# George Mason University

## SCHOOL of LAW

**The Limits of Reciprocity for Social Cooperation**

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**03-08**

LAW AND ECONOMICS
WORKING PAPER SERIES

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# The Limits of Reciprocity for Social Cooperation

Abstract: Reciprocity constraints facilitate the achievement of cooperative outcomes in many game-theoretic settings. Yet, in some situations the equilibrium induced by a reciprocity constraint may not be socially optimal. After presenting the case in which reciprocity yields privately and socially optimal levels of cooperation, this paper identifies the conditions under which reciprocity generates inefficient cooperation. Two groups of cases are presented. In one group reciprocity undershoots (i.e., the parties cooperate less than is socially optimal). In the other, more puzzling case, reciprocity constraints overshoot (i.e., the parties are induced to cooperate more than is socially optimal). This paper identifies the conditions for such occurrences. The paper then examines the ability of a reciprocity constraint to induce a reciprocal social optimum, where a social optimum requires equal levels of effort by the two parties, and identifies situations where reciprocity fails to induce such an optimum.

JEL Codes: K10, D70, C7, Z13
Keywords: Reciprocity, Cooperation, Conditions for Social Optimum

In recent years the notion of reciprocity has gained increasing attention in the social science literature. Experimental and behavioral economists have provided evidence of human attitudes towards reciprocity. Likewise, sociologists and anthropologists have studied the emergence of reciprocity as part of the social and cultural norms that govern human relationships. In the law and economics literature, attention has shifted towards reciprocity operating as an exogenous constraint on human behavior. In many legal situations, reciprocity rules do not rely on the internalization of a "taste" for reciprocity or spontaneous compliance with social norms of reciprocity. Rather, the legal system creates an external reciprocity constraint imposed on human behavior. In particular, Fon and Parisi (2003) examined the role of reciprocity when reciprocity operated as a binding constraint.

In that context, Fon and Parisi considered the effect of exogenous reciprocity constraints on the parties' strategies in simultaneous prisoner's dilemma games. They showed that reciprocity facilitates the achievement of cooperative outcomes in many strategic settings.

This paper extends the results of Fon and Parisi, examining the welfare properties of the reciprocity-induced equilibrium and looking at the *limits* of reciprocity in inducing socially

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optimal levels of cooperation. The paper is structured as follows. Section 1 presents the concept of induced reciprocity. Using a model of reciprocity introduced in Fon and Parisi, the reciprocity-induced equilibrium, the Nash equilibrium and the social optimum are discussed.

Section 2 compares the reciprocity-induced equilibrium to the social optimum. First, situations under which the reciprocity-induced equilibrium is identical to the social optimum are investigated. Next, the possibility for the reciprocity-induced equilibrium to induce less than the optimal level of cooperation efforts is studied, and conditions for such occurrence are identified. Third, the possibility that excessive levels of cooperation effort will be generated under a reciprocity-induced equilibrium is discussed.

Section 3 introduces the notion of reciprocal social optimum, requiring the parties to provide the same levels of cooperation. The reciprocal social optimum is then compared to the reciprocity-induced equilibrium. The analysis reveals that, even when the social optimum requires the parties to provide equal levels of cooperation, reciprocity may fail to induce efficient levels of cooperation. Section 4 concludes the paper by outlining cases of convergence and divergence between private and social optima under reciprocity.

## *1. Reciprocity in a Prisoner's Dilemma Problem*

In a simultaneous prisoner's dilemma with continuous strategies, Fon and Parisi examined the role of reciprocity in cooperation problems. They considered a weak form of reciprocity, which allows the party who prefers a higher level of cooperation to revert to the lesser amount of cooperation chosen by the other party. Reciprocity was treated as an exogenous constraint on the parties' choice of strategy. The results show that reciprocity facilitates the achievement of cooperative outcomes in many strategic settings.

Following the framework set forth by Fon and Parisi and assuming the existence of a reciprocity constraint in one-shot Prisoner's dilemma games, we examine the effects of induced reciprocity constraints on parties' levels of cooperation. Similar to the earlier contribution, our model treats reciprocity as a rule of the game, which exogenously constrains the parties' behavior. Unlike the case of endogenous reciprocity based on individuals' distaste for inequality, internalized norms of fairness, or fear of retaliation (e.g., Fehr and Gächter (2000), Hoffman, McCabe, and Smith (1998), Axelrod and Hamilton (1981), Axelrod (1984)), our reciprocity is

driven by the protocol of the game. This departure from conventional formalizations of reciprocity is motivated by a desire to isolate the effects of reciprocity in cooperation problems from other incentives brought about by utility profiles, fear of retaliation, and expectations of reciprocation. By treating reciprocity as a binding constraint, we consider the best-case scenario in which reciprocal behavior is always mechanically guaranteed by the protocol of the game. Thus, players maximize payoffs and independently choose their strategies, subject to a binding reciprocity constraint. For policy purposes, this will help identify the strengths and weaknesses of legal and social instruments fostering reciprocity as an instrument to achieve efficient cooperation and conflict resolution.

### 1.1 Induced Reciprocity

Building on the above premises, we assume the existence of a weak reciprocity constraint and consider the effects of this reciprocity constraint on the parties' levels of cooperation. If the parties' reciprocity-induced levels of cooperation yield different levels of cooperation for the two players, the weak form of reciprocity allows the lesser of the two amounts of cooperation to become the mutually binding level of cooperation for both individuals.[3] This corresponds to a weak form of the golden rule of reciprocity, which binds each player's strategy to that of his opponent (Parisi, 1998 and 2000).[4] Thus, for example, if one party's desired level of reciprocity-induced cooperation equals $\alpha$ and the other party's desired level equals $\beta$ and $\alpha < \beta$, then the reciprocity-induced equilibrium cooperation will be $\alpha$ for both parties.

We should note that the main virtue of this notion of reciprocity is that it encourages the truthful expression of preferences for both parties. Parties choose strategies under such reciprocity constraints without engaging in preference falsification, since neither party has an incentive to withhold cooperation below the privately optimal level of reciprocal cooperation. As a consequence, the reciprocity mechanism triggers a level of cooperation equal to the level

[3] In the economic literature the "weakest link" problem provides a good illustration of the weak reciprocity concept. For example, Hirshleifer (1983) points out that the effectiveness of a dam depends on the weakest (or lowest) section of the protective dam, voluntarily provided by owners of properties adjacent to a river. Interesting applications and extensions are also found in Arce (2001), showing how reciprocity arises endogenously in "weakest link" and other environments, and Sandler (1998), applying the weakest link paradigm to the foreign aid problem.

desired by the least cooperative player. This level of cooperation, as shown in Fon and Parisi, always improves upon the Nash level of cooperation. In the following, we extend those findings to investigate the relationship between reciprocity-induced equilibria and socially optimal outcomes.

### 1.2 The Model of Reciprocity

Following the asymmetric nonlinear payoff model of reciprocity presented in Fon and Parisi, we consider two parties, each choosing a cooperation effort $s_i$, where $s_i \in [0,1]$. When $s_i = 0$, there is no cooperation. When $s_i = 1$, there is full cooperation.

Assume that the payoff functions for the two parties are $P_1(s_1,s_2) = -as_1^2 + bs_2$, where $a,b > 0$ and $P_2(s_1,s_2) = -cs_2^2 + ds_1$ where $c,d > 0$. Each party faces a cost to provide cooperation effort, as $\partial P_i / \partial s_i < 0$, and each party derives a benefit from the cooperation effort of the other party, as $\partial P_i / \partial s_j > 0$. Asymmetric payoffs for the two players are allowed, meaning that $a$ and $c$ are not necessarily equal and similarly for $b$ and $d$.[5]

Without loss of generality, we assume that one player has a comparative advantage in cooperation. Specifically, party 1 faces lower net benefits from reciprocal cooperation. That is, the ratio of reciprocity-induced benefit to cost at full cooperation for party 1 is lower than that for party 2: $b/2a < d/2c$. In all cases involving asymmetric players we thus maintain the assumption that $bc < ad$.[6]

**1.2.1** We first consider the Nash Equilibrium of this cooperation problem. Since $\partial P_1 / \partial s_1 = -2as_1 < 0$ for all $s_2$, $s_1 = 0$ becomes the dominant strategy for party 1. Likewise, the assumption $c > 0$ makes $s_2 = 0$ the dominant strategy for party 2. Thus, the Nash equilibrium strategies are: $(s_1^N, s_2^N) = (0,0)$.

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[4] In the different context of negative reciprocity, Parisi (2001) examined the historical transition from norms of strong reciprocity to norms of weak reciprocity in biblical times.

[5] Hence, symmetric parties mean that *a* and *c* are equal and *b* and *d* are equal.

[6] Strictly speaking, $bc \le ad$ should have been assumed throughout the paper. However, excluding equality as a possibility often sharpens our understanding of the asymmetric cases examined in this paper. For this reason, we usually assume $bc < ad$.

To make the problem more interesting, we concentrate on the case in which parties are faced with a Prisoner's Dilemma problem. This leads to the introduction of two further assumptions, $0 < a < b$ and $0 < c < d$. These assumptions imply that $P_1(1,1) > P_1^N(0,0)$ and $P_2(1,1) > P_2^N(0,0)$. Both parties would be better off with full cooperation than with no cooperation, as is the case under the Nash equilibrium. This is to be expected in a classic prisoner's dilemma scenario.

**1.2.2** The equilibrium obtained in the presence of a binding reciprocity constraint can be found next. Under reciprocity, each party knows that the other party will reciprocate, within the limits of a mutually agreeable level of cooperation. The smaller of the levels of cooperation chosen by the players becomes the *de facto* level of cooperation for both. The payoff functions to parties 1 and 2, given reciprocity, thus become:

$$\pi_1(s_1,s_2) = \begin{cases} -as_1^2 + bs_1 & \text{if } s_1 \le s_2 \\ -as_2^2 + bs_2 & \text{if } s_1 > s_2 \end{cases} \quad \text{and} \quad \pi_2(s_1,s_2) = \begin{cases} -cs_2^2 + ds_2 & \text{if } s_2 \le s_1 \\ -cs_1^2 + ds_1 & \text{if } s_2 > s_1 \end{cases}.$$

Unlike the case without reciprocity, where cooperation efforts increase costs without generating direct benefits, under reciprocity the parties' own cooperation efforts lead to benefits as well as costs. Since $\frac{b}{2a} = \arg\max_{s_1} -as_1^2 + bs_1$ and $\frac{d}{2c} = \arg\max_{s_2} -cs_2^2 + ds_2$, the maximum levels of agreeable cooperation for party 1 and party 2 are $\frac{b}{2a}$ and $\frac{d}{2c}$ respectively. Note that the maximum agreeable cooperation levels depend on how marginal cost at full cooperation compares with marginal benefit under reciprocity.

Thus, when $1 \le \frac{b}{2a} \le \frac{d}{2c}$, given the expectation of reciprocity the two parties' desired levels of cooperation within the feasible region are $s_1' = 1$ and $s_2' = 1$. Here, the parties are willing to extend full cooperation under reciprocity. Given such willingness, the strategy chosen by each party matches the expected reciprocal strategy of the other party. Thus full cooperation becomes the reciprocity-induced equilibrium strategy for both parties: $(s_1^R, s_2^R) = (1,1)$.[7]

[7] We adopt a refinement criterion according to which, if there are multiple mutually acceptable equilibria under reciprocity and one of them is Pareto superior to the others, parties will pursue the highest mutual payoff, coordinating towards such a level of cooperation.

Next, when $\frac{b}{2a} < 1$, the desired level of cooperation for party 1 is $s_1' = \frac{b}{2a}$. Thus, if party 2 chooses a level of cooperation less than $\frac{b}{2a}$, party 1 would want to match party 2. On the other hand, if party 2 chooses a level of cooperation greater than $\frac{b}{2a}$, party 1 would not match party 2 and would instead choose $\frac{b}{2a}$. Therefore, the reaction function of party 1 is given by $s_1 = \begin{cases} s_2 & \text{if } s_2 \le b/2a \\ b/2a & \text{if } s_2 > b/2a \end{cases}$. Likewise, if $\frac{d}{2c} < 1$, the desired level of cooperation for party 2 would be $s_2' = \frac{d}{2c}$, and his reaction function is $s_2 = \begin{cases} s_1 & \text{if } s_1 \le d/2c \\ d/2c & \text{if } s_1 > d/2c \end{cases}$.

Given the asymmetry, the desirable levels of cooperation $s_1'$ and $s_2'$ may not coincide for the two players. If $\frac{b}{2a} < 1$ , the maximum agreeable cooperation level chosen by party 1 is less than full. Given that party 1 is the high-cost cooperator, his comparative disadvantage in cooperation acquires relevance. The lower net benefits from mutual cooperation lead him to prefer an interior level of cooperation below the level preferred by party 2: $s_1' = \frac{b}{2a} \le \frac{d}{2c} = s_2'$. Under our framework of weak reciprocity, in equilibrium the parties are only bound to cooperate to the lesser level of cooperation. Thus, party 1's maximum agreeable cooperation level $s_1' = \frac{b}{2a}$ becomes the binding strategy for both parties. Hence the reciprocity-induced equilibrium strategies are $(s_1^R, s_2^R) = (\frac{b}{2a}, \frac{b}{2a})$.[8]

Summarizing the two cases, we have the following reciprocity-induced equilibria.

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[8] It is easy to show that the equilibrium payoff for party 2 is $\pi_2^R(s_2^R) = \frac{b(ad-bc)}{4a^2} > 0$. If $d/2c < 1$, party 2 would have been happier if $s_2' = d/2c$ was the reciprocal strategy chosen by both because $\pi_2^R(s_2^R) < \pi_2^R(s_2')$. Likewise, if $d/2c \ge 1$, party 2 prefers the reciprocal strategy 1. In spite of these facts, party 2 is still better off under the reciprocity-induced equilibrium with $\pi_2^R(s_2^R) > 0$ than under the Nash equilibrium where the payoff would have been 0.

1. If $1 \le \frac{b}{2a}$, then $(s_1^R, s_2^R) = (1,1)$.[9]

2. If $\frac{b}{2a} < 1$, then $(s_1^R, s_2^R) = (\frac{b}{2a}, \frac{b}{2a})$.[10]

In both cases the reciprocity-induced equilibrium constitutes an improvement over the alternative Nash equilibrium obtained in the absence of reciprocity.[11] In the following, we identify the socially optimal levels of cooperation for the parties and later verify the extent to which the reciprocity-induced equilibrium approaches the social optimum.

**1.2.3** We now consider the efficiency of the reciprocity-induced outcome in light of the Kaldor-Hicks criterion of welfare. Socially optimal strategies are those that maximize the aggregate payoff for the 2 parties. The social optimization problem thus becomes:

$$\max_{s_1,s_2} P^S(s_1,s_2) = P_1(s_1,s_2) + P_2(s_1,s_2) = (-as_1^2 + bs_2) + (-cs_2^2 + ds_1) \quad \text{s.t.} \quad 0 \le s_1 \le 1,\ 0 \le s_2 \le 1.$$

To find the social optimum, it is now important to compare the marginal cost of a strategy, say $s_1$, with its social marginal benefit. That is, the social incentives are driven by balancing of the marginal cost of $s_1$, $MC_1 = 2as_1$ with its social marginal benefit $MB_1^S = d$. The social incentives will thus be contrasted with the private incentives of the parties, which, as shown in the previous Section, are driven by balancing the marginal cost of $s_1$, $MC_1 = 2as_1$ with the private marginal benefit induced by reciprocity $MB_1^R = b$.[12] In this context, we can identify four alternative social optima.

1. If $\frac{d}{2a} < 1$ & $\frac{b}{2c} < 1$, then $s_1^S = \frac{d}{2a} < 1$, $s_2^S = \frac{b}{2c} < 1$.

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[9] The equilibrium payoffs for the two parties are: $\pi_1^R(1) = b - a > 0$ and $\pi_2^R(1) = d - c > 0$.

[10] The equilibrium payoffs for the two parties are: $\pi_1^R(\frac{b}{2a}) = \frac{b^2}{4a} > 0$ and $\pi_2^R(\frac{b}{2a}) = \frac{b(ad-bc)}{4a^2} > 0$.

[11] From the previous two footnotes, we know that $\pi_1^R > P_1^N = 0$ and $\pi_2^R > P_2^N = 0$.

[12] Note that social marginal cost of cooperation corresponds to the private marginal cost of cooperation. Hence we refer to both simply as marginal cost of cooperation.

2. If $\frac{d}{2a} < 1 \leq \frac{b}{2c}$, then $s_1^S = \frac{d}{2a} < 1$, $s_2^S = 1$.

3. If $\frac{b}{2c} < 1 \leq \frac{d}{2a}$, then $s_1^S = 1$, $s_2^S = \frac{b}{2c} < 1$.

4. If $1 \leq \frac{d}{2a}$ & $1 \leq \frac{b}{2c}$, then $s_1^S = 1$, $s_2^S = 1$.

From this list, we see that the socially optimal levels of cooperation depend on relative magnitudes of social marginal benefit and marginal cost of cooperation, and that the social optimum may require partial cooperation or full cooperation from either or both parties. In particular, note that the social optimum does not necessarily require equal levels of cooperation by the two parties. Since reciprocity requires equal amounts of cooperation effort from both parties, we do not expect the reciprocity-induced equilibrium to be the same as the social optimum in general. Hence it is important to ask whether it is possible to have insufficient cooperation or excessive cooperation under reciprocity-induced equilibrium.

Since our main interest is in the extent to which reciprocity can solve the social cooperation problem, and a social optimum is likely to require unequal levels of cooperation for asymmetric parties, we further focus on social optima that yield identical cooperation levels. In order to appraise the efficiency of the reciprocity-induced equilibrium, we introduce the notion of "reciprocal social optimum." This represents the case in which the aggregate payoff for the parties is maximized subject to equal levels of cooperation. After introducing this concept, we verify the extent to which a reciprocity constraint can induce parties to adopt a level of cooperation equal to the reciprocal social optimum.

## *2. Comparing the reciprocity-induced equilibrium and the social optimum*

The economic model of reciprocity studied in Fon and Parisi verified the general intuition that binding reciprocity provides a viable solution to the prisoner's dilemma problem. In that study, the reciprocity-induced outcome was further shown to be both privately and socially

optimal in partial as well as full cooperation cases with *symmetric players*.[13] We now explore the extent to which this result holds in general for asymmetric players.

In particular, three alternative situations are examined. First, we inquire whether there are situations in which, in spite of the players' asymmetries, the reciprocity-induced equilibrium coincides with the social optimum. Second, we ask whether it is possible for the reciprocity-induced equilibrium to lead to less than optimal levels of cooperation. Third, we inquire whether the reciprocity-induced equilibrium can lead to too much cooperation, where the parties are induced to undertake cooperation efforts in excess of the socially optimal level.

## 2.1 When is the reciprocity-induced equilibrium socially optimal?

In this subsection, we find the necessary conditions under which the reciprocity-induced equilibrium is identical to the social optimum, for the cases of full cooperation and partial cooperation.

**2.1.1** In the case of *full cooperation*, if the reciprocity-induced equilibrium strategies $s_1^R$, $s_2^R$, and the social optimum strategies $s_1^S$, $s_2^S$ all equal 1, the parameters of the model must satisfy the following: $\frac{b}{2a} \geq 1$ (as $s_1^R = 1$), $\frac{d}{2c} \geq 1$ (as $s_2^R = 1$), $\frac{d}{2a} \geq 1$ (as $s_1^S = 1$), and $\frac{b}{2c} \geq 1$ (as $s_2^S = 1$). In other words, $b \geq \max\{2a, 2c\}$ and $d \geq \max\{2a, 2c\}$ must hold. These conditions reflect the fact that in order for the optimal strategies to lead to full cooperation in equilibrium, the marginal benefits of both cooperation efforts from the two parties must be large. More specifically, for private optimality, marginal benefits of cooperation (given the expectation of reciprocal cooperation from the other party) should be at least as large as marginal cost at full cooperation. Likewise, for social optimality, social marginal benefits must be at least as large as marginal cost at full cooperation.

**2.1.2** In the case of *partial cooperation*, two conditions must hold for the reciprocity-induced equilibrium and the social optimum to coincide. First, party 1's socially optimal strategy must equal its reciprocity-induced equilibrium strategy. Since party 1 has a comparative disadvantage in cooperation, its privately optimal cooperation level becomes the binding strategy

[13] Recall that symmetric parties means that parameters *a* and *c* are equal and parameters *b* and *d* are equal.

under our rule of weak reciprocity. Hence $s_1^S = s_1^R < 1$ must hold. Second, the socially optimal strategies chosen by the two parties must be equal, since the reciprocity constraint requires equal levels of cooperation in equilibrium. Thus $s_1^S = s_2^S$ must hold. Translating these conditions to the parameters of the model, we have:

$$s_1^S = s_1^R < 1 \Rightarrow \frac{d}{2a} = \frac{b}{2a} < 1 \Rightarrow b = d < 2a \quad \text{and} \quad s_1^S = s_2^S \Rightarrow \frac{d}{2a} = \frac{b}{2c} \Rightarrow a = c\,.$$

Since $a = c,\ b = d < 2a$ must hold, we see that the conditions for convergence of the reciprocity-induced equilibrium with the social optimum are fairly restrictive for the case of partial cooperation. Indeed, in this case, the convergence of private and social incentives can only happen if the two parties are symmetric. That is, we should expect a partial cooperation outcome to be socially optimal only if the two parties face symmetric payoff functions.

**2.1.3** It is interesting to see that the reciprocity-induced levels of cooperation for asymmetric parties will be socially optimal only under fairly restrictive conditions.[14] Except when $\frac{d}{2a} = \frac{b}{2c}$, the social optimum will be characterized by unequal levels of cooperation between the parties, and thus rendered unobtainable by a reciprocity constraint. Two important conclusions can be drawn from this section.

First, the reciprocity-induced equilibrium may be socially optimal when taking place at full cooperation. The intuition behind this result is that when social marginal benefits of cooperation exceed marginal costs at full levels of cooperation the socially optimal levels of cooperation are also characterized by full cooperation, given the feasibility constraint. Likewise, when private marginal benefits of cooperation for the parties under reciprocity exceed marginal costs at full levels of cooperation, the parties would happily extend reciprocal cooperation beyond full cooperation, if they had an option to do so. This implies that the differences between the privately optimal levels of cooperation for the two parties are revealed only in the infeasible region of more-than-full cooperation, and are thus hidden behind the parties' visible equilibrium at full cooperation. Put differently, the parties converge to a full level of cooperation, not because they have identical preferences, but because such a corner solution gives them the highest

obtainable payoff in the region of feasible cooperation. This privately optimal corner solution then happens to coincide with the socially optimal level of cooperation in the feasible region.

Second, partial cooperation outcomes among *heterogeneous* players acting under reciprocity will never be efficient. This is because in order to have an efficient equilibrium strategy under reciprocity, the privately and socially optimal levels of cooperation for party 1 must coincide, since party 1's strategy is the binding strategy under reciprocity equilibrium. This coincidence of private and social optima for party 1 requires that marginal benefit under reciprocity $b$ must equal social marginal benefit $d$. Further, for a reciprocity-induced equilibrium to be efficient, the social optimum must fall along the reciprocal diagonal with equal levels of cooperation. This implies that social marginal cost of cooperation for the two parties must be the same since, from above, the social marginal benefits, $b$ and $d$, are the same.[15] We conclude that in a reciprocity-induced equilibrium, partial cooperation outcomes can be efficient only if the two parties are homogeneous in that they face the same benefits and costs of cooperation.

### 2.2 The case of insufficient cooperation: When does the social optimum require more cooperation effort than the reciprocity-induced equilibrium?

Having considered the conditions for socially optimal cooperation among parties, we now investigate the conditions under which reciprocity may induce cooperation efforts that fall short of the socially optimal levels. As before, we proceed by investigating cases of full cooperation and partial cooperation in turn.

**2.2.1** Consider the case in which the social optimum requires *full cooperation* from both parties, so that $\frac{d}{2a} \geq 1 = s_1^S, \frac{b}{2c} \geq 1 = s_2^S$. If the privately optimal strategy for party 1 was characterized by less than full cooperation, the reciprocity-induced equilibrium would also be characterized by partial cooperation, since the strategy adopted by party 1 is binding under equilibrium. That is, $s_1^R = s_1' = \frac{b}{2a} < 1$. Collecting the necessary inequalities, we have

[14] Note that the efficiency results induced by reciprocity constraints for the case of symmetric parties shown in Fon and Parisi do not necessarily hold for the asymmetric case.

[15] Note that when looking at the private payoff function, the parameter $d$ represents the marginal benefit under reciprocity for party 1. This value also represents the social marginal benefit of party 1's cooperation.

$d \geq 2a,\ b \geq 2c,\ b < 2a$. Equivalently, the following inequalities must hold: $d \geq 2a > b \geq 2c$.[16] These inequalities further imply the necessary conditions: $b < d$ and $c < a$.[17]

If $b < 2a$, marginal benefit under reciprocity for party 1 is less than marginal cost at full cooperation, hence party 1 prefers less than full cooperation. However, if $d \geq 2a$, social marginal benefit for party 1 is larger than marginal cost at full cooperation, and party 1 could produce some net social surplus by raising his level of cooperation. When these conditions occur, private and social incentives towards cooperation may diverge, in spite of a binding reciprocity constraint. Note that the above conditions imply $b < d$, suggesting that social and private incentives under reciprocity diverge because party 1 does not fully internalize the social value of his cooperation.

Further, in order for the socially optimal level of cooperation to exceed the reciprocity-induced level, the ratio of party 2's social marginal benefit to marginal cost at full cooperation ($\frac{b}{2c}$) must exceed party 1's ratio of marginal benefit under cooperation to marginal cost at full cooperation ($\frac{b}{2a}$) in a reciprocity-induced equilibrium. This implies that $a > c$ must hold.

**2.2.2** Consider the case in which the social optimum requires *equal levels of partial cooperation* effort for both parties. That is, assume that $s_1^S = s_2^S = \frac{d}{2a} = \frac{b}{2c} < 1$ is true. The above conditions imply that $ab = cd$ must hold. Combining this with the assumption that party 1 has a comparative disadvantage in cooperation, such that $bc < ad$, leads to the following:

$$bc < ad \quad \Rightarrow \quad b \cdot \frac{ab}{d} < ad \quad \Rightarrow \quad b^2 < d^2 \quad \Rightarrow \quad b < d\ .$$

Meanwhile, $ab = cd$ and $b < d$ imply that $c < a$ holds. These are the familiar conditions found in the previous subsection. The condition $b < d$ means that party 1's marginal benefit under cooperation is lower than the social marginal benefit. As a result party 1 undertakes a level

[16] Recall that the original assumption of $b > a$ to generate the prisoner's dilemma must also hold. Meanwhile, the maintained assumption that party 1 is the relative high cost-benefit cooperator $bc < ad$ is implied by this inequality.

[17] For a better understanding of the results, we continue to highlight relative magnitudes between marginal benefit parameters (*b* and *d*) and between marginal cost parameters (*a* and *c*).

of reciprocity-induced cooperation falling short of the social optimum. The condition $c < a$ implies that party 2's marginal cost is lower than party 1's marginal cost, which determines what party 2 does in a reciprocity-induced equilibrium. Hence party 2 chooses a level of reciprocity-induced cooperation that also falls short of the social optimum. Both parties thus fail to reach the socially optimal level of cooperation, in spite of the binding reciprocity constraint.

**2.2.3** In both cases of full and partial cooperation, the conditions $b < d$ and $c < a$ assure that the reciprocity-induced equilibrium leads to less cooperation effort than the social optimum. These conditions indicate that the high-cost cooperator, while having a comparative disadvantage in cooperation, would still produce some net social surplus if engaging in higher levels of cooperation. In these cases, however, the existence of a reciprocity constraint is not sufficient to induce him to do so. Note that private incentives towards cooperation lead party 1 to compare the reciprocity-induced marginal benefit $MB_1^R = b$ with marginal cost $MC_1 = 2as_1$. Social optimum instead requires comparison between social marginal benefit $MB_1^S = d$ and marginal cost $MC_1 = 2as_1$. Hence whenever the reciprocity-induced marginal benefit *b* is less than the social marginal benefit *d*, private and social incentives towards cooperation diverge, in spite of a binding reciprocity constraint, and party 1 chooses a level of cooperation that is less than socially optimal.

When the social optimal cooperation effort for party 2, determined by the ratio of social marginal benefit to marginal cost at full cooperation $\frac{b}{2c}$, exceeds the reciprocity-induced equilibrium cooperation level, determined by the ratio of party 1's marginal benefit under cooperation to his marginal cost at full cooperation $\frac{b}{2a}$, the social optimal level of cooperation for party 2 exceeds the level of reciprocity-induced cooperation and $c < a$ must hold.[18] The efficiency of party 2's level of cooperation thus depends on comparison of the parties' costs of cooperation *a* and *c*.

[18] Note that in the cases considered in this subsection, given $b < d$, the comparative disadvantage condition $ad > bc$ does not necessarily require $a > c$.

## 2.3 The case of excessive cooperation: When does the reciprocity-induced optimum lead to more cooperation effort than the social optimum?

The previous Section considered conditions under which the reciprocity-induced equilibrium may induce cooperation efforts that fall short of socially optimal levels. We now consider the more puzzling possibility that reciprocity may induce more cooperation effort than is socially desirable. As before, we give separate treatments to cases of full cooperation and partial cooperation.

**2.3.1** Consider the case in which the reciprocity-induced equilibrium leads to *full cooperation*. That is, we have $\frac{b}{2a} \geq 1 = s_1^R$ and $\frac{d}{2c} \geq 1 = s_2^R$. Naturally, a social optimum could also require full cooperation from both parties, as was considered in Section 2.1.1. Alternatively, a social optimum may require less than full cooperation for one or both parties, even though parties are willing to cooperate at full level in equilibrium.

Consider first the case in which the socially optimal strategies require partial cooperation for both parties, but the reciprocity-induced equilibrium would instead be one of full cooperation. We show that this is impossible through proof by contradiction. For this to happen, we would need: $1 > s_1^S = \frac{d}{2a}$ and $1 > s_2^S = \frac{b}{2c}$. This in turn would yield:

$$\frac{b}{2a} \geq 1 = s_1^R > s_1^S = \frac{d}{2a} \quad \Rightarrow \quad b > d \quad \text{and} \quad \frac{d}{2c} \geq 1 = s_2^R > s_2^S = \frac{b}{2c} \quad \Rightarrow \quad d > b.$$

Clearly this is not possible. Hence, if the reciprocity-induced equilibrium leads to full cooperation, the social optimal strategies cannot require partial cooperation effort from both parties.

The second possibility is for the social optimum to require partial cooperation effort from party 1, $1 > s_1^S = \frac{d}{2a}$, but full cooperation effort from party 2, $\frac{b}{2c} \geq 1 = s_2^S$. Combining these conditions with the fact that reciprocity-induced equilibrium leads to full cooperation, the following must hold:

$$\frac{b}{2a} \geq 1 = s_1^R,\ \frac{d}{2c} \geq 1 = s_2^R,\ 1 > s_1^S = \frac{d}{2a},\ \frac{b}{2c} \geq 1 = s_2^S \ \Rightarrow\ b \geq 2a,\ d \geq 2c,\ 2a > d,\ b \geq 2c.$$

This implies that parameters of the model must satisfy $b \geq 2a > d \geq 2c$. In turn, this further implies that $b > d$ and $a > c$. The condition $b > d$ suggests that party 1 has an absolute advantage in capturing the benefits of mutual cooperation, although he faces a comparative disadvantage in cooperation. This condition further reveals that party 1's private incentives to cooperate are too strong, since the private benefit obtained from mutual cooperation exceeds the social benefit of such cooperation. This leads party 1 to undertake a level of reciprocity-induced cooperation exceeding the social optimum. The condition $a > c$ means that party 2 has an absolute advantage in the cost of cooperation.[19]

In the third case, the reciprocity-induced equilibrium yields full cooperation, but the social optimum requires full cooperation effort from party 1 and partial cooperation effort from party 2. Putting all the conditions together, we have:

$$\frac{b}{2a} \geq 1 = s_1^R,\ \frac{d}{2c} \geq 1 = s_2^R, \frac{d}{2a} \geq 1 = s_1^S,\ 1 > s_2^S = \frac{b}{2c} \ \Rightarrow\ b \geq 2a,\ d \geq 2c,\ d \geq 2a,\ 2c > b\ .$$

Thus, the necessary condition $d \geq 2c > b \geq 2a$ must hold. These conditions further imply that $b < d$ and $a < c$. These conditions are the exact opposite of those found in the previous case.

The condition $b < d$ suggests that party 1 has an absolute disadvantage in capturing the benefits of cooperation, while $a < c$ suggests that party 2 has an absolute disadvantage in the cost of providing cooperation. Here, party 2's reciprocity-induced level of cooperation exceeds the social optimum because party 1 undertakes a choice of cooperation that does not fully take into account the cost of reciprocal cooperation faced by party 2 under reciprocity. Party 2 is willing to cooperate at party 1's chosen level, given his *comparative advantage* in cost of cooperation, but does so beyond the socially optimal level, given his *absolute disadvantage* in cost of cooperation.

To summarize, given a reciprocity-induced equilibrium with full cooperation, no social optimum can be found which requires strictly less cooperation effort by both parties. It is however possible for the reciprocity-induced equilibrium to "overshoot" in one dimension. Namely, a social optimum may require less than full cooperation from one party, even when the reciprocity-induced equilibrium is characterized by full cooperation for both parties.

[19] In this case, the additional condition $a > c$ is necessary in order to preserve the assumption that party 1 has a comparative disadvantage in cooperation.

**2.3.2** Consider now the case in which the reciprocity-induced equilibrium yields *partial cooperation*: $s_1^R = s_2^R = \frac{b}{2a} < 1$. In this case, excessive cooperation implies that reciprocity induces levels of cooperation exceeding the socially optimal levels for one or both parties. Consider these possibilities in turn.

In the first case, socially optimal strategies require lower levels of partial cooperation than those induced by reciprocity for both parties. We prove that this is not possible. Assume otherwise, so that $s_1^S < s_1^R$ and $s_2^S < s_2^R$ hold. These conditions imply the following:

$$s_1^S < s_1^R \Leftrightarrow s_1^S = \frac{d}{2a} < s_1^R = \frac{b}{2a} \Rightarrow d < b \text{ and } s_2^S < s_2^R \Leftrightarrow s_2^S = \frac{b}{2c} < s_2^R = \frac{b}{2a} \Rightarrow a < c.$$

But $d < b$ and $a < c$ imply $a\,d < b\,c$. This contradicts our assumption that party 1 has a comparative disadvantage in reciprocal cooperation. Therefore it is not possible for the socially optimal cooperation efforts of both parties to fall below the levels of partial cooperation induced by reciprocity.

An almost identical proof would show that, instead, it is possible that socially optimal cooperation efforts by both parties be greater than or equal to the cooperation effort induced by a reciprocity constraint in equilibrium: $s_1^S \geq s_1^R$ and $s_2^S \geq s_2^R$. The necessary conditions for such occurrence can easily be shown to be $b \leq d$ and $c \leq a$. This case is in fact touched upon in Section 2.2.2. Lastly, it is interesting to point out the possibilities of having $s_1^S \leq s_1^R = s_2^R \leq s_2^S$ or $s_2^S \leq s_2^R = s_1^R \leq s_1^S$. The necessary conditions for $s_1^S \leq s_1^R = s_2^R \leq s_2^S$ to hold are $d \leq b$ and $c \leq a$, and the necessary conditions for $s_2^S \leq s_2^R = s_1^R \leq s_1^S$ to hold would be $b \leq d$ and $a \leq c$.

To conclude, when the reciprocity-induced equilibrium leads to partial cooperation efforts, the resulting level of cooperation will never be higher than both socially optimal levels for the two parties. A weak reciprocity constraint may lead to too little cooperation by one party and too much cooperation by the other. This combination of overshooting and undershooting effects may indeed be expected in cases of asymmetric parties acting under a binding reciprocity constraint.

**2.3.3** Given a reciprocity-induced equilibrium with full cooperation, no social optimum can be found which requires strictly less cooperation effort by both parties. Likewise, when the

reciprocity-induced equilibrium leads to partial cooperation efforts, the resulting level of cooperation is never higher than the socially optimal level for both parties. However, overshooting in one dimension is possible in the partial cooperation case.

Differences in parties' benefits and costs of cooperation efforts often lead to asymmetric optimal levels of cooperation in a social optimum. When this happens, the reciprocity-induced equilibrium cannot easily be, and perhaps should not be, compared to the social optimum, since a comparison involves symmetric versus asymmetric combinations of strategies. Only under special circumstances would the social optimum lead to identical cooperation efforts. For this reason, in Section 3, we consider a different concept of social optimum which focuses on socially optimal levels of cooperation within the subset of equal levels of cooperation.

## *3. The reciprocity-induced equilibrium and the reciprocal social optimum*

The above analysis revealed the difficulties in evaluating the efficiency of reciprocity-induced equilibrium where a social optimum leads to unequal levels of cooperation by the parties. We thus introduce the notion of "reciprocal social optimum." This concept describes the situation under which the aggregate payoffs for the parties are maximized, subject to the additional requirement that the same level of cooperation efforts be undertaken by the parties. In this Section, we first find the reciprocal social optimum. Next we compare this reciprocal social optimum with the (unconstrained) social optimum discussed in previous sections. Lastly, we compare the reciprocity-induced equilibrium and the reciprocal social optimum.

### 3.1 The reciprocal social optimum

The reciprocal social optimum can be found by maximizing aggregate payoffs for the parties subject to the constraint of equal levels of cooperation. Consider the following:

$$\max_{s_1,s_2} P(s_1,s_2) = (-a\, s_1^2 + b\, s_2) + (-c\, s_2^2 + d\, s_1) \quad \text{s.t.} \quad s_1 = s_2,\, 0 \le s_1 \le 1,\; 0 \le s_2 \le 1.$$

This is equivalent to the following optimization problem:

$$\max_{s_1} P(s_1) = -(a+c)\, s_1^2 + (b+d)\, s_1 \quad \text{s.t.} \quad 0 \le s_1 \le 1.$$

Possible reciprocal social optima depend on the values of the parameters.[20]

If $\frac{b+d}{2(a+c)} \geq 1$, then $\tilde{s}_1 = \tilde{s}_2 = 1$.

If $\frac{b+d}{2(a+c)} < 1$, then $\tilde{s}_1 = \tilde{s}_2 = \frac{b+d}{2(a+c)} < 1$.

These two possibilities describe the alternative cases of full and partial cooperation. We now consider the relation between unconstrained social optimum and reciprocal social optimum.

**3.1.1** Whenever the unconstrained social optimum leads to *full cooperation*, $(s_1^S, s_2^S) = (1, 1)$, the reciprocal social optimum is also characterized by full cooperation, $(\tilde{s}_1, \tilde{s}_2) = (1, 1)$. To see this, note that $s_1^S = s_2^S = 1$ implies the following:

$$\frac{d}{2a} \geq 1 = s_1^S \text{ and } \frac{b}{2c} \geq 1 = s_2^S \quad \Rightarrow \quad d \geq 2a \text{ and } b \geq 2c.$$

This then implies that $\frac{b+d}{2(a+c)} \geq \frac{2c+2a}{2(a+c)} = 1$. Hence, if the unconstrained social optimum is characterized by mutual full cooperation, the reciprocal social optimum also requires full cooperation: $\tilde{s}_1 = \tilde{s}_2 = 1$.

**3.1.2** Likewise, whenever the social optimum leads to *partial cooperation* from both parties ($s_1^S < 1, s_2^S < 1$), the reciprocal social optimum also leads to partial cooperation ($\tilde{s}_1 = \tilde{s}_2 < 1$). To see this, consider the case in which unconstrained social optimum is characterized by partial cooperation efforts for both parties. We have the following:

$$s_1^S = \frac{d}{2a} < 1 \text{ and } s_2^S = \frac{b}{2c} < 1 \quad \Rightarrow \quad d < 2a \text{ and } b < 2c.$$

This implies that $\frac{b+d}{2(a+c)} < \frac{2c+2a}{2(a+c)} = 1$. Hence $\tilde{s}_1 = \tilde{s}_2 = \frac{b+d}{2(a+c)} < 1$. This indicates that the reciprocal social optimum also leads to partial cooperation effort.

[20] We use a ~ above the variables and the functions to denote the reciprocal socially optimal strategies and outcomes.

Further, in this case we show that it is not possible for the reciprocal socially optimal cooperation levels $\tilde{s}_1 = \tilde{s}_2$ to be strictly less than both unconstrained socially optimal levels of cooperation $s_1^S$ and $s_2^S$. This can be proved by contradiction. Assume the contrary, so that $\tilde{s}_1 < s_1^S$ and $\tilde{s}_2 < s_2^S$. Then

$$\tilde{s}_1 < s_1^S \Rightarrow \frac{b+d}{2(a+c)} < \frac{d}{2a} \Rightarrow ab < cd \quad \text{and} \quad \tilde{s}_2 < s_2^S \Rightarrow \frac{b+d}{2(a+c)} < \frac{b}{2c} \Rightarrow cd < ab$$

must both hold. Clearly this is impossible. Likewise, similar logic can show that it is also not possible that the level of cooperation $\tilde{s}_1 = \tilde{s}_2$ required for a reciprocal social optimum be strictly greater than both cooperation levels required for an unconstrained social optimum $s_1^S$ and $s_2^S$.

This leaves two possibilities. First, if $ab \neq cd$, then the reciprocal social optimum is characterized by cooperation efforts $\tilde{s}_1 = \tilde{s}_2$ that lie between the unconstrained socially optimal cooperation efforts $s_1^S$ and $s_2^S$. Second, whenever $ab = cd$, all socially optimal cooperation efforts, constrained or unconstrained, are equal: $\tilde{s}_1 = \tilde{s}_2 = s_1^S = s_2^S$.[21] This result is quite intuitive since in this case the unconstrained social optimum is already characterized by symmetric strategies. This renders the added constraint immaterial for finding a reciprocal social optimum.

From the above, we can conclude that if the social optimum requires partial cooperation for both parties ($s_1^S < 1, s_2^S < 1$), the reciprocal social optimum also leads to partial cooperation ($\tilde{s}_1 = \tilde{s}_2 < 1$). Whenever $ab = cd$, the unconstrained social optimum coincides with the reciprocal social optimum. On the other hand, if $ab \neq cd$, the reciprocal social optimum is characterized by cooperation levels that lie between the two unconstrained socially optimal strategies for the parties.

### 3.2 Comparing the reciprocity-induced equilibrium and the reciprocal social optimum

We now compare the equilibrium induced by a reciprocity constraint with the reciprocal social optimum. As before, we start from the reciprocity-induced equilibrium that leads to full cooperation and then look at the alternative case of partial cooperation.

[21] Note that what we find here is consistent with what we found in subsection 2.2.2. In particular, earlier we show that if $s_1^S = s_2^S < 1$, then $ab = cd$ must hold.

**3.2.1** When a reciprocity-induced equilibrium leads to *full cooperation*, such equilibrium always coincides with the reciprocal social optimum. Assume the contrary. Then the following hold:

$$\frac{b}{2a} \geq 1 = s_1^R \text{ and } 1 > \tilde{s}_1 = \frac{b+d}{2(a+c)} \quad \Rightarrow \quad b \geq 2a \text{ and } 2(a+c) > b+d \quad \Rightarrow \quad 2c > d .$$

This implies that $1 > \frac{d}{2c}$ But the assumption that party 1 has the comparative disadvantage means that $\frac{d}{2c} > \frac{b}{2a}$, thus $1 > \frac{b}{2a}$. This contradicts the assumption that the reciprocity-induced equilibrium leads to full cooperation in the first place. We conclude that, full cooperation under reciprocity obtains only if full cooperation is also socially efficient according to criterion of reciprocal optimality. When the reciprocal social optimum requires partial levels of cooperation, parties never reach full cooperation in equilibrium.

This result is the analogue of the previous result according to which the parties' reciprocity-induced levels of cooperation could never simultaneously exceed the socially optimal levels. In the present context, a reciprocal social optimum falling below the reciprocity-induced cooperation constitutes one such unobtainable equilibrium in which both parties would overshoot the social optimum.

**3.2.2** Along similar lines, it will be shown that when the reciprocity-induced equilibrium leads to *partial cooperation*, such level of cooperation never exceeds the level required for a reciprocal social optimum. Assume the contrary so that the level of cooperation induced by reciprocity is greater than the reciprocal social optimum. That is, assume that $s_1^R = s_2^R < 1$ and $\tilde{s}_1 = \tilde{s}_2 < s_1^R = s_2^R$ . We know that $\tilde{s}_1 = \tilde{s}_2$ equal either 1 or $\frac{b+d}{2(a+c)}$. If $\tilde{s}_1 = \tilde{s}_2 = 1$, then the second assumption $\tilde{s}_1 = \tilde{s}_2 < s_1^R = s_2^R$ implies that $1 < s_1^R = s_2^R$. This contradicts the assumption that the reciprocity-induced equilibrium requires partial cooperation in the first place. Consider next the alternative case in which $\tilde{s}_1 = \tilde{s}_2 = \frac{b+d}{2(a+c)}$. Since $s_1^R < 1$, $s_1^R = \frac{b}{2a}$. We thus have the following:

$$\widetilde{s}_1 < s_1^R \quad \Rightarrow \quad \frac{b+d}{2(a+c)} < \frac{b}{2a} \quad \Rightarrow \quad a\,d < b\,c\,.$$

This last inequality contradicts the assumption $b\,c \leq a\,d$ according to which party 1 has a comparative disadvantage in reciprocal cooperation. Therefore, we conclude that in the case of partial cooperation it is also not possible for the reciprocal social optimum to require less cooperation than the reciprocity-induced equilibrium. That is, if $s_1^R = s_2^R < 1$ then we have either $\widetilde{s}_1 = \widetilde{s}_2 > s_1^R = s_2^R$ or $\widetilde{s}_1 = \widetilde{s}_2 = s_1^R = s_2^R$.[22]

## *4. Conclusion*

In the case of symmetric players studied in Fon and Parisi, reciprocity constraints always induce socially optimal outcomes. In the case of asymmetric players, several conditions need to be satisfied in order for the reciprocity-induced equilibrium to coincide with the social optimum. In this paper, we extend the previous analysis by studying the general relationship between the reciprocity-induced equilibrium and the social optimum.

With asymmetric players, the privately optimal levels of cooperation likely differ between the two parties. Equilibrium level of cooperation under our notion of reciprocity is always dictated by the party with the higher cost-benefit ratio, or comparatively less willing cooperator. Further, reciprocity-induced equilibria are always constrained along the principal diagonal of the game, but social optima may require unequal levels of cooperation for the two players in response to differences in their benefit-cost ratios. This may lead to a tension between the social and private incentives for cooperation under reciprocity. Asymmetries in the benefits and costs of cooperation often require asymmetric levels of cooperation for a social optimum and such a combination of strategies is rendered unachievable by the reciprocity constraint. Reciprocity-induced cooperation would thus rarely lead to a global social maximum when applied to heterogeneous players. In this paper, we have shown the conditions under which reciprocity may lead to too little, or, interestingly, too much cooperation compared to the social optimum.

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[22] It is easy to see that $\widetilde{s}_1 = \widetilde{s}_2 > s_1^R = s_2^R$ requires $b\,c < a\,d$ while $\widetilde{s}_1 = \widetilde{s}_2 = s_1^R = s_2^R$ requires $b\,c = a\,d$.

In order to facilitate the assessment of the efficiency of reciprocity constraints when the unconstrained social optimum necessitates asymmetric combinations of strategies, we have additionally introduced the concept of reciprocal social optimum. This allowed us to appraise the relative efficiency of the reciprocity-induced equilibrium in comparison with other reciprocal combinations of strategies. Here, similar to the case of unconstrained social optimum, the reciprocity-induced equilibrium never exceeds the reciprocal socially optimal levels of cooperation.

In situations of asymmetry between the parties, reciprocity constraints may be unable to generate efficient outcomes. Whenever the reciprocity-induced equilibrium and the socially optimal equilibrium do not coincide, the reciprocity-induced equilibrium leaves some unexploited surplus for the parties: a social loss that is likely to increase with an increase in the asymmetries between the players. In these situations, a move to the socially optimal levels of cooperation would increase the aggregate payoffs for the parties. The gainers could fully compensate the losers for the additional cost of cooperation, yet still capture some of the unexploited surplus.

These results unveil the strengths and limits of reciprocity constraints in inducing optimal cooperation among heterogeneous players. Future applications should investigate the relevance of these limits of reciprocity in international contexts, where reciprocity rules govern relationships among highly heterogeneous sovereign states. Different mechanisms of cooperation, such as explicit trading and enforceable contracting, could yield better results than binding reciprocity constraints, allowing the parties to undertake asymmetric obligations and converge towards global maxima. These considerations are also in line with the findings of evolutionary socio-biology, showing that behavioral patterns of reciprocity tend to emerge in close-knit environments with homogeneous players, but do not thrive in highly heterogeneous groups. Future extensions should build on these results to consider different mechanisms of reciprocity that, by allowing asymmetric reciprocation, may facilitate the achievement of optimal levels of cooperation when players are known to be heterogeneous.

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