor_arguments * core_type option
  | Pext_rebind of Longident.t Asttypes.loc
```

22.6.3 Class language

```
type class_type =
{  pcty_desc : class_type_desc ;
  pcty_loc : Location.t ;
  pcty_attributes : attributes ;
}
type class_type_desc =
  | Pcty_constr of Longident.t Asttypes.loc * core_type list
  | Pcty_signature of class_signature
  | Pcty_arrow of Asttypes.arg_label * core_type * class_type
  | Pcty_extension of extension
type class_signature =
{  pcsig_self : core_type ;
  pcsig_fields : class_type_field list ;
}
type class_type_field =
{  pctf_desc : class_type_field_desc ;
  pctf_loc : Location.t ;
  pctf_attributes : attributes ;
}
type class_type_field_desc =
  | Pctf_inherit of class_type
  | Pctf_val of (string * Asttypes.mutable_flag * Asttypes.virtual_flag * core_type)
  | Pctf_method of (string * Asttypes.private_flag * Asttypes.virtual_flag * core_type)
  | Pctf_constraint of (core_type * core_type)
  | Pctf_attribute of attribute
  | Pctf_extension of extension
type 'a class_infos =
{  pci_virt : Asttypes.virtual_flag ;
  pci_params : (core_type * Asttypes.variance) list ;
  pci_name : string Asttypes.loc ;
  pci_expr : 'a ;
  pci_loc : Location.t ;
  pci_attributes : attributes ;
}
type class_description = class_type class_infos
type class_type_declaration = class_type class_infos
type class_expr =
{  pcl_desc : class_expr_desc ;
  pcl_loc : Location.t ;
  pcl_attributes : attributes ;
}
type class_expr_desc =
```

```
  | Pcl_constr of Longident.t Asttypes.loc * core_type list
  | Pcl_structure of class_structure
  | Pcl_fun of Asttypes.arg_label * expression option * pattern
   * class_expr
  | Pcl_apply of class_expr * (Asttypes.arg_label * expression) list
  | Pcl_let of Asttypes.rec_flag * value_binding list * class_expr
  | Pcl_constraint of class_expr * class_type
  | Pcl_extension of extension
type class_structure =
{  pcstr_self : pattern ;
  pcstr_fields : class_field list ;
}
type class_field =
{  pcf_desc : class_field_desc ;
  pcf_loc : Location.t ;
  pcf_attributes : attributes ;
}
type class_field_desc =
  | Pcf_inherit of Asttypes.override_flag * class_expr * string option
  | Pcf_val of (string Asttypes.loc * Asttypes.mutable_flag * class_field_kind)
  | Pcf_method of (string Asttypes.loc * Asttypes.private_flag * class_field_kind)
  | Pcf_constraint of (core_type * core_type)
  | Pcf_initializer of expression
  | Pcf_attribute of attribute
  | Pcf_extension of extension
type class_field_kind =
  | Cfk_virtual of core_type
  | Cfk_concrete of Asttypes.override_flag * expression
type class_declaration = class_expr class_infos
```

22.6.4 Module language

```
type module_type =
{  pmty_desc : module_type_desc ;
  pmty_loc : Location.t ;
  pmty_attributes : attributes ;
}
type module_type_desc =
  | Pmty_ident of Longident.t Asttypes.loc
  | Pmty_signature of signature
  | Pmty_functor of string Asttypes.loc * module_type option * module_type
  | Pmty_with of module_type * with_constraint list
  | Pmty_typeof of module_expr
  | Pmty_extension of extension
```

```
  | Pmty_alias of Longident.t Asttypes.loc
type signature = signature_item list
type signature_item =
{  psig_desc : signature_item_desc ;
  psig_loc : Location.t ;
}
type signature_item_desc =
  | Psig_value of value_description
  | Psig_type of Asttypes.rec_flag * type_declaration list
  | Psig_typext of type_extension
  | Psig_exception of extension_constructor
  | Psig_module of module_declaration
  | Psig_recmodule of module_declaration list
  | Psig_modtype of module_type_declaration
  | Psig_open of open_description
  | Psig_include of include_description
  | Psig_class of class_description list
  | Psig_class_type of class_type_declaration list
  | Psig_attribute of attribute
  | Psig_extension of extension * attributes
type module_declaration =
{  pmd_name : string Asttypes.loc ;
  pmd_type : module_type ;
  pmd_attributes : attributes ;
  pmd_loc : Location.t ;
}
type module_type_declaration =
{  pmtd_name : string Asttypes.loc ;
  pmtd_type : module_type option ;
  pmtd_attributes : attributes ;
  pmtd_loc : Location.t ;
}
type open_description =
{  popen_lid : Longident.t Asttypes.loc ;
  popen_override : Asttypes.override_flag ;
  popen_loc : Location.t ;
  popen_attributes : attributes ;
}
type 'a include_infos =
{  pincl_mod : 'a ;
  pincl_loc : Location.t ;
  pincl_attributes : attributes ;
}
type include_description = module_type include_infos
```

```
type include_declaration = module_expr include_infos
type with_constraint =
  | Pwith_type of Longident.t Asttypes.loc * type_declaration
  | Pwith_module of Longident.t Asttypes.loc * Longident.t Asttypes.loc
  | Pwith_typesubst of type_declaration
  | Pwith_modsubst of string Asttypes.loc * Longident.t Asttypes.loc
type module_expr =
{  pmod_desc : module_expr_desc ;
  pmod_loc : Location.t ;
  pmod_attributes : attributes ;
}
type module_expr_desc =
  | Pmod_ident of Longident.t Asttypes.loc
  | Pmod_structure of structure
  | Pmod_functor of string Asttypes.loc * module_type option * module_expr
  | Pmod_apply of module_expr * module_expr
  | Pmod_constraint of module_expr * module_type
  | Pmod_unpack of expression
  | Pmod_extension of extension
type structure = structure_item list
type structure_item =
{  pstr_desc : structure_item_desc ;
  pstr_loc : Location.t ;
}
type structure_item_desc =
  | Pstr_eval of expression * attributes
  | Pstr_value of Asttypes.rec_flag * value_binding list
  | Pstr_primitive of value_description
  | Pstr_type of Asttypes.rec_flag * type_declaration list
  | Pstr_typext of type_extension
  | Pstr_exception of extension_constructor
  | Pstr_module of module_binding
  | Pstr_recmodule of module_binding list
  | Pstr_modtype of module_type_declaration
  | Pstr_open of open_description
  | Pstr_class of class_declaration list
  | Pstr_class_type of class_type_declaration list
  | Pstr_include of include_declaration
  | Pstr_attribute of attribute
  | Pstr_extension of extension * attributes
type value_binding =
{  pvb_pat : pattern ;
  pvb_expr : expression ;
  pvb_attributes : attributes ;
```

```
  pvb_loc : Location.t ;
}
type module_binding =
{  pmb_name : string Asttypes.loc ;
  pmb_expr : module_expr ;
  pmb_attributes : attributes ;
  pmb_loc : Location.t ;
}
```

22.6.5 Toplevel

```
type toplevel_phrase =
  | Ptop_def of structure
  | Ptop_dir of string * directive_argument
type directive_argument =
  | Pdir_none  | Pdir_string of string
  | Pdir_int of string * char option
  | Pdir_ident of Longident.t
  | Pdir_bool of bool
```

22.7 Module Pprintast

```
type space_formatter = (unit, Format.formatter, unit) Pervasives.format
val toplevel_phrase : Format.formatter -> Parsetree.toplevel_phrase -> unit
val expression : Format.formatter -> Parsetree.expression -> unit
val string_of_expression : Parsetree.expression -> string
val top_phrase : Format.formatter -> Parsetree.toplevel_phrase -> unit
val core_type : Format.formatter -> Parsetree.core_type -> unit
val pattern : Format.formatter -> Parsetree.pattern -> unit
val signature : Format.formatter -> Parsetree.signature -> unit
val structure : Format.formatter -> Parsetree.structure -> unit
val string_of_structure : Parsetree.structure -> string
```

Chapter 23

The unix library: Unix system calls

The `unix` library makes many Unix system calls and system-related library functions available to OCaml programs. This chapter describes briefly the functions provided. Refer to sections 2 and 3 of the Unix manual for more details on the behavior of these functions.

Not all functions are provided by all Unix variants. If some functions are not available, they will raise `Invalid_arg` when called.

Programs that use the `unix` library must be linked as follows:

```
ocamlc other options unix.cma other files
ocamlopt other options unix.cmxa other files
```

For interactive use of the `unix` library, do:

```
ocamlmktop -o mytop unix.cma
./mytop
```

or (if dynamic linking of C libraries is supported on your platform), start `ocaml` and type `#load "unix.cma";;`.

Windows:

A fairly complete emulation of the Unix system calls is provided in the Windows version of OCaml. The end of this chapter gives more information on the functions that are not supported under Windows.

23.1 Module `Unix` : Interface to the Unix system.

Note: all the functions of this module (except `error_message` and `handle_unix_error`) are liable to raise the `Unix_error` exception whenever the underlying system call signals an error.

Error report

`type error =`
— E2BIG

Argument list too long
— EACCES
Permission denied
— EAGAIN
Resource temporarily unavailable; try again
— EBADF
Bad file descriptor
— EBUSY
Resource unavailable
— ECHILD
No child process
— EDEADLK
Resource deadlock would occur
— EDOM
Domain error for math functions, etc.
— EEXIST
File exists
— EFAULT
Bad address
— EFBIG
File too large
— EINTR
Function interrupted by signal
— EINVAL
Invalid argument
— EIO
Hardware I/O error
— EISDIR
Is a directory
— EMFILE
Too many open files by the process
— EMLINK
Too many links
— ENAMETOOLONG
Filename too long
— ENFILE
Too many open files in the system
— ENODEV
No such device
— ENOENT
No such file or directory
— ENOEXEC
Not an executable file
— ENOLCK
No locks available

— ENOMEM
    Not enough memory
— ENOSPC
    No space left on device
— ENOSYS
    Function not supported
— ENOTDIR
    Not a directory
— ENOTEMPTY
    Directory not empty
— ENOTTY
    Inappropriate I/O control operation
— ENXIO
    No such device or address
— EPERM
    Operation not permitted
— EPIPE
    Broken pipe
— ERANGE
    Result too large
— EROFS
    Read-only file system
— ESPIPE
    Invalid seek e.g. on a pipe
— ESRCH
    No such process
— EXDEV
    Invalid link
— EWOULDBLOCK
    Operation would block
— EINPROGRESS
    Operation now in progress
— EALREADY
    Operation already in progress
— ENOTSOCK
    Socket operation on non-socket
— EDESTADDRREQ
    Destination address required
— EMSGSIZE
    Message too long
— EPROTOTYPE
    Protocol wrong type for socket
— ENOPROTOOPT
    Protocol not available
— EPROTONOSUPPORT

Protocol not supported
— ESOCKTNOSUPPORT
Socket type not supported
— EOPNOTSUPP
Operation not supported on socket
— EPFNOSUPPORT
Protocol family not supported
— EAFNOSUPPORT
Address family not supported by protocol family
— EADDRINUSE
Address already in use
— EADDRNOTAVAIL
Can’t assign requested address
— ENETDOWN
Network is down
— ENETUNREACH
Network is unreachable
— ENETRESET
Network dropped connection on reset
— ECONNABORTED
Software caused connection abort
— ECONNRESET
Connection reset by peer
— ENOBUFS
No buffer space available
— EISCONN
Socket is already connected
— ENOTCONN
Socket is not connected
— ESHUTDOWN
Can’t send after socket shutdown
— ETOOMANYREFS
Too many references: can’t splice
— ETIMEDOUT
Connection timed out
— ECONNREFUSED
Connection refused
— EHOSTDOWN
Host is down
— EHOSTUNREACH
No route to host
— ELOOP
Too many levels of symbolic links
— EOVERFLOW
File size or position not representable

```
  | EUNKNOWNERR of int
```

Unknown error

The type of error codes. Errors defined in the POSIX standard and additional errors from UNIX98 and BSD. All other errors are mapped to EUNKNOWNERR.

```
exception Unix_error of error * string * string
```

Raised by the system calls below when an error is encountered. The first component is the error code; the second component is the function name; the third component is the string parameter to the function, if it has one, or the empty string otherwise.

```
val error_message : error -> string
```

Return a string describing the given error code.

```
val handle_unix_error : ('a -> 'b) -> 'a -> 'b
```

`handle_unix_error f x` applies `f` to `x` and returns the result. If the exception `Unix_error` is raised, it prints a message describing the error and exits with code 2.

Access to the process environment

```
val environment : unit -> string array
```

Return the process environment, as an array of strings with the format "variable=value".

```
val getenv : string -> string
```

Return the value associated to a variable in the process environment.

Raises `Not_found` if the variable is unbound.

(This function is identical to `Sys.getenv`[21.38].)

```
val putenv : string -> string -> unit
```

`Unix.putenv name value` sets the value associated to a variable in the process environment. `name` is the name of the environment variable, and `value` its new associated value.

Process handling

```
type process_status =
  | WEXITED of int
```

The process terminated normally by `exit`; the argument is the return code.

```
  | WSIGNALED of int
```

The process was killed by a signal; the argument is the signal number.

```
  | WSTOPPED of int
```

The process was stopped by a signal; the argument is the signal number.

The termination status of a process. See module `Sys`[21.38] for the definitions of the standard signal numbers. Note that they are not the numbers used by the OS.

`type wait_flag =`
— WNOHANG
Do not block if no child has died yet, but immediately return with a pid equal to 0.
— WUNTRACED
Report also the children that receive stop signals.

Flags for `Unix.waitpid`[23.1].

`val execv : string -> string array -> 'a`

`execv prog args` execute the program in file `prog`, with the arguments `args`, and the current process environment. These `execv*` functions never return: on success, the current program is replaced by the new one.

Raises `Unix.Unix_error` on failure.

`val execve : string -> string array -> string array -> 'a`

Same as `Unix.execv`[23.1], except that the third argument provides the environment to the program executed.

`val execvp : string -> string array -> 'a`

Same as `Unix.execv`[23.1], except that the program is searched in the path.

`val execvpe : string -> string array -> string array -> 'a`

Same as `Unix.execve`[23.1], except that the program is searched in the path.

`val fork : unit -> int`

Fork a new process. The returned integer is 0 for the child process, the pid of the child process for the parent process.

On Windows: not implemented, use `Unix.create_process`[23.1] or threads.

`val wait : unit -> int * process_status`

Wait until one of the children processes die, and return its pid and termination status.

On Windows: Not implemented, use `Unix.waitpid`[23.1].

`val waitpid : wait_flag list -> int -> int * process_status`

Same as `Unix.wait`[23.1], but waits for the child process whose pid is given. A pid of `-1` means wait for any child. A pid of `0` means wait for any child in the same process group as the current process. Negative pid arguments represent process groups. The list of options indicates whether `waitpid` should return immediately without waiting, and whether it should report stopped children.

On Windows, this function can only wait for a given PID, not any child process.

`val system : string -> process_status`

Execute the given command, wait until it terminates, and return its termination status. The string is interpreted by the shell `/bin/sh` (or the command interpreter `cmd.exe` on Windows) and therefore can contain redirections, quotes, variables, etc. The result `WEXITED 127` indicates that the shell couldn't be executed.

`val getpid : unit -> int`

Return the pid of the process.

`val getppid : unit -> int`

Return the pid of the parent process. On Windows: not implemented (because it is meaningless).

`val nice : int -> int`

Change the process priority. The integer argument is added to the "nice" value. (Higher values of the "nice" value mean lower priorities.) Return the new nice value.

On Windows: not implemented.

Basic file input/output

`type file_descr`

The abstract type of file descriptors.

`val stdin : file_descr`

File descriptor for standard input.

`val stdout : file_descr`

File descriptor for standard output.

`val stderr : file_descr`

File descriptor for standard error.

`type open_flag =`

— O_RDONLY
: Open for reading

— O_WRONLY
: Open for writing

— O_RDWR
: Open for reading and writing

— O_NONBLOCK
: Open in non-blocking mode

— O_APPEND
: Open for append

— O_CREAT
: Create if nonexistent

— O_TRUNC
: Truncate to 0 length if existing
— O_EXCL
: Fail if existing
— O_NOCTTY
: Don't make this dev a controlling tty
— O_DSYNC
: Writes complete as 'Synchronised I/O data integrity completion'
— O_SYNC
: Writes complete as 'Synchronised I/O file integrity completion'
— O_RSYNC
: Reads complete as writes (depending on O_SYNC/O_DSYNC)
— O_SHARE_DELETE
: Windows only: allow the file to be deleted while still open
— O_CLOEXEC
: Set the close-on-exec flag on the descriptor returned by `Unix.openfile`[23.1]

The flags to `Unix.openfile`[23.1].

`type file_perm = int`

The type of file access rights, e.g. `0o640` is read and write for user, read for group, none for others

`val openfile : string -> open_flag list -> file_perm -> file_descr`

Open the named file with the given flags. Third argument is the permissions to give to the file if it is created (see `Unix.umask`[23.1]). Return a file descriptor on the named file.

`val close : file_descr -> unit`

Close a file descriptor.

`val read : file_descr -> bytes -> int -> int -> int`

`read fd buff ofs len` reads `len` bytes from descriptor `fd`, storing them in byte sequence `buff`, starting at position `ofs` in `buff`. Return the number of bytes actually read.

`val write : file_descr -> bytes -> int -> int -> int`

`write fd buff ofs len` writes `len` bytes to descriptor `fd`, taking them from byte sequence `buff`, starting at position `ofs` in `buff`. Return the number of bytes actually written. `write` repeats the writing operation until all bytes have been written or an error occurs.

`val single_write : file_descr -> bytes -> int -> int -> int`

Same as `write`, but attempts to write only once. Thus, if an error occurs, `single_write` guarantees that no data has been written.

`val write_substring : file_descr -> string -> int -> int -> int`

Same as `write`, but take the data from a string instead of a byte sequence.

`val single_write_substring : file_descr -> string -> int -> int -> int`

Same as `single_write`, but take the data from a string instead of a byte sequence.

Interfacing with the standard input/output library

`val in_channel_of_descr : file_descr -> Pervasives.in_channel`

Create an input channel reading from the given descriptor. The channel is initially in binary mode; use `set_binary_mode_in ic false` if text mode is desired. Text mode is supported only if the descriptor refers to a file or pipe, but is not supported if it refers to a socket. On Windows, `set_binary_mode_in` always fails on channels created with this function.

Beware that channels are buffered so more characters may have been read from the file descriptor than those accessed using channel functions. Channels also keep a copy of the current position in the file.

You need to explicitly close all channels created with this function. Closing the channel also closes the underlying file descriptor (unless it was already closed).

`val out_channel_of_descr : file_descr -> Pervasives.out_channel`

Create an output channel writing on the given descriptor. The channel is initially in binary mode; use `set_binary_mode_out oc false` if text mode is desired. Text mode is supported only if the descriptor refers to a file or pipe, but is not supported if it refers to a socket. On Windows, `set_binary_mode_out` always fails on channels created with this function.

Beware that channels are buffered so you may have to `flush` them to ensure that all data has been sent to the file descriptor. Channels also keep a copy of the current position in the file.

You need to explicitly close all channels created with this function. Closing the channel flushes the data and closes the underlying file descriptor (unless it has already been closed, in which case the buffered data is lost).

`val descr_of_in_channel : Pervasives.in_channel -> file_descr`

Return the descriptor corresponding to an input channel.

`val descr_of_out_channel : Pervasives.out_channel -> file_descr`

Return the descriptor corresponding to an output channel.

Seeking and truncating

`type seek_command =`

— SEEK_SET
: indicates positions relative to the beginning of the file

— SEEK_CUR
: indicates positions relative to the current position

— SEEK_END

indicates positions relative to the end of the file

Positioning modes for `Unix.lseek`[23.1].

`val lseek : file_descr -> int -> seek_command -> int`

Set the current position for a file descriptor, and return the resulting offset (from the beginning of the file).

`val truncate : string -> int -> unit`

Truncates the named file to the given size.

On Windows: not implemented.

`val ftruncate : file_descr -> int -> unit`

Truncates the file corresponding to the given descriptor to the given size.

On Windows: not implemented.

File status

`type file_kind =`

— S_REG

Regular file

— S_DIR

Directory

— S_CHR

Character device

— S_BLK

Block device

— S_LNK

Symbolic link

— S_FIFO

Named pipe

— S_SOCK

Socket

```
type stats =
{  st_dev : int ;
```

Device number

`  st_ino : int ;`

Inode number

`  st_kind : file_kind ;`

Kind of the file

`  st_perm : file_perm ;`

Access rights

`st_nlink : int ;`
: Number of links

`st_uid : int ;`
: User id of the owner

`st_gid : int ;`
: Group ID of the file's group

`st_rdev : int ;`
: Device minor number

`st_size : int ;`
: Size in bytes

`st_atime : float ;`
: Last access time

`st_mtime : float ;`
: Last modification time

`st_ctime : float ;`
: Last status change time

`}`

The information returned by the `Unix.stat`[23.1] calls.

`val stat : string -> stats`
: Return the information for the named file.

`val lstat : string -> stats`
: Same as `Unix.stat`[23.1], but in case the file is a symbolic link, return the information for the link itself.

`val fstat : file_descr -> stats`
: Return the information for the file associated with the given descriptor.

`val isatty : file_descr -> bool`
: Return `true` if the given file descriptor refers to a terminal or console window, `false` otherwise.

File operations on large files

```
module LargeFile :
  sig
    val lseek : Unix.file_descr -> int64 -> Unix.seek_command -> int64
```

See `Unix.lseek`[23.1].

```
val truncate : string -> int64 -> unit
```

See `Unix.truncate`[23.1].

```
val ftruncate : Unix.file_descr -> int64 -> unit
```

See `Unix.ftruncate`[23.1].

```
type stats =
{  st_dev : int ;
```

Device number

```
  st_ino : int ;
```

Inode number

```
  st_kind : Unix.file_kind ;
```

Kind of the file

```
  st_perm : Unix.file_perm ;
```

Access rights

```
  st_nlink : int ;
```

Number of links

```
  st_uid : int ;
```

User id of the owner

```
  st_gid : int ;
```

Group ID of the file's group

```
  st_rdev : int ;
```

Device minor number

```
  st_size : int64 ;
```

Size in bytes

```
  st_atime : float ;
```

Last access time

```
  st_mtime : float ;
```

Last modification time

```
  st_ctime : float ;
```

Last status change time

```
    }
    val stat : string -> stats
    val lstat : string -> stats
    val fstat : Unix.file_descr -> stats
  end
```

File operations on large files. This sub-module provides 64-bit variants of the functions `Unix.lseek`[23.1] (for positioning a file descriptor), `Unix.truncate`[23.1] and `Unix.ftruncate`[23.1] (for changing the size of a file), and `Unix.stat`[23.1], `Unix.lstat`[23.1] and `Unix.fstat`[23.1] (for obtaining information on files). These alternate functions represent positions and sizes by 64-bit integers (type `int64`) instead of regular integers (type `int`), thus allowing operating on files whose sizes are greater than `max_int`.

Operations on file names

`val unlink : string -> unit`

Removes the named file.

`val rename : string -> string -> unit`

`rename old new` changes the name of a file from `old` to `new`.

`val link : string -> string -> unit`

`link source dest` creates a hard link named `dest` to the file named `source`.

File permissions and ownership

`type access_permission =`

— R_OK
: Read permission

— W_OK
: Write permission

— X_OK
: Execution permission

— F_OK
: File exists

Flags for the `Unix.access`[23.1] call.

`val chmod : string -> file_perm -> unit`

Change the permissions of the named file.

`val fchmod : file_descr -> file_perm -> unit`

Change the permissions of an opened file. On Windows: not implemented.

`val chown : string -> int -> int -> unit`

Change the owner uid and owner gid of the named file. On Windows: not implemented (make no sense on a DOS file system).

`val fchown : file_descr -> int -> int -> unit`

Change the owner uid and owner gid of an opened file. On Windows: not implemented (make no sense on a DOS file system).

`val umask : int -> int`

Set the process's file mode creation mask, and return the previous mask. On Windows: not implemented.

`val access : string -> access_permission list -> unit`

Check that the process has the given permissions over the named file.

Raises `Unix_error` otherwise.

On Windows, execute permission `X_OK`, cannot be tested, it just tests for read permission instead.

Operations on file descriptors

`val dup : file_descr -> file_descr`

Return a new file descriptor referencing the same file as the given descriptor.

`val dup2 : file_descr -> file_descr -> unit`

`dup2 fd1 fd2` duplicates `fd1` to `fd2`, closing `fd2` if already opened.

`val set_nonblock : file_descr -> unit`

Set the "non-blocking" flag on the given descriptor. When the non-blocking flag is set, reading on a descriptor on which there is temporarily no data available raises the `EAGAIN` or `EWOULDBLOCK` error instead of blocking; writing on a descriptor on which there is temporarily no room for writing also raises `EAGAIN` or `EWOULDBLOCK`.

`val clear_nonblock : file_descr -> unit`

Clear the "non-blocking" flag on the given descriptor. See `Unix.set_nonblock`[23.1].

`val set_close_on_exec : file_descr -> unit`

Set the "close-on-exec" flag on the given descriptor. A descriptor with the close-on-exec flag is automatically closed when the current process starts another program with one of the `exec` functions.

`val clear_close_on_exec : file_descr -> unit`

Clear the "close-on-exec" flag on the given descriptor. See `Unix.set_close_on_exec`[23.1].

Directories

`val mkdir : string -> file_perm -> unit`
Create a directory with the given permissions (see `Unix.umask`[23.1]).

`val rmdir : string -> unit`
Remove an empty directory.

`val chdir : string -> unit`
Change the process working directory.

`val getcwd : unit -> string`
Return the name of the current working directory.

`val chroot : string -> unit`
Change the process root directory. On Windows: not implemented.

`type dir_handle`
The type of descriptors over opened directories.

`val opendir : string -> dir_handle`
Open a descriptor on a directory

`val readdir : dir_handle -> string`
Return the next entry in a directory.

Raises `End_of_file` when the end of the directory has been reached.

`val rewinddir : dir_handle -> unit`
Reposition the descriptor to the beginning of the directory

`val closedir : dir_handle -> unit`
Close a directory descriptor.

Pipes and redirections

`val pipe : unit -> file_descr * file_descr`
Create a pipe. The first component of the result is opened for reading, that's the exit to the pipe. The second component is opened for writing, that's the entrance to the pipe.

`val mkfifo : string -> file_perm -> unit`
Create a named pipe with the given permissions (see `Unix.umask`[23.1]). On Windows: not implemented.

High-level process and redirection management

```
val create_process :
  string ->
  string array -> file_descr -> file_descr -> file_descr -> int
```

`create_process prog args new_stdin new_stdout new_stderr` forks a new process that executes the program in file `prog`, with arguments `args`. The pid of the new process is returned immediately; the new process executes concurrently with the current process. The standard input and outputs of the new process are connected to the descriptors `new_stdin`, `new_stdout` and `new_stderr`. Passing e.g. `stdout` for `new_stdout` prevents the redirection and causes the new process to have the same standard output as the current process. The executable file `prog` is searched in the path. The new process has the same environment as the current process.

```
val create_process_env :
  string ->
  string array ->
  string array -> file_descr -> file_descr -> file_descr -> int
```

`create_process_env prog args env new_stdin new_stdout new_stderr` works as `Unix.create_process`[23.1], except that the extra argument `env` specifies the environment passed to the program.

```
val open_process_in : string -> Pervasives.in_channel
```

High-level pipe and process management. This function runs the given command in parallel with the program. The standard output of the command is redirected to a pipe, which can be read via the returned input channel. The command is interpreted by the shell `/bin/sh` (or `cmd.exe` on Windows), cf. `system`.

```
val open_process_out : string -> Pervasives.out_channel
```

Same as `Unix.open_process_in`[23.1], but redirect the standard input of the command to a pipe. Data written to the returned output channel is sent to the standard input of the command. Warning: writes on output channels are buffered, hence be careful to call `Pervasives.flush`[20.2] at the right times to ensure correct synchronization.

```
val open_process : string -> Pervasives.in_channel * Pervasives.out_channel
```

Same as `Unix.open_process_out`[23.1], but redirects both the standard input and standard output of the command to pipes connected to the two returned channels. The input channel is connected to the output of the command, and the output channel to the input of the command.

```
val open_process_full :
  string ->
  string array ->
  Pervasives.in_channel * Pervasives.out_channel * Pervasives.in_channel
```

Similar to `Unix.open_process`[23.1], but the second argument specifies the environment passed to the command. The result is a triple of channels connected respectively to the standard output, standard input, and standard error of the command.

```
val close_process_in : Pervasives.in_channel -> process_status
```

Close channels opened by `Unix.open_process_in`[23.1], wait for the associated command to terminate, and return its termination status.

```
val close_process_out : Pervasives.out_channel -> process_status
```

Close channels opened by `Unix.open_process_out`[23.1], wait for the associated command to terminate, and return its termination status.

```
val close_process :
  Pervasives.in_channel * Pervasives.out_channel -> process_status
```

Close channels opened by `Unix.open_process`[23.1], wait for the associated command to terminate, and return its termination status.

```
val close_process_full :
  Pervasives.in_channel * Pervasives.out_channel * Pervasives.in_channel ->
  process_status
```

Close channels opened by `Unix.open_process_full`[23.1], wait for the associated command to terminate, and return its termination status.

Symbolic links

```
val symlink : ?to_dir:bool -> string -> string -> unit
```

`symlink ?to_dir source dest` creates the file `dest` as a symbolic link to the file `source`. On Windows, `~to_dir` indicates if the symbolic link points to a directory or a file; if omitted, `symlink` examines `source` using `stat` and picks appropriately, if `source` does not exist then `false` is assumed (for this reason, it is recommended that the `~to_dir` parameter be specified in new code). On Unix, `~to_dir` ignored.

Windows symbolic links are available in Windows Vista onwards. There are some important differences between Windows symlinks and their POSIX counterparts.

Windows symbolic links come in two flavours: directory and regular, which designate whether the symbolic link points to a directory or a file. The type must be correct - a directory symlink which actually points to a file cannot be selected with chdir and a file symlink which actually points to a directory cannot be read or written (note that Cygwin's emulation layer ignores this distinction).

When symbolic links are created to existing targets, this distinction doesn't matter and `symlink` will automatically create the correct kind of symbolic link. The distinction matters when a symbolic link is created to a non-existent target.

The other caveat is that by default symbolic links are a privileged operation. Administrators will always need to be running elevated (or with UAC disabled) and by

default normal user accounts need to be granted the SeCreateSymbolicLinkPrivilege via Local Security Policy (secpol.msc) or via Active Directory.

`Unix.has_symlink`[23.1] can be used to check that a process is able to create symbolic links.

```
val has_symlink : unit -> bool
```

Returns `true` if the user is able to create symbolic links. On Windows, this indicates that the user not only has the SeCreateSymbolicLinkPrivilege but is also running elevated, if necessary. On other platforms, this is simply indicates that the symlink system call is available.

```
val readlink : string -> string
```

Read the contents of a symbolic link.

Polling

```
val select :
  file_descr list ->
  file_descr list ->
  file_descr list ->
  float -> file_descr list * file_descr list * file_descr list
```

Wait until some input/output operations become possible on some channels. The three list arguments are, respectively, a set of descriptors to check for reading (first argument), for writing (second argument), or for exceptional conditions (third argument). The fourth argument is the maximal timeout, in seconds; a negative fourth argument means no timeout (unbounded wait). The result is composed of three sets of descriptors: those ready for reading (first component), ready for writing (second component), and over which an exceptional condition is pending (third component).

Locking

```
type lock_command =
```

— F_ULOCK
: Unlock a region

— F_LOCK
: Lock a region for writing, and block if already locked

— F_TLOCK
: Lock a region for writing, or fail if already locked

— F_TEST
: Test a region for other process locks

— F_RLOCK
: Lock a region for reading, and block if already locked

— F_TRLOCK
: Lock a region for reading, or fail if already locked

Commands for `Unix.lockf`[23.1].

```
val lockf : file_descr -> lock_command -> int -> unit
```

`lockf fd cmd size` puts a lock on a region of the file opened as `fd`. The region starts at the current read/write position for `fd` (as set by `Unix.lseek`[23.1]), and extends `size` bytes forward if `size` is positive, `size` bytes backwards if `size` is negative, or to the end of the file if `size` is zero. A write lock prevents any other process from acquiring a read or write lock on the region. A read lock prevents any other process from acquiring a write lock on the region, but lets other processes acquire read locks on it.

The `F_LOCK` and `F_TLOCK` commands attempts to put a write lock on the specified region. The `F_RLOCK` and `F_TRLOCK` commands attempts to put a read lock on the specified region. If one or several locks put by another process prevent the current process from acquiring the lock, `F_LOCK` and `F_RLOCK` block until these locks are removed, while `F_TLOCK` and `F_TRLOCK` fail immediately with an exception. The `F_ULOCK` removes whatever locks the current process has on the specified region. Finally, the `F_TEST` command tests whether a write lock can be acquired on the specified region, without actually putting a lock. It returns immediately if successful, or fails otherwise.

Signals

Note: installation of signal handlers is performed via the functions `Sys.signal`[21.38] and `Sys.set_signal`[21.38].

```
val kill : int -> int -> unit
```

`kill pid sig` sends signal number `sig` to the process with id `pid`. On Windows, only the `Sys.sigkill` signal is emulated.

```
type sigprocmask_command =
```

```
val sigprocmask : sigprocmask_command -> int list -> int list
```

`sigprocmask cmd sigs` changes the set of blocked signals. If `cmd` is `SIG_SETMASK`, blocked signals are set to those in the list `sigs`. If `cmd` is `SIG_BLOCK`, the signals in `sigs` are added to the set of blocked signals. If `cmd` is `SIG_UNBLOCK`, the signals in `sigs` are removed from the set of blocked signals. `sigprocmask` returns the set of previously blocked signals.

On Windows: not implemented (no inter-process signals on Windows).

```
val sigpending : unit -> int list
```

Return the set of blocked signals that are currently pending.

On Windows: not implemented (no inter-process signals on Windows).

```
val sigsuspend : int list -> unit
```

`sigsuspend sigs` atomically sets the blocked signals to `sigs` and waits for a non-ignored, non-blocked signal to be delivered. On return, the blocked signals are reset to their initial value.

On Windows: not implemented (no inter-process signals on Windows).

```
val pause : unit -> unit
```

Wait until a non-ignored, non-blocked signal is delivered.

On Windows: not implemented (no inter-process signals on Windows).

Time functions

```
type process_times =
{  tms_utime : float ;
```

User time for the process

```
  tms_stime : float ;
```

System time for the process

```
  tms_cutime : float ;
```

User time for the children processes

```
  tms_cstime : float ;
```

System time for the children processes

```
}
```

The execution times (CPU times) of a process.

```
type tm =
{  tm_sec : int ;
```

Seconds 0..60

```
  tm_min : int ;
```

Minutes 0..59

```
  tm_hour : int ;
```

Hours 0..23

```
  tm_mday : int ;
```

Day of month 1..31

```
  tm_mon : int ;
```

Month of year 0..11

```
  tm_year : int ;
```

Year - 1900

```
  tm_wday : int ;
```

Day of week (Sunday is 0)

```
  tm_yday : int ;
```

Day of year 0..365

```
  tm_isdst : bool ;
```

Daylight time savings in effect

}

The type representing wallclock time and calendar date.

`val time : unit -> float`

Return the current time since 00:00:00 GMT, Jan. 1, 1970, in seconds.

`val gettimeofday : unit -> float`

Same as `Unix.time`[23.1], but with resolution better than 1 second.

`val gmtime : float -> tm`

Convert a time in seconds, as returned by `Unix.time`[23.1], into a date and a time. Assumes UTC (Coordinated Universal Time), also known as GMT.

`val localtime : float -> tm`

Convert a time in seconds, as returned by `Unix.time`[23.1], into a date and a time. Assumes the local time zone.

`val mktime : tm -> float * tm`

Convert a date and time, specified by the `tm` argument, into a time in seconds, as returned by `Unix.time`[23.1]. The `tm_isdst`, `tm_wday` and `tm_yday` fields of `tm` are ignored. Also return a normalized copy of the given `tm` record, with the `tm_wday`, `tm_yday`, and `tm_isdst` fields recomputed from the other fields, and the other fields normalized (so that, e.g., 40 October is changed into 9 November). The `tm` argument is interpreted in the local time zone.

`val alarm : int -> int`

Schedule a `SIGALRM` signal after the given number of seconds.

On Windows: not implemented.

`val sleep : int -> unit`

Stop execution for the given number of seconds.

`val sleepf : float -> unit`

Stop execution for the given number of seconds. Like `sleep`, but fractions of seconds are supported.

Since: 4.03.0

`val times : unit -> process_times`

Return the execution times of the process. On Windows, it is partially implemented, will not report timings for child processes.

`val utimes : string -> float -> float -> unit`

Set the last access time (second arg) and last modification time (third arg) for a file. Times are expressed in seconds from 00:00:00 GMT, Jan. 1, 1970. If both times are `0.0`, the access and last modification times are both set to the current time.

```
type interval_timer =
```
— ITIMER_REAL
: decrements in real time, and sends the signal `SIGALRM` when expired.

— ITIMER_VIRTUAL
: decrements in process virtual time, and sends `SIGVTALRM` when expired.

— ITIMER_PROF
: (for profiling) decrements both when the process is running and when the system is running on behalf of the process; it sends `SIGPROF` when expired.

The three kinds of interval timers.

```
type interval_timer_status =
{  it_interval : float ;
```
Period

```
  it_value : float ;
```
Current value of the timer

```
}
```
The type describing the status of an interval timer

```
val getitimer : interval_timer -> interval_timer_status
```
Return the current status of the given interval timer.

On Windows: not implemented.

```
val setitimer :
  interval_timer ->
  interval_timer_status -> interval_timer_status
```
`setitimer t s` sets the interval timer `t` and returns its previous status. The `s` argument is interpreted as follows: `s.it_value`, if nonzero, is the time to the next timer expiration; `s.it_interval`, if nonzero, specifies a value to be used in reloading `it_value` when the timer expires. Setting `s.it_value` to zero disables the timer. Setting `s.it_interval` to zero causes the timer to be disabled after its next expiration.

On Windows: not implemented.

User id, group id

```
val getuid : unit -> int
```
Return the user id of the user executing the process. On Windows, always return `1`.

```
val geteuid : unit -> int
```

Return the effective user id under which the process runs. On Windows, always return `1`.

`val setuid : int -> unit`

Set the real user id and effective user id for the process. On Windows: not implemented.

`val getgid : unit -> int`

Return the group id of the user executing the process. On Windows, always return `1`.

`val getegid : unit -> int`

Return the effective group id under which the process runs. On Windows, always return `1`.

`val setgid : int -> unit`

Set the real group id and effective group id for the process. On Windows: not implemented.

`val getgroups : unit -> int array`

Return the list of groups to which the user executing the process belongs. On Windows, always return `[|1|]`.

`val setgroups : int array -> unit`

`setgroups groups` sets the supplementary group IDs for the calling process. Appropriate privileges are required. On Windows: not implemented.

`val initgroups : string -> int -> unit`

`initgroups user group` initializes the group access list by reading the group database /etc/group and using all groups of which `user` is a member. The additional group `group` is also added to the list. On Windows: not implemented.

```
type passwd_entry =
{  pw_name : string ;
  pw_passwd : string ;
  pw_uid : int ;
  pw_gid : int ;
  pw_gecos : string ;
  pw_dir : string ;
  pw_shell : string ;
}
```

Structure of entries in the `passwd` database.

```
type group_entry =
{  gr_name : string ;
  gr_passwd : string ;
  gr_gid : int ;
  gr_mem : string array ;
}
```

Structure of entries in the `groups` database.

`val getlogin : unit -> string`

Return the login name of the user executing the process.

`val getpwnam : string -> passwd_entry`

Find an entry in `passwd` with the given name.

Raises `Not_found` if no such entry exist.

On Windows, always raise `Not_found`.

`val getgrnam : string -> group_entry`

Find an entry in `group` with the given name.

Raises `Not_found` if no such entry exist.

On Windows, always raise `Not_found`.

`val getpwuid : int -> passwd_entry`

Find an entry in `passwd` with the given user id.

Raises `Not_found` if no such entry exist.

On Windows, always raise `Not_found`.

`val getgrgid : int -> group_entry`

Find an entry in `group` with the given group id.

Raises `Not_found` if no such entry exist.

On Windows, always raise `Not_found`.

Internet addresses

`type inet_addr`

The abstract type of Internet addresses.

`val inet_addr_of_string : string -> inet_addr`

Conversion from the printable representation of an Internet address to its internal representation. The argument string consists of 4 numbers separated by periods (`XXX.YYY.ZZZ.TTT`) for IPv4 addresses, and up to 8 numbers separated by colons for IPv6 addresses.

Raises `Failure` when given a string that does not match these formats.

`val string_of_inet_addr : inet_addr -> string`

Return the printable representation of the given Internet address. See `Unix.inet_addr_of_string`[23.1] for a description of the printable representation.

`val inet_addr_any : inet_addr`

A special IPv4 address, for use only with `bind`, representing all the Internet addresses that the host machine possesses.

`val inet_addr_loopback : inet_addr`

A special IPv4 address representing the host machine (`127.0.0.1`).

`val inet6_addr_any : inet_addr`

A special IPv6 address, for use only with `bind`, representing all the Internet addresses that the host machine possesses.

`val inet6_addr_loopback : inet_addr`

A special IPv6 address representing the host machine (`::1`).

Sockets

`type socket_domain =`
— PF_UNIX
Unix domain
— PF_INET
Internet domain (IPv4)
— PF_INET6
Internet domain (IPv6)

The type of socket domains. Not all platforms support IPv6 sockets (type `PF_INET6`). Windows does not support `PF_UNIX`.

`type socket_type =`
— SOCK_STREAM
Stream socket
— SOCK_DGRAM
Datagram socket
— SOCK_RAW
Raw socket
— SOCK_SEQPACKET
Sequenced packets socket

The type of socket kinds, specifying the semantics of communications. `SOCK_SEQPACKET` is included for completeness, but is rarely supported by the OS, and needs system calls that are not available in this library.

```
type sockaddr =
  | ADDR_UNIX of string
  | ADDR_INET of inet_addr * int
```

The type of socket addresses. `ADDR_UNIX name` is a socket address in the Unix domain; `name` is a file name in the file system. `ADDR_INET(addr,port)` is a socket address in the Internet domain; `addr` is the Internet address of the machine, and `port` is the port number.

```
val socket : socket_domain -> socket_type -> int -> file_descr
```

Create a new socket in the given domain, and with the given kind. The third argument is the protocol type; 0 selects the default protocol for that kind of sockets.

```
val domain_of_sockaddr : sockaddr -> socket_domain
```

Return the socket domain adequate for the given socket address.

```
val socketpair :
  socket_domain ->
  socket_type -> int -> file_descr * file_descr
```

Create a pair of unnamed sockets, connected together.

```
val accept : file_descr -> file_descr * sockaddr
```

Accept connections on the given socket. The returned descriptor is a socket connected to the client; the returned address is the address of the connecting client.

```
val bind : file_descr -> sockaddr -> unit
```

Bind a socket to an address.

```
val connect : file_descr -> sockaddr -> unit
```

Connect a socket to an address.

```
val listen : file_descr -> int -> unit
```

Set up a socket for receiving connection requests. The integer argument is the maximal number of pending requests.

```
type shutdown_command =
```

— SHUTDOWN_RECEIVE
: Close for receiving

— SHUTDOWN_SEND
: Close for sending

— SHUTDOWN_ALL
: Close both

The type of commands for `shutdown`.

```
val shutdown : file_descr -> shutdown_command -> unit
```

Shutdown a socket connection. `SHUTDOWN_SEND` as second argument causes reads on the other end of the connection to return an end-of-file condition. `SHUTDOWN_RECEIVE` causes writes on the other end of the connection to return a closed pipe condition (`SIGPIPE` signal).

```
val getsockname : file_descr -> sockaddr
```

Return the address of the given socket.

```
val getpeername : file_descr -> sockaddr
```

Return the address of the host connected to the given socket.

```
type msg_flag =
```
— MSG_OOB — MSG_DONTROUTE — MSG_PEEK
: The flags for `Unix.recv`[23.1], `Unix.recvfrom`[23.1], `Unix.send`[23.1] and `Unix.sendto`[23.1].

```
val recv : file_descr -> bytes -> int -> int -> msg_flag list -> int
```
Receive data from a connected socket.

```
val recvfrom :
  file_descr ->
  bytes -> int -> int -> msg_flag list -> int * sockaddr
```
Receive data from an unconnected socket.

```
val send : file_descr -> bytes -> int -> int -> msg_flag list -> int
```
Send data over a connected socket.

```
val send_substring :
  file_descr -> string -> int -> int -> msg_flag list -> int
```
Same as `send`, but take the data from a string instead of a byte sequence.

```
val sendto :
  file_descr ->
  bytes -> int -> int -> msg_flag list -> sockaddr -> int
```
Send data over an unconnected socket.

```
val sendto_substring :
  file_descr ->
  string -> int -> int -> msg_flag list -> sockaddr -> int
```
Same as `sendto`, but take the data from a string instead of a byte sequence.

Socket options

```
type socket_bool_option =
```
— SO_DEBUG
: Record debugging information

— SO_BROADCAST
: Permit sending of broadcast messages

— SO_REUSEADDR
: Allow reuse of local addresses for bind

— SO_KEEPALIVE
: Keep connection active

— SO_DONTROUTE
: Bypass the standard routing algorithms

— SO_OOBINLINE
: Leave out-of-band data in line

— SO_ACCEPTCONN
: Report whether socket listening is enabled

— TCP_NODELAY
: Control the Nagle algorithm for TCP sockets

— IPV6_ONLY
: Forbid binding an IPv6 socket to an IPv4 address

The socket options that can be consulted with `Unix.getsockopt`[23.1] and modified with `Unix.setsockopt`[23.1]. These options have a boolean (`true`/`false`) value.

```
type socket_int_option =
```

— SO_SNDBUF
: Size of send buffer

— SO_RCVBUF
: Size of received buffer

— SO_ERROR
: Deprecated. Use `Unix.getsockopt_error`[23.1] instead.

— SO_TYPE
: Report the socket type

— SO_RCVLOWAT
: Minimum number of bytes to process for input operations

— SO_SNDLOWAT
: Minimum number of bytes to process for output operations

The socket options that can be consulted with `Unix.getsockopt_int`[23.1] and modified with `Unix.setsockopt_int`[23.1]. These options have an integer value.

```
type socket_optint_option =
```

— SO_LINGER
: Whether to linger on closed connections that have data present, and for how long (in seconds)

The socket options that can be consulted with `Unix.getsockopt_optint`[23.1] and modified with `Unix.setsockopt_optint`[23.1]. These options have a value of type `int option`, with `None` meaning "disabled".

```
type socket_float_option =
```

— SO_RCVTIMEO
: Timeout for input operations

— SO_SNDTIMEO
: Timeout for output operations

The socket options that can be consulted with `Unix.getsockopt_float`[23.1] and modified with `Unix.setsockopt_float`[23.1]. These options have a floating-point value representing a time in seconds. The value 0 means infinite timeout.

```
val getsockopt : file_descr -> socket_bool_option -> bool
```

Return the current status of a boolean-valued option in the given socket.

```
val setsockopt : file_descr -> socket_bool_option -> bool -> unit
```
Set or clear a boolean-valued option in the given socket.

```
val getsockopt_int : file_descr -> socket_int_option -> int
```
Same as `Unix.getsockopt`[23.1] for an integer-valued socket option.

```
val setsockopt_int : file_descr -> socket_int_option -> int -> unit
```
Same as `Unix.setsockopt`[23.1] for an integer-valued socket option.

```
val getsockopt_optint : file_descr -> socket_optint_option -> int option
```
Same as `Unix.getsockopt`[23.1] for a socket option whose value is an `int option`.

```
val setsockopt_optint :
  file_descr -> socket_optint_option -> int option -> unit
```
Same as `Unix.setsockopt`[23.1] for a socket option whose value is an `int option`.

```
val getsockopt_float : file_descr -> socket_float_option -> float
```
Same as `Unix.getsockopt`[23.1] for a socket option whose value is a floating-point number.

```
val setsockopt_float : file_descr -> socket_float_option -> float -> unit
```
Same as `Unix.setsockopt`[23.1] for a socket option whose value is a floating-point number.

```
val getsockopt_error : file_descr -> error option
```
Return the error condition associated with the given socket, and clear it.

High-level network connection functions

```
val open_connection :
  sockaddr -> Pervasives.in_channel * Pervasives.out_channel
```
Connect to a server at the given address. Return a pair of buffered channels connected to the server. Remember to call `Pervasives.flush`[20.2] on the output channel at the right times to ensure correct synchronization.

```
val shutdown_connection : Pervasives.in_channel -> unit
```
"Shut down" a connection established with `Unix.open_connection`[23.1]; that is, transmit an end-of-file condition to the server reading on the other side of the connection. This does not fully close the file descriptor associated with the channel, which you must remember to free via `Pervasives.close_in`[20.2].

```
val establish_server :
  (Pervasives.in_channel -> Pervasives.out_channel -> unit) ->
  sockaddr -> unit
```

Establish a server on the given address. The function given as first argument is called for each connection with two buffered channels connected to the client. A new process is created for each connection. The function `Unix.establish_server`[23.1] never returns normally.

On Windows, it is not implemented. Use threads.

Host and protocol databases

```
type host_entry =
{  h_name : string ;
  h_aliases : string array ;
  h_addrtype : socket_domain ;
  h_addr_list : inet_addr array ;
}
```

Structure of entries in the `hosts` database.

```
type protocol_entry =
{  p_name : string ;
  p_aliases : string array ;
  p_proto : int ;
}
```

Structure of entries in the `protocols` database.

```
type service_entry =
{  s_name : string ;
  s_aliases : string array ;
  s_port : int ;
  s_proto : string ;
}
```

Structure of entries in the `services` database.

```
val gethostname : unit -> string
```

Return the name of the local host.

```
val gethostbyname : string -> host_entry
```

Find an entry in `hosts` with the given name.

Raises `Not_found` if no such entry exist.

```
val gethostbyaddr : inet_addr -> host_entry
```

Find an entry in `hosts` with the given address.

Raises `Not_found` if no such entry exist.

```
val getprotobyname : string -> protocol_entry
```

Find an entry in `protocols` with the given name.

Raises `Not_found` if no such entry exist.

`val getprotobynumber : int -> protocol_entry`

Find an entry in `protocols` with the given protocol number.

Raises `Not_found` if no such entry exist.

`val getservbyname : string -> string -> service_entry`

Find an entry in `services` with the given name.

Raises `Not_found` if no such entry exist.

`val getservbyport : int -> string -> service_entry`

Find an entry in `services` with the given service number.

Raises `Not_found` if no such entry exist.

```
type addr_info =
{  ai_family : socket_domain ;
```

Socket domain

```
  ai_socktype : socket_type ;
```

Socket type

```
  ai_protocol : int ;
```

Socket protocol number

```
  ai_addr : sockaddr ;
```

Address

```
  ai_canonname : string ;
```

Canonical host name

```
}
```

Address information returned by `Unix.getaddrinfo`[23.1].

```
type getaddrinfo_option =
  | AI_FAMILY of socket_domain
```

Impose the given socket domain

```
  | AI_SOCKTYPE of socket_type
```

Impose the given socket type

```
  | AI_PROTOCOL of int
```

Impose the given protocol

— AI_NUMERICHOST

Do not call name resolver, expect numeric IP address

— AI_CANONNAME

Fill the `ai_canonname` field of the result

— AI_PASSIVE
Set address to “any” address for use with `Unix.bind`[23.1]

Options to `Unix.getaddrinfo`[23.1].

```
val getaddrinfo :
  string -> string -> getaddrinfo_option list -> addr_info list
```

`getaddrinfo host service opts` returns a list of `Unix.addr_info`[23.1] records describing socket parameters and addresses suitable for communicating with the given host and service. The empty list is returned if the host or service names are unknown, or the constraints expressed in `opts` cannot be satisfied.

`host` is either a host name or the string representation of an IP address. `host` can be given as the empty string; in this case, the “any” address or the “loopback” address are used, depending whether `opts` contains `AI_PASSIVE`. `service` is either a service name or the string representation of a port number. `service` can be given as the empty string; in this case, the port field of the returned addresses is set to 0. `opts` is a possibly empty list of options that allows the caller to force a particular socket domain (e.g. IPv6 only or IPv4 only) or a particular socket type (e.g. TCP only or UDP only).

```
type name_info =
{  ni_hostname : string ;
```
Name or IP address of host

```
  ni_service : string ;
```
Name of service or port number

```
}
```

Host and service information returned by `Unix.getnameinfo`[23.1].

```
type getnameinfo_option =
```
— NI_NOFQDN
Do not qualify local host names

— NI_NUMERICHOST
Always return host as IP address

— NI_NAMEREQD
Fail if host name cannot be determined

— NI_NUMERICSERV
Always return service as port number

— NI_DGRAM
Consider the service as UDP-based instead of the default TCP

Options to `Unix.getnameinfo`[23.1].

```
val getnameinfo : sockaddr -> getnameinfo_option list -> name_info
```

`getnameinfo addr opts` returns the host name and service name corresponding to the socket address `addr`. `opts` is a possibly empty list of options that governs how these names are obtained.

Raises `Not_found` if an error occurs.

Terminal interface

The following functions implement the POSIX standard terminal interface. They provide control over asynchronous communication ports and pseudo-terminals. Refer to the `termios` man page for a complete description.

```
type terminal_io =
{  mutable c_ignbrk : bool ;
```

Ignore the break condition.

```
  mutable c_brkint : bool ;
```

Signal interrupt on break condition.

```
  mutable c_ignpar : bool ;
```

Ignore characters with parity errors.

```
  mutable c_parmrk : bool ;
```

Mark parity errors.

```
  mutable c_inpck : bool ;
```

Enable parity check on input.

```
  mutable c_istrip : bool ;
```

Strip 8th bit on input characters.

```
  mutable c_inlcr : bool ;
```

Map NL to CR on input.

```
  mutable c_igncr : bool ;
```

Ignore CR on input.

```
  mutable c_icrnl : bool ;
```

Map CR to NL on input.

```
  mutable c_ixon : bool ;
```

Recognize XON/XOFF characters on input.

```
  mutable c_ixoff : bool ;
```

Emit XON/XOFF chars to control input flow.

```
  mutable c_opost : bool ;
```

Enable output processing.

```
  mutable c_obaud : int ;
```

Output baud rate (0 means close connection).

`mutable c_ibaud : int ;`
Input baud rate.

`mutable c_csize : int ;`
Number of bits per character (5-8).

`mutable c_cstopb : int ;`
Number of stop bits (1-2).

`mutable c_cread : bool ;`
Reception is enabled.

`mutable c_parenb : bool ;`
Enable parity generation and detection.

`mutable c_parodd : bool ;`
Specify odd parity instead of even.

`mutable c_hupcl : bool ;`
Hang up on last close.

`mutable c_clocal : bool ;`
Ignore modem status lines.

`mutable c_isig : bool ;`
Generate signal on INTR, QUIT, SUSP.

`mutable c_icanon : bool ;`
Enable canonical processing (line buffering and editing)

`mutable c_noflsh : bool ;`
Disable flush after INTR, QUIT, SUSP.

`mutable c_echo : bool ;`
Echo input characters.

`mutable c_echoe : bool ;`
Echo ERASE (to erase previous character).

`mutable c_echok : bool ;`
Echo KILL (to erase the current line).

`mutable c_echonl : bool ;`
Echo NL even if c_echo is not set.

`mutable c_vintr : char ;`
Interrupt character (usually ctrl-C).

`mutable c_vquit : char ;`

Quit character (usually ctrl-“).

`mutable c_verase : char ;`
Erase character (usually DEL or ctrl-H).

`mutable c_vkill : char ;`
Kill line character (usually ctrl-U).

`mutable c_veof : char ;`
End-of-file character (usually ctrl-D).

`mutable c_veol : char ;`
Alternate end-of-line char. (usually none).

`mutable c_vmin : int ;`
Minimum number of characters to read before the read request is satisfied.

`mutable c_vtime : int ;`
Maximum read wait (in 0.1s units).

`mutable c_vstart : char ;`
Start character (usually ctrl-Q).

`mutable c_vstop : char ;`
Stop character (usually ctrl-S).

`}`

`val tcgetattr : file_descr -> terminal_io`

Return the status of the terminal referred to by the given file descriptor. On Windows, not implemented.

`type setattr_when =`

`val tcsetattr : file_descr -> setattr_when -> terminal_io -> unit`

Set the status of the terminal referred to by the given file descriptor. The second argument indicates when the status change takes place: immediately (`TCSANOW`), when all pending output has been transmitted (`TCSADRAIN`), or after flushing all input that has been received but not read (`TCSAFLUSH`). `TCSADRAIN` is recommended when changing the output parameters; `TCSAFLUSH`, when changing the input parameters.

On Windows, not implemented.

`val tcsendbreak : file_descr -> int -> unit`

Send a break condition on the given file descriptor. The second argument is the duration of the break, in 0.1s units; 0 means standard duration (0.25s).

On Windows, not implemented.

`val tcdrain : file_descr -> unit`

Waits until all output written on the given file descriptor has been transmitted.

On Windows, not implemented.

```
type flush_queue =
```

```
val tcflush : file_descr -> flush_queue -> unit
```

Discard data written on the given file descriptor but not yet transmitted, or data received but not yet read, depending on the second argument: `TCIFLUSH` flushes data received but not read, `TCOFLUSH` flushes data written but not transmitted, and `TCIOFLUSH` flushes both.

On Windows, not implemented.

```
type flow_action =
```

```
val tcflow : file_descr -> flow_action -> unit
```

Suspend or restart reception or transmission of data on the given file descriptor, depending on the second argument: `TCOOFF` suspends output, `TCOON` restarts output, `TCIOFF` transmits a STOP character to suspend input, and `TCION` transmits a START character to restart input.

On Windows, not implemented.

```
val setsid : unit -> int
```

Put the calling process in a new session and detach it from its controlling terminal.

On Windows, not implemented.

23.2 Module `UnixLabels`: labelized version of the interface

This module is identical to `Unix` (23.1), and only differs by the addition of labels. You may see these labels directly by looking at `unixLabels.mli`, or by using the `ocamlbrowser` tool.

Windows:

The Cygwin port of OCaml fully implements all functions from the Unix module. The native Win32 ports implement a subset of them. Below is a list of the functions that are not implemented, or only partially implemented, by the Win32 ports. Functions not mentioned are fully implemented and behave as described previously in this chapter.

Functions	Comment
`fork`	not implemented, use `create_process` or threads
`wait`	not implemented, use `waitpid`
`waitpid`	can only wait for a given PID, not any child process
`getppid`	not implemented (meaningless under Windows)
`nice`	not implemented
`truncate`, `ftruncate`	not implemented
`link`	implemented (since 3.02)
`symlink`, `readlink`	implemented (since 4.03.0)
`access`	execute permission `X_OK` cannot be tested, it just tests for read permission instead
`fchmod`	not implemented
`chown`, `fchown`	not implemented (make no sense on a DOS file system)
`umask`	not implemented
`mkfifo`	not implemented
`kill`	partially implemented (since 4.00.0): only the `sigkill` signal is implemented
`pause`	not implemented (no inter-process signals in Windows)
`alarm`	not implemented
`times`	partially implemented, will not report timings for child processes
`getitimer`, `setitimer`	not implemented
`getuid`, `geteuid`, `getgid`, `getegid`	always return 1
`getgroups`	always returns `[|1|]` (since 2.00)
`setuid`, `setgid`, `setgroups`	not implemented
`getpwnam`, `getpwuid`	always raise `Not_found`
`getgrnam`, `getgrgid`	always raise `Not_found`
type `socket_domain`	`PF_INET` is fully supported; `PF_INET6` is fully supported (since 4.01.0); `PF_UNIX` is not supported
`establish_server`	not implemented; use threads
terminal functions (`tc*`)	not implemented

Chapter 24

The num library: arbitrary-precision rational arithmetic

The `num` library implements integer arithmetic and rational arithmetic in arbitrary precision.

More documentation on the functions provided in this library can be found in *The CAML Numbers Reference Manual* by Valérie Ménissier-Morain, technical report 141, INRIA, july 1992 (available electronically, `http://hal.inria.fr/docs/00/07/00/27/PDF/RT-0141.pdf`).

Programs that use the `num` library must be linked as follows:

```
ocamlc other options nums.cma other files
ocamlopt other options nums.cmxa other files
```

For interactive use of the `nums` library, do:

```
ocamlmktop -o mytop nums.cma
./mytop
```

or (if dynamic linking of C libraries is supported on your platform), start `ocaml` and type `#load "nums.cma";;`.

24.1 Module `Num` : Operation on arbitrary-precision numbers.

Numbers (type `num`) are arbitrary-precision rational numbers, plus the special elements `1/0` (infinity) and `0/0` (undefined).

```
type num =
  | Int of int
  | Big_int of Big_int.big_int
  | Ratio of Ratio.ratio
```

The type of numbers.

Arithmetic operations

`val (+/) : num -> num -> num`
Same as `Num.add_num`[24.1].

`val add_num : num -> num -> num`
Addition

`val minus_num : num -> num`
Unary negation.

`val (-/) : num -> num -> num`
Same as `Num.sub_num`[24.1].

`val sub_num : num -> num -> num`
Subtraction

`val ( */ ) : num -> num -> num`
Same as `Num.mult_num`[24.1].

`val mult_num : num -> num -> num`
Multiplication

`val square_num : num -> num`
Squaring

`val (//) : num -> num -> num`
Same as `Num.div_num`[24.1].

`val div_num : num -> num -> num`
Division

`val quo_num : num -> num -> num`
Euclidean division: quotient.

`val mod_num : num -> num -> num`
Euclidean division: remainder.

`val ( **/ ) : num -> num -> num`
Same as `Num.power_num`[24.1].

`val power_num : num -> num -> num`
Exponentiation

`val abs_num : num -> num`

Absolute value.

`val succ_num : num -> num`
`succ n` is `n+1`

`val pred_num : num -> num`
`pred n` is `n-1`

`val incr_num : num Pervasives.ref -> unit`
`incr r` is `r:=!r+1`, where `r` is a reference to a number.

`val decr_num : num Pervasives.ref -> unit`
`decr r` is `r:=!r-1`, where `r` is a reference to a number.

`val is_integer_num : num -> bool`
Test if a number is an integer

The four following functions approximate a number by an integer :

`val integer_num : num -> num`
`integer_num n` returns the integer closest to `n`. In case of ties, rounds towards zero.

`val floor_num : num -> num`
`floor_num n` returns the largest integer smaller or equal to `n`.

`val round_num : num -> num`
`round_num n` returns the integer closest to `n`. In case of ties, rounds off zero.

`val ceiling_num : num -> num`
`ceiling_num n` returns the smallest integer bigger or equal to `n`.

`val sign_num : num -> int`
Return `-1`, `0` or `1` according to the sign of the argument.

Comparisons between numbers

```
val (=/) : num -> num -> bool
val (</) : num -> num -> bool
val (>/) : num -> num -> bool
val (<=/) : num -> num -> bool
val (>=/) : num -> num -> bool
val (<>/) : num -> num -> bool
val eq_num : num -> num -> bool
val lt_num : num -> num -> bool
```

```
val le_num : num -> num -> bool
val gt_num : num -> num -> bool
val ge_num : num -> num -> bool
val compare_num : num -> num -> int
```
Return `-1`, `0` or `1` if the first argument is less than, equal to, or greater than the second argument.

```
val max_num : num -> num -> num
```
Return the greater of the two arguments.

```
val min_num : num -> num -> num
```
Return the smaller of the two arguments.

Coercions with strings

```
val string_of_num : num -> string
```
Convert a number to a string, using fractional notation.

```
val approx_num_fix : int -> num -> string
```
See `Num.approx_num_exp`[24.1].

```
val approx_num_exp : int -> num -> string
```
Approximate a number by a decimal. The first argument is the required precision. The second argument is the number to approximate. `Num.approx_num_fix`[24.1] uses decimal notation; the first argument is the number of digits after the decimal point. `approx_num_exp` uses scientific (exponential) notation; the first argument is the number of digits in the mantissa.

```
val num_of_string : string -> num
```
Convert a string to a number. Raise `Failure "num_of_string"` if the given string is not a valid representation of an integer

Coercions between numerical types

```
val int_of_num : num -> int
val num_of_int : int -> num
val nat_of_num : num -> Nat.nat
val num_of_nat : Nat.nat -> num
val num_of_big_int : Big_int.big_int -> num
val big_int_of_num : num -> Big_int.big_int
val ratio_of_num : num -> Ratio.ratio
val num_of_ratio : Ratio.ratio -> num
val float_of_num : num -> float
```

24.2 Module `Big_int` : Operations on arbitrary-precision integers.

Big integers (type `big_int`) are signed integers of arbitrary size.

`type big_int`
The type of big integers.

`val zero_big_int : big_int`
The big integer `0`.

`val unit_big_int : big_int`
The big integer `1`.

Arithmetic operations

`val minus_big_int : big_int -> big_int`
Unary negation.

`val abs_big_int : big_int -> big_int`
Absolute value.

`val add_big_int : big_int -> big_int -> big_int`
Addition.

`val succ_big_int : big_int -> big_int`
Successor (add 1).

`val add_int_big_int : int -> big_int -> big_int`
Addition of a small integer to a big integer.

`val sub_big_int : big_int -> big_int -> big_int`
Subtraction.

`val pred_big_int : big_int -> big_int`
Predecessor (subtract 1).

`val mult_big_int : big_int -> big_int -> big_int`
Multiplication of two big integers.

`val mult_int_big_int : int -> big_int -> big_int`
Multiplication of a big integer by a small integer

`val square_big_int : big_int -> big_int`

Return the square of the given big integer

`val sqrt_big_int : big_int -> big_int`

`sqrt_big_int a` returns the integer square root of `a`, that is, the largest big integer `r` such that `r * r <= a`. Raise `Invalid_argument` if `a` is negative.

`val quomod_big_int : big_int -> big_int -> big_int * big_int`

Euclidean division of two big integers. The first part of the result is the quotient, the second part is the remainder. Writing `(q,r) = quomod_big_int a b`, we have `a = q * b + r` and `0 <= r < |b|`. Raise `Division_by_zero` if the divisor is zero.

`val div_big_int : big_int -> big_int -> big_int`

Euclidean quotient of two big integers. This is the first result `q` of `quomod_big_int` (see above).

`val mod_big_int : big_int -> big_int -> big_int`

Euclidean modulus of two big integers. This is the second result `r` of `quomod_big_int` (see above).

`val gcd_big_int : big_int -> big_int -> big_int`

Greatest common divisor of two big integers.

`val power_int_positive_int : int -> int -> big_int`

`val power_big_int_positive_int : big_int -> int -> big_int`

`val power_int_positive_big_int : int -> big_int -> big_int`

`val power_big_int_positive_big_int : big_int -> big_int -> big_int`

Exponentiation functions. Return the big integer representing the first argument `a` raised to the power `b` (the second argument). Depending on the function, `a` and `b` can be either small integers or big integers. Raise `Invalid_argument` if `b` is negative.

Comparisons and tests

`val sign_big_int : big_int -> int`

Return `0` if the given big integer is zero, `1` if it is positive, and `-1` if it is negative.

`val compare_big_int : big_int -> big_int -> int`

`compare_big_int a b` returns `0` if `a` and `b` are equal, `1` if `a` is greater than `b`, and `-1` if `a` is smaller than `b`.

`val eq_big_int : big_int -> big_int -> bool`

`val le_big_int : big_int -> big_int -> bool`

`val ge_big_int : big_int -> big_int -> bool`

`val lt_big_int : big_int -> big_int -> bool`

`val gt_big_int : big_int -> big_int -> bool`

Usual boolean comparisons between two big integers.

`val max_big_int : big_int -> big_int -> big_int`

Return the greater of its two arguments.

`val min_big_int : big_int -> big_int -> big_int`

Return the smaller of its two arguments.

`val num_digits_big_int : big_int -> int`

Return the number of machine words used to store the given big integer.

`val num_bits_big_int : big_int -> int`

Return the number of significant bits in the absolute value of the given big integer. `num_bits_big_int a` returns 0 if `a` is 0; otherwise it returns a positive integer `n` such that `2^(n-1) <= |a| < 2^n`.

Since: 4.03.0

Conversions to and from strings

`val string_of_big_int : big_int -> string`

Return the string representation of the given big integer, in decimal (base 10).

`val big_int_of_string : string -> big_int`

Convert a string to a big integer, in decimal. The string consists of an optional `-` or `+` sign, followed by one or several decimal digits.

Conversions to and from other numerical types

`val big_int_of_int : int -> big_int`

Convert a small integer to a big integer.

`val is_int_big_int : big_int -> bool`

Test whether the given big integer is small enough to be representable as a small integer (type `int`) without loss of precision. On a 32-bit platform, `is_int_big_int a` returns `true` if and only if `a` is between 2^{30} and 2^{30}-1. On a 64-bit platform, `is_int_big_int a` returns `true` if and only if `a` is between -2^{62} and 2^{62}-1.

`val int_of_big_int : big_int -> int`

Convert a big integer to a small integer (type `int`). Raises `Failure "int_of_big_int"` if the big integer is not representable as a small integer.

`val big_int_of_int32 : int32 -> big_int`

Convert a 32-bit integer to a big integer.

`val big_int_of_nativeint : nativeint -> big_int`

Convert a native integer to a big integer.

`val big_int_of_int64 : int64 -> big_int`

Convert a 64-bit integer to a big integer.

`val int32_of_big_int : big_int -> int32`

Convert a big integer to a 32-bit integer. Raises `Failure` if the big integer is outside the range [-2^{31}, 2^{31}-1].

`val nativeint_of_big_int : big_int -> nativeint`

Convert a big integer to a native integer. Raises `Failure` if the big integer is outside the range `[Nativeint.min_int, Nativeint.max_int]`.

`val int64_of_big_int : big_int -> int64`

Convert a big integer to a 64-bit integer. Raises `Failure` if the big integer is outside the range [-2^{63}, 2^{63}-1].

`val float_of_big_int : big_int -> float`

Returns a floating-point number approximating the given big integer.

Bit-oriented operations

`val and_big_int : big_int -> big_int -> big_int`

Bitwise logical 'and'. The arguments must be positive or zero.

`val or_big_int : big_int -> big_int -> big_int`

Bitwise logical 'or'. The arguments must be positive or zero.

`val xor_big_int : big_int -> big_int -> big_int`

Bitwise logical 'exclusive or'. The arguments must be positive or zero.

`val shift_left_big_int : big_int -> int -> big_int`

`shift_left_big_int b n` returns `b` shifted left by `n` bits. Equivalent to multiplication by 2^n.

`val shift_right_big_int : big_int -> int -> big_int`

`shift_right_big_int b n` returns `b` shifted right by `n` bits. Equivalent to division by 2^n with the result being rounded towards minus infinity.

`val shift_right_towards_zero_big_int : big_int -> int -> big_int`

`shift_right_towards_zero_big_int b n` returns `b` shifted right by `n` bits. The shift is performed on the absolute value of `b`, and the result has the same sign as `b`. Equivalent to division by 2^n with the result being rounded towards zero.

`val extract_big_int : big_int -> int -> int -> big_int`

`extract_big_int bi ofs n` returns a nonnegative number corresponding to bits `ofs` to `ofs + n - 1` of the binary representation of `bi`. If `bi` is negative, a two's complement representation is used.

24.3 Module `Arith_status` : Flags that control rational arithmetic.

`val arith_status : unit -> unit`

Print the current status of the arithmetic flags.

`val get_error_when_null_denominator : unit -> bool`

See `Arith_status.set_error_when_null_denominator`[24.3].

`val set_error_when_null_denominator : bool -> unit`

Get or set the flag `null_denominator`. When on, attempting to create a rational with a null denominator raises an exception. When off, rationals with null denominators are accepted. Initially: on.

`val get_normalize_ratio : unit -> bool`

See `Arith_status.set_normalize_ratio`[24.3].

`val set_normalize_ratio : bool -> unit`

Get or set the flag `normalize_ratio`. When on, rational numbers are normalized after each operation. When off, rational numbers are not normalized until printed. Initially: off.

`val get_normalize_ratio_when_printing : unit -> bool`

See `Arith_status.set_normalize_ratio_when_printing`[24.3].

`val set_normalize_ratio_when_printing : bool -> unit`

Get or set the flag `normalize_ratio_when_printing`. When on, rational numbers are normalized before being printed. When off, rational numbers are printed as is, without normalization. Initially: on.

`val get_approx_printing : unit -> bool`

See `Arith_status.set_approx_printing`[24.3].

`val set_approx_printing : bool -> unit`

Get or set the flag `approx_printing`. When on, rational numbers are printed as a decimal approximation. When off, rational numbers are printed as a fraction. Initially: off.

`val get_floating_precision : unit -> int`

See `Arith_status.set_floating_precision`[24.3].

`val set_floating_precision : int -> unit`

Get or set the parameter `floating_precision`. This parameter is the number of digits displayed when `approx_printing` is on. Initially: 12.

Chapter 25

The str library: regular expressions and string processing

The `str` library provides high-level string processing functions, some based on regular expressions. It is intended to support the kind of file processing that is usually performed with scripting languages such as `awk`, `perl` or `sed`.

Programs that use the `str` library must be linked as follows:

```
ocamlc other options str.cma other files
ocamlopt other options str.cmxa other files
```

For interactive use of the `str` library, do:

```
ocamlmktop -o mytop str.cma
./mytop
```

or (if dynamic linking of C libraries is supported on your platform), start `ocaml` and type `#load "str.cma";;`.

25.1 Module `Str` : Regular expressions and high-level string processing

Regular expressions

`type regexp`

The type of compiled regular expressions.

`val regexp : string -> regexp`

Compile a regular expression. The following constructs are recognized:

- `.` Matches any character except newline.
- `*` (postfix) Matches the preceding expression zero, one or several times

- `+` (postfix) Matches the preceding expression one or several times
- `?` (postfix) Matches the preceding expression once or not at all
- `[..]` Character set. Ranges are denoted with `-`, as in `[a-z]`. An initial `^`, as in `[^0-9]`, complements the set. To include a `]` character in a set, make it the first character of the set. To include a `-` character in a set, make it the first or the last character of the set.
- `^` Matches at beginning of line: either at the beginning of the matched string, or just after a '"n' character.
- `$` Matches at end of line: either at the end of the matched string, or just before a '"n' character.
- `\|` (infix) Alternative between two expressions.
- `\(..\)` Grouping and naming of the enclosed expression.
- `\1` The text matched by the first `\(...\)` expression (`\2` for the second expression, and so on up to `\9`).
- `\b` Matches word boundaries.
- `\` Quotes special characters. The special characters are `$^\.*+?[]`.

Note: the argument to `regexp` is usually a string literal. In this case, any backslash character in the regular expression must be doubled to make it past the OCaml string parser. For example, the following expression:

```
let r = Str.regexp "hello \\([A-Za-z]+\\)" in
     Str.replace_first r "\\1" "hello world"
```

returns the string `"world"`.

In particular, if you want a regular expression that matches a single backslash character, you need to quote it in the argument to `regexp` (according to the last item of the list above) by adding a second backslash. Then you need to quote both backslashes (according to the syntax of string constants in OCaml) by doubling them again, so you need to write four backslash characters: `Str.regexp "\\\\"`.

`val regexp_case_fold : string -> regexp`

Same as `regexp`, but the compiled expression will match text in a case-insensitive way: uppercase and lowercase letters will be considered equivalent.

`val quote : string -> string`

`Str.quote s` returns a regexp string that matches exactly `s` and nothing else.

`val regexp_string : string -> regexp`

`Str.regexp_string s` returns a regular expression that matches exactly `s` and nothing else.

`val regexp_string_case_fold : string -> regexp`

`Str.regexp_string_case_fold` is similar to `Str.regexp_string`[25.1], but the regexp matches in a case-insensitive way.

String matching and searching

`val string_match : regexp -> string -> int -> bool`

`string_match r s start` tests whether a substring of `s` that starts at position `start` matches the regular expression `r`. The first character of a string has position `0`, as usual.

`val search_forward : regexp -> string -> int -> int`

`search_forward r s start` searches the string `s` for a substring matching the regular expression `r`. The search starts at position `start` and proceeds towards the end of the string. Return the position of the first character of the matched substring.

Raises `Not_found` if no substring matches.

`val search_backward : regexp -> string -> int -> int`

`search_backward r s last` searches the string `s` for a substring matching the regular expression `r`. The search first considers substrings that start at position `last` and proceeds towards the beginning of string. Return the position of the first character of the matched substring.

Raises `Not_found` if no substring matches.

`val string_partial_match : regexp -> string -> int -> bool`

Similar to `Str.string_match`[25.1], but also returns true if the argument string is a prefix of a string that matches. This includes the case of a true complete match.

`val matched_string : string -> string`

`matched_string s` returns the substring of `s` that was matched by the last call to one of the following matching or searching functions:

- `Str.string_match`[25.1]
- `Str.search_forward`[25.1]
- `Str.search_backward`[25.1]
- `Str.string_partial_match`[25.1]
- `Str.global_substitute`[25.1]
- `Str.substitute_first`[25.1]

provided that none of the following functions was called inbetween:

- `Str.global_replace`[25.1]
- `Str.replace_first`[25.1]
- `Str.split`[25.1]
- `Str.bounded_split`[25.1]
- `Str.split_delim`[25.1]
- `Str.bounded_split_delim`[25.1]

- `Str.full_split`[25.1]
- `Str.bounded_full_split`[25.1]

Note: in the case of `global_substitute` and `substitute_first`, a call to `matched_string` is only valid within the `subst` argument, not after `global_substitute` or `substitute_first` returns.

The user must make sure that the parameter `s` is the same string that was passed to the matching or searching function.

`val match_beginning : unit -> int`

`match_beginning()` returns the position of the first character of the substring that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details).

`val match_end : unit -> int`

`match_end()` returns the position of the character following the last character of the substring that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details).

`val matched_group : int -> string -> string`

`matched_group n s` returns the substring of `s` that was matched by the `n`th group `\(...\)` of the regular expression that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details). The user must make sure that the parameter `s` is the same string that was passed to the matching or searching function.

Raises `Not_found` if the `n`th group of the regular expression was not matched. This can happen with groups inside alternatives `\|`, options `?` or repetitions `*`. For instance, the empty string will match `\(a\)*`, but `matched_group 1 ""` will raise `Not_found` because the first group itself was not matched.

`val group_beginning : int -> int`

`group_beginning n` returns the position of the first character of the substring that was matched by the `n`th group of the regular expression that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details).

Raises

- `Not_found` if the `n`th group of the regular expression was not matched.
- `Invalid_argument` if there are fewer than `n` groups in the regular expression.

`val group_end : int -> int`

`group_end n` returns the position of the character following the last character of substring that was matched by the `n`th group of the regular expression that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details).

Raises

- `Not_found` if the `n`th group of the regular expression was not matched.
- `Invalid_argument` if there are fewer than `n` groups in the regular expression.

Replacement

`val global_replace : regexp -> string -> string -> string`

`global_replace regexp templ s` returns a string identical to `s`, except that all substrings of `s` that match `regexp` have been replaced by `templ`. The replacement template `templ` can contain `\1`, `\2`, etc; these sequences will be replaced by the text matched by the corresponding group in the regular expression. `\0` stands for the text matched by the whole regular expression.

`val replace_first : regexp -> string -> string -> string`

Same as `Str.global_replace`[25.1], except that only the first substring matching the regular expression is replaced.

`val global_substitute : regexp -> (string -> string) -> string -> string`

`global_substitute regexp subst s` returns a string identical to `s`, except that all substrings of `s` that match `regexp` have been replaced by the result of function `subst`. The function `subst` is called once for each matching substring, and receives `s` (the whole text) as argument.

`val substitute_first : regexp -> (string -> string) -> string -> string`

Same as `Str.global_substitute`[25.1], except that only the first substring matching the regular expression is replaced.

`val replace_matched : string -> string -> string`

`replace_matched repl s` returns the replacement text `repl` in which `\1`, `\2`, etc. have been replaced by the text matched by the corresponding groups in the regular expression that was matched by the last call to a matching or searching function (see `Str.matched_string`[25.1] for details). `s` must be the same string that was passed to the matching or searching function.

Splitting

`val split : regexp -> string -> string list`

`split r s` splits `s` into substrings, taking as delimiters the substrings that match `r`, and returns the list of substrings. For instance, `split (regexp "[ \t]+") s` splits `s` into blank-separated words. An occurrence of the delimiter at the beginning or at the end of the string is ignored.

`val bounded_split : regexp -> string -> int -> string list`

Same as `Str.split`[25.1], but splits into at most `n` substrings, where `n` is the extra integer parameter.

`val split_delim : regexp -> string -> string list`

Same as `Str.split`[25.1] but occurrences of the delimiter at the beginning and at the end of the string are recognized and returned as empty strings in the result. For instance, `split_delim (regexp " ") " abc "` returns `["", "abc", ""]`, while `split` with the same arguments returns `["abc"]`.

`val bounded_split_delim : regexp -> string -> int -> string list`

Same as `Str.bounded_split`[25.1], but occurrences of the delimiter at the beginning and at the end of the string are recognized and returned as empty strings in the result.

```
type split_result =
  | Text of string
  | Delim of string
```

`val full_split : regexp -> string -> split_result list`

Same as `Str.split_delim`[25.1], but returns the delimiters as well as the substrings contained between delimiters. The former are tagged `Delim` in the result list; the latter are tagged `Text`. For instance, `full_split (regexp "[{}]") "{ab}"` returns `[Delim "{"; Text "ab"; Delim "}"]`.

`val bounded_full_split : regexp -> string -> int -> split_result list`

Same as `Str.bounded_split_delim`[25.1], but returns the delimiters as well as the substrings contained between delimiters. The former are tagged `Delim` in the result list; the latter are tagged `Text`.

Extracting substrings

`val string_before : string -> int -> string`

`string_before s n` returns the substring of all characters of `s` that precede position `n` (excluding the character at position `n`).

`val string_after : string -> int -> string`

`string_after s n` returns the substring of all characters of `s` that follow position `n` (including the character at position `n`).

`val first_chars : string -> int -> string`

`first_chars s n` returns the first `n` characters of `s`. This is the same function as `Str.string_before`[25.1].

`val last_chars : string -> int -> string`

`last_chars s n` returns the last `n` characters of `s`.

Chapter 26

The threads library

The `threads` library allows concurrent programming in OCaml. It provides multiple threads of control (also called lightweight processes) that execute concurrently in the same memory space. Threads communicate by in-place modification of shared data structures, or by sending and receiving data on communication channels.

The `threads` library is implemented by time-sharing on a single processor. It will not take advantage of multi-processor machines. Using this library will therefore never make programs run faster. However, many programs are easier to write when structured as several communicating processes.

Two implementations of the `threads` library are available, depending on the capabilities of the operating system:

- System threads. This implementation builds on the OS-provided threads facilities: POSIX 1003.1c threads for Unix, and Win32 threads for Windows. When available, system threads support both bytecode and native-code programs.
- VM-level threads. This implementation performs time-sharing and context switching at the level of the OCaml virtual machine (bytecode interpreter). It is available on Unix systems, and supports only bytecode programs. It cannot be used with native-code programs.

Programs that use system threads must be linked as follows:

```
ocamlc -thread other options unix.cma threads.cma other files
ocamlopt -thread other options unix.cmxa threads.cmxa other files
```

Compilation units that use the `threads` library must also be compiled with the `-thread` option (see chapter 8).

Programs that use VM-level threads must be compiled with the `-vmthread` option to `ocamlc` (see chapter 8), and be linked as follows:

```
ocamlc -vmthread other options threads.cma other files
```

Compilation units that use `threads` library must also be compiled with the `-vmthread` option (see chapter 8).

26.1 Module `Thread` : Lightweight threads for Posix `1003.1c` and Win32.

`type t`

The type of thread handles.

Thread creation and termination

`val create : ('a -> 'b) -> 'a -> t`

`Thread.create funct arg` creates a new thread of control, in which the function application `funct arg` is executed concurrently with the other threads of the program. The application of `Thread.create` returns the handle of the newly created thread. The new thread terminates when the application `funct arg` returns, either normally or by raising an uncaught exception. In the latter case, the exception is printed on standard error, but not propagated back to the parent thread. Similarly, the result of the application `funct arg` is discarded and not directly accessible to the parent thread.

`val self : unit -> t`

Return the thread currently executing.

`val id : t -> int`

Return the identifier of the given thread. A thread identifier is an integer that identifies uniquely the thread. It can be used to build data structures indexed by threads.

`val exit : unit -> unit`

Terminate prematurely the currently executing thread.

`val kill : t -> unit`

Terminate prematurely the thread whose handle is given.

Suspending threads

`val delay : float -> unit`

`delay d` suspends the execution of the calling thread for `d` seconds. The other program threads continue to run during this time.

`val join : t -> unit`

`join th` suspends the execution of the calling thread until the thread `th` has terminated.

`val wait_read : Unix.file_descr -> unit`

See `Thread.wait_write`[26.1].

`val wait_write : Unix.file_descr -> unit`

This function does nothing in this implementation.

`val wait_timed_read : Unix.file_descr -> float -> bool`

See `Thread.wait_timed_read`[26.1].

`val wait_timed_write : Unix.file_descr -> float -> bool`

Suspend the execution of the calling thread until at least one character is available for reading (`wait_read`) or one character can be written without blocking (`wait_write`) on the given Unix file descriptor. Wait for at most the amount of time given as second argument (in seconds). Return `true` if the file descriptor is ready for input/output and `false` if the timeout expired.

These functions return immediately `true` in the Win32 implementation.

```
val select :
  Unix.file_descr list ->
  Unix.file_descr list ->
  Unix.file_descr list ->
  float -> Unix.file_descr list * Unix.file_descr list * Unix.file_descr list
```

Suspend the execution of the calling thead until input/output becomes possible on the given Unix file descriptors. The arguments and results have the same meaning as for `Unix.select`. This function is not implemented yet under Win32.

`val wait_pid : int -> int * Unix.process_status`

`wait_pid p` suspends the execution of the calling thread until the process specified by the process identifier `p` terminates. Returns the pid of the child caught and its termination status, as per `Unix.wait`. This function is not implemented under MacOS.

`val yield : unit -> unit`

Re-schedule the calling thread without suspending it. This function can be used to give scheduling hints, telling the scheduler that now is a good time to switch to other threads.

Management of signals

Signal handling follows the POSIX thread model: signals generated by a thread are delivered to that thread; signals generated externally are delivered to one of the threads that does not block it. Each thread possesses a set of blocked signals, which can be modified using `Thread.sigmask`[26.1]. This set is inherited at thread creation time. Per-thread signal masks are supported only by the system thread library under Unix, but not under Win32, nor by the VM thread library.

`val sigmask : Unix.sigprocmask_command -> int list -> int list`

`sigmask cmd sigs` changes the set of blocked signals for the calling thread. If `cmd` is `SIG_SETMASK`, blocked signals are set to those in the list `sigs`. If `cmd` is `SIG_BLOCK`, the signals in `sigs` are added to the set of blocked signals. If `cmd` is `SIG_UNBLOCK`, the signals in `sigs` are removed from the set of blocked signals. `sigmask` returns the set of previously blocked signals for the thread.

`val wait_signal : int list -> int`

`wait_signal sigs` suspends the execution of the calling thread until the process receives one of the signals specified in the list `sigs`. It then returns the number of the signal received. Signal handlers attached to the signals in `sigs` will not be invoked. The signals `sigs` are expected to be blocked before calling `wait_signal`.

26.2 Module `Mutex` : Locks for mutual exclusion.

Mutexes (mutual-exclusion locks) are used to implement critical sections and protect shared mutable data structures against concurrent accesses. The typical use is (if `m` is the mutex associated with the data structure `D`):

```
Mutex.lock m;
(* Critical section that operates over D *);
Mutex.unlock m
```

`type t`

The type of mutexes.

`val create : unit -> t`

Return a new mutex.

`val lock : t -> unit`

Lock the given mutex. Only one thread can have the mutex locked at any time. A thread that attempts to lock a mutex already locked by another thread will suspend until the other thread unlocks the mutex.

`val try_lock : t -> bool`

Same as `Mutex.lock`[26.2], but does not suspend the calling thread if the mutex is already locked: just return `false` immediately in that case. If the mutex is unlocked, lock it and return `true`.

`val unlock : t -> unit`

Unlock the given mutex. Other threads suspended trying to lock the mutex will restart.

26.3 Module `Condition` : Condition variables to synchronize between threads.

Condition variables are used when one thread wants to wait until another thread has finished doing something: the former thread 'waits' on the condition variable, the latter thread 'signals' the

condition when it is done. Condition variables should always be protected by a mutex. The typical use is (if `D` is a shared data structure, `m` its mutex, and `c` is a condition variable):

```
Mutex.lock m;
while (* some predicate P over D is not satisfied *) do
  Condition.wait c m
done;
(* Modify D *)
if (* the predicate P over D is now satified *) then Condition.signal c;
Mutex.unlock m
```

`type t`

The type of condition variables.

`val create : unit -> t`

Return a new condition variable.

`val wait : t -> Mutex.t -> unit`

`wait c m` atomically unlocks the mutex `m` and suspends the calling process on the condition variable `c`. The process will restart after the condition variable `c` has been signalled. The mutex `m` is locked again before `wait` returns.

`val signal : t -> unit`

`signal c` restarts one of the processes waiting on the condition variable `c`.

`val broadcast : t -> unit`

`broadcast c` restarts all processes waiting on the condition variable `c`.

26.4 Module `Event` : First-class synchronous communication.

This module implements synchronous inter-thread communications over channels. As in John Reppy's Concurrent ML system, the communication events are first-class values: they can be built and combined independently before being offered for communication.

`type 'a channel`

The type of communication channels carrying values of type `'a`.

`val new_channel : unit -> 'a channel`

Return a new channel.

`type +'a event`

The type of communication events returning a result of type `'a`.

`val send : 'a channel -> 'a -> unit event`

`send ch v` returns the event consisting in sending the value `v` over the channel `ch`. The result value of this event is `()`.

`val receive : 'a channel -> 'a event`

`receive ch` returns the event consisting in receiving a value from the channel `ch`. The result value of this event is the value received.

`val always : 'a -> 'a event`

`always v` returns an event that is always ready for synchronization. The result value of this event is `v`.

`val choose : 'a event list -> 'a event`

`choose evl` returns the event that is the alternative of all the events in the list `evl`.

`val wrap : 'a event -> ('a -> 'b) -> 'b event`

`wrap ev fn` returns the event that performs the same communications as `ev`, then applies the post-processing function `fn` on the return value.

`val wrap_abort : 'a event -> (unit -> unit) -> 'a event`

`wrap_abort ev fn` returns the event that performs the same communications as `ev`, but if it is not selected the function `fn` is called after the synchronization.

`val guard : (unit -> 'a event) -> 'a event`

`guard fn` returns the event that, when synchronized, computes `fn()` and behaves as the resulting event. This allows to compute events with side-effects at the time of the synchronization operation.

`val sync : 'a event -> 'a`

'Synchronize' on an event: offer all the communication possibilities specified in the event to the outside world, and block until one of the communications succeed. The result value of that communication is returned.

`val select : 'a event list -> 'a`

'Synchronize' on an alternative of events. `select evl` is shorthand for `sync(choose evl)`.

`val poll : 'a event -> 'a option`

Non-blocking version of `Event.sync`[26.4]: offer all the communication possibilities specified in the event to the outside world, and if one can take place immediately, perform it and return `Some r` where `r` is the result value of that communication. Otherwise, return `None` without blocking.

26.5 Module `ThreadUnix` : Thread-compatible system calls.

The functionality of this module has been merged back into the `Unix`[23.1] module. Threaded programs can now call the functions from module `Unix`[23.1] directly, and still get the correct behavior (block the calling thread, if required, but do not block all threads in the process).Thread-compatible system calls.

Process handling

```
val execv : string -> string array -> unit
val execve : string -> string array -> string array -> unit
val execvp : string -> string array -> unit
val wait : unit -> int * Unix.process_status
val waitpid : Unix.wait_flag list -> int -> int * Unix.process_status
val system : string -> Unix.process_status
```

Basic input/output

```
val read : Unix.file_descr -> bytes -> int -> int -> int
val write : Unix.file_descr -> bytes -> int -> int -> int
val write_substring : Unix.file_descr -> string -> int -> int -> int
```

Input/output with timeout

```
val timed_read : Unix.file_descr -> bytes -> int -> int -> float -> int
```

See `ThreadUnix.timed_write`[26.5].

```
val timed_write : Unix.file_descr -> bytes -> int -> int -> float -> int
```

Behave as `ThreadUnix.read`[26.5] and `ThreadUnix.write`[26.5], except that `Unix_error(ETIMEDOUT,_,_)` is raised if no data is available for reading or ready for writing after `d` seconds. The delay `d` is given in the fifth argument, in seconds.

```
val timed_write_substring :
  Unix.file_descr -> string -> int -> int -> float -> int
```

See `ThreadUnix.timed_write`[26.5].

Polling

```
val select :
  Unix.file_descr list ->
  Unix.file_descr list ->
  Unix.file_descr list ->
  float -> Unix.file_descr list * Unix.file_descr list * Unix.file_descr list
```

Pipes and redirections

```
val pipe : unit -> Unix.file_descr * Unix.file_descr
val open_process_in : string -> Pervasives.in_channel
val open_process_out : string -> Pervasives.out_channel
val open_process : string -> Pervasives.in_channel * Pervasives.out_channel
```

Time

```
val sleep : int -> unit
```

Sockets

```
val socket : Unix.socket_domain -> Unix.socket_type -> int -> Unix.file_descr
val accept : Unix.file_descr -> Unix.file_descr * Unix.sockaddr
val connect : Unix.file_descr -> Unix.sockaddr -> unit
val recv :
  Unix.file_descr -> bytes -> int -> int -> Unix.msg_flag list -> int
val recvfrom :
  Unix.file_descr ->
  bytes -> int -> int -> Unix.msg_flag list -> int * Unix.sockaddr
val send :
  Unix.file_descr -> bytes -> int -> int -> Unix.msg_flag list -> int
val send_substring :
  Unix.file_descr -> string -> int -> int -> Unix.msg_flag list -> int
val sendto :
  Unix.file_descr ->
  bytes -> int -> int -> Unix.msg_flag list -> Unix.sockaddr -> int
val sendto_substring :
  Unix.file_descr ->
  string -> int -> int -> Unix.msg_flag list -> Unix.sockaddr -> int
val open_connection :
  Unix.sockaddr -> Pervasives.in_channel * Pervasives.out_channel
```

Chapter 27

The graphics library

The `graphics` library provides a set of portable drawing primitives. Drawing takes place in a separate window that is created when `Graphics.open_graph` is called.

Unix:

This library is implemented under the X11 windows system. Programs that use the `graphics` library must be linked as follows:

```
ocamlc other options graphics.cma other files
```

For interactive use of the `graphics` library, do:

```
ocamlmktop -o mytop graphics.cma
./mytop
```

or (if dynamic linking of C libraries is supported on your platform), start `ocaml` and type `#load "graphics.cma";;`.

Here are the graphics mode specifications supported by `Graphics.open_graph` on the X11 implementation of this library: the argument to `Graphics.open_graph` has the format `"`*display-name geometry*`"`, where *display-name* is the name of the X-windows display to connect to, and *geometry* is a standard X-windows geometry specification. The two components are separated by a space. Either can be omitted, or both. Examples:

`Graphics.open_graph "foo:0"`
: connects to the display `foo:0` and creates a window with the default geometry

`Graphics.open_graph "foo:0 300x100+50-0"`
: connects to the display `foo:0` and creates a window 300 pixels wide by 100 pixels tall, at location $(50, 0)$

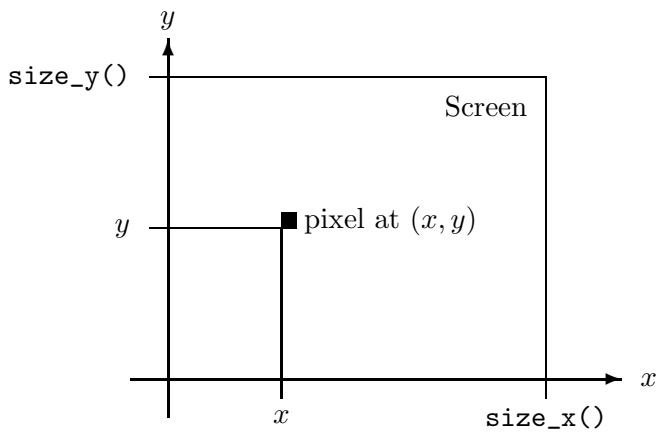
`Graphics.open_graph " 300x100+50-0"`
: connects to the default display and creates a window 300 pixels wide by 100 pixels tall, at location $(50, 0)$

`Graphics.open_graph ""`
: connects to the default display and creates a window with the default geometry.

Windows:
This library is available both for standalone compiled programs and under the toplevel application `ocamlwin.exe`. For the latter, this library must be loaded in-core by typing

```
#load "graphics.cma";;
```

The screen coordinates are interpreted as shown in the figure below. Notice that the coordinate system used is the same as in mathematics: y increases from the bottom of the screen to the top of the screen, and angles are measured counterclockwise (in degrees). Drawing is clipped to the screen.



27.1 Module `Graphics` : Machine-independent graphics primitives.

```
exception Graphic_failure of string
```

Raised by the functions below when they encounter an error.

Initializations

```
val open_graph : string -> unit
```

Show the graphics window or switch the screen to graphic mode. The graphics window is cleared and the current point is set to (0, 0). The string argument is used to pass optional information on the desired graphics mode, the graphics window size, and so on. Its interpretation is implementation-dependent. If the empty string is given, a sensible default is selected.

```
val close_graph : unit -> unit
```

Delete the graphics window or switch the screen back to text mode.

```
val set_window_title : string -> unit
```

Set the title of the graphics window.

`val resize_window : int -> int -> unit`

Resize and erase the graphics window.

`val clear_graph : unit -> unit`

Erase the graphics window.

`val size_x : unit -> int`

See `Graphics.size_y`[27.1].

`val size_y : unit -> int`

Return the size of the graphics window. Coordinates of the screen pixels range over `0 .. size_x()-1` and `0 .. size_y()-1`. Drawings outside of this rectangle are clipped, without causing an error. The origin (0,0) is at the lower left corner.

Colors

`type color = int`

A color is specified by its R, G, B components. Each component is in the range `0..255`. The three components are packed in an `int`: `0xRRGGBB`, where `RR` are the two hexadecimal digits for the red component, `GG` for the green component, `BB` for the blue component.

`val rgb : int -> int -> int -> color`

`rgb r g b` returns the integer encoding the color with red component `r`, green component `g`, and blue component `b`. `r`, `g` and `b` are in the range `0..255`.

`val set_color : color -> unit`

Set the current drawing color.

`val background : color`

See `Graphics.foreground`[27.1].

`val foreground : color`

Default background and foreground colors (usually, either black foreground on a white background or white foreground on a black background). `Graphics.clear_graph`[27.1] fills the screen with the `background` color. The initial drawing color is `foreground`.

Some predefined colors

`val black : color`

`val white : color`

`val red : color`

`val green : color`

```
val blue : color
val yellow : color
val cyan : color
val magenta : color
```

Point and line drawing

```
val plot : int -> int -> unit
```
Plot the given point with the current drawing color.

```
val plots : (int * int) array -> unit
```
Plot the given points with the current drawing color.

```
val point_color : int -> int -> color
```
Return the color of the given point in the backing store (see "Double buffering" below).

```
val moveto : int -> int -> unit
```
Position the current point.

```
val rmoveto : int -> int -> unit
```
`rmoveto dx dy` translates the current point by the given vector.

```
val current_x : unit -> int
```
Return the abscissa of the current point.

```
val current_y : unit -> int
```
Return the ordinate of the current point.

```
val current_point : unit -> int * int
```
Return the position of the current point.

```
val lineto : int -> int -> unit
```
Draw a line with endpoints the current point and the given point, and move the current point to the given point.

```
val rlineto : int -> int -> unit
```
Draw a line with endpoints the current point and the current point translated of the given vector, and move the current point to this point.

```
val curveto : int * int -> int * int -> int * int -> unit
```
`curveto b c d` draws a cubic Bezier curve starting from the current point to point `d`, with control points `b` and `c`, and moves the current point to `d`.

```
val draw_rect : int -> int -> int -> int -> unit
```

`draw_rect x y w h` draws the rectangle with lower left corner at `x,y`, width `w` and height `h`. The current point is unchanged. Raise `Invalid_argument` if `w` or `h` is negative.

```
val draw_poly_line : (int * int) array -> unit
```

`draw_poly_line points` draws the line that joins the points given by the array argument. The array contains the coordinates of the vertices of the polygonal line, which need not be closed. The current point is unchanged.

```
val draw_poly : (int * int) array -> unit
```

`draw_poly polygon` draws the given polygon. The array contains the coordinates of the vertices of the polygon. The current point is unchanged.

```
val draw_segments : (int * int * int * int) array -> unit
```

`draw_segments segments` draws the segments given in the array argument. Each segment is specified as a quadruple `(x0, y0, x1, y1)` where `(x0, y0)` and `(x1, y1)` are the coordinates of the end points of the segment. The current point is unchanged.

```
val draw_arc : int -> int -> int -> int -> int -> int -> unit
```

`draw_arc x y rx ry a1 a2` draws an elliptical arc with center `x,y`, horizontal radius `rx`, vertical radius `ry`, from angle `a1` to angle `a2` (in degrees). The current point is unchanged. Raise `Invalid_argument` if `rx` or `ry` is negative.

```
val draw_ellipse : int -> int -> int -> int -> unit
```

`draw_ellipse x y rx ry` draws an ellipse with center `x,y`, horizontal radius `rx` and vertical radius `ry`. The current point is unchanged. Raise `Invalid_argument` if `rx` or `ry` is negative.

```
val draw_circle : int -> int -> int -> unit
```

`draw_circle x y r` draws a circle with center `x,y` and radius `r`. The current point is unchanged. Raise `Invalid_argument` if `r` is negative.

```
val set_line_width : int -> unit
```

Set the width of points and lines drawn with the functions above. Under X Windows, `set_line_width 0` selects a width of 1 pixel and a faster, but less precise drawing algorithm than the one used when `set_line_width 1` is specified. Raise `Invalid_argument` if the argument is negative.

Text drawing

```
val draw_char : char -> unit
```

See `Graphics.draw_string`[27.1].

```
val draw_string : string -> unit
```

Draw a character or a character string with lower left corner at current position. After drawing, the current position is set to the lower right corner of the text drawn.

`val set_font : string -> unit`

Set the font used for drawing text. The interpretation of the argument to `set_font` is implementation-dependent.

`val set_text_size : int -> unit`

Set the character size used for drawing text. The interpretation of the argument to `set_text_size` is implementation-dependent.

`val text_size : string -> int * int`

Return the dimensions of the given text, if it were drawn with the current font and size.

Filling

`val fill_rect : int -> int -> int -> int -> unit`

`fill_rect x y w h` fills the rectangle with lower left corner at `x,y`, width `w` and height `h`, with the current color. Raise `Invalid_argument` if `w` or `h` is negative.

`val fill_poly : (int * int) array -> unit`

Fill the given polygon with the current color. The array contains the coordinates of the vertices of the polygon.

`val fill_arc : int -> int -> int -> int -> int -> int -> unit`

Fill an elliptical pie slice with the current color. The parameters are the same as for `Graphics.draw_arc`[27.1].

`val fill_ellipse : int -> int -> int -> int -> unit`

Fill an ellipse with the current color. The parameters are the same as for `Graphics.draw_ellipse`[27.1].

`val fill_circle : int -> int -> int -> unit`

Fill a circle with the current color. The parameters are the same as for `Graphics.draw_circle`[27.1].

Images

`type image`

The abstract type for images, in internal representation. Externally, images are represented as matrices of colors.

`val transp : color`

In matrices of colors, this color represent a 'transparent' point: when drawing the corresponding image, all pixels on the screen corresponding to a transparent pixel in the image will not be modified, while other points will be set to the color of the corresponding point in the image. This allows superimposing an image over an existing background.

`val make_image : color array array -> image`

Convert the given color matrix to an image. Each sub-array represents one horizontal line. All sub-arrays must have the same length; otherwise, exception `Graphic_failure` is raised.

`val dump_image : image -> color array array`

Convert an image to a color matrix.

`val draw_image : image -> int -> int -> unit`

Draw the given image with lower left corner at the given point.

`val get_image : int -> int -> int -> int -> image`

Capture the contents of a rectangle on the screen as an image. The parameters are the same as for `Graphics.fill_rect`[27.1].

`val create_image : int -> int -> image`

`create_image w h` returns a new image `w` pixels wide and `h` pixels tall, to be used in conjunction with `blit_image`. The initial image contents are random, except that no point is transparent.

`val blit_image : image -> int -> int -> unit`

`blit_image img x y` copies screen pixels into the image `img`, modifying `img` in-place. The pixels copied are those inside the rectangle with lower left corner at `x,y`, and width and height equal to those of the image. Pixels that were transparent in `img` are left unchanged.

Mouse and keyboard events

`type status =`
`{  mouse_x : int ;`

X coordinate of the mouse

`  mouse_y : int ;`

Y coordinate of the mouse

`  button : bool ;`

true if a mouse button is pressed

`  keypressed : bool ;`

true if a key has been pressed

`  key : char ;`

the character for the key pressed

}

To report events.

type event =
— Button_down
A mouse button is pressed
— Button_up
A mouse button is released
— Key_pressed
A key is pressed
— Mouse_motion
The mouse is moved
— Poll
Don't wait; return immediately

To specify events to wait for.

val wait_next_event : event list -> status

Wait until one of the events specified in the given event list occurs, and return the status of the mouse and keyboard at that time. If Poll is given in the event list, return immediately with the current status. If the mouse cursor is outside of the graphics window, the mouse_x and mouse_y fields of the event are outside the range 0..size_x()-1, 0..size_y()-1. Keypresses are queued, and dequeued one by one when the Key_pressed event is specified.

val loop_at_exit : event list -> (status -> unit) -> unit

Loop before exiting the program, the list given as argument is the list of handlers and the events on which these handlers are called. To exit cleanly the loop, the handler should raise Exit. Any other exception will be propagated outside of the loop.

Since: 4.01

Mouse and keyboard polling

val mouse_pos : unit -> int * int

Return the position of the mouse cursor, relative to the graphics window. If the mouse cursor is outside of the graphics window, mouse_pos() returns a point outside of the range 0..size_x()-1, 0..size_y()-1.

val button_down : unit -> bool

Return true if the mouse button is pressed, false otherwise.

val read_key : unit -> char

Wait for a key to be pressed, and return the corresponding character. Keypresses are queued.

`val key_pressed : unit -> bool`

Return `true` if a keypress is available; that is, if `read_key` would not block.

Sound

`val sound : int -> int -> unit`

`sound freq dur` plays a sound at frequency `freq` (in hertz) for a duration `dur` (in milliseconds).

Double buffering

`val auto_synchronize : bool -> unit`

By default, drawing takes place both on the window displayed on screen, and in a memory area (the 'backing store'). The backing store image is used to re-paint the on-screen window when necessary.

To avoid flicker during animations, it is possible to turn off on-screen drawing, perform a number of drawing operations in the backing store only, then refresh the on-screen window explicitly.

`auto_synchronize false` turns on-screen drawing off. All subsequent drawing commands are performed on the backing store only.

`auto_synchronize true` refreshes the on-screen window from the backing store (as per `synchronize`), then turns on-screen drawing back on. All subsequent drawing commands are performed both on screen and in the backing store.

The default drawing mode corresponds to `auto_synchronize true`.

`val synchronize : unit -> unit`

Synchronize the backing store and the on-screen window, by copying the contents of the backing store onto the graphics window.

`val display_mode : bool -> unit`

Set display mode on or off. When turned on, drawings are done in the graphics window; when turned off, drawings do not affect the graphics window. This occurs independently of drawing into the backing store (see the function `Graphics.remember_mode`[27.1] below). Default display mode is on.

`val remember_mode : bool -> unit`

Set remember mode on or off. When turned on, drawings are done in the backing store; when turned off, the backing store is unaffected by drawings. This occurs independently of drawing onto the graphics window (see the function `Graphics.display_mode`[27.1] above). Default remember mode is on.

Chapter 28

The dynlink library: dynamic loading and linking of object files

The `dynlink` library supports type-safe dynamic loading and linking of bytecode object files (`.cmo` and `.cma` files) in a running bytecode program, or of native plugins (usually `.cmxs` files) in a running native program. Type safety is ensured by limiting the set of modules from the running program that the loaded object file can access, and checking that the running program and the loaded object file have been compiled against the same interfaces for these modules. In native code, there are also some compatibility checks on the implementations (to avoid errors with cross-module optimizations); it might be useful to hide `.cmx` files when building native plugins so that they remain independent of the implementation of modules in the main program.

Programs that use the `dynlink` library simply need to link `dynlink.cma` or `dynlink.cmxa` with their object files and other libraries.

28.1 Module `Dynlink` : Dynamic loading of object files.

```
val is_native : bool
```

`true` if the program is native, `false` if the program is bytecode.

Dynamic loading of compiled files

```
val loadfile : string -> unit
```

In bytecode: load the given bytecode object file (`.cmo` file) or bytecode library file (`.cma` file), and link it with the running program. In native code: load the given OCaml plugin file (usually `.cmxs`), and link it with the running program. All toplevel expressions in the loaded compilation units are evaluated. No facilities are provided to access value names defined by the unit. Therefore, the unit must register itself its entry points with the main program, e.g. by modifying tables of functions.

```
val loadfile_private : string -> unit
```

Same as `loadfile`, except that the compilation units just loaded are hidden (cannot be referenced) from other modules dynamically loaded afterwards.

`val adapt_filename : string -> string`

In bytecode, the identity function. In native code, replace the last extension with `.cmxs`.

Access control

`val allow_only : string list -> unit`

`allow_only units` restricts the compilation units that dynamically-linked units can reference: it forbids all references to units other than those named in the list `units`. References to any other compilation unit will cause a `Unavailable_unit` error during `loadfile` or `loadfile_private`.

Initially (or after calling `default_available_units`) all compilation units composing the program currently running are available for reference from dynamically-linked units. `allow_only` can be used to restrict access to a subset of these units, e.g. to the units that compose the API for dynamically-linked code, and prevent access to all other units, e.g. private, internal modules of the running program. If `allow_only` is called several times, access will be restricted to the intersection of the given lists (i.e. a call to `allow_only` can never increase the set of available units).

`val prohibit : string list -> unit`

`prohibit units` prohibits dynamically-linked units from referencing the units named in list `units`. This can be used to prevent access to selected units, e.g. private, internal modules of the running program.

`val default_available_units : unit -> unit`

Reset the set of units that can be referenced from dynamically-linked code to its default value, that is, all units composing the currently running program.

`val allow_unsafe_modules : bool -> unit`

Govern whether unsafe object files are allowed to be dynamically linked. A compilation unit is 'unsafe' if it contains declarations of external functions, which can break type safety. By default, dynamic linking of unsafe object files is not allowed. In native code, this function does nothing; object files with external functions are always allowed to be dynamically linked.

Deprecated, low-level API for access control

`val add_interfaces : string list -> string list -> unit`

`add_interfaces units path` grants dynamically-linked object files access to the compilation units named in list `units`. The interfaces (`.cmi` files) for these units are searched in `path` (a list of directory names).

```
val add_available_units : (string * Digest.t) list -> unit
```

Same as `Dynlink.add_interfaces`[28.1], but instead of searching `.cmi` files to find the unit interfaces, uses the interface digests given for each unit. This way, the `.cmi` interface files need not be available at run-time. The digests can be extracted from `.cmi` files using the `extract_crc` program installed in the OCaml standard library directory.

```
val clear_available_units : unit -> unit
```

Empty the list of compilation units accessible to dynamically-linked programs.

Deprecated, initialization

```
val init : unit -> unit
```

Deprecated. Initialize the `Dynlink` library. This function is called automatically when needed.

Error reporting

```
type linking_error =
  | Undefined_global of string
  | Unavailable_primitive of string
  | Uninitialized_global of string
type error =
  | Not_a_bytecode_file of string
  | Inconsistent_import of string
  | Unavailable_unit of string
  | Unsafe_file  | Linking_error of string * linking_error
  | Corrupted_interface of string
  | File_not_found of string
  | Cannot_open_dll of string
  | Inconsistent_implementation of string
exception Error of error
```

Errors in dynamic linking are reported by raising the `Error` exception with a description of the error.

```
val error_message : error -> string
```

Convert an error description to a printable message.

612

Chapter 29

The bigarray library

The `bigarray` library implements large, multi-dimensional, numerical arrays. These arrays are called "big arrays" to distinguish them from the standard OCaml arrays described in section 21.2. The main differences between "big arrays" and standard OCaml arrays are as follows:

- Big arrays are not limited in size, unlike OCaml arrays (`float array` are limited to 2097151 elements on a 32-bit platform, other `array` types to 4194303 elements).
- Big arrays are multi-dimensional. Any number of dimensions between 1 and 16 is supported. In contrast, OCaml arrays are mono-dimensional and require encoding multi-dimensional arrays as arrays of arrays.
- Big arrays can only contain integers and floating-point numbers, while OCaml arrays can contain arbitrary OCaml data types. However, big arrays provide more space-efficient storage of integer and floating-point elements, in particular because they support "small" types such as single-precision floats and 8 and 16-bit integers, in addition to the standard OCaml types of double-precision floats and 32 and 64-bit integers.
- The memory layout of big arrays is entirely compatible with that of arrays in C and Fortran, allowing large arrays to be passed back and forth between OCaml code and C / Fortran code with no data copying at all.
- Big arrays support interesting high-level operations that normal arrays do not provide efficiently, such as extracting sub-arrays and "slicing" a multi-dimensional array along certain dimensions, all without any copying.

Programs that use the `bigarray` library must be linked as follows:

```
ocamlc other options bigarray.cma other files
ocamlopt other options bigarray.cmxa other files
```

For interactive use of the `bigarray` library, do:

```
ocamlmktop -o mytop bigarray.cma
./mytop
```

or (if dynamic linking of C libraries is supported on your platform), start `ocaml` and type `#load "bigarray.cma";;`.

29.1 Module `Bigarray` : Large, multi-dimensional, numerical arrays.

This module implements multi-dimensional arrays of integers and floating-point numbers, thereafter referred to as 'big arrays'. The implementation allows efficient sharing of large numerical arrays between OCaml code and C or Fortran numerical libraries.

Concerning the naming conventions, users of this module are encouraged to do `open Bigarray` in their source, then refer to array types and operations via short dot notation, e.g. `Array1.t` or `Array2.sub`.

Big arrays support all the OCaml ad-hoc polymorphic operations:

- comparisons (`=`, `<>`, `<=`, etc, as well as `Pervasives.compare`[20.2]);
- hashing (module `Hash`);
- and structured input-output (the functions from the `Marshal`[21.21] module, as well as `Pervasives.output_value`[20.2] and `Pervasives.input_value`[20.2]).

Element kinds

Big arrays can contain elements of the following kinds:

- IEEE single precision (32 bits) floating-point numbers (`Bigarray.float32_elt`[29.1]),
- IEEE double precision (64 bits) floating-point numbers (`Bigarray.float64_elt`[29.1]),
- IEEE single precision (2 * 32 bits) floating-point complex numbers (`Bigarray.complex32_elt`[29.1]),
- IEEE double precision (2 * 64 bits) floating-point complex numbers (`Bigarray.complex64_elt`[29.1]),
- 8-bit integers (signed or unsigned) (`Bigarray.int8_signed_elt`[29.1] or `Bigarray.int8_unsigned_elt`[29.1
- 16-bit integers (signed or unsigned) (`Bigarray.int16_signed_elt`[29.1] or `Bigarray.int16_unsigned_elt`[
- OCaml integers (signed, 31 bits on 32-bit architectures, 63 bits on 64-bit architectures) (`Bigarray.int_elt`[29.1]),
- 32-bit signed integer (`Bigarray.int32_elt`[29.1]),
- 64-bit signed integers (`Bigarray.int64_elt`[29.1]),
- platform-native signed integers (32 bits on 32-bit architectures, 64 bits on 64-bit architectures) (`Bigarray.nativeint_elt`[29.1]).

Each element kind is represented at the type level by one of the `*_elt` types defined below (defined with a single constructor instead of abstract types for technical injectivity reasons).

```
type float32_elt =
type float64_elt =
```

```
type int8_signed_elt =
type int8_unsigned_elt =
type int16_signed_elt =
type int16_unsigned_elt =
type int32_elt =
type int64_elt =
type int_elt =
type nativeint_elt =
type complex32_elt =
type complex64_elt =
type ('a, 'b) kind =
  | Float32 :  -> (float, float32_elt) kind
  | Float64 :  -> (float, float64_elt) kind
  | Int8_signed :  -> (int, int8_signed_elt) kind
  | Int8_unsigned :  -> (int, int8_unsigned_elt) kind
  | Int16_signed :  -> (int, int16_signed_elt) kind
  | Int16_unsigned :  -> (int, int16_unsigned_elt) kind
  | Int32 :  -> (int32, int32_elt) kind
  | Int64 :  -> (int64, int64_elt) kind
  | Int :  -> (int, int_elt) kind
  | Nativeint :  -> (nativeint, nativeint_elt) kind
  | Complex32 :  -> (Complex.t, complex32_elt) kind
  | Complex64 :  -> (Complex.t, complex64_elt) kind
  | Char :  -> (char, int8_unsigned_elt) kind
```

To each element kind is associated an OCaml type, which is the type of OCaml values that can be stored in the big array or read back from it. This type is not necessarily the same as the type of the array elements proper: for instance, a big array whose elements are of kind `float32_elt` contains 32-bit single precision floats, but reading or writing one of its elements from OCaml uses the OCaml type `float`, which is 64-bit double precision floats.

The GADT type `('a, 'b) kind` captures this association of an OCaml type `'a` for values read or written in the big array, and of an element kind `'b` which represents the actual contents of the big array. Its constructors list all possible associations of OCaml types with element kinds, and are re-exported below for backward-compatibility reasons.

Using a generalized algebraic datatype (GADT) here allows to write well-typed polymorphic functions whose return type depend on the argument type, such as:

```
let zero : type a b. (a, b) kind -> a = function
  | Float32 -> 0.0 | Complex32 -> Complex.zero
  | Float64 -> 0.0 | Complex64 -> Complex.zero
  | Int8_signed -> 0 | Int8_unsigned -> 0
  | Int16_signed -> 0 | Int16_unsigned -> 0
  | Int32 -> 0l | Int64 -> 0L
```

```
        | Int -> 0 | Nativeint -> 0n
        | Char -> '\000'
```

```
val float32 : (float, float32_elt) kind
```
See `Bigarray.char`[29.1].

```
val float64 : (float, float64_elt) kind
```
See `Bigarray.char`[29.1].

```
val complex32 : (Complex.t, complex32_elt) kind
```
See `Bigarray.char`[29.1].

```
val complex64 : (Complex.t, complex64_elt) kind
```
See `Bigarray.char`[29.1].

```
val int8_signed : (int, int8_signed_elt) kind
```
See `Bigarray.char`[29.1].

```
val int8_unsigned : (int, int8_unsigned_elt) kind
```
See `Bigarray.char`[29.1].

```
val int16_signed : (int, int16_signed_elt) kind
```
See `Bigarray.char`[29.1].

```
val int16_unsigned : (int, int16_unsigned_elt) kind
```
See `Bigarray.char`[29.1].

```
val int : (int, int_elt) kind
```
See `Bigarray.char`[29.1].

```
val int32 : (int32, int32_elt) kind
```
See `Bigarray.char`[29.1].

```
val int64 : (int64, int64_elt) kind
```
See `Bigarray.char`[29.1].

```
val nativeint : (nativeint, nativeint_elt) kind
```
See `Bigarray.char`[29.1].

```
val char : (char, int8_unsigned_elt) kind
```

As shown by the types of the values above, big arrays of kind `float32_elt` and `float64_elt` are accessed using the OCaml type `float`. Big arrays of complex kinds `complex32_elt`, `complex64_elt` are accessed with the OCaml type `Complex.t`[21.7]. Big arrays of integer kinds are accessed using the smallest OCaml integer type large enough to represent the array elements: `int` for 8- and 16-bit integer bigarrays, as well as OCaml-integer bigarrays; `int32` for 32-bit integer bigarrays; `int64` for 64-bit integer bigarrays; and `nativeint` for platform-native integer bigarrays. Finally, big arrays of kind `int8_unsigned_elt` can also be accessed as arrays of characters instead of arrays of small integers, by using the kind value `char` instead of `int8_unsigned`.

```
val kind_size_in_bytes : ('a, 'b) kind -> int
```

`kind_size_in_bytes k` is the number of bytes used to store an element of type `k`.

Since: 4.03.0

Array layouts

```
type c_layout =
```

See `Bigarray.fortran_layout`[29.1].

```
type fortran_layout =
```

To facilitate interoperability with existing C and Fortran code, this library supports two different memory layouts for big arrays, one compatible with the C conventions, the other compatible with the Fortran conventions.

In the C-style layout, array indices start at 0, and multi-dimensional arrays are laid out in row-major format. That is, for a two-dimensional array, all elements of row 0 are contiguous in memory, followed by all elements of row 1, etc. In other terms, the array elements at `(x,y)` and `(x, y+1)` are adjacent in memory.

In the Fortran-style layout, array indices start at 1, and multi-dimensional arrays are laid out in column-major format. That is, for a two-dimensional array, all elements of column 0 are contiguous in memory, followed by all elements of column 1, etc. In other terms, the array elements at `(x,y)` and `(x+1, y)` are adjacent in memory.

Each layout style is identified at the type level by the phantom types `Bigarray.c_layout`[29.1] and `Bigarray.fortran_layout`[29.1] respectively.

Supported layouts

The GADT type `'a layout` represents one of the two supported memory layouts: C-style or Fortran-style. Its constructors are re-exported as values below for backward-compatibility reasons.

```
type 'a layout =
  | C_layout :  -> c_layout layout
  | Fortran_layout :  -> fortran_layout layout
val c_layout : c_layout layout
val fortran_layout : fortran_layout layout
```

Generic arrays (of arbitrarily many dimensions)

```
module Genarray :
  sig
```

```
    type ('a, 'b, 'c) t
```

The type `Genarray.t` is the type of big arrays with variable numbers of dimensions. Any number of dimensions between 1 and 16 is supported.

The three type parameters to `Genarray.t` identify the array element kind and layout, as follows:

- the first parameter, `'a`, is the OCaml type for accessing array elements (`float`, `int`, `int32`, `int64`, `nativeint`);
- the second parameter, `'b`, is the actual kind of array elements (`float32_elt`, `float64_elt`, `int8_signed_elt`, `int8_unsigned_elt`, etc);
- the third parameter, `'c`, identifies the array layout (`c_layout` or `fortran_layout`).

For instance, `(float, float32_elt, fortran_layout) Genarray.t` is the type of generic big arrays containing 32-bit floats in Fortran layout; reads and writes in this array use the OCaml type `float`.

```
    val create :
      ('a, 'b) Bigarray.kind ->
      'c Bigarray.layout -> int array -> ('a, 'b, 'c) t
```

`Genarray.create kind layout dimensions` returns a new big array whose element kind is determined by the parameter `kind` (one of `float32`, `float64`, `int8_signed`, etc) and whose layout is determined by the parameter `layout` (one of `c_layout` or `fortran_layout`). The `dimensions` parameter is an array of integers that indicate the size of the big array in each dimension. The length of `dimensions` determines the number of dimensions of the bigarray.

For instance, `Genarray.create int32 c_layout [|4;6;8|]` returns a fresh big array of 32-bit integers, in C layout, having three dimensions, the three dimensions being 4, 6 and 8 respectively.

Big arrays returned by `Genarray.create` are not initialized: the initial values of array elements is unspecified.

`Genarray.create` raises `Invalid_argument` if the number of dimensions is not in the range 1 to 16 inclusive, or if one of the dimensions is negative.

```
    val num_dims : ('a, 'b, 'c) t -> int
```

Return the number of dimensions of the given big array.

```
    val dims : ('a, 'b, 'c) t -> int array
```

`Genarray.dims a` returns all dimensions of the big array `a`, as an array of integers of length `Genarray.num_dims a`.

```
val nth_dim : ('a, 'b, 'c) t -> int -> int
```

Genarray.nth_dim a n returns the n-th dimension of the big array a. The first dimension corresponds to n = 0; the second dimension corresponds to n = 1; the last dimension, to n = Genarray.num_dims a - 1. Raise Invalid_argument if n is less than 0 or greater or equal than Genarray.num_dims a.

```
val kind : ('a, 'b, 'c) t -> ('a, 'b) Bigarray.kind
```

Return the kind of the given big array.

```
val layout : ('a, 'b, 'c) t -> 'c Bigarray.layout
```

Return the layout of the given big array.

```
val change_layout : ('a, 'b, 'c) t ->
  'd Bigarray.layout -> ('a, 'b, 'd) t
```

Genarray.change_layout a layout returns a bigarray with the specified layout, sharing the data with a (and hence having the same dimensions as a). No copying of elements is involved: the new array and the original array share the same storage space. The dimensions are reversed, such that get v [| a; b |] in C layout becomes get v [| b+1; a+1 |] in Fortran layout.

Since: 4.04.0

```
val size_in_bytes : ('a, 'b, 'c) t -> int
```

size_in_bytes a is the number of elements in a multiplied by a's Bigarray.kind_size_in_bytes[29.1].

Since: 4.03.0

```
val get : ('a, 'b, 'c) t -> int array -> 'a
```

Read an element of a generic big array. Genarray.get a [|i1; ...; iN|] returns the element of a whose coordinates are i1 in the first dimension, i2 in the second dimension, ..., iN in the N-th dimension.

If a has C layout, the coordinates must be greater or equal than 0 and strictly less than the corresponding dimensions of a. If a has Fortran layout, the coordinates must be greater or equal than 1 and less or equal than the corresponding dimensions of a. Raise Invalid_argument if the array a does not have exactly N dimensions, or if the coordinates are outside the array bounds.

If N > 3, alternate syntax is provided: you can write a.{i1, i2, ..., iN} instead of Genarray.get a [|i1; ...; iN|]. (The syntax a.{...} with one, two or three coordinates is reserved for accessing one-, two- and three-dimensional arrays as described below.)

```
val set : ('a, 'b, 'c) t -> int array -> 'a -> unit
```

Assign an element of a generic big array. `Genarray.set a [|i1; ...; iN|] v` stores the value `v` in the element of `a` whose coordinates are `i1` in the first dimension, `i2` in the second dimension, ..., `iN` in the `N`-th dimension.

The array `a` must have exactly `N` dimensions, and all coordinates must lie inside the array bounds, as described for `Genarray.get`; otherwise, `Invalid_argument` is raised.

If `N > 3`, alternate syntax is provided: you can write `a.{i1, i2, ..., iN} <- v` instead of `Genarray.set a [|i1; ...; iN|] v`. (The syntax `a.{...} <- v` with one, two or three coordinates is reserved for updating one-, two- and three-dimensional arrays as described below.)

```
val sub_left :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> int -> ('a, 'b, Bigarray.c_layout) t
```

Extract a sub-array of the given big array by restricting the first (left-most) dimension. `Genarray.sub_left a ofs len` returns a big array with the same number of dimensions as `a`, and the same dimensions as `a`, except the first dimension, which corresponds to the interval `[ofs ... ofs + len - 1]` of the first dimension of `a`. No copying of elements is involved: the sub-array and the original array share the same storage space. In other terms, the element at coordinates `[|i1; ...; iN|]` of the sub-array is identical to the element at coordinates `[|i1+ofs; ...; iN|]` of the original array `a`.

`Genarray.sub_left` applies only to big arrays in C layout. Raise `Invalid_argument` if `ofs` and `len` do not designate a valid sub-array of `a`, that is, if `ofs < 0`, or `len < 0`, or `ofs + len > Genarray.nth_dim a 0`.

```
val sub_right :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> int -> ('a, 'b, Bigarray.fortran_layout) t
```

Extract a sub-array of the given big array by restricting the last (right-most) dimension. `Genarray.sub_right a ofs len` returns a big array with the same number of dimensions as `a`, and the same dimensions as `a`, except the last dimension, which corresponds to the interval `[ofs ... ofs + len - 1]` of the last dimension of `a`. No copying of elements is involved: the sub-array and the original array share the same storage space. In other terms, the element at coordinates `[|i1; ...; iN|]` of the sub-array is identical to the element at coordinates `[|i1; ...; iN+ofs|]` of the original array `a`.

`Genarray.sub_right` applies only to big arrays in Fortran layout. Raise `Invalid_argument` if `ofs` and `len` do not designate a valid sub-array of `a`, that is, if `ofs < 1`, or `len < 0`, or `ofs + len > Genarray.nth_dim a (Genarray.num_dims a - 1)`.

```
val slice_left :
  ('a, 'b, Bigarray.c_layout) t ->
  int array -> ('a, 'b, Bigarray.c_layout) t
```

Extract a sub-array of lower dimension from the given big array by fixing one or several of the first (left-most) coordinates. `Genarray.slice_left a [|i1; ... ; iM|]` returns the 'slice' of `a` obtained by setting the first `M` coordinates to `i1`, ..., `iM`. If `a` has `N` dimensions, the slice has dimension `N - M`, and the element at coordinates `[|j1; ...; j(N-M)|]` in the slice is identical to the element at coordinates `[|i1; ...; iM; j1; ...; j(N-M)|]` in the original array `a`. No copying of elements is involved: the slice and the original array share the same storage space.

`Genarray.slice_left` applies only to big arrays in C layout. Raise `Invalid_argument` if `M >= N`, or if `[|i1; ... ; iM|]` is outside the bounds of `a`.

```
val slice_right :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int array -> ('a, 'b, Bigarray.fortran_layout) t
```

Extract a sub-array of lower dimension from the given big array by fixing one or several of the last (right-most) coordinates. `Genarray.slice_right a [|i1; ... ; iM|]` returns the 'slice' of `a` obtained by setting the last `M` coordinates to `i1`, ..., `iM`. If `a` has `N` dimensions, the slice has dimension `N - M`, and the element at coordinates `[|j1; ...; j(N-M)|]` in the slice is identical to the element at coordinates `[|j1; ...; j(N-M); i1; ...; iM|]` in the original array `a`. No copying of elements is involved: the slice and the original array share the same storage space.

`Genarray.slice_right` applies only to big arrays in Fortran layout. Raise `Invalid_argument` if `M >= N`, or if `[|i1; ... ; iM|]` is outside the bounds of `a`.

```
val blit : ('a, 'b, 'c) t -> ('a, 'b, 'c) t -> unit
```

Copy all elements of a big array in another big array. `Genarray.blit src dst` copies all elements of `src` into `dst`. Both arrays `src` and `dst` must have the same number of dimensions and equal dimensions. Copying a sub-array of `src` to a sub-array of `dst` can be achieved by applying `Genarray.blit` to sub-array or slices of `src` and `dst`.

```
val fill : ('a, 'b, 'c) t -> 'a -> unit
```

Set all elements of a big array to a given value. `Genarray.fill a v` stores the value `v` in all elements of the big array `a`. Setting only some elements of `a` to `v` can be achieved by applying `Genarray.fill` to a sub-array or a slice of `a`.

```
val map_file :
  Unix.file_descr ->
  ?pos:int64 ->
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> bool -> int array -> ('a, 'b, 'c) t
```

Memory mapping of a file as a big array. `Genarray.map_file fd kind layout shared dims` returns a big array of kind `kind`, layout `layout`, and dimensions as specified in `dims`. The data contained in this big array are the contents of the file referred to by the file descriptor `fd` (as opened previously with `Unix.openfile`, for

example). The optional `pos` parameter is the byte offset in the file of the data being mapped; it defaults to 0 (map from the beginning of the file).

If `shared` is `true`, all modifications performed on the array are reflected in the file. This requires that `fd` be opened with write permissions. If `shared` is `false`, modifications performed on the array are done in memory only, using copy-on-write of the modified pages; the underlying file is not affected.

`Genarray.map_file` is much more efficient than reading the whole file in a big array, modifying that big array, and writing it afterwards.

To adjust automatically the dimensions of the big array to the actual size of the file, the major dimension (that is, the first dimension for an array with C layout, and the last dimension for an array with Fortran layout) can be given as `-1`. `Genarray.map_file` then determines the major dimension from the size of the file. The file must contain an integral number of sub-arrays as determined by the non-major dimensions, otherwise `Failure` is raised.

If all dimensions of the big array are given, the file size is matched against the size of the big array. If the file is larger than the big array, only the initial portion of the file is mapped to the big array. If the file is smaller than the big array, the file is automatically grown to the size of the big array. This requires write permissions on `fd`.

Array accesses are bounds-checked, but the bounds are determined by the initial call to `map_file`. Therefore, you should make sure no other process modifies the mapped file while you're accessing it, or a SIGBUS signal may be raised. This happens, for instance, if the file is shrunk.

This function raises `Sys_error` in the case of any errors from the underlying system calls. `Invalid_argument` or `Failure` may be raised in cases where argument validation fails.

```
  end
```

One-dimensional arrays

```
module Array1 :
  sig
```

```
    type ('a, 'b, 'c) t
```

The type of one-dimensional big arrays whose elements have OCaml type `'a`, representation kind `'b`, and memory layout `'c`.

```
    val create :
      ('a, 'b) Bigarray.kind ->
      'c Bigarray.layout -> int -> ('a, 'b, 'c) t
```

`Array1.create kind layout dim` returns a new bigarray of one dimension, whose size is `dim`. `kind` and `layout` determine the array element kind and the array layout as described for `Genarray.create`.

```
val dim : ('a, 'b, 'c) t -> int
```

Return the size (dimension) of the given one-dimensional big array.

```
val kind : ('a, 'b, 'c) t -> ('a, 'b) Bigarray.kind
```

Return the kind of the given big array.

```
val layout : ('a, 'b, 'c) t -> 'c Bigarray.layout
```

Return the layout of the given big array.

```
val size_in_bytes : ('a, 'b, 'c) t -> int
```

`size_in_bytes a` is the number of elements in `a` multiplied by `a`'s `Bigarray.kind_size_in_bytes`[29.1].

Since: 4.03.0

```
val get : ('a, 'b, 'c) t -> int -> 'a
```

`Array1.get a x`, or alternatively `a.{x}`, returns the element of `a` at index `x`. `x` must be greater or equal than `0` and strictly less than `Array1.dim a` if `a` has C layout. If `a` has Fortran layout, `x` must be greater or equal than `1` and less or equal than `Array1.dim a`. Otherwise, `Invalid_argument` is raised.

```
val set : ('a, 'b, 'c) t -> int -> 'a -> unit
```

`Array1.set a x v`, also written `a.{x} <- v`, stores the value `v` at index `x` in `a`. `x` must be inside the bounds of `a` as described in `Bigarray.Array1.get`[29.1]; otherwise, `Invalid_argument` is raised.

```
val sub : ('a, 'b, 'c) t ->
  int -> int -> ('a, 'b, 'c) t
```

Extract a sub-array of the given one-dimensional big array. See `Genarray.sub_left` for more details.

```
val blit : ('a, 'b, 'c) t -> ('a, 'b, 'c) t -> unit
```

Copy the first big array to the second big array. See `Genarray.blit` for more details.

```
val fill : ('a, 'b, 'c) t -> 'a -> unit
```

Fill the given big array with the given value. See `Genarray.fill` for more details.

```
val of_array :
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> 'a array -> ('a, 'b, 'c) t
```

Build a one-dimensional big array initialized from the given array.

```
val map_file :
  Unix.file_descr ->
  ?pos:int64 ->
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> bool -> int -> ('a, 'b, 'c) t
```

Memory mapping of a file as a one-dimensional big array. See `Bigarray.Genarray.map_file`[29.1] for more details.

```
val unsafe_get : ('a, 'b, 'c) t -> int -> 'a
```

Like `Bigarray.Array1.get`[29.1], but bounds checking is not always performed. Use with caution and only when the program logic guarantees that the access is within bounds.

```
val unsafe_set : ('a, 'b, 'c) t -> int -> 'a -> unit
```

Like `Bigarray.Array1.set`[29.1], but bounds checking is not always performed. Use with caution and only when the program logic guarantees that the access is within bounds.

```
end
```

One-dimensional arrays. The `Array1` structure provides operations similar to those of `Bigarray.Genarray`[29.1], but specialized to the case of one-dimensional arrays. (The `Array2` and `Array3` structures below provide operations specialized for two- and three-dimensional arrays.) Statically knowing the number of dimensions of the array allows faster operations, and more precise static type-checking.

Two-dimensional arrays

```
module Array2 :
  sig
```

```
type ('a, 'b, 'c) t
```

The type of two-dimensional big arrays whose elements have OCaml type `'a`, representation kind `'b`, and memory layout `'c`.

```
val create :
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> int -> int -> ('a, 'b, 'c) t
```

`Array2.create kind layout dim1 dim2` returns a new bigarray of two dimension, whose size is `dim1` in the first dimension and `dim2` in the second dimension. `kind` and `layout` determine the array element kind and the array layout as described for `Bigarray.Genarray.create`[29.1].

```
val dim1 : ('a, 'b, 'c) t -> int
```

Return the first dimension of the given two-dimensional big array.

```
val dim2 : ('a, 'b, 'c) t -> int
```

Return the second dimension of the given two-dimensional big array.

```
val kind : ('a, 'b, 'c) t -> ('a, 'b) Bigarray.kind
```

Return the kind of the given big array.

```
val layout : ('a, 'b, 'c) t -> 'c Bigarray.layout
```

Return the layout of the given big array.

```
val size_in_bytes : ('a, 'b, 'c) t -> int
```

`size_in_bytes a` is the number of elements in `a` multiplied by `a`'s `Bigarray.kind_size_in_bytes`[29.1].
Since: 4.03.0

```
val get : ('a, 'b, 'c) t -> int -> int -> 'a
```

`Array2.get a x y`, also written `a.{x,y}`, returns the element of `a` at coordinates (`x`, `y`). `x` and `y` must be within the bounds of `a`, as described for `Bigarray.Genarray.get`[29.1]; otherwise, `Invalid_argument` is raised.

```
val set : ('a, 'b, 'c) t -> int -> int -> 'a -> unit
```

`Array2.set a x y v`, or alternatively `a.{x,y} <- v`, stores the value `v` at coordinates (`x`, `y`) in `a`. `x` and `y` must be within the bounds of `a`, as described for `Bigarray.Genarray.set`[29.1]; otherwise, `Invalid_argument` is raised.

```
val sub_left :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> int -> ('a, 'b, Bigarray.c_layout) t
```

Extract a two-dimensional sub-array of the given two-dimensional big array by restricting the first dimension. See `Bigarray.Genarray.sub_left`[29.1] for more details. `Array2.sub_left` applies only to arrays with C layout.

```
val sub_right :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> int -> ('a, 'b, Bigarray.fortran_layout) t
```

Extract a two-dimensional sub-array of the given two-dimensional big array by restricting the second dimension. See `Bigarray.Genarray.sub_right`[29.1] for more details. `Array2.sub_right` applies only to arrays with Fortran layout.

```
val slice_left :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> ('a, 'b, Bigarray.c_layout) Bigarray.Array1.t
```

Extract a row (one-dimensional slice) of the given two-dimensional big array. The integer parameter is the index of the row to extract. See `Bigarray.Genarray.slice_left`[29.1] for more details. `Array2.slice_left` applies only to arrays with C layout.

```
val slice_right :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> ('a, 'b, Bigarray.fortran_layout) Bigarray.Array1.t
```

Extract a column (one-dimensional slice) of the given two-dimensional big array. The integer parameter is the index of the column to extract. See `Bigarray.Genarray.slice_right`[29.1] for more details. `Array2.slice_right` applies only to arrays with Fortran layout.

```
val blit : ('a, 'b, 'c) t -> ('a, 'b, 'c) t -> unit
```

Copy the first big array to the second big array. See `Bigarray.Genarray.blit`[29.1] for more details.

```
val fill : ('a, 'b, 'c) t -> 'a -> unit
```

Fill the given big array with the given value. See `Bigarray.Genarray.fill`[29.1] for more details.

```
val of_array :
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> 'a array array -> ('a, 'b, 'c) t
```

Build a two-dimensional big array initialized from the given array of arrays.

```
val map_file :
  Unix.file_descr ->
  ?pos:int64 ->
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> bool -> int -> int -> ('a, 'b, 'c) t
```

Memory mapping of a file as a two-dimensional big array. See `Bigarray.Genarray.map_file`[29.1] for more details.

```
val unsafe_get : ('a, 'b, 'c) t -> int -> int -> 'a
```

Like `Bigarray.Array2.get`[29.1], but bounds checking is not always performed.

```
val unsafe_set : ('a, 'b, 'c) t -> int -> int -> 'a -> unit
```

Like `Bigarray.Array2.set`[29.1], but bounds checking is not always performed.

```
end
```

Two-dimensional arrays. The `Array2` structure provides operations similar to those of `Bigarray.Genarray`[29.1], but specialized to the case of two-dimensional arrays.

Three-dimensional arrays

```
module Array3 :
  sig
```

```
    type ('a, 'b, 'c) t
```

The type of three-dimensional big arrays whose elements have OCaml type `'a`, representation kind `'b`, and memory layout `'c`.

```
    val create :
      ('a, 'b) Bigarray.kind ->
      'c Bigarray.layout -> int -> int -> int -> ('a, 'b, 'c) t
```

`Array3.create kind layout dim1 dim2 dim3` returns a new bigarray of three dimension, whose size is `dim1` in the first dimension, `dim2` in the second dimension, and `dim3` in the third. `kind` and `layout` determine the array element kind and the array layout as described for `Bigarray.Genarray.create`[29.1].

```
    val dim1 : ('a, 'b, 'c) t -> int
```

Return the first dimension of the given three-dimensional big array.

```
    val dim2 : ('a, 'b, 'c) t -> int
```

Return the second dimension of the given three-dimensional big array.

```
    val dim3 : ('a, 'b, 'c) t -> int
```

Return the third dimension of the given three-dimensional big array.

```
    val kind : ('a, 'b, 'c) t -> ('a, 'b) Bigarray.kind
```

Return the kind of the given big array.

```
    val layout : ('a, 'b, 'c) t -> 'c Bigarray.layout
```

Return the layout of the given big array.

```
    val size_in_bytes : ('a, 'b, 'c) t -> int
```

`size_in_bytes a` is the number of elements in `a` multiplied by `a`'s `Bigarray.kind_size_in_bytes`[29.1].
Since: 4.03.0

```
    val get : ('a, 'b, 'c) t -> int -> int -> int -> 'a
```

`Array3.get a x y z`, also written `a.{x,y,z}`, returns the element of `a` at coordinates (`x`, `y`, `z`). `x`, `y` and `z` must be within the bounds of `a`, as described for `Bigarray.Genarray.get`[29.1]; otherwise, `Invalid_argument` is raised.

```
    val set : ('a, 'b, 'c) t -> int -> int -> int -> 'a -> unit
```

`Array3.set a x y v`, or alternatively `a.{x,y,z} <- v`, stores the value `v` at coordinates (`x`, `y`, `z`) in `a`. `x`, `y` and `z` must be within the bounds of `a`, as described for `Bigarray.Genarray.set`[29.1]; otherwise, `Invalid_argument` is raised.

```
val sub_left :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> int -> ('a, 'b, Bigarray.c_layout) t
```

Extract a three-dimensional sub-array of the given three-dimensional big array by restricting the first dimension. See `Bigarray.Genarray.sub_left`[29.1] for more details. `Array3.sub_left` applies only to arrays with C layout.

```
val sub_right :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> int -> ('a, 'b, Bigarray.fortran_layout) t
```

Extract a three-dimensional sub-array of the given three-dimensional big array by restricting the second dimension. See `Bigarray.Genarray.sub_right`[29.1] for more details. `Array3.sub_right` applies only to arrays with Fortran layout.

```
val slice_left_1 :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> int -> ('a, 'b, Bigarray.c_layout) Bigarray.Array1.t
```

Extract a one-dimensional slice of the given three-dimensional big array by fixing the first two coordinates. The integer parameters are the coordinates of the slice to extract. See `Bigarray.Genarray.slice_left`[29.1] for more details. `Array3.slice_left_1` applies only to arrays with C layout.

```
val slice_right_1 :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> int -> ('a, 'b, Bigarray.fortran_layout) Bigarray.Array1.t
```

Extract a one-dimensional slice of the given three-dimensional big array by fixing the last two coordinates. The integer parameters are the coordinates of the slice to extract. See `Bigarray.Genarray.slice_right`[29.1] for more details. `Array3.slice_right_1` applies only to arrays with Fortran layout.

```
val slice_left_2 :
  ('a, 'b, Bigarray.c_layout) t ->
  int -> ('a, 'b, Bigarray.c_layout) Bigarray.Array2.t
```

Extract a two-dimensional slice of the given three-dimensional big array by fixing the first coordinate. The integer parameter is the first coordinate of the slice to extract. See `Bigarray.Genarray.slice_left`[29.1] for more details. `Array3.slice_left_2` applies only to arrays with C layout.

```
val slice_right_2 :
  ('a, 'b, Bigarray.fortran_layout) t ->
  int -> ('a, 'b, Bigarray.fortran_layout) Bigarray.Array2.t
```

Extract a two-dimensional slice of the given three-dimensional big array by fixing the last coordinate. The integer parameter is the coordinate of the slice to extract. See `Bigarray.Genarray.slice_right`[29.1] for more details. `Array3.slice_right_2` applies only to arrays with Fortran layout.

```
val blit : ('a, 'b, 'c) t -> ('a, 'b, 'c) t -> unit
```

Copy the first big array to the second big array. See `Bigarray.Genarray.blit`[29.1] for more details.

```
val fill : ('a, 'b, 'c) t -> 'a -> unit
```

Fill the given big array with the given value. See `Bigarray.Genarray.fill`[29.1] for more details.

```
val of_array :
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout -> 'a array array array -> ('a, 'b, 'c) t
```

Build a three-dimensional big array initialized from the given array of arrays of arrays.

```
val map_file :
  Unix.file_descr ->
  ?pos:int64 ->
  ('a, 'b) Bigarray.kind ->
  'c Bigarray.layout ->
  bool -> int -> int -> int -> ('a, 'b, 'c) t
```

Memory mapping of a file as a three-dimensional big array. See `Bigarray.Genarray.map_file`[29.1] for more details.

```
val unsafe_get : ('a, 'b, 'c) t -> int -> int -> int -> 'a
```

Like `Bigarray.Array3.get`[29.1], but bounds checking is not always performed.

```
val unsafe_set : ('a, 'b, 'c) t -> int -> int -> int -> 'a -> unit
```

Like `Bigarray.Array3.set`[29.1], but bounds checking is not always performed.

```
end
```

Three-dimensional arrays. The `Array3` structure provides operations similar to those of `Bigarray.Genarray`[29.1], but specialized to the case of three-dimensional arrays.

Coercions between generic big arrays and fixed-dimension big arrays

`val genarray_of_array1 : ('a, 'b, 'c) Array1.t -> ('a, 'b, 'c) Genarray.t`

Return the generic big array corresponding to the given one-dimensional big array.

`val genarray_of_array2 : ('a, 'b, 'c) Array2.t -> ('a, 'b, 'c) Genarray.t`

Return the generic big array corresponding to the given two-dimensional big array.

`val genarray_of_array3 : ('a, 'b, 'c) Array3.t -> ('a, 'b, 'c) Genarray.t`

Return the generic big array corresponding to the given three-dimensional big array.

`val array1_of_genarray : ('a, 'b, 'c) Genarray.t -> ('a, 'b, 'c) Array1.t`

Return the one-dimensional big array corresponding to the given generic big array. Raise `Invalid_argument` if the generic big array does not have exactly one dimension.

`val array2_of_genarray : ('a, 'b, 'c) Genarray.t -> ('a, 'b, 'c) Array2.t`

Return the two-dimensional big array corresponding to the given generic big array. Raise `Invalid_argument` if the generic big array does not have exactly two dimensions.

`val array3_of_genarray : ('a, 'b, 'c) Genarray.t -> ('a, 'b, 'c) Array3.t`

Return the three-dimensional big array corresponding to the given generic big array. Raise `Invalid_argument` if the generic big array does not have exactly three dimensions.

Re-shaping big arrays

```
val reshape :
  ('a, 'b, 'c) Genarray.t ->
  int array -> ('a, 'b, 'c) Genarray.t
```

`reshape b [|d1;...;dN|]` converts the big array `b` to a `N`-dimensional array of dimensions `d1`...`dN`. The returned array and the original array `b` share their data and have the same layout. For instance, assuming that `b` is a one-dimensional array of dimension 12, `reshape b [|3;4|]` returns a two-dimensional array `b'` of dimensions 3 and 4. If `b` has C layout, the element `(x,y)` of `b'` corresponds to the element `x * 3 + y` of `b`. If `b` has Fortran layout, the element `(x,y)` of `b'` corresponds to the element `x + (y - 1) * 4` of `b`. The returned big array must have exactly the same number of elements as the original big array `b`. That is, the product of the dimensions of `b` must be equal to `i1 * ... * iN`. Otherwise, `Invalid_argument` is raised.

`val reshape_1 : ('a, 'b, 'c) Genarray.t -> int -> ('a, 'b, 'c) Array1.t`

Specialized version of `Bigarray.reshape`[29.1] for reshaping to one-dimensional arrays.

```
val reshape_2 :
  ('a, 'b, 'c) Genarray.t ->
  int -> int -> ('a, 'b, 'c) Array2.t
```

Specialized version of `Bigarray.reshape`[29.1] for reshaping to two-dimensional arrays.

```
val reshape_3 :
  ('a, 'b, 'c) Genarray.t ->
  int -> int -> int -> ('a, 'b, 'c) Array3.t
```

Specialized version of `Bigarray.reshape`[29.1] for reshaping to three-dimensional arrays.

29.2 Big arrays in the OCaml-C interface

C stub code that interface C or Fortran code with OCaml code, as described in chapter 18, can exploit big arrays as follows.

29.2.1 Include file

The include file `<caml/bigarray.h>` must be included in the C stub file. It declares the functions, constants and macros discussed below.

29.2.2 Accessing an OCaml bigarray from C or Fortran

If v is a OCaml `value` representing a big array, the expression `Caml_ba_data_val(`v`)` returns a pointer to the data part of the array. This pointer is of type `void *` and can be cast to the appropriate C type for the array (e.g. `double []`, `char [][10]`, etc).

Various characteristics of the OCaml big array can be consulted from C as follows:

C expression	Returns
`Caml_ba_array_val(`v`)->num_dims`	number of dimensions
`Caml_ba_array_val(`v`)->dim[`i`]`	i-th dimension
`Caml_ba_array_val(`v`)->flags & BIGARRAY_KIND_MASK`	kind of array elements

The kind of array elements is one of the following constants:

Constant	Element kind
`CAML_BA_FLOAT32`	32-bit single-precision floats
`CAML_BA_FLOAT64`	64-bit double-precision floats
`CAML_BA_SINT8`	8-bit signed integers
`CAML_BA_UINT8`	8-bit unsigned integers
`CAML_BA_SINT16`	16-bit signed integers
`CAML_BA_UINT16`	16-bit unsigned integers
`CAML_BA_INT32`	32-bit signed integers
`CAML_BA_INT64`	64-bit signed integers
`CAML_BA_CAML_INT`	31- or 63-bit signed integers
`CAML_BA_NATIVE_INT`	32- or 64-bit (platform-native) integers

The following example shows the passing of a two-dimensional big array to a C function and a Fortran function.

```
extern void my_c_function(double * data, int dimx, int dimy);
extern void my_fortran_function_(double * data, int * dimx, int * dimy);

value caml_stub(value bigarray)
{
  int dimx = Caml_ba_array_val(bigarray)->dim[0];
  int dimy = Caml_ba_array_val(bigarray)->dim[1];
  /* C passes scalar parameters by value */
  my_c_function(Caml_ba_data_val(bigarray), dimx, dimy);
  /* Fortran passes all parameters by reference */
  my_fortran_function_(Caml_ba_data_val(bigarray), &dimx, &dimy);
  return Val_unit;
}
```

29.2.3 Wrapping a C or Fortran array as an OCaml big array

A pointer *p* to an already-allocated C or Fortran array can be wrapped and returned to OCaml as a big array using the `caml_ba_alloc` or `caml_ba_alloc_dims` functions.

- `caml_ba_alloc(`*kind* `|` *layout*, *numdims*, *p*, *dims*`)`

  Return an OCaml big array wrapping the data pointed to by *p*. *kind* is the kind of array elements (one of the `CAML_BA_` kind constants above). *layout* is `CAML_BA_C_LAYOUT` for an array with C layout and `CAML_BA_FORTRAN_LAYOUT` for an array with Fortran layout. *numdims* is the number of dimensions in the array. *dims* is an array of *numdims* long integers, giving the sizes of the array in each dimension.

- `caml_ba_alloc_dims(`*kind* `|` *layout*, *numdims*, *p*, `(long)` dim_1, `(long)` dim_2, ..., `(long)` $dim_{numdims}$`)`

  Same as `caml_ba_alloc`, but the sizes of the array in each dimension are listed as extra arguments in the function call, rather than being passed as an array.

The following example illustrates how statically-allocated C and Fortran arrays can be made available to OCaml.

```
extern long my_c_array[100][200];
extern float my_fortran_array_[300][400];

value caml_get_c_array(value unit)
{
  long dims[2];
  dims[0] = 100; dims[1] = 200;
  return caml_ba_alloc(CAML_BA_NATIVE_INT | CAML_BA_C_LAYOUT,
                       2, my_c_array, dims);
}

value caml_get_fortran_array(value unit)
```

```
{
  return caml_ba_alloc_dims(CAML_BA_FLOAT32 | CAML_BA_FORTRAN_LAYOUT,
                            2, my_fortran_array_, 300L, 400L);
}
```

Part V

Appendix

Index to the library

(*), 358
(*/), 576
(**), 360
(**/), 576
(*.), 360
(&), 356
(&&), 356
(@), 365
(@@), 357
(!), 372
(!=), 356
(:=), 372
(=), 354
(==), 355
(=/), 577
(^), 363
(^^), 374
(>), 355
(>=), 355
(>=/), 577
(>/), 577
(<), 355
(<=), 355
(<=/), 577
(<>), 355
(<>/), 577
(</), 577
(-), 358
(-/), 576
(-.), 360
(|>), 357
(||), 356
(+), 358
(+/), 576
(+.), 359
(/), 358
(//), 576
(/.), 360
(~-), 358
(~-.), 359
(~+), 358
(~+.), 359
(asr), 359
(land), 359
(lor), 359
(lsl), 359
(lsr), 359
(lxor), 359
(mod), 358
(or), 356
__FILE__, 356
__LINE__, 356
__LINE_OF__, 357
__LOC__, 356
__LOC_OF__, 357
__MODULE__, 357
__POS__, 357
__POS_OF__, 357

abs, 358, 440, 443, 467
abs_big_int, 579
abs_float, 361
abs_num, 576
absname, 525
absolute_path, 525
accept, 562, 598
access, 550
access_permission, 549
acos, 360
adapt_filename, 610
add, 397, 433, 437, 438, 440, 443, 456, 462–465, 467, 479, 494, 516
add_available_units, 611
add_big_int, 579
add_buffer, 388
add_bytes, 388
add_channel, 388
add_char, 387
add_implementation, 239
add_implementation_binding, 239
add_int_big_int, 579
add_interfaces, 610
add_num, 576
add_ppx_context_sig, 522

add_ppx_context_str, 522
add_signature, 239
add_signature_binding, 239
add_string, 388
add_subbytes, 388
add_substitute, 388
add_substring, 388
add_use_file, 239
addr_info, 567
alarm, 431, 557
align, 382
allocated_bytes, 429
allow_only, 610
allow_unsafe_modules, 610
always, 596
and_big_int, 582
anon_fun, 380
append, 383, 450
apply, 521
approx_num_exp, 578
approx_num_fix, 578
Arg, 379
arg, 398
arg_label, 523
argv, 506
Arith_status, 583
arith_status, 583
Array, 382, 500
array, 352, 497
Array1, 622
array1_of_genarray, 630
Array2, 624
array2_of_genarray, 630
Array3, 627
array3_of_genarray, 630
asin, 361
asprintf, 422
Assert_failure, 120, 353
assoc, 453
assq, 453
Ast_mapper, 519
Asttypes, 523
at_exit, 375
atan, 361
atan2, 361
attribute, 527
attribute_of_warning, 522
attributes, 527
auto_synchronize, 607

backend_type, 508
background, 601
backtrace_slot, 473
backtrace_slots, 473
backtrace_status, 472
Bad, 381
basename, 409
beginning_of_input, 486
big_endian, 508
Big_int, 579
big_int, 579
big_int_of_int, 581
big_int_of_int32, 581
big_int_of_int64, 582
big_int_of_nativeint, 582
big_int_of_num, 578
big_int_of_string, 581
Bigarray, 614
bind, 562
bindings, 457, 465
bits, 481, 482
bits_of_float, 442, 445
black, 601
blit, 384, 387, 390, 503, 515, 621, 623, 626, 629
blit_data, 403, 405, 406
blit_image, 605
blit_key, 402, 406
blit_key1, 404
blit_key12, 404
blit_key2, 404
blit_string, 390
blue, 602
bool, 352, 481, 482
bool_of_string, 364
bound_map, 239
bounded_full_split, 590
bounded_split, 589
bounded_split_delim, 590
bprintf, 423, 478

Break, 512
broadcast, 595
bscanf, 487
bscanf_format, 491
Buffer, 386
button_down, 606
Bytes, 389, 500
bytes, 351, 399

c_layout, 617
Callback, 395
capitalize, 392, 505
capitalize_ascii, 393, 505
cardinal, 457, 465, 466, 495
case, 529
cat, 391
catch, 471
catch_break, 512
ceil, 361
ceiling_num, 577
change_layout, 619
channel, 399, 595
Char, 396
char, 351, 616
char_of_int, 363
chdir, 507, 551
check, 515
check_data, 403, 405, 406
check_key, 402, 405, 407
check_key1, 404
check_key2, 404
check_suffix, 408
chmod, 549
choose, 458, 465, 466, 496, 596
chop_extension, 409
chop_suffix, 408
chown, 550
chr, 396
chroot, 551
class_declaration, 532
class_description, 531
class_expr, 531
class_expr_desc, 532
class_field, 532
class_field_desc, 532
class_field_kind, 532
class_infos, 531
class_signature, 531
class_structure, 532
class_type, 531
class_type_declaration, 531
class_type_desc, 531
class_type_field, 531
class_type_field_desc, 531
classify_float, 363
clean, 401
clear, 387, 433, 437, 438, 461–463, 480, 499, 516
clear_available_units, 611
clear_close_on_exec, 550
clear_graph, 601
clear_nonblock, 550
clear_parser, 470
close, 544
close_box, 411
close_graph, 600
close_in, 371, 485
close_in_noerr, 371
close_out, 369
close_out_noerr, 369
close_process, 553
close_process_full, 553
close_process_in, 553
close_process_out, 553
close_tag, 416
close_tbox, 424
closed_flag, 523
closedir, 551
code, 396
color, 601
combine, 453
command, 507
compact, 428
compare, 355, 393, 396, 399, 442, 445, 455, 456, 464, 465, 469, 493, 494, 506, 514
compare_big_int, 580
compare_num, 578
Complex, 397
complex32, 616
complex32_elt, 615

complex64, 616
complex64_elt, 615
concat, 383, 391, 408, 450, 503
Condition, 594
conj, 397
connect, 562, 598
cons, 449
constant, 523, 527
constructor_arguments, 530
constructor_declaration, 530
container, 407
contains, 392, 505
contains_from, 392, 505
contents, 387
control, 427
convert_raw_backtrace_slot, 475
copy, 384, 390, 433, 437, 438, 462, 463, 469, 480, 482, 499, 503
copysign, 361
core_type, 526, 527, 535
core_type_desc, 528
cos, 360
cosh, 361
count, 501, 517
counters, 428
create, 347, 383, 386, 389, 401, 403, 405, 407, 432, 437, 438, 461–463, 479, 498, 499, 502, 514, 516, 592, 594, 595, 618, 622, 624, 627
create_alarm, 431
create_float, 383
create_image, 605
create_matrix, 383
create_process, 552
create_process_env, 552
curr, 524
current, 382
current_dir_name, 408
current_point, 602
current_x, 602
current_y, 602
curveto, 602
cyan, 602
cygwin, 508
data, 516
data_size, 461
decr, 373
decr_num, 577
default_available_units, 610
default_error_reporter, 526
default_mapper, 521
default_warning_printer, 525
delay, 592
delete_alarm, 431
Depend, 239
descr_of_in_channel, 545
descr_of_out_channel, 545
diff, 465, 494
Digest, 398
dim, 623
dim1, 624, 627
dim2, 625, 627
dim3, 627
dims, 618
dir_handle, 551
dir_sep, 408
direction_flag, 523
directive_argument, 535
dirname, 409
display_mode, 607
div, 398, 440, 443, 467
div_big_int, 580
div_num, 576
Division_by_zero, 353
doc, 380
domain_of_sockaddr, 562
draw_arc, 603
draw_char, 603
draw_circle, 603
draw_ellipse, 603
draw_image, 605
draw_poly, 603
draw_poly_line, 603
draw_rect, 602
draw_segments, 603
draw_string, 603
drop_ppx_context_sig, 523
drop_ppx_context_str, 523
dummy_pos, 447

dump, 514
dump_image, 605
dup, 550
dup2, 550
Dynlink, 609

echo_eof, 525
elements, 466, 495
elt, 465, 493
Empty, 479, 499
empty, 389, 455, 464, 465, 493, 501
enable_runtime_warnings, 512
end_of_input, 486
End_of_file, 353
environment, 541
Ephemeron, 400
eprintf, 422, 478
epsilon_float, 363
eq_big_int, 580
eq_num, 577
equal, 393, 397, 399, 407, 436, 437, 442, 445, 456, 464, 465, 469, 494, 506, 514
err_formatter, 418
Error, 500, 525, 611
error, 525, 541, 611
error_message, 541, 611
error_of_exn, 526
error_of_printer, 526
error_of_printer_file, 526
error_reporter, 526
errorf, 526
escaped, 391, 396, 504
establish_server, 565
Event, 595
event, 595, 606
executable_name, 507
execv, 542, 597
execve, 542, 597
execvp, 542, 597
execvpe, 542
exists, 385, 452, 457, 464, 466, 495
exists2, 452
Exit, 354
exit, 374, 592
exn, 352
exn_slot_id, 476
exn_slot_name, 476
exp, 360, 398
expm1, 360
expression, 527, 528, 535
expression_desc, 529
extend, 390
extension, 408, 527
extension_constructor, 530
extension_constructor_kind, 530
extension_of_error, 522
extern_flags, 459
extract_big_int, 583

Failure, 353, 500
failwith, 354
fast_sort, 386, 454
fchmod, 549
fchown, 550
file, 399
file_descr, 543
file_exists, 507
file_kind, 546
file_name, 484
file_perm, 544
Filename, 408
fill, 384, 390, 503, 515, 621, 623, 626, 629
fill_arc, 604
fill_circle, 604
fill_ellipse, 604
fill_poly, 604
fill_rect, 604
filter, 452, 457, 464, 466, 495
filter_map_inplace, 434, 437, 438, 462, 463
finalise, 429
finalise_last, 430
finalise_release, 431
find, 433, 437, 438, 452, 458, 462, 463, 465, 466, 496, 516
find_all, 433, 437, 438, 452, 462, 463, 516
first_chars, 590
flatten, 450, 526
float, 352, 362, 481, 482
float_of_big_int, 582
float_of_bits, 442, 445

float_of_int, 362
float_of_num, 578
float_of_string, 364
float32, 616
float32_elt, 614
float64, 616
float64_elt, 614
floor, 361
floor_num, 577
flow_action, 572
flush, 368
flush_all, 368
flush_input, 449
flush_queue, 572
flush_str_formatter, 419
fold, 434, 437, 438, 457, 462–464, 466, 480, 495, 499, 516
fold_left, 385, 451
fold_left2, 451
fold_right, 385, 451
fold_right2, 451
for_all, 385, 452, 457, 464, 466, 495
for_all2, 452
force, 141, 446
force_newline, 413
force_val, 446
foreground, 601
fork, 542
Format, 410
format, 374, 475
format_from_string, 492
format_of_string, 374
format4, 352, 374
format6, 374
formatter, 418
formatter_for_warnings, 525
formatter_of_buffer, 418
formatter_of_out_channel, 418
formatter_out_functions, 417
formatter_tag_functions, 417
fortran_layout, 617
fpclass, 363
fprintf, 421, 476
free_structure_names, 239
frexp, 362
from, 500
from_bytes, 461
from_channel, 448, 460, 485
from_file, 485
from_file_bin, 485
from_fun, 446
from_function, 448, 485
from_hex, 400
from_string, 448, 461, 485
from_val, 446
fscanf, 492
fst, 365
fstat, 547, 549
ftruncate, 546, 548
full_init, 481
full_major, 428
full_split, 590

Gc, 425
gcd_big_int, 580
ge_big_int, 580
ge_num, 578
Genarray, 618
genarray_of_array1, 630
genarray_of_array2, 630
genarray_of_array3, 630
GenHashTable, 406
Genlex, 431
get, 382, 389, 428, 502, 515, 619, 623, 625, 627
get_all_formatter_output_functions, 424
get_approx_printing, 583
get_backtrace, 471
get_bucket, 429
get_callstack, 473
get_cookie, 523
get_copy, 515
get_credit, 429
get_data, 402, 404, 406, 407
get_data_copy, 402, 404, 406
get_ellipsis_text, 415
get_error_when_null_denominator, 583
get_floating_precision, 583
get_formatter_out_functions, 417

get_formatter_output_functions, 416
get_formatter_tag_functions, 418
get_image, 605
get_key, 402, 405, 407
get_key_copy, 402, 405
get_key1, 403
get_key1_copy, 403
get_key2, 404
get_key2_copy, 404
get_margin, 413
get_mark_tags, 416
get_max_boxes, 414
get_max_indent, 413
get_minor_free, 429
get_normalize_ratio, 583
get_normalize_ratio_when_printing, 583
get_pos_info, 524
get_print_tags, 416
get_raw_backtrace, 472
get_raw_backtrace_next_slot, 475
get_raw_backtrace_slot, 475
get_state, 482
get_temp_dir_name, 410
getaddrinfo, 568
getaddrinfo_option, 568
getcwd, 507, 551
getegid, 559
getenv, 507, 541
geteuid, 558
getgid, 559
getgrgid, 560
getgrnam, 560
getgroups, 559
gethostbyaddr, 566
gethostbyname, 566
gethostname, 566
getitimer, 558
getlogin, 560
getnameinfo, 568
getnameinfo_option, 568
getpeername, 562
getpid, 543
getppid, 543
getprotobyname, 566
getprotobynumber, 567
getpwnam, 560
getpwuid, 560
getservbyname, 567
getservbyport, 567
getsockname, 562
getsockopt, 564
getsockopt_error, 565
getsockopt_float, 565
getsockopt_int, 565
getsockopt_optint, 565
gettimeofday, 557
getuid, 558
global_replace, 589
global_substitute, 589
gmtime, 557
Graphic_failure, 600
Graphics, 600
green, 601
group_beginning, 588
group_end, 588
group_entry, 559
gt_big_int, 580
gt_num, 578
guard, 596

handle_unix_error, 541
has_symlink, 554
hash, 407, 436, 437, 439, 464, 514
hash_param, 439, 464
HashedType, 436, 462
Hashtbl, 432, 461
hd, 449
header_size, 461
Help, 381
highlight_locations, 525
host_entry, 566
huge_fallback_count, 429
hypot, 361

i, 397
id, 469, 592
ifprintf, 423, 478
ignore, 364
ikfprintf, 423, 478
image, 604
implementation, 526

in_channel, 365, 484
in_channel_length, 371, 372
in_channel_of_descr, 545
in_file, 524
include_declaration, 534
include_description, 533
include_infos, 533
incr, 372
incr_num, 577
index, 391, 504
index_from, 392, 504
inet_addr, 560
inet_addr_any, 560
inet_addr_loopback, 561
inet_addr_of_string, 560
inet6_addr_any, 561
inet6_addr_loopback, 561
infinity, 362
init, 383, 389, 480, 502, 524, 611
initgroups, 559
input, 370, 399
input_binary_int, 371
input_byte, 371
input_char, 370
input_lexbuf, 524
input_line, 370
input_name, 524
input_value, 371
int, 351, 481, 482, 616
int_elt, 615
int_of_big_int, 581
int_of_char, 363
int_of_float, 362
int_of_num, 578
int_of_string, 364
int_size, 508
int16_signed, 616
int16_signed_elt, 615
int16_unsigned, 616
int16_unsigned_elt, 615
Int32, 439
int32, 139, 352, 481, 482, 616
int32_elt, 615
int32_of_big_int, 582
Int64, 442
int64, 139, 352, 481, 482, 616
int64_elt, 615
int64_of_big_int, 582
int8_signed, 616
int8_signed_elt, 615
int8_unsigned, 616
int8_unsigned_elt, 615
integer_num, 577
inter, 465, 494
interactive, 507
interface, 526
interval_timer, 558
interval_timer_status, 558
inv, 398
invalid_arg, 354
Invalid_argument, 353
is_char, 513
is_directory, 507
is_empty, 455, 464, 465, 480, 494, 499
is_implicit, 408
is_inline, 474
is_int_big_int, 581
is_integer_num, 577
is_native, 609
is_raise, 474
is_randomized, 435
is_relative, 408
is_val, 446
is_valid, 513
isatty, 547
iter, 384, 391, 434, 437, 438, 450, 456, 462–464, 466, 480, 494, 499, 501, 503, 516
iter2, 385, 451
iteri, 384, 391, 450, 503

join, 592
junk, 501

K1, 401
K2, 403
kasprintf, 423
kbprintf, 479
key, 380, 437, 438, 455, 462–464
key_pressed, 607
kfprintf, 423, 478
kfscanf, 492

kill, 555, 592
kind, 615, 619, 623, 625, 627
kind_size_in_bytes, 617
Kn, 405
kprintf, 423, 479
kscanf, 491
ksprintf, 423, 479
ksscanf, 491

label, 523
label_declaration, 530
LargeFile, 372, 547
last, 526
last_chars, 590
layout, 617, 619, 623, 625, 627
Lazy, 445
Lazy (module), 141
lazy_from_fun, 446
lazy_from_val, 447
lazy_is_val, 447
lazy_t, 352
ldexp, 362
le_big_int, 580
le_num, 578
length, 382, 387, 389, 434, 437, 438, 449, 462, 463, 480, 499, 502, 514
lexbuf, 448
lexeme, 448
lexeme_char, 448
lexeme_end, 449
lexeme_end_p, 449
lexeme_start, 448
lexeme_start_p, 449
Lexing, 447
lineto, 602
link, 549
linking_error, 611
List, 449, 500
list, 352, 496
listen, 562
lnot, 359
loadfile, 609
loadfile_private, 609
loc, 524, 525
localtime, 557
Location, 524
location, 474
lock, 594
lock_command, 554
lockf, 555
log, 360, 398
log10, 360
log1p, 360
logand, 441, 443, 468
lognot, 441, 444, 468
logor, 441, 443, 468
logxor, 441, 444, 468
Longident, 526
loop_at_exit, 606
lowercase, 392, 396, 505
lowercase_ascii, 393, 396, 505
lseek, 546, 547
lstat, 547, 549
lt_big_int, 580
lt_num, 577

magenta, 602
major, 428
major_slice, 428
Make, 403, 405, 406, 437, 458, 463, 465, 466, 496, 517
make, 382, 389, 482, 502
make_float, 383
make_formatter, 419
make_image, 605
make_leaf, 239
make_lexer, 432
make_matrix, 383
make_node, 239
make_self_init, 482
MakeSeeded, 403, 405–407, 438, 463
Map, 454, 464
map, 384, 391, 450, 458, 465, 466, 495, 503
map_file, 621, 624, 626, 629
map_opt, 522
map_tree, 239
map2, 385, 451
mapi, 384, 391, 450, 458, 465, 503
mapper, 521
Marshal, 459

match_beginning, 588
match_end, 588
matched_group, 588
matched_string, 587
Match_failure, 111–113, 353
max, 355, 513
max_array_length, 509
max_big_int, 581
max_binding, 458, 465
max_elt, 466, 496
max_float, 362
max_int, 358, 440, 443, 467
max_num, 578
max_string_length, 509
mem, 385, 433, 437, 438, 452, 455, 462–465, 494, 516
mem_assoc, 453
mem_assq, 453
memq, 385, 452
merge, 454, 456, 464, 497, 516
min, 355, 513
min_big_int, 581
min_binding, 457, 465
min_elt, 466, 495
min_float, 362
min_int, 358, 440, 443, 467
min_num, 578
minor, 428
minor_words, 428
minus_big_int, 579
minus_num, 576
minus_one, 440, 443, 467
mkdir, 551
mkfifo, 551
mkloc, 525
mknoloc, 525
mktime, 557
mod_big_int, 580
mod_float, 362
mod_num, 576
modf, 362
module_binding, 535
module_declaration, 533
module_expr, 534
module_expr_desc, 534
module_type, 532
module_type_declaration, 533
module_type_desc, 533
MoreLabels, 461
mouse_pos, 606
moveto, 602
msg_flag, 563
mul, 397, 440, 443, 467
mult_big_int, 579
mult_int_big_int, 579
mult_num, 576
mutable_flag, 523
Mutex, 594

name_info, 568
name_of_input, 486
nan, 362
nat_of_num, 578
Nativeint, 466
nativeint, 139, 352, 481, 482, 616
nativeint_elt, 615
nativeint_of_big_int, 582
neg, 397, 440, 443, 467
neg_infinity, 362
new_channel, 595
new_line, 449
next, 501
nice, 543
none, 524
norm, 398
norm2, 398
not, 356
Not_found, 353
npeek, 501
nth, 387, 450
nth_dim, 619
Num, 575
num, 575
num_bits_big_int, 581
num_digits_big_int, 581
num_dims, 618
num_of_big_int, 578
num_of_int, 578
num_of_nat, 578
num_of_ratio, 578

num_of_string, 578

ocaml_version, 512
of_array, 623, 626, 629
of_bytes, 501
of_channel, 501
of_char, 513
of_float, 441, 444, 468
of_int, 441, 444, 468, 513
of_int32, 444, 468
of_list, 384, 466, 496, 500
of_nativeint, 445
of_string, 390, 441, 445, 469, 500
one, 397, 440, 442, 466
Oo, 469
opaque_identity, 512
open_box, 411
open_connection, 565, 598
open_description, 533
open_flag, 367, 544
open_graph, 600
open_hbox, 414
open_hovbox, 414
open_hvbox, 414
open_in, 370, 485
open_in_bin, 370, 485
open_in_gen, 370
open_module, 239
open_out, 367
open_out_bin, 367
open_out_gen, 368
open_process, 552, 598
open_process_full, 552
open_process_in, 552, 598
open_process_out, 552, 598
open_tag, 415
open_tbox, 424
open_temp_file, 409
open_vbox, 414
opendir, 551
openfile, 544
option, 352
or_big_int, 582
OrderedType, 455, 464, 465, 493
os_type, 508
out_channel, 365
out_channel_length, 369, 372
out_channel_of_descr, 545
Out_of_memory, 353
output, 368, 399
output_binary_int, 368
output_buffer, 388
output_byte, 368
output_bytes, 368
output_char, 368
output_string, 368
output_substring, 368
output_value, 369
over_max_boxes, 414
override_flag, 523

package_type, 528
parent_dir_name, 408
Parse, 526
parse, 380, 526
parse_argv, 381
parse_argv_dynamic, 381
parse_dynamic, 381
Parse_error, 470
Parsetree, 527
Parsing, 470
partition, 452, 457, 465, 466, 495
passwd_entry, 559
pattern, 527, 528, 535
pattern_desc, 528
pause, 556
payload, 527
peek, 480, 501
Pervasives, 354
pipe, 551, 598
plot, 602
plots, 602
point_color, 602
polar, 398
poll, 596
pop, 480, 499
pos_in, 371, 372
pos_out, 369, 372
position, 447
pow, 398

power_big_int_positive_big_int, 580
power_big_int_positive_int, 580
power_int_positive_big_int, 580
power_int_positive_int, 580
power_num, 576
pp_close_box, 419
pp_close_tag, 419
pp_close_tbox, 424
pp_flush_formatter, 420
pp_force_newline, 419
pp_get_all_formatter_output_functions, 424
pp_get_ellipsis_text, 420
pp_get_formatter_out_functions, 420
pp_get_formatter_output_functions, 420
pp_get_formatter_tag_functions, 420
pp_get_margin, 420
pp_get_mark_tags, 420
pp_get_max_boxes, 420
pp_get_max_indent, 420
pp_get_print_tags, 420
pp_open_box, 419
pp_open_hbox, 419
pp_open_hovbox, 419
pp_open_hvbox, 419
pp_open_tag, 419
pp_open_tbox, 424
pp_open_vbox, 419
pp_over_max_boxes, 420
pp_print_as, 419
pp_print_bool, 419
pp_print_break, 419
pp_print_char, 419
pp_print_cut, 419
pp_print_float, 419
pp_print_flush, 419
pp_print_if_newline, 420
pp_print_int, 419
pp_print_list, 421
pp_print_newline, 419
pp_print_space, 419
pp_print_string, 419
pp_print_tab, 424
pp_print_tbreak, 424
pp_print_text, 421
pp_set_all_formatter_output_functions, 424
pp_set_ellipsis_text, 420
pp_set_formatter_out_channel, 420
pp_set_formatter_out_functions, 420
pp_set_formatter_output_functions, 420
pp_set_formatter_tag_functions, 420
pp_set_margin, 420
pp_set_mark_tags, 420
pp_set_max_boxes, 420
pp_set_max_indent, 420
pp_set_print_tags, 420
pp_set_tab, 424
pp_set_tags, 420
Pprintast, 535
pred, 358, 440, 443, 467, 513
pred_big_int, 579
pred_num, 577
prerr_bytes, 366
prerr_char, 366
prerr_endline, 366
prerr_float, 366
prerr_int, 366
prerr_newline, 366
prerr_string, 366
prerr_warning, 525
print, 471, 525
print_as, 412
print_backtrace, 471
print_bool, 412
print_break, 412
print_bytes, 365
print_char, 365, 412
print_compact, 525
print_cut, 412
print_endline, 366
print_error, 524
print_error_cur_file, 524
print_error_prefix, 525
print_filename, 525
print_float, 366, 412
print_flush, 413
print_if_newline, 413
print_int, 366, 412
print_loc, 524

print_newline, 366, 413
print_raw_backtrace, 472
print_space, 412
print_stat, 429
print_string, 365, 412
print_tab, 425
print_tbreak, 424
print_warning, 525
Printexc, 471
Printf, 476
printf, 422, 478
private_flag, 523
process_status, 542
process_times, 556
prohibit, 610
protocol_entry, 566
push, 479, 499
putenv, 541

Queue, 479
quick_stat, 428
quo_num, 576
quomod_big_int, 580
quote, 410, 586

raise, 354
raise_errorf, 526
raise_notrace, 354
Random, 480
randomize, 435, 462
ratio_of_num, 578
raw_backtrace, 472
raw_backtrace_length, 475
raw_backtrace_slot, 475
raw_backtrace_to_string, 473
rcontains_from, 392, 505
read, 544, 597
read_float, 367
read_int, 367
read_key, 606
read_line, 367
readdir, 507, 551
readlink, 554
really_input, 370
really_input_string, 370
rec_flag, 523
receive, 596
record_backtrace, 471
recv, 563, 598
recvfrom, 563, 598
red, 601
ref, 372
regexp, 585
regexp_case_fold, 586
regexp_string, 586
regexp_string_case_fold, 586
register, 395, 522
register_error_of_exn, 526
register_exception, 396
register_function, 522
register_printer, 472
rem, 440, 443, 467
remember_mode, 607
remove, 433, 437, 438, 456, 462–465, 494, 507, 516
remove_assoc, 453
remove_assq, 453
remove_extension, 408
rename, 507, 549
replace, 434, 437, 438, 462, 463
replace_first, 589
replace_matched, 589
report_error, 526
report_exception, 526
reset, 387, 433, 437, 438, 462, 463, 525
reshape, 630
reshape_1, 630
reshape_2, 630
reshape_3, 631
resize_window, 601
result, 373
rev, 450
rev_append, 450
rev_map, 451
rev_map2, 451
rewinddir, 551
rgb, 601
rhs_end, 470
rhs_end_pos, 470
rhs_loc, 524
rhs_start, 470

rhs_start_pos, 470
rindex, 391, 504
rindex_from, 392, 504
rlineto, 602
rmdir, 551
rmoveto, 602
round_num, 577
row_field, 528
run_main, 522
runtime_parameters, 509
runtime_variant, 509
runtime_warnings_enabled, 512

S, 400, 436, 455, 462, 464, 465, 493, 515
save_and_close, 347, 498
save_event, 347, 498
save_event_for_automatic_snapshots, 348, 498
Scan_failure, 486
scanbuf, 484
Scanf, 483
scanf, 491
scanner, 486
Scanning, 484
search_backward, 587
search_forward, 587
seeded_hash, 439, 464
seeded_hash_param, 439, 464
SeededHashedType, 437, 462
SeededS, 401, 438, 463
seek_command, 546
seek_in, 371, 372
seek_out, 369, 372
select, 554, 593, 596, 597
self, 592
self_init, 481
send, 563, 596, 598
send_substring, 563, 598
sendto, 563, 598
sendto_substring, 563, 598
Series, 347, 498
service_entry, 566
Set, 465, 492
set, 382, 389, 428, 502, 515, 619, 623, 625, 627
set_all_formatter_output_functions, 423
set_approx_printing, 583
set_binary_mode_in, 371
set_binary_mode_out, 369
set_close_on_exec, 550
set_color, 601
set_cookie, 523
set_data, 402, 404, 406
set_ellipsis_text, 415
set_error_when_null_denominator, 583
set_floating_precision, 584
set_font, 604
set_formatter_out_channel, 416
set_formatter_out_functions, 417
set_formatter_output_functions, 416
set_formatter_tag_functions, 417
set_key, 402, 405
set_key_data, 407
set_key1, 403
set_key2, 404
set_line_width, 603
set_margin, 413
set_mark_tags, 416
set_max_boxes, 414
set_max_indent, 413
set_nonblock, 550
set_normalize_ratio, 583
set_normalize_ratio_when_printing, 583
set_print_tags, 416
set_signal, 509
set_state, 482
set_tab, 425
set_tags, 416
set_temp_dir_name, 410
set_text_size, 604
set_trace, 470
set_uncaught_exception_handler, 473
set_window_title, 600
setattr_when, 571
setgid, 559
setgroups, 559
setitimer, 558
setsid, 572
setsockopt, 565

setsockopt_float, 565
setsockopt_int, 565
setsockopt_optint, 565
setuid, 559
shift_left, 441, 444, 468
shift_left_big_int, 582
shift_right, 441, 444, 468
shift_right_big_int, 582
shift_right_logical, 441, 444, 468
shift_right_towards_zero_big_int, 582
show_filename, 525
shutdown, 562
shutdown_command, 562
shutdown_connection, 565
sigabrt, 510
sigalrm, 510
sigbus, 511
sigchld, 510
sigcont, 510
sigfpe, 510
sighup, 510
sigill, 510
sigint, 510
sigkill, 510
sigmask, 593
sign_big_int, 580
sign_num, 577
signal, 509, 595
signal_behavior, 509
signature, 533, 535
signature_item, 533
signature_item_desc, 533
sigpending, 555
sigpipe, 510
sigpoll, 511
sigprocmask, 555
sigprocmask_command, 555
sigprof, 511
sigquit, 510
sigsegv, 510
sigstop, 511
sigsuspend, 555
sigsys, 511
sigterm, 510
sigtrap, 511
sigtstp, 511
sigttin, 511
sigttou, 511
sigurg, 511
sigusr1, 510
sigusr2, 510
sigvtalrm, 511
sigxcpu, 511
sigxfsz, 512
sin, 360
single_write, 544
single_write_substring, 545
singleton, 456, 464, 465, 494
sinh, 361
size, 467
size_in_bytes, 619, 623, 625, 627
size_x, 601
size_y, 601
sleep, 557, 598
sleepf, 557
slice_left, 620, 625
slice_left_1, 628
slice_left_2, 628
slice_right, 621, 626
slice_right_1, 628
slice_right_2, 628
Slot, 474
Snapshot, 347, 498
snd, 365
sockaddr, 562
socket, 562, 598
socket_bool_option, 564
socket_domain, 561
socket_float_option, 564
socket_int_option, 564
socket_optint_option, 564
socket_type, 561
socketpair, 562
Sort, 496
sort, 386, 453
sort_uniq, 454
sound, 607
space_formatter, 535
Spacetime, 346, 497
spec, 380

split, 453, 458, 465, 466, 496, 589
split_delim, 590
split_on_char, 506
split_result, 590
sprintf, 422, 478
sqrt, 360, 398
sqrt_big_int, 580
square_big_int, 579
square_num, 576
sscanf, 491
sscanf_format, 491
stable_sort, 386, 454
Stack, 499
Stack_overflow, 353
stat, 426, 427, 547, 549
State, 482
statistics, 435, 462
stats, 435, 437, 438, 462, 463, 517, 547, 549
stats_alive, 401
status, 606
std_formatter, 418
stdbuf, 419
stderr, 365, 543
stdib, 486
stdin, 365, 484, 543
StdLabels, 500
stdout, 365, 543
Str, 585
str_formatter, 419
Stream, 500
String, 500, 502
string, 352, 399
string_after, 590
string_before, 590
string_match, 587
string_of_big_int, 581
string_of_bool, 364
string_of_expression, 535
string_of_float, 364
string_of_format, 374
string_of_inet_addr, 560
string_of_int, 364
string_of_num, 578
string_of_structure, 535
string_partial_match, 587
StringMap, 239
StringSet, 239
structure, 534, 535
structure_item, 534
structure_item_desc, 534
sub, 383, 387, 390, 397, 440, 443, 467, 503, 623
sub_big_int, 579
sub_left, 620, 625, 628
sub_num, 576
sub_right, 620, 625, 628
sub_string, 390
subbytes, 399
subset, 466, 494
substitute_first, 589
substring, 399
succ, 358, 440, 443, 467, 513
succ_big_int, 579
succ_num, 577
symbol_end, 470
symbol_end_pos, 470
symbol_gloc, 524
symbol_rloc, 524
symbol_start, 470
symbol_start_pos, 470
symlink, 553
sync, 596
synchronize, 607
Sys, 506
Sys_blocked_io, 354
Sys_error, 353
system, 542, 597

t, 347, 386, 393, 396–398, 401, 403, 405, 407, 432, 436–438, 442, 445, 455, 461–465, 469, 474, 479, 482, 493, 498–500, 506, 513, 514, 516, 524, 526, 592, 594, 595, 618, 622, 624, 627
tag, 415
take, 347, 479, 498
tan, 360
tanh, 361
tcdrain, 571
tcflow, 572
tcflush, 572

tcgetattr, 571
tcsendbreak, 571
tcsetattr, 571
temp_dir_name, 410
temp_file, 409
terminal_io, 571
text_size, 604
Thread, 592
ThreadUnix, 597
time, 507, 557
timed_read, 597
timed_write, 597
timed_write_substring, 597
times, 557
tl, 450
tm, 557
to_buffer, 460
to_bytes, 387, 460
to_channel, 459
to_char, 513
to_float, 441, 444, 468
to_hex, 399
to_int, 441, 444, 468, 513
to_int32, 444, 469
to_list, 384
to_nativeint, 445
to_string, 390, 442, 445, 460, 469, 471
token, 432
tool_name, 521
top, 480, 499
top_phrase, 535
toplevel_phrase, 526, 535
total_size, 461
transfer, 480
transp, 604
trim, 391, 504
truncate, 362, 546, 548
try_lock, 594
type_declaration, 530
type_extension, 530
type_kind, 530

Uchar, 513
umask, 550
uncapitalize, 392, 505
uncapitalize_ascii, 393, 506
Undefined, 446
Undefined_recursive_module, 354
unescaped, 492
union, 456, 464, 465, 494
unit, 352
unit_big_int, 579
Unix, 537
unix, 508
Unix_error, 541
UnixLabels (module), 572
unlink, 549
unlock, 594
unsafe_get, 624, 626, 629
unsafe_of_string, 395
unsafe_set, 624, 626, 629
unsafe_to_string, 393
unset_data, 402, 404, 406
unset_key, 402, 405
unset_key1, 403
unset_key2, 404
uppercase, 392, 396, 505
uppercase_ascii, 393, 396, 505
usage, 381
usage_msg, 380
usage_string, 382
use_file, 526
utimes, 557

value_binding, 535
value_description, 529
variance, 524
virtual_flag, 523

wait, 542, 595, 597
wait_flag, 542
wait_next_event, 606
wait_pid, 593
wait_read, 592
wait_signal, 594
wait_timed_read, 593
wait_timed_write, 593
wait_write, 593
waitpid, 542, 597
warning_printer, 525
Weak, 514

weaken_map, 239
white, 601
win32, 508
with_constraint, 534
word_size, 508
wrap, 596
wrap_abort, 596
write, 544, 597
write_substring, 544, 597

xor_big_int, 582

yellow, 602
yield, 593

zero, 397, 440, 442, 466
zero_big_int, 579

Index of keywords

`and`, 108, 121, 125, 129, 130, 134, 141, 149
`as`, 100, 101, 104, 105, 125, 127
`asr`, 98, 109, 116
`assert`, 120

`begin`, 103, 108, 110

`class`, 129, 130, 132, 134, 135
`constraint`, 121, 123, 125, 128

`do`, *see* `while`, `for`
`done`, *see* `while`, `for`
`downto`, *see* `for`

`else`, *see* `if`
`end`, 103, 108, 110, 123, 125, 130, 134, 135
`exception`, 123, 130, 132, 134, 135, 173
`external`, 130, 131, 134, 135

`false`, 103
`for`, 108, 114
`fun`, 108, 109, 111, 125, 147
`function`, 108, 109, 111
`functor`, 130, 133, 134, 136

`if`, 108, 109, 113
`in`, *see* `let`
`include`, 130, 133, 134, 136, 151
`inherit`, 123–125, 127
`inherit!`, 154
`initializer`, 125, 129

`land`, 98, 109, 116
`lazy`, 108, 120, 141
`let`, 108, 109, 112, 120, 125, 134, 135, 145, 147, 173
`lor`, 98, 109, 116
`lsl`, 98, 109, 116
`lsr`, 98, 109, 116
`lxor`, 98, 109, 116

`match`, 108, 109, 113, 155
`method`, 123, 125, 128
`method!`, 154
`mod`, 98, 109, 116
`module`, 120, 130, 132, 134–136, 141, 149, 151, 152
`mutable`, 121–123, 125, 127, 128

`new`, 108, 117
`nonrec`, 121

`object`, 108, 118, 123, 125
`of`, 102, 121, 151
`open`, 130, 133, 134, 136, 145
`open!`, 154
`or`, 108, 109, 114

`private`, 123, 125, 128, 142, 144

`rec`, *see* `let`, `module`

`sig`, 130
`struct`, 134, 135

`then`, *see* `if`
`to`, *see* `for`
`true`, 103
`try`, 108, 109, 114
`type`, 121, 129–132, 134–136, 147, 151, 155

`val`, 123, 125, 127, 128, 130, 131, 149
`val!`, 154
`virtual`, *see* `val`, `method`, `class`

`when`, 108, 112, 160
`while`, 114
`with`, 108, 130, 133, 146, 149, 151