Economics Bulletin

Volume 30, Issue 1

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Abstract

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1 Introduction

In the last decades, experimental research on private provision of public goods has been successfully conducted within the well-known Public Goods Game (PGG) or Voluntary Contributions Mechanism (VCM) setting, where a low number of subjects are given identical initial endowments and allowed to either invest (possibly part of) it in a public account or keep it in a private account. As Masclet et al. (2003) observe: this game is appealing as “it starkly isolates the conflict between self-interest and group interest and allows a simple measure of the extent of group-interested behavior” (p. 366). Lab evidence indicates that economic theory overestimates the relevance of free riding, as subjects cooperate *significantly more* than would be predicted on the basis of the so called ‘selfishness axiom’. However, while within unrepeated PGG environments, as well as in the first rounds of repeated PGGs, average contribution levels are relatively high, iteration of strategic interaction for a finite number of rounds leads to the well-known ‘decay’ phenomenon, so that, as the game unfolds, contribution levels gradually decline and almost full free riding prevails in the last round (Ledyard 1995). By contrast, the introduction of costly punishment options turns out to make the difference: insofar as subjects are allowed to sanction each other, high average contribution levels become sustainable and the decay phenomenon does not occur (see Fehr and Gächter 2000; 2002). This result is surprising, due to the presence of clear financial incentives to act selfishly and, hence, to abstain from both contributing to the public good and punishing others - since punishment itself is a (second-order) public good for the group. Experimental research has also shown that the relatively high average contribution levels observed within repeated PGGs with punishment options are associated with a significant degree of *behavioral heterogeneity.* In particular, some players turn out to play selfishly and ride free on others’ generosity, while others both contribute to the public account and are willing to costly sanction low contributors - even though this is ‘irrational’ from the viewpoint of standard economic theory. In other words, two behavioral types seem to prevail: some individuals act as first-order and second-order free riders, as they both abstain from contributing to the public good (first-order free riding) and from sanctioning others (second-order free riding; for this expression, see Oliver 1980). On the contrary, other subjects are high contributors who are also ready to sanction low contributors (see Fehr and Gächter 2000; 2002 and Ones and Putterman 2007). The latter players have been termed 'strong reciprocators' and display so called 'altruistic punishment': Fehr and Fischbacher (2005) maintain that "Theory as well as empirical evidence suggest that the interaction between strongly reciprocal and selfish types is of first-order importance for many economic questions" (p. 155).

By means of an evolutionary analysis, our paper provides theoretical support for this coexistence between strongly reciprocal and selfish players within a PGG environment with punishment opportunities. More specifically, we show, to our knowledge for the first time, that within a PGG framework with *four* players simultaneously involved (as it is often the case in the lab), where we suppose that public good provision occurs insofar as at least two players do contribute, stable coexistence between free riders and strong reciprocators is possible, in line with the experimental papers recalled above. Well-known 4-player PGG experiments include Fehr and Gaechter (2000; 2002), Fischbacher et al. (2001), Masclet et al. (2003), Kurzban and Houser (2005) and Ones and Putterman (2007).

The structure of the remainder of the paper is as follows. Section 2 contains the structure of the model. Section 3 contains our major results and Section 4 concludes.

2 The model

Let us consider a (very large) community of individuals continuously interacting over time and enjoying the benefits of a given collective good. Randomly occurring encounters involve four players at a time, with a material PGG to be played. While in many experimental PGG environments multiple contribution options are available, we introduce a simplifying assumption and suppose instead that each single player has to make a binary, 'all-or-nothing' choice: he may either contribute to the public good (by giving a certain amount of money) or free ride. Therefore, material consequences for the players depend on their choosing between contribute (or 'cooperate', C) and free ride (or 'defect', D) only[1]. Further, we assume that the collective good to

[1]We claim that this modelling choice allows us to maintain tractability by retaining the key qualitative features of the experimental setting we refer to. Dreber et al. (2008) conducted an experiment based on repeated pairwise encounters in which subjects could choose either between C and D only or among C, D and P (costly punishment). Their results show that the introduction of punishment options increases the amount of cooperation over time, in line with public goods experiments where multiple contribution

be provided is a *threshold* public good: actual provision occurs only insofar as a sufficiently large proportion of individuals do contribute to it (Cadsby and Maynes 1999). In particular, we suppose that if n_C is the number of players cooperating in each matching, $n_C = 2$ is the 'critical threshold' of cooperators needed for the public good to be privately provided[2]. Hence, the material consequences of each 4-player interaction (for the row player) are captured by the following payoff matrix:

	DDD	DDC	DCC	CCC
D	a	a	b	c
C	d	e	f	g

(1)

Table 1 *4-player PGG payoff matrix*

where:
$c > b > a$
$c > f$ $b > e$, $a > d$
$g > f > e > d$ [3].

Moreover, we suppose that costly punishment options are available, so that in each matching players can also decide to incur costs in order to punish

choices (rather than binary choices) are available to the players. We view their evidence as confirming that the well-known conclusion that cooperation is sustainable over time when costly punishment options are available is robust to the specification of players' contribution set.

[2]Like in our model, most threshold PGG experiments assume that players can either decide not to contribute or to contribute by a given amount.

[3]By assuming that $g > f > e$, we are supposing that the threshold public good under study also possesses the following feature. Once a specific *provision-point* (the 'threshold') is met (Isaac et al. 1989), the amount of the public good may further increase, provided that the aggregate level of contributions increases. This is equivalent to assuming that contributions beyond the threshold levels, far from being wasted, result in further benefits to the group. In our model, this is captured by the assumption that the individual payoff from playing C when the other three players also cooperate (that is, g) is greater than the individual payoff from playing C when only two out of three opponents cooperate (that is, f), which in turn is greater than the individual payoff from playing C when only one of the three opponents cooperates (that is, e). For the same reason, we suppose that the individual payoff from playing D when the other three players cooperate (that is, c) is greater than the individual payoff from playing D when only two out of three opponents cooperate (that is, b). The inequalities $c > f$, $b > e$ and $a > d$, capture the fact that, at the individual level, for a given number of cooperators in the group (that is 3, 2 or 1, respectively), choosing to cooperate systematically yields a lower material payoff than choosing to defect.

others. However, we also stick to the traditional evolutionary methodology by assuming that a low number of behavioral types are present in the population and play 'hardwired' programmed strategies over their lifetimes[4]. In particular, on the basis of the experimental studies recalled above, we decided to focus on a 2-type population where only *Egoists* and *Strongly Reciprocal players* are initially present. An *Egoist* or *Selfish* player (SEL) is defined as a *Homo Oeconomicus* who always plays D and systematically abstains from punishing others. Hence, SELs act as classic free riders (first-order free riding) and never use the available (costly) punishment opportunities (second-order free riding). By contrast, a *Strong Reciprocator* (SR) is willing to both (conditionally) cooperate and incur costs in order to punish defectors[5]. As Fehr and Fischbacher (2005) point out, available empirical evidence shows that strong reciprocity is thus far the quantitatively most important type of social preference. Furthermore, experiments suggest that the presence of explicit, targeted punishment opportunities crucially affects the final aggregate outcomes (see Fehr and Gächter 2000; 2002 and Ones and Putterman 2007).

As Ok and Vega-Redondo (2001) highlight, the answer to the question concerning how the material payoffs of the individualistic and non-individualistic agents compare in equilibrium at various population compositions crucially depends inter alia on the extent of *information* agents have on their opponent's type. In this regard, though it has been argued that players tend to subconsciously signal their type via facial expressions and other emotional factors (Frank 1988), economists have been skeptical towards the assumption that individuals can correctly identify their opponents' 'type'. In this light, we suppose that SRs do *not* recognize their opponents' type *ex ante* and that they bravely play C in each matching[6]. However, we also assume that, after cooperating, they can recognize their opponents' type (ex post recognition assumption) and that if SRs see that their opponent is a SEL, they are willing to incur material costs in order to punish her, by displaying 'altruistic

[4]For an experimental paper based on the PGG with punishment options documenting the existence of heterogeneous but *stable* player types in the lab, see Ones and Putterman (2007).

[5]Kocher et al. (2008) run PGG experiments on three continents and show that both free riding and conditional cooperation are ubiquitous, though the distribution of types differs across countries. Fehr and Gächter (2002) interestingly find that a clear relationship exists between contributing and punishing: in their PGG experiment, 75% of the punishment acts carried out by the 240 subjects have been executed by above-average contributors.

[6]This attitude resembles Sugden's (1986) notion of 'brave reciprocity'.

punishment'. In the laboratory, subjects involved in PGG games are usually informed, round after round, either about their group's average contribution levels or about their opponents' individual contribution levels. In the light of this, we claim that strongly reciprocal players use this information as a signal that allows them to gradually learn the composition of their (usually small) group and to identify (and punish) free riders. In PGG experiments, if within a group only two behavioral patterns prevail (that is systematic defection and systematic cooperation, associated with the decision to punish defectors), it can be plausibly argued that over time strong reciprocators realize that those who defect, far from making a mistake, are acting as classic free riders and, therefore, deserve to be sanctioned.

More specifically, we assume that the level of punishment costs critically depends on the number of SELs and SRs involved in the 4-player matching. As a consequence, each matching will lead to one of the (material) outcomes captured by the matrix below:

$$\begin{array}{ccccc} & SEL, SEL, SEL & SEL, SEL, SR & SEL, SR, SR & SR, SR, SR \\ SEL & a & a-\frac{\varepsilon}{3} & b-\varepsilon & c-3\varepsilon \\ SR & d-\lambda & e-\lambda & f-\lambda & g \end{array} \tag{2}$$

Table 2 *4-player matchings in a SEL-SR population*

where $\lambda > 0$ indicates the *cost of punishing* and $\varepsilon > 0$ indicates the *cost, for a punishee, of being punished by a single punisher*. As table 2 shows, we suppose that while the cost of punishing (λ) is the same regardless of the number of SELs in the 4-player group, the cost of being punished, for a single punishee, crucially depends on the number of SRs and SELs who are present in the group: in particular, it will be $\frac{\varepsilon}{3}$ if a SEL is in a group with only one SR and two other SELs (in this case, the SR is the only punisher and the cost of being punished gets divided by 3); it will be ε if a SEL is in a group with two SRs and another SEL; finally, it will be 3ε if a SEL is in a group with three SRs. In other words, we suppose that for a single punishee the cost of being punished depends on both the number of punishers and the number of punishees.

Expected payoffs can be calculated by using conditional probabilities. By indicating with x and $1-x$ the shares of individuals of the types SEL and SR, respectively, we have:

$$\Pi_{SEL}(x) = ax^3 + (a - \frac{\varepsilon}{3})x^2(1-x) + (b-\varepsilon)x(1-x)^2 + (c-3\varepsilon)(1-x)^3$$

$$\Pi_{SR}(x) = (d-\lambda)x^3 + (e-\lambda)x^2(1-x) + (f-\lambda)x(1-x)^2 + g(1-x)^3$$

where x^3 is the probability for a player to be matched with three SELs, $x^2(1-x)$ is the probability to be matched with two SELs and one SR, and so on.

We suppose that social evolution is driven by *material* payoffs *only*: players imitate the individuals who achieve the best performances in purely material terms. As Ok and Vega-Redondo (2001) observe: "it is possible that non-individualistic preferences are materially more rewarding than individualistic preferences in certain strategic environments" (p. 233). In particular, we assume that the time evolution of x is given by the following differential equation:

$$\dot{x} = F\left[\Pi_{SEL}(x) - \Pi_{SR}(x)\right] \quad (3)$$

where $\dot{x}$ represents the time derivative of x and F is a payoff-positive function (see Weibull 1995, p. 149) satisfying the condition $F \gtreqless 0$ for $\Pi_{SEL} - \Pi_{SR} \gtreqless 0$ when $x \in (0,1)$ and the usual boundary conditions: $F = 0$ if $x = 0$ and $\Pi_{SEL}(0) - \Pi_{SR}(0) \leq 0$, $F = 0$ if $x = 1$ and $\Pi_{SEL}(1) - \Pi_{SR}(1) \geq 0$[7]. Under (3), the point $\overline{x} \in (0,1)$ is a stationary state of (3) if and only if $\Pi_{SEL}(\overline{x}) = \Pi_{SR}(\overline{x})$, while $x = 0$ and $x = 1$ are stationary states if $\Pi_{SEL}(0) - \Pi_{SR}(0) \leq 0$ and $\Pi_{SEL}(1) - \Pi_{SR}(1) \geq 0$ respectively hold; if such conditions are not satisfied, they may or may not be stationary states, according to the particular specification of (3)[8]. However, in any case they are repulsive.

[7] In a 2-type population context, the assumptions of payoff-monotonicity and payoff-positivity give rise to the same dynamics (see Weibull 1995, p. 149).

[8] For example, under the replicator equation $\dot{x} = x(1-x)\left[\Pi_{SEL}(x) - \Pi_{SR}(x)\right]$, $x = 0$ and $x = 1$ are always stationary states.

3 Dynamics

The payoff difference in (3) can be written as:

$$\Pi_{SEL}(x) - \Pi_{SR}(x) = \alpha x^3 + \beta x^2 + \gamma x + \delta \tag{4}$$

where:

$\alpha := -f + b + \lambda + \frac{7}{3}\varepsilon + e - d + g - c$

$\beta := -2b + 2f - \lambda - \frac{22}{3}\varepsilon - e + a - 3g + 3c$

$\gamma := -f + b + \lambda + 8\varepsilon + 3g - 3c$

$\delta := -g + c - 3\varepsilon$

Being (4) a polynomial of degree three, at most three interior stationary states exist. In such states, SEL and SR types coexist. The basic properties of the dynamics are given in the following proposition[9].

Proposition 1 *Dynamics (3) are characterized by the following features:*

1) At most five stationary states in the interval $[0, 1]$*, and at most three stationary states in* $(0, 1)$*, exist.*

2) $x = 1$ *(where all players are SELs) is always a locally attractive stationary state.*

3) $x = 0$ *(where all players are SRs) is a stationary state if* $\varepsilon \geq \frac{c-g}{3}$ *(locally attractive if* $\varepsilon > \frac{c-g}{3}$*)*[10].

4) If $x = 0$ *is locally attractive (repulsive), then an odd (even) number of interior stationary states generically*[11] *exists. When a unique interior stationary state exists, then it is repulsive; if two or three interior stationary states exist, then only one is attractive while the others are repulsive.*

Proof. The polynomial (4) has at most three real roots, so at most three interior stationary states exist; $x = 0$ and $x = 1$ may be stationary states

[9] The conditions over parameter values under which 0, 1, 2 or 3 interior stationary states exist can be provided to the interested reader upon request. Such conditions are algebraically complex and cannot be easily interpreted. However, they are useful in order to think of numerical examples accounting for all the different dynamic regimes that can be observed (see on this figure 1 below).

[10] If $\varepsilon < \frac{c-g}{3}$, the state $x = 0$ may or may not be a stationary state, according to the specification of equation (3); in such case, however, $\dot{x} > 0$ holds if x is near enough to 0 and consequently the state $x = 0$ is repulsive.

[11] That is, we exclude the cases in which the graph of (4) is tangent to the x-axis.

even if they are not roots of (4). This completes the proof of point 1). To prove points 2) and 3), notice that $\Pi_{SEL}(1)-\Pi_{SR}(1)>0$ always holds while $\Pi_{SEL}(0)-\Pi_{SR}(0)\lesseqqgtr 0$ holds if $\varepsilon \gtreqqless \frac{c-g}{3}$; as a consequence, $\dot{x}>0$ always holds for x near enough to 1 while, for x near enough to 0, $\dot{x}\lesseqqgtr 0$ if $\varepsilon \gtreqqless \frac{c-g}{3}$. To prove point 4), let us first consider the case in which $x=0$ is locally attractive; in such case, by the intermediate values theorem, at least one interior stationary state exists. Since attractive stationary states alternate with repulsive ones, we have that: a) if a unique interior stationary state exists, then it is repulsive; b) the possibility that only two interior stationary states, $x_1$and x_2, with $x_1<x_2$, exist is excluded; c) if three interior stationary states, x_1, x_2 and x_3, with $x_1<x_2<x_3$, exist, then the stationary state x_3 must be repulsive because $x=1$ is attractive; consequently, x_2 and x_1 are attractive and repulsive, respectively. Let us note that the attractivity of $x=0$ is a necessary condition for the existence of three interior stationary states.

The statement of point 4) concerning the case in which $x=0$ is repulsive can be checked following the same steps. ■

Let us note that when the population is almost entirely composed of SELs (that is, x is close to 1), all the components of expected payoffs $\Pi_{SEL}(x)$ and $\Pi_{SR}(x)$ are negligible except for ax^3 and $(d-\lambda)x^3$: the stationary state $x=1$ is attractive as $a>d-\lambda$ always holds. Analogously, when the population is almost entirely composed of SRs (that is, x is close to 0), all the components of expected payoffs are negligible except for $(c-3\varepsilon)(1-x)^3$ and $g(1-x)^3$: therefore, the state $x=0$ is attractive if $g>c-3\varepsilon$, that is if $\varepsilon>\frac{c-g}{3}$. Furthermore, it is worth observing that this condition depends on the cost of being punished ε, but not on the cost of punishing λ.

Figure 1 shows the complete taxonomy of dynamic regimes that can be observed. The graphs of the payoff difference (4) and the trajectories that the population follows are obtained posing $a=0.3$, $b=6$, $c=13.5$, $d=0.1$, $e=0.4$, $f=1$, $g=2$, $\lambda=0.01$. Full (open) dots represent attractive (repulsive) stationary states. Notice that the payoff difference (4) is not monotonic in x; in particular, it is always increasing near $x=1$ while it is decreasing near the attractive interior stationary state, when existing.

Other things equal, (4) is decreasing due to the increase in the probability to meet two SELs and one SR, that is the probability that the choices of a player (a SEL or a SR) are crucial for the provision of the public good to occur (as it is important to recall that public good provision occurs only within groups where at least two SRs are present). In this context, the public good will be provided only if the fourth player is a SR. The probability is given by $x^2(1-x)$ and it is increasing in x in the interval $(0, 2/3)$, whereas it is decreasing in x in the interval $(2/3, 1)$. Therefore, as x increases, it is possible that the SR payoff increases compared to the SEL payoff, so that (4) turns out to be decreasing.

The next proposition shows how the basin of attraction of the stationary state $x = 1$ varies in response to variations in the parameters ε and λ.

Proposition 2 *Other things being equal, the basin of attraction of the stationary state $x = 1$ (where all players are SELs) shrinks if the cost of being punished ε increases or if the cost of punishing λ decreases.*

Proof. If ε increases, then (ceteris paribus) the payoff $\Pi_{SEL}(x)$ decreases (given x), while $\Pi_{SR}(x)$ remains constant. Consequently, the subsets of the interval $(0, 1)$ where $\Pi_{SEL}(x) > \Pi_{SR}(x)$ (i.e. where $\dot{x} > 0$) shrink. The same effect is generated by a decrease in λ, which determines an increase in $\Pi_{SR}(x)$, while $\Pi_{SEL}(x)$ remains constant. ■

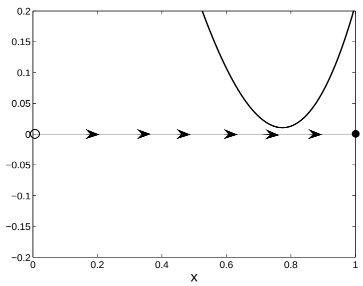
Figure 2 shows how the stationary states vary in response to a variation in the parameter ε. The other parameters are the same as in the example showed in figure 1. Continuous (dotted) lines represent attractive (repulsive) stationary states. It is worth noting that the basin of attraction of $x = 1$ has a lower bound given by the highest dotted line. Therefore, it is straightforward to notice that this basin of attraction shrinks as ε increases. As the cost of being punished increases, the probability to end up in a all-SEL population, ceteris paribus, decreases. The same occurs as the cost of punishing decreases. These two variations in the costs of punishment favor punishers and are detrimental to punishees.

4 Conclusion

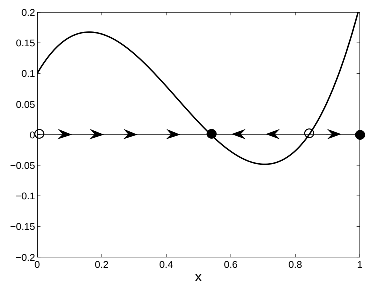
Almost two decades ago, in concluding their pioneering theoretical work on the dynamics of free riding in PGG experiments, Miller and Andreoni (1991) pointed out: “our understanding of the private provision of public goods may be improved by more careful research into evolutionary game theory, and by theory and experiments that examine the motives, decision processes, and dynamics of public goods games” (p 14). By using the evolutionary methodology, we proceeded along these lines and succeeded in ‘mapping’ some robust findings emerging from last years' growing experimental research on PGGs. On the whole, with regard to a SEL-SR population where a 4-player PGG is continuously played, we found that the equilibrium critically depends on both information and behavioral assumptions concerning SRs. In particular, it is the case that, under ex post recognition, coexistence of SELs and SRs may occur. Our major result is that we are able to evolutionarily account for experimental evidence by showing that the equilibrium population, far from being systematically monomorphic, might be a *mixture* of selfish and non-selfish types[12]. To our knowledge, this is the first work where such mixed equilibrium emerges within a PGG setting[13]. Finally, in line with experimental evidence, we shed light on the crucial role played by both the costs of sanctioning and the costs of being sanctioned. Sethi and Somanathan (1996) observe that the use of evolutionary dynamics in their analysis provides us with a confirmation of what can be seen as the centrepiece of economic reasoning, that is "the tendency of human behaviour to adjust in response to persistent differential in material incentives" (p. 783). We can also read their model as providing key insights into the factors which may lead to the breakdown of a norm of cooperation, as the size of the set of stable states (with its corresponding basin of attraction) critically depends on the parameters of the model. On a similar vein, the second proposition illustrated in the previous section shows that, within our evolutionary environment, both egoists' costs of being punished and strong reciprocators' costs of punish crucially affect the probability that social evolution will lead to an individualistic society dominated by defection.

[12]Here we are able to reach this conclusion with reference to a PGG framework where 4-player matchings continuously occur within a 2-type population, whereas Antoci and Zarri (2008) show that this does not occur with *pairwise* random matchings (so that the material PD, rather than the PGG, is played) and several 3-type populations (composed of Altruists, Egoists and various forms of Strong Reciprocators).

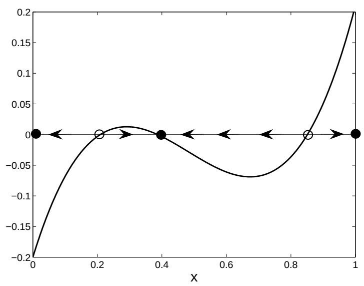
[13]Under some conditions, Guttman (2000) finds stable coexistence of selfish and unselfish players by studying a 2-type population made of opportunists and reciprocators. However, he does not focus on a PGG framework. Moreover, in his model all the players are expected payoff maximizers and reciprocators are not allowed to explicitly sanction defectors.



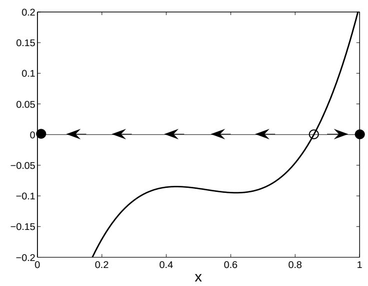
(a) $\lambda = 0.01$, $\epsilon = 3.6$



(b) $\lambda = 0.01$, $\epsilon = 3.8$



(c) $\lambda = 0.01$, $\epsilon = 3.9$



(d) $\lambda = 0.01$, $\epsilon = 4$

Figure 1: Possible dynamic regimes.

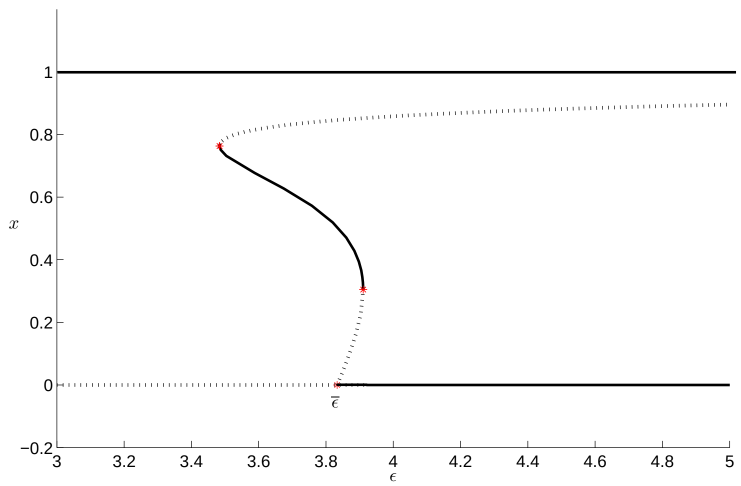


Figure 2: Stationary state configurations, varying the parameter ϵ.

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