

# ON MULTIPLE POSITIVE SOLUTIONS OF POSITONE AND NON-POSITONE PROBLEMS

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## 1. Introduction

In this paper, we consider the following problem:

$$-\Delta u = f(u) \quad \text{in } \Omega, \quad u = 0 \quad \text{on } \partial\Omega, \quad (1.1)$$

where  $\Omega$  is the ball  $B_R = \{x \in \mathbb{R}^N; |x| < R\}$ ,  $|\cdot|$  is the Euclidean norm in  $\mathbb{R}^N$ , and  $f: \mathbb{R}^+ \rightarrow \mathbb{R}$  is a locally Lipschitzian continuous function. We are concerned with two classes of problems, namely,

- (i) the positone problem:  $f(0) \geq 0$ ;
- (ii) the non-positone problem:  $f(0) < 0$ .

The study of positone problems was initiated by Keller and Cohen [14], see also [15], motivated by problems arose from the theory of nonlinear heat generation. In the past twenty five years there has been considerable interest in this class of semilinear elliptic boundary value problems and there is a wide literature on this subject. The reader may consult the survey by Lions [17], and the references therein, where many interesting questions are studied under a different point of view.

In the positone case we consider the following assumptions:

- (f1) there exist  $0 < a_1 < a_2 < a_3$  so that  $f(a_1) = f(a_2) = 0$  and  $F(a_3) > F(a_1)$ , where  $F(t) = \int_0^t f$ ;
- (f2)  $|f(t)| \leq \alpha$ , for all  $t \in \mathbb{R}^+$ , for some constant  $\alpha > 0$ ;
- (P)  $f(0) > 0$  or, if  $f(0) = 0$ , then  $f'_+(0) > 0$ , where  $f'_+(0) = \lim_{t \rightarrow 0^+} (f(t)/t)$  and prove the result below.

**THEOREM 1.1.** *Suppose that  $f: \mathbb{R}^+ \rightarrow \mathbb{R}$  satisfies (f1), (f2), and (P). If  $R$  is sufficiently large, problem (1.1) possesses at least three radial positive solutions  $u_1$ ,  $u_2$ , and  $u_3$  such that  $\partial u_i / \partial r < 0$ , for  $i = 1, 2, 3$  and  $0 < r < R$ . In particular*

$$0 < \|u_1\|_\infty < a_1 < a_2 < \|u_2\|_\infty, \quad (1.2)$$

where  $\|\cdot\|_\infty$  is the sup norm.

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*Remark 1.2.* Some results like the one above have been obtained by several authors when the area condition  $F(a_3) > F(a_1)$  has been considered. This condition was first used by Brown and Budin [3] who proved a result similar to Theorem 1.1 by using a combination of variational and monotone iteration methods. Later Hess [13] studied this problem by using variational methods and degree theory. In [9], the above condition is also used and, by using solely variational methods, the existence of three ordered positive solutions is shown. These authors studied the case in which  $f$  has a third root, that is,  $f(a_3) = 0$ . In Theorem 1.1 this assumption is not made and we use only variational methods. Also, Theorem 1.1 is used as an essential tool in the study of non-positone case.

The non-positone case has been studied in recent years mainly by Brown, Castro, Shivaji, Arcoya, and Calahorrano, among others. See, for example, [2, 4, 5]. In this case the following assumption is posed:

$$f(0) < 0. \quad (1.3)$$

Motivated by the study of discontinuous nonlinear problems we consider, as in [2], the following multivalued problem:

$$-\Delta u(x) \in \hat{f}(u(x)) \quad \text{a.e in } \Omega, \quad u = 0 \text{ on } \partial\Omega, \quad (1.4)$$

where  $\hat{f}$  is the multivalued function defined by

$$\hat{f}(t) = \begin{cases} 0, & \text{if } t < 0 \\ [f(0), 0], & \text{if } t = 0 \\ f(t), & \text{if } t > 0. \end{cases} \quad (1.5)$$

By a solution of (1.4), we mean a function  $u \in C^1(\overline{\Omega}) \cap C^2(\Omega^*(u))$  with  $\Omega^*(u) = \{x \in \Omega; u(x) \neq 0\}$  and verifying (1.4).

*Remark 1.3.* Some authors (cf. Chang [6]) have treated discontinuous problems by using a direct variational approach. In the present case, we consider the multivalued problem (1.4) as the limit of smooth approximating problems in order to use Theorem 1.1. Thus two nonnegative solutions  $u_0$  and  $v_0$ , in the sense of (1.4), are obtained as limits of smooth approximating solutions. Then we use the symmetry results in [11] and the maximum principle to show that  $u_0$  and  $v_0$  are positive classical solutions of (1.1). For this a crucial step is to show that the set  $\Omega_0(u) = \Omega / \Omega^*(u)$  has null Lebesgue measure for  $u = u_0, v_0$ .

The following assumptions on  $f$  are considered:

(f3) there exists  $\theta > 0$  such that  $f(t) < 0$  if  $0 \leq t < \theta$  and  $f(\theta) = 0$ ,

(f4) there is  $a > \theta$  satisfying  $F(a) > 0$ .

We are now ready to state the following theorem.

**THEOREM 1.4.** *Suppose that  $f : \mathbb{R}^+ \rightarrow \mathbb{R}$  is a bounded  $C^1$ -function satisfying (f3), (f4), and (1.3). Then problem (1.4) has at least two radial positive solutions  $u_0$  and  $v_0$  if  $R$*

is sufficiently large. In fact  $\Omega_0(u_0) = \Omega_0(v_0) = \phi$ , which implies  $u_0$  and  $v_0$  are radial classical positive solutions of (1.1) such that  $\partial u / \partial r < 0$ , for  $0 < r < R$  and  $u = v_0, u_0$ .

**Remark 1.5.** It is well known in the positone case, see, for example, Cohen and Laetsch [7], that if  $f$  is concave, problem (1.1) has at most one positive solution, but may have multiple solutions when  $f$  is convex. In contrast with this case Theorem 1.4 shows that in the non-positone problem we may obtain multiplicity of positive solutions with  $f$  concave. The function  $f(t) = \alpha - e^{-t}$ ,  $0 < \alpha < 1$  and  $t \geq 0$ , is a simple example of a bounded concave function satisfying (f3), (f4), and (1.3).

## 2. Proof of Theorem 1.1

**First solution.** Let us consider the following function:

$$f_1(t) = \begin{cases} f(0), & \text{if } t \leq 0; \\ f(t), & \text{if } 0 \leq t \leq a_1; \\ 0, & \text{if } a_1 \leq t; \end{cases} \quad (2.1)$$

and the functional  $I_1 : E \rightarrow \mathbb{R}$ ,  $E := H_0^1(\Omega)$  with the usual norm  $\|u\|^2 = \int |\nabla u|^2$ , where the integrals are taken over all  $\Omega$ , unless we state the contrary, defined by

$$I_1(u) = \frac{1}{2} \int |\nabla u|^2 - \int F_1(u), \quad F_1(u) = \int_0^u f_1. \quad (2.2)$$

Note that  $I_1$  is the Euler-Lagrange functional associated to the problem

$$-\Delta u = f_1(u) \quad \text{in } \Omega, \quad u = 0 \quad \text{on } \partial\Omega. \quad (2.3)$$

Since  $I_1$  is coercive and weakly lower semi-continuous (w.l.s.c.), see [10], it achieves its minimum at some point  $u_1 \in E$ , which is a weak solution of (2.3) and a bootstrap argument shows that  $u_1$  is a classical solution of (2.3). Assumption (P) implies that  $\liminf_{t \rightarrow 0^+} (f(t)/t) > \lambda_1 := \lambda_1(R)$ , if  $R$  is sufficiently large, where  $\lambda_1$  is the first eigenvalue of  $(-\Delta, H_0^1(\Omega))$ . In particular, this yields  $I_1(u_1) < 0$ , that is,  $u_1 \not\equiv 0$  in  $\Omega$ . So the maximum principle provides  $0 < u_1(x) < a_1$  in  $\Omega$  and then  $u_1$  satisfies (1.1). Moreover, it is easy to show that

$$I_1(u_1) > -K_N F(a_1) R^N, \quad (2.4)$$

where  $K_N$  is a positive constant depending only on  $N$ . Actually (2.4) is valid for all  $u \in E$  satisfying  $0 < u(x) < a_1$  a.e. in  $\Omega$ .

**Second solution.** We now consider the function  $I : E \rightarrow \mathbb{R}$  given by

$$I(u) = \frac{1}{2} \int |\nabla u|^2 - \int F(u), \quad F(u) = \int_0^u f, \quad (2.5)$$

where we still denote by  $f$  the extension of the former function  $f$  and defined by

$$f(t) = \begin{cases} f(0), & \text{if } t \leq 0; \\ f(t), & \text{if } 0 < t. \end{cases} \quad (2.6)$$

A standard calculation shows that  $I$  is coercive and w.l.s.c. Hence  $I$  attains its minimum at  $u_2 \in E$ . We may not guarantee, up to now, that  $u_1 \neq u_2$ . For this we consider the following function used by Klaasen and Mitidieri [16]:

$$u_R(x) = \begin{cases} a_3, & \text{if } |x| \leq R-1; \\ (R-|x|)a_3, & \text{if } R-1 < |x| < R. \end{cases} \quad (2.7)$$

Setting  $C_R = \{x \in \mathbb{R}^N; R-1 < |x| < R\}$  we obtain

$$\begin{aligned} I(u_R) &\leq \frac{1}{2} \int_{C_R} |\nabla u_R|^2 - \int_{B_{R-1}} F(a_3) - \int_{C_R} F(u_R) \\ &\leq \frac{a_3^2}{2} |C_R| - F(a_3) |B_{R-1}| + C_1 |C_R| \\ &\leq \frac{a_3^2}{2} h_N R^{N-1} - F(a_3) K_N (R-1)^N + C_1 h_N R^{N-1}. \end{aligned} \quad (2.8)$$

Thus

$$I(u_R) \leq C_N R^{N-1} - K_N F(a_3) R^N, \quad (2.9)$$

where the constants  $C_1$ ,  $K_N$ ,  $h_N$ , and  $C_N$  do not depend on  $R$ . Since  $F(a_3) - F(a_1) > 0$  one has, for  $R$  sufficiently large,

$$K_N (F(a_3) - F(a_1)) R^N > C_N R^{N-1} \quad (2.10)$$

which implies

$$I(u_R) < -K_N F(a_1) R^N < I_1(u_1) = I(u_1). \quad (2.11)$$

Then the minimum  $u_2$  of  $I$  satisfies

$$I(u_2) \leq I(u_R) < I(u_1). \quad (2.12)$$

This shows that  $u_1 \neq u_2$ . A bootstrap argument guarantees that  $u_2 \in C^{2,\alpha}(\overline{\Omega})$  and the maximum principle implies that  $0 < u_2(x)$ , for all  $x \in \Omega$ , and  $a_2 < |u_2|_\infty$ , because  $I(u_2) < -K_N F(a_1) R^N < I(u)$ , for all  $u$  so that  $0 < u(x) < a_1$  in  $\Omega$ .

**Third solution.** Using an argument as in de Figueiredo [10] we may prove that  $u_1$  is a local minimum of  $I$ . A straightforward computation shows that  $I$  satisfies the Palais-Smale condition, see [1]. So by the Ambrosetti and Rabinowitz's Mountain Pass Theorem, see [1], we find a third solution (positive)  $u_3$  of (1.1) satisfying

$$I(u_3) \geq -K_N F(a_1) R^N. \quad (2.13)$$

Finally we observe, in view of symmetry results in Gidas, Ni, and Nirenberg [11], that  $u_i$ ,  $i = 1, 2, 3$ , are radial and  $\partial u_i / \partial r < 0$ ,  $i = 1, 2, 3$ , for all  $0 < r < R$ . This proves Theorem 1.1.  $\square$

*Remark 2.1.* If  $f$  is decreasing on  $[0, a_1]$ , there exists only the solution  $u_1$  such that  $0 < u_1(x) < a_1$ . Hence, in this case,  $u_3$  also satisfies  $a_2 < |u_3|_\infty$ . In fact the Cosner and Schmitt's result, see [8], implies that  $|u_2|_\infty, |u_3|_\infty > a_3$ .

### 3. Proof of Theorem 1.4

To prove Theorem 1.4 we use mainly Theorem 1.1.

For this, we first consider smooth approximations of  $\hat{f}$  given by

$$f_n(t) = \begin{cases} f(t), & \text{if } \frac{1}{n} \leq t; \\ f_n(t) \geq f(t), & \text{if } 0 \leq t \leq \frac{1}{n}; \\ f_n(t) = \frac{1}{n}, & \text{if } t \leq 0; \end{cases} \quad (3.1)$$

$f_n$  is  $C^1$ , there is  $a_{1n} \in (0, 1/n)$  such that  $F_n(a) > F_n(a_{1n})$  and  $f_n(t) \rightarrow f(t)$ , for all  $t > 0$ . As usual  $F_n(t) = \int_0^t f_n$ . Let us now consider the problem

$$-\Delta u = f_n(u) \quad \text{in } \Omega, \quad u = 0 \text{ on } \partial\Omega. \quad (3.2)$$

In order to apply Theorem 1.1 to problem (3.2) we consider the functional  $I_n$  on  $E$  defined by

$$I_n(u) = \frac{1}{2} \int |\nabla u|^2 - \int F_n(u). \quad (3.3)$$

Since  $f_n : \mathbb{R} \rightarrow \mathbb{R}$  satisfies the assumptions of Theorem 1.1, problem (3.2) possesses at least three positive solutions  $u_{1n}, u_{2n}$ , and  $u_{3n}$ . In particular

$$I_n(u_{2n}) \leq C_N R^{N-1} - K_N F_n(a) R^N < -K_N F_n(a_{1n}) R^N \leq I_n(u_{3n}). \quad (3.4)$$

Elliptic regularity yields  $|u_{2n}|_{w^{2,p}}, |u_{3n}|_{w^{2,p}} \leq C_p$ , for all  $p \geq 1$ . For  $p > N$  one has  $u_{2n} \rightarrow u_0$  and  $u_{3n} \rightarrow v_0$  in  $C^{1,\alpha}(\overline{\Omega})$  for some  $0 < \alpha < 1$ , eventually for subsequences. Since  $F_n(a) \rightarrow F(a)$  and  $F_n(a_{1n}) \rightarrow 0$  as  $n \rightarrow \infty$ , one has

$$\begin{aligned} \int |\nabla u_{2n}|^2 &\longrightarrow \int |\nabla u_0|^2, & \int |\nabla u_{3n}|^2 &\longrightarrow \int |\nabla v_0|^2, \\ \int F(u_{2n}) &\longrightarrow \int F(u_0), & \int F(u_{3n}) &\longrightarrow \int F(v_0). \end{aligned} \quad (3.5)$$

Taking limits in the inequalities in (3.4) we obtain

$$I(u_0) \leq C_N R^{N-1} - K_N F(a) R^N \leq I(v_0). \quad (3.6)$$

Noticing that  $-K_N F_n(a_{1n})R^N \leq I_n(u_{3n})$  and  $F_n(a_{1n}) \rightarrow 0$  one has  $0 \leq I(v_0)$ . Because  $F(a) > 0$  we obtain  $C_N R^{N-1} - K_N F(a)R^N < 0$  if  $R$  is sufficiently large.

Thus

$$I(u_0) \leq C_N R^{N-1} - K_N F(a)R^N < 0 \leq I(v_0) \quad (3.7)$$

and so  $u_0 \neq v_0$ .

We show that  $u_0$  and  $v_0$  are nontrivial nonnegative solutions of (1.4). First we observe that  $f_n$  may be chosen decreasing in  $(0, 1/n)$ , for each  $n = 1, 2, \dots$ . Thus problem (3.2) possesses a unique positive solution  $u_{1n}$  satisfying  $0 < u_{1n}(x) < 1/n$ , for each  $n = 1, 2, \dots$ . Hence  $|u_{2n}|_\infty, |u_{3n}|_\infty > \theta$ , for all  $n = 1, 2, \dots$ . In fact, the result in Cosner-Schmitt [8] implies that  $|u_{2n}|_\infty, |u_{3n}|_\infty \geq a$  for all  $n = 1, 2, \dots$ . Consequently,  $|u_0|_\infty, |v_0|_\infty \geq a$  and  $u_0$  and  $v_0$  are not identically zero.

If  $t_n > 0$  and  $t_n \rightarrow t > 0$ , then  $f_n(t_n) \rightarrow f(t)$ . From now on, we set  $u = u_0$  or  $u = v_0$ . Thus if  $x \in \Omega^*(u)$  one has  $\lim_{n \rightarrow \infty} f_n(u_n(x)) = f(u(x))$ , where  $u_n = u_{2n}$  or  $u_n = u_{3n}$ . Taking  $\varphi \in C_0^\infty(\Omega^*(u))$  and using the fact that

$$-\Delta u_n(x) = f_n(u_n(x)) \quad \text{in } \Omega, \quad u_n = 0 \text{ on } \partial\Omega, \quad (3.8)$$

we obtain

$$\int_{\Omega^*} \nabla u_n \cdot \nabla \varphi = \int_{\Omega^*(u)} f_n(u_n) \varphi \implies \int_{\Omega^*(u)} \nabla u \cdot \nabla \varphi = \int_{\Omega^*(u)} f(u) \varphi. \quad (3.9)$$

Consequently,  $u \in C^2(\Omega^*(u))$  and  $-\Delta u = f(u)$  in  $\Omega^*(u)$ . In  $\Omega_0(u)$  we have, as a consequence of a well-known result by Stampacchia (cf. [15, Lemma A.4]),  $-\Delta u(x) = 0 \in [f(0), 0]$  a.e., and so  $u_0$  and  $v_0$  are both nontrivial nonnegative solutions of (1.4). Let us now prove that if  $u(x_0) = 0$  for some  $|x_0| = r < R$ , it follows that  $u(x) = 0$  for all  $r < |x| < R$ . Actually, if  $u(x) > 0$  for some  $r < |x| < R$ , then  $(\partial u / \partial r)(y) > 0$ , for some  $r < |y| < R$ , which is a contradiction in view of  $(\partial u / \partial r)(x) \leq 0$  if  $0 < |x| < R$ . Remember that  $\partial u_n / \partial r < 0$  for  $0 < r < R$  which implies that  $\partial u / \partial r \leq 0$  because  $u_n \rightarrow u$  in  $C^{1,\alpha}(\bar{\Omega})$ . So  $\Omega_0(u)$  is a set like  $A_\rho = B_R - B_{R-\rho}$ , for some  $\rho \geq 0$ . Suppose that  $\rho > 0$ . In view of  $f(u) \in C^1(\bar{B}_{R-\rho})$  one has

$$-\Delta \left( \frac{\partial u}{\partial r} \right) = f'(u) \frac{\partial u}{\partial r} \quad \text{in } B_{R-\rho}. \quad (3.10)$$

Since  $f$  is  $C^1$  there is  $\mu > 0$  satisfying  $f'(t) + \mu \geq 0$ , for all  $t \in [0, M]$ , with  $M = \max\{|u_0|_\infty, |v_0|_\infty\}$ . Consequently,

$$-\Delta \left( -\frac{\partial u}{\partial r} \right) + \mu \left( -\frac{\partial u}{\partial r} \right) = (f'(u) + \mu) \left( -\frac{\partial u}{\partial r} \right) \quad \text{in } B_{R-\rho}. \quad (3.11)$$

Therefore, in view of  $\partial u / \partial r = 0$  in  $A_\rho$  we have by applying the generalized Green's formula on  $B_{R-\rho}$  that

$$-\Delta \left( -\frac{\partial u}{\partial r} \right) + \mu \left( -\frac{\partial u}{\partial r} \right) \geq 0 \quad \text{in } \Omega \quad (3.12)$$

in the weak sense and as  $u > 0$  in  $B_{R-\rho}$  we have  $\partial u / \partial r \neq 0$  and so, by using the generalized maximum principle, (cf. [12, Theorem 8.19]),  $\partial u / \partial r < 0$  in  $\Omega$ , which is a

contradiction with assumption  $\rho > 0$ . Hence,  $\rho = 0$ . This implies that  $\Omega_0(u) = \phi$ , then  $u > 0$  in  $\Omega$  and  $\partial u / \partial r < 0$  if  $0 < r < R$ . It follows that  $u_0$  and  $v_0$  are classical solutions of (1.1). This concludes the proof of Theorem 1.4.  $\square$

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