On Rational Trust and Cooperation

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This paper studies the evolution of preferences for reciprocity and the self-enforcement of agreements in a society composed exclusively of rational, Bayesian optimisers. Unlike conventional evolutionary models, player types are defined not by their *strategies,* but by their *preferences,* as in standard economic theory. Thus agents do not play fixed, 'wired-in' strategies, but rather choose strategies that maximise their expected utilities. The paper studies the evolution of a community consisting of 'opportunists,' who simply maximise material payoffs, and 'reciprocators,' who prefer joint cooperation to exploiting their opponents, and choose their strategies accordingly. While individual interactions are one-shot, agents play this game T periods over their careers, and players know the history of play of all others in the community. Moreover, players can choose not to play the game with opponents with whom they are randomly matched. These features of the model create incentives for opportunists to maintain reputations for being reciprocators, in order to find 'trading partners' over the course of their careers. It is shown that, if T is sufficiently large, and if players observe a noisy signal that has an arbitrarily small but positive correlation with the opponent's type, then in the unique evolutionary equilibrium, the two types coexist. In this equilibrium, the reciprocators cooperate throughout their careers, and the opportunists cooperate up to, but not including, stage T of their careers.

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> I want ... to conclude by calling attention to a less visible form of social action: norms of social behavior, including ethical and moral codes. I suggest as one possible interpretation that they are reactions of society to compensate for market failures. It is useful for individuals to have some trust in each other's word. In the absence of trust, it would become very costly to arrange for alternative sanctions and guarantees, and many opportunities for mutually beneficial cooperation would have to be foregone... There is a whole set of customs and norms which might be similarly interpreted as agreements to improve the efficiency of the economic system (in the broad sense of satisfaction of individual values) by providing commodities to which the price system is inapplicable. [Arrow (1970), p. 20]

In the 30 years since Arrow's remarks, economists have become steadily more interested in the logic of trust and cooperation. A large and growing amount of experimental and other empirical evidence supports the proposition that real-world agents behave non-opportunistically in games like the Prisoner's Dilemma and the ultimatum game, contribute voluntarily to the provision of public goods, and so forth.[1] Several recent theoretical models [e.g., Banerjee et al. (1994), Besley and Coate (1995), Bolton and Ockenfels (2000), and Fehr and Schmidt (forthcoming)] interpret these empirical observations by introducing the assumption that agents have preferences for reciprocity and fairness. Economists, however, would prefer to *explain* such preferences endogenously, rather than simply introduce them by assumption. This paper provides such an endogenisation, by demonstrating the evolutionary stability of a population consisting of positive proportions of 'reciprocators' and 'opportunists,' in which *both* types of agent rationally cooperate in equilibrium.

The seminal 'Gang of Four' paper of Kreps et al. (1982) proved that if one of two rational players assigns a small probability to the proposition that his or her opponent is an irrational 'tit-for-tat' (TFT) type, or alternatively if each player assigns a small probability to the proposition that the other

[1] For surveys of the literature on public good experiments, see Ledyard (1995) and Fehr and Schmidt (forthcoming). On the ultimatum game, see the surveys of Güth and Tietz (1990), Camerer and Thaler (1995), and Roth (1995). For a discussion of early Prisoner's Dilemma experiments as well as field experiments by social psychologists, see Guttman (2000). For a general survey of experimental results and theoretical work on reciprocity, see Ostrom (forthcoming).

has a taste for reciprocity (preferring joint cooperation to exploiting his or her opponent), then, in a finitely repeated Prisoner's Dilemma (PD) game, cooperation is an equilibrium outcome for at least some of the stages of the game. The assumed 'seed' of uncertainty leads the player (incorrectly) suspected of being an irrational TFT type or being a reciprocator to justify this doubt, by cultivating a reputation for being the suspected type. This carefully preserved reputation induces the opponent to cooperate, at least in the initial stages of the game.

Kreps et al. simply introduced the players' prior beliefs (i.e., the uncertainty of one or both players regarding the other player's type) by assumption. Their assumption seems arbitrary: one or both players have slightly mistaken priors about their opponents. A natural solution to this problem would be to assume that the two players are drawn from a larger population in which players of the suspected type exist, and rational players, who know the population proportions of the various types, use these proportions to develop their prior beliefs regarding their opponents' type. The present paper develops this solution and endogenises the uncertainty assumed by Kreps et al. in their 'Model 2' (which assumes two-sided uncertainty regarding the opponent's preferences). A theory is developed in which 'reciprocator types'—players having preferences for reciprocity—survive in a competitive, evolutionary environment where such players must compete with 'opportunistic types' who prefer to exploit their opponents over jointly cooperating.

Evolutionary models are usually understood to embody an alternative paradigm to that of standard economic theory, since they generally do not assume rationality. Rather than assuming maximising behaviour, these models typically assume that agents play pre-programmed strategies such as simply cooperating or defecting all the time, or (more realistically) rewarding cooperation and punishing defection by some strategy such as TFT. This paper proposes to use a somewhat less conventional methodology in order to endogenise the prior beliefs of rational players regarding their opponents' type. I employ what Güth (1995) has coined the 'indirect' evolutionary approach, in which all players are assumed to be rational, and the evolutionary mechanism determines the population mixture of players with differing preferences. In other words, agent types are defined not by the agents' *strategies* but by their *preferences.* Thus agents choose strategies to maximise expected payoff, just as in standard economic theory. All outcomes are assumed to be consistent with a Nash equilibrium.

Readers who are used to regarding the evolutionary and the conventional economic paradigms as diametrically opposed may wonder what is gained by this marriage of the two approaches. The answer is simply that by joining these approaches, we can explain endogenously why players rationally expect their opponents to be reciprocators, rather than simply introducing these expectations by assumption, as in standard models employing the idea of reputation. Thus we obtain a self-contained theory of rational cooperation, rather than one that can predict any outcome by the introduction of appropriate prior beliefs.

In the remainder of this paper, Section 1 introduces the two player types, 'opportunist' and 'reciprocator,' and sets out the other assumptions of the model. Section 2 shows how, for a given prior belief regarding the opponent's type, one obtains a Perfect Bayesian Equilibrium (PBE) in which players cooperate over a well-defined segment of a finitely repeated Prisoner's Dilemma. Section 3 endogenises these prior beliefs in an indirect evolutionary framework. Section 4 discusses related theoretical work. Section 5 offers concluding observations.

1 Assumptions

1.1 Basic Structure of the Model

Consider a market transaction between a buyer and a seller, in which no legal framework exists to enforce the agreement made between these two agents, or the costs of employing the legal framework are prohibitive. Each party to the transaction may choose to uphold his or her side of the bargain, a move we denote by C (cooperate), or to renege, which we denote by D (defect). The two agents are assumed to move simultaneously. Let each agent's surplus

Figure 1. Payoff Matrix for Market Transaction

Consider the case in which the seller cheats the buyer, and does not deliver the goods. The seller then obtains his or her surplus from the transaction, 1, and also saves his or her marginal cost, b. The buyer pays (thus losing the same cost b) without gaining the promised goods. In the opposite case, in which the buyer cheats the seller and does not pay but still receives the goods, the seller loses his or her marginal cost b while the buyer receives his or her surplus, 1, plus saving the cost of the goods, b. The payoffs in the market transaction thus are appropriate to a special case of the PD game.[2]

I assume that, in each of T time periods which constitute an agent's career, he or she plays this game once. For simplicity, all agents in a given generation start and end their careers at the same time.[3] In the first time period ($t = 1$), the initial matching of agents to play the game is assumed to be random, but a player can refuse to play the game with the opponent initially drawn, and be costlessly re-matched with another agent. In subsequent stages, the players initially matched in the first period can continue to transact, or either player can break off the relationship and be costlessly re-matched with another agent.[4]

The social interaction between the community's members intense enough for information on each agent's past moves in his or her market transactions to become common knowledge of all community members in all subsequent stages. One could define the time period in such a way that one time period is the time required for information on all agents' moves in that stage to become common knowledge to the entire community.[5]

[2]This payoff matrix could be made to represent a more general PD game, as follows. Suppose player 1 plays D against player 2, who plays C. Let the payoff of player 1 be greater than unity, while the payoff of player 2 be negative. Moreover, assume that the sum of these payoffs is less than 2, so that the outcome that maximizes the sum of the payoffs remains CC. Such a generalization, while complicating the analysis, would not change the basic results.

[3]If we were to allow for overlapping generations of players, the conclusions of the analysis would be unaltered, as is pointed out in Section V.

[4]This clearly assumes a fairly sizable community, so that players easily find other partners with whom to be re-matched if they refuse to play with the partner initially "drawn".

[5]I am indebted to Frank Cowell for pointing out this interpretation of a time period.

1.2 Opportunist Types and Reciprocator Types

While the payoff matrix in Figure 1 shows the material payoffs received by the two players in a given market transaction, only the preference ordering of the *opportunist type* follows the same ordering as his or her material payoffs and is therefore reflected in this matrix. The second type of player in the community, which we call the *reciprocator type*, has a preference ordering differing slightly from that shown in Figure 1. Specifically, while the reciprocator's payoffs from the CC and DD outcomes, and his or her payoff from being cheated, $-b$, are the same as in Figure 1, the reciprocator's payoff from cheating the other player is $a \in (0, 1)$, rather than $1 + b$ as shown in Figure 1. Thus the reciprocator prefers the joint-cooperate outcome CC to outcomes in which he or she exploits his or her partner, while the opportunist has the opposite preference ordering over these two types of outcomes.

Thus Figure 1 shows the actual *utility matrix* only for a matching of two opportunists. The dominant strategy equilibrium in such a matching is the joint-defect outcome, DD, yielding a payoff (and utility) of zero to each player. Figure 2 shows the utility matrix for a matching of two reciprocators, whose preference ordering differ from the PD-type preferences of the payoff matrix in Figure 1. This matrix, which depicts the 'Assurance Game' due to Sen (1967), has two Nash equilibria, CC and DD. We assume that a 'social norm', which is nothing more than a device for coordinating on a particular Nash equilibrium, specifies that the Pareto-preferred equilibrium, CC, be played. Thus the payoffs (and utilities) of two reciprocators, if each knew that his or her partner is a reciprocator, would be 1.

	C	D
C	1, 1	$-b, a$
D	$a, -b$	0, 0

Figure 2. Utility Matrix for Matching of Two Reciprocators

Finally, consider a matching of a reciprocator with an opportunist. Let the opportunist be the column player, and let the reciprocator be the row player. Figure 3 shows the resulting utility matrix. Since the opportunist has a dominant strategy to defect, and the reciprocator's best response to defection is to defect as well, the resulting Nash equilibrium is DD, yielding zero payoffs (and utilities) to both players.

	C	D
C	1, 1	$-b, 1+b$
D	$a, -b$	0, 0

Figure 3. Utility Matrix, Reciprocator (Row) and Opportunist (Column)

1.3 Information Available to Players

If players knew each other's type, it is obvious that reciprocators would choose to transact only with other reciprocators, thus receiving expected payoffs of unity in their T market interactions. The opportunists, who would be forced to transact with each other, would receive expected payoffs of zero from their market transactions. Thus, in an evolutionary model, the opportunists would become extinct.

Following traditional game-theoretic models, I assume that the only completely reliable or *certain* information players have is (a) the proportion r of reciprocators in the community, and (b) the past choices of C versus D of all members of the community. In addition, however, players in this model observe a noisy, dichotomous signal, denoted X, of their partner's type before transacting. Frank (1987, 1988) has argued that individuals can obtain information of each other's type through a variety of signs like emotional reactions, an 'honest face,' 'body language', etc., which are difficult for individuals who are not of that type to mimic. We will follow Frank to the extent of assuming that this 'specific information' has some small, positive correlation with the actual type of the opponent. (To obtain the main result of the model—that if T is sufficiently large, reciprocators will survive at any evolutionary equilibrium point—it is sufficient for this correlation to be *any* positive value, however small.)

1.4 Evolutionary Selection Mechanism

Let us now introduce a *monotonic evolutionary selection mechanism*, which determines how the proportion of reciprocators in the population, r, evolves from one generation to the next. I assume that the proportion of reciprocators in a given generation g will be greater (less) than that of the previous generation $g-1$ if the previous-generation reciprocator's expected *material payoff* $E\pi_r(g-1)$ was greater (less) than that of the opportunist in that generation $E\pi_o(g-1)$. If $E\pi_r(g-1) = E\pi_o(g-1)$, then r stays constant to the current generation. These expected payoffs are the undiscounted sums, over the T stages of the player's career, of his or her expected payoffs in market transactions.

Note that the variable determining the spread or disappearance of a type is assumed to be the type's material *payoff* or 'fitness' $E\pi$, and not the type's *utility.* This assumption makes the model compatible with models in the biological literature, but is not critical to the results of the model. The evolutionary mechanism could be genetic, if more materially successful parents tend, on the average, to have larger numbers of children.[6] Alternatively, one could adopt the 'cultural evolution' approach of Boyd and Richerson (1985). According to this approach, the children of a given generation observe the relative 'success' of the two types in their parents' generation, and adopt the preference ordering of that type through a kind of 'self-wiring'. Since children cannot directly observe the utilities of the members of the previous generation, but only their material payoffs, the mechanism is assumed to depend on these payoffs and not utilities.

Since the types of individual agents are unobservable in the model (though agents observe a signal correlated with the reciprocator type), assuming a cultural evolutionary process raises the question as to how individuals estimate the relative expected payoffs of the two types. Two answers can be given

[6] The observed negative correlation of income and numbers of children, in developed economies, is usually explained by the "new home economics" to result from higher-income individuals tending to have higher wage rates and thus higher shadow prices of time, thus raising the relative full price of (time-intensive) children. Here, however, higher material payoffs do not directly affect the productivity of agents' time, so that the only relevant effect (to a first approximation) would be a wealth effect on the demand for children.

to this question: (1) At stage T, the end of the agent's career, the agent's (equilibrium) C or D move reveals his or her type, provided that r is at least some threshold value (see Section 2.1 below). Thus, by looking at the behaviour of agents of previous generation at the end of their 'careers', the relative payoffs of the two types can be observed. (2) The signal X, being positively correlated with the reciprocator type, provides an indication of the relative expected payoffs of the two types. If agents exhibiting X tend to have relatively high (low) material payoffs, this would indicate that reciprocators receive, on the average, relatively high (low) payoffs.

Given that parents are in a better position than children to observe both the stage-T choices of their generation and the signal X for individual agents of their generation, one can adopt Güth's (1995) suggestion that parents try to instill a norm of 'fair' behaviour in their children, and add that the incentive of (altruistic) parents to instill such a norm will be positively related to the relative material success of reciprocators (fair players) in the population. Thus the mechanism of cultural evolution may work more through parents' 'wiring' preferences for reciprocity into their children, than self-wiring by the children themselves, as envisaged by Boyd and Richerson (1985).[7]

2 Analysis of the Game

This section analyzes the Perfect Bayesian Equilibrium behaviour of a population consisting of a proportion r of reciprocators and $1-r$ of opportunists. The variable r will first be taken as an exogenous parameter, and will be endogenised only in Section 3. We will first consider the extreme cases of $r=0$ and $r=1$, and then analyze the intermediate case. The intermediate case is of independent interest, because, given the assumed rationality of all players, agents' strategies will change as r changes, so that the evolution of r in the intermediate range $(0,1)$ cannot be inferred from what happens at the endpoints. To simplify the exposition, I begin by assuming that players know only r and the history of all other agents' play. This assumption will be relaxed in Section 2.2.

Let $r=0$ and consider the last stage T of the careers of the individuals in the community. In this last stage, it is obvious that the opportunists

[7] For models explicitly modeling the attempt by agents to instill preferences for fair behavior or trustworthiness, see Raub (1990), Becker (1993), Bisin and Verdier (1998), and Guttman (forthcoming *a,b*).

will defect in their market transactions, since this is the opportunist's dominant strategy in the stage game. In an all-opportunist population, a lone reciprocator 'mutant' would behave identically to the opportunists, since the reciprocator prefers the DD outcome in his or her market transactions, yielding a payoff of zero, to being cheated by his or her opponent, yielding a payoff of $-b$. Given that all players defect in the last stage of the game, the same behaviour would obtain in stage $T-1$, and so forth back to the beginning of the game, by backwards induction. We thus obtain our first result:

Proposition 1 *When $r = 0$, the payoffs (and utilities) of all players (including a lone reciprocator mutant whose proportion in the population is negligible) will be zero.*

Consider now the opposite case, in which all players are reciprocators ($r = 1$). By our assumption that a 'social norm' coordinates players' expectations on the Pareto-preferred equilibrium, in all market transactions the reciprocators would cooperate. The expected payoffs (and utilities) of all members of the community would then be unity.

Now let a sole opportunist mutant enter this all-reciprocator community. In the last stage of his or her career, the opportunist would optimally defect, this being his or her dominant strategy in the stage game. Thus the opportunist's expected payoff (and utility, these being identical for an opportunist) would be

$$E\pi_o = (T-1) + (1+b) = T + b, \tag{1}$$

since, for the first $T-1$ stages, the opportunist cooperates, yielding a payoff of 1 from cooperation in his or her market transactions; in the final stage T, the opportunist would defect in his or her market transaction, yielding a payoff of $1+b$.

Note that a unilateral defection by any player i, at any stage $t < T$, would result in the inability of i to find trading partners in all future stages of the game (in equilibrium). By defecting, player i reveals that he or she is an opportunist, since reciprocators would never find it optimal to defect unilaterally. The revelation of i's type immediately makes it common knowledge that i will defect at stage T, so that no other agent will trade with i at stage T. Given this common knowledge, i will defect at stage $T-1$ as well, since he or she will find no trading partners at stage T regardless of his or her move at stage $T-1$. But this, in turn, implies that i will defect at stage $T-2$ as well, and so forth back to stage $t+1$. All other agents are aware of this fact, and therefore i will find no trading partners after his or her defection at t.

Thus the opportunist mutant would have no incentive to defect before stage T. If he or she were to defect, say, one stage earlier, the mutant would receive a payoff of zero in stage T. Thus the $(1+b)$ term in (1) will be obtained one stage earlier, while the left-hand term would be $T-2$ rather than $T-1$, implying a smaller expected payoff. Thus (1) expresses the highest attainable expected payoff for the opportunist.

The expected (material) payoff of the reciprocators would be

$$E\pi_r = T < E\pi_o. \tag{2}$$

Anticipating the evolutionary analysis of Section 3, we find that the all-reciprocator population can be invaded by an opportunist mutant. Summarising our results, we have the following result.

Proposition 2 *In an all-reciprocator population, players will cooperate in all market transactions. Such a population, however, can be invaded by an opportunist mutant.*

Let us now analyze the intermediate case, $0 < r < 1$. We first note that there is a critical, minimum value for r, to be denoted r_0, which will make it optimal for reciprocators to cooperate in all stages of their careers (provided all other reciprocators do the same), just as they did in the extreme case just analyzed, in which r was unity. Provided that $r \geq r_0$, the reciprocators cooperate even in the last stage T. We thus require that in stage T, the expected payoff of cooperating to the individual reciprocator, $r-(1-r)b$, at least equals the expected payoff of defecting, ar. This condition is fulfilled if

$$r \geq \frac{b}{1+b-a}. \tag{3}$$

Recall that $a < 1$, so that the denominator of (3) is positive and greater than b. Thus the r.h.s. of (3) is the desired r_0.

It turns out that the equilibrium is fundamentally different, depending on whether r is greater or less than r_0. We therefore divide the analysis into two cases. In Case A, $r \geq r_0$; in Case B, $r < r_0$.

2.1 $r \geq r_0$

In this case, the reciprocators cooperate in stage T. Therefore opportunists have an incentive to cooperate in stage $T-1$, since by defecting in stage $T-1$ they will not be able to transact with any player at stage T. In effect, the condition that $r \geq r_0$ implies that the backwards induction argument no longer applies, at least in the simple form familiar to economists and game theorists.

Recall that if an opportunist defects at any stage t, this will reveal his or her type to all other agents. No agent will then choose to transact with the opportunist in future stages, in equilibrium. Therefore a unilateral defection by an opportunist will not be followed, in equilibrium, by cooperation by the opportunist in any subsequent stage.

These observations lead to the conclusion that there are only three basic types of pure strategies that are consistent with Perfect Bayesian Equilibrium (PBE):

- *Preempt.* If opportunist i expects all other opportunists to defect at stage t, then i defects at stage $t-1$. Afterwards, i defects in all future stages.

- *Simultaneous Switch (SS).* If opportunist i expects all other opportunists to defect at stage t, then i defects at stage t as well. Afterwards, i defects in all future stages.

- *Wait.* Even though i expects all other opportunists to defect at stage t, he or she 'waits' and continues to cooperate, thus permitting him or her to transact with the reciprocators (having preserved his or her reputation as a reciprocator, which is believed with probability r by the reciprocators). In the last stage T, the opportunist defects.

We will consider mixed strategies later in the analysis, but it is worth noting at this point that any PBE-consistent mixed strategy has the same basic form as the above three pure strategies: i.e., it is composed of pure strategies which prescribe defection at some stage t, followed by defection in all subsequent stages. Denote such a strategy as s_t, where t is the planned defection stage. Note that the Wait strategy is simply a special case of this general type of strategy, where $t = T$. That is, the Wait strategy is identical to s_T.

It is easy to calculate the expected payoffs of the three basic pure strategies listed above. If opportunist i expects all other opportunists to defect at stage t, and i preempts at stage $t-1$, his or her expected payoff will be

$$E\pi(preempt) = (t-2) + (1+b) = t - 1 + b, \tag{4}$$

since, in each stage up to and including stage $t-2$, all players cooperate, giving a payoff of 1 per stage; at $t-1$, only opportunist i defects, giving a payoff of $1+b$; and in the remaining stages, the opportunist receives a zero payoff.

The corresponding equation for the SS strategy is similar to (4):

$$E\pi(SS) = (t-1) + (1+b)r, \tag{5}$$

since, for $t-1$ stages, opportunist i cooperates (giving a payoff of 1 per stage). In stage t, he or she defects, yielding a payoff of $(1+b)$ if the opponent is a reciprocator, which has probability r, and zero if the opponent is an opportunist, since all opportunists defect at stage t. After stage t, the opportunist receives a zero payoff.

Finally, the expected payoff of the Wait strategy is

$$E\pi(wait) = (T-2) + [r - b(1-r)] + (1+b) = T - 1 + r(1+b). \tag{6}$$

In (6), the first term to the right is the opportunist's payoff from $T-2$ stages of cooperation with the reciprocators (or, up to stage $t-1$, with other opportunists). The second term is the opportunist's expected payoff in stage t, when the opportunist allows himself or herself to be cheated by the opponent, if the opponent is an opportunist. The final term is the opportunist's payoff from cheating the reciprocators in stage T, giving a (certain) payoff of $(1+b)$.

By subtracting (5) from (4), we obtain a critical r which equates $E\pi(preempt)$ to $E\pi(SS)$:

$$\widetilde{r} \equiv \frac{b}{1+b}. \tag{7}$$

Note, however, that r_0, as defined above in (3), is strictly greater than $\widetilde{r}$. Thus given that $r \geq r_0$ in Case A, we have $r > \widetilde{r}$, by transitivity. This, in turn, implies that

$$E\pi(SS) > E\pi(preempt).$$

Figure 4 shows the expected payoff functions of the three pure strategy types as a function of t, the stage at which all opportunists, except the opportunist in question, are expected to defect. From (4) and (5), note that the coefficients of $E\pi(preempt)$ and $E\pi(SS)$ with respect to t are the same, so that the lines plotting these two equations in Figure 4 are parallel. The relative positions of these two lines reflect the result, noted above, that $r > \widetilde{r}$, so that $E\pi(SS) > E\pi(preempt)$ for all t. The point at which the $E\pi(SS)$ function intersects the $E\pi(wait)$ function, which has a zero slope with respect to t, is designated t^*. By equating (5) to (6), we obtain

$$t^* = T.$$

Thus there is a unique pure strategy equilibrium, involving a simultaneous switch of all opportunists from cooperation to defection in their market interactions at stage t^*. This is formalised in the following proposition.

Proposition 3 *When $r \geq r_0$ and therefore $r > \widetilde{r}$, there is a unique pure strategy PBE, in which the opportunists will cooperate in their market interactions up to, but not including, stage $t^* = T$. The reciprocators will cooperate throughout their careers. Moreover, there is no non-trivially mixed equilibrium strategy in which the probability of defections is positive at stage $t < T$.*

Proof. See Appendix. □

2.2 $r < r_0$

When $r < r_0$, it is optimal for the reciprocators to defect in the last round, since the probability that their opponent is a reciprocator is too low to justify the risk of being defected by an opportunist. Thus all players will defect in the last round, and, by backwards induction, this will lead all players to defect throughout their careers. Thus we obtain

Proposition 4 *If $r < r_0$, in the absence of specific information of the opponent's type, all agents will defect throughout their careers.*

Figure 5 illustrates our results so far. The figure shows $\widetilde{r}$ and r_0, and indicates the region supporting cooperation in PBE.

Let us now relax the assumption made up to this point, that agents have no specific information of their opponent's type. We have just seen that, when $r < r_0$, no agent will cooperate with his or her partner without having specific information, denoted in Section 1.3 as X, that the partner is a reciprocator.

Let $p(X\,|R)$ denote the probability that the signs X are observed, given that the opponent is an R type (reciprocator), and let $p(X\,|O)$ be the probability of observing these signs if the opponent is an O type (opportunist). Define a parameter, $\phi \equiv p(X\,|O)/p(X\,|R)$, which is less than unity if X is positively correlated with the reciprocator type, as the *emission ratio* of X. If ϕ were equal to unity, this would indicate that X has no informational content. The smaller is ϕ, the larger the informational content of X; thus $1-\phi$ measures the informational content of X. Similarly, denote X' as the absence of X being 'emitted' by a given agent, and define $\psi \equiv p(X'\,|O)/p(X'\,|R) > 1$ as the *non-emission ratio* of X. Finally, let $p(X)$ be the probability of observing X in the overall population.

We have

$$p(X) \equiv p(X\,|R)r + p(X\,|O)(1-r).$$

Dividing through by $p(X\,|R)$,

$$\frac{p(X)}{p(X\,|R)} = r + \phi(1-r).$$

Recall that the agent's *prior* probability that his or her opponent is a reciprocator is simply r, the proportion of reciprocators in the population. Thus, by Bayes' Theorem, we can write the agent's *posterior* probability that his or her opponent is a reciprocator given that X is observed, as

$$p(R\,|X) = \frac{p(X\,|R)r}{p(X)} = \frac{r}{r+\phi(1-r)}. \tag{8}$$

Similarly, regarding the event that X is *not* observed, we have

$$p(X') \equiv p(X'\,|R)r + p(X'\,|O)(1-r).$$

Dividing through by $p(X'\,|R)$,

$$\frac{p(X')}{p(X'\,|R)} = r + \psi(1-r).$$

Thus the agent's posterior probability that his or her opponent is a reciprocator, if X is *not* observed, is

$$p(R\,|X') = \frac{p(X'\,|R)r}{p(X')} = \frac{r}{r + \psi(1-r)}. \tag{8'}$$

If $p(R\,|X) \geq r_0$, a reciprocator's *posterior* probability that his or her partner is a reciprocator will be sufficiently high (provided that the partner exhibits X) to induce him or her to cooperate with such a partner, even at stage T. Denote the minimum r required to make $p(R\,|X)$ at least equal to r_0, as $r_{\min}$. Using (8), we have

$$r_{\min} \equiv \frac{\phi r_0}{1 + r_0(\phi - 1)},$$

which is less than r_0, since $\phi < 1$.

Now consider the case in which a reciprocator is matched with an agent who does *not* exhibit X. There is a minimum prior probability r, greater than r_0, which will make the posterior probability $p(R\,|X') \geq r_0$, so that even though the opponent does not exhibit X, the posterior probability that the opponent is a reciprocator is nevertheless at least the critical value r_0 that will induce the reciprocator to cooperate even in the last stage T of the game. Using (8′), this minimum prior probability is

$$r^* \equiv \frac{\psi r_0}{1 + r_0(\psi - 1)}$$

If $r_{\min} \leq r < r^*$, only agents exhibiting X (who may be either reciprocators or opportunists) will transact with each other, while those who do not exhibit X will be left without trading partners.[8] Thus the introduction of specific information allows us to extend the analysis of Section 2.1 down to the point where $r = r_{\min}$, and we need only replace r in the relevant equations by $p(R\,|X)$.

If r reaches r^*, even agents who do not exhibit X can find trading partners. The community would now consist of two 'trading groups,' one comprising those agents who exhibit X and one comprising agents who do not exhibit X, since those agents exhibiting X will prefer to transact with others

[8]Recall that agents cannot mimic the signs X. Note that we are assuming, for simplicity, that there is only one type of specific information, X, and not a spectrum of types of such information with varying informational content.

who also exhibit X, thus maximising the probability that their partner is a reciprocator.

To summarise our results up to this point, we have the following proposition.

Proposition 5 *(a) If $r < r_{\min}$, all agents would defect in PBE, resulting in zero expected payoffs for all agents. (b) If $r \in [r_{\min}, r^*)$, only players exhibiting X transact. (c) If $r \geq r^*$, a second 'trading group,' consisting of players not exhibiting X, emerges. In cases (b) and (c), among players who transact, the reciprocators cooperate in PBE throughout their careers, and the opportunists cooperate up to, but not including, stage T (by Proposition 3).*

Figure 6 depicts the content of Proposition 5 graphically. The figure shows the relationship between $r_{\min}$ and r^* to r_0, as well as the equilibrium behaviour of the two types along the interval $r \in [0, 1]$ for agents exhibiting X and not exhibiting X.

3 Endogenising r: Indirect Evolutionary Equilibrium

We divide the evolutionary analysis into three parts, corresponding to the three regions delineated by Proposition 5: (1) $r < r_{\min}$, (2) $r \in [r_{\min}, r^*)$, and (3) $r > r^*$.

3.1 Case 1: $r < r_{\min}$

We noted above that if $r < r_{\min}$, the reciprocators' posterior probability that their partner is a reciprocator (after observing X) will be too small to make it optimal for them to cooperate at stage T. Therefore there will be no cooperation in the society, and the payoffs of all players will be equal at zero. Let us define, following Martinez Coll and Hirshleifer (1991), a *critical point* as a vector of population proportions $(r, 1-r)$ having the property that $E\pi_o = E\pi_r$. Each such point constitutes a (possibly unstable) evolutionary rest-point. Then we immediately can conclude that

Proposition 6 *All points r in the line segment $[0, r_{\min})$ are critical points. At each such point, the expected payoffs of both types are zero.*

3.2 Case 2: $r \in [r_{\min}, r^*)$

Proposition 5 states that, in this case, the opportunists exhibiting X will, in PBE, cooperate up to, but not including, stage T. Thus, in the last stage, the opportunists will receive a payoff of $1+b$ in their transactions with reciprocators, while the reciprocators will receive a payoff of $-b$ when transacting with opportunists. Note that the expected payoff of each type must be multiplied by the proportion of the type exhibiting X in the overall subpopulation of that type. (By Proposition 5, the agents not exhibiting X will simply have no one with whom to transact, and thus receive zero payoffs.) These proportions are $p(X|R)$ and $p(X|O)$ for the reciprocator and opportunist types, respectively. We thus can write the expected payoffs of the reciprocators[9] and opportunists:

$$E\pi_r = p(X|R)\,[p(R|X)T + (1 - p(R|X))(T - 1 - b)] \tag{9}$$

$$E\pi_o = p(X|O)\,[p(R|X)(T + b) + (1 - p(R|X))(T - 1)] \tag{10}$$

Let

$$T_{\min}(r) \equiv \frac{\frac{\phi b}{1-\phi} + \phi(1 - r)}{r + \phi(1 - r)}. \tag{11}$$

We then obtain

Proposition 7 *If $T > T_{\min}(r_{\min})$,[10] then $E\pi_r - E\pi_o > 0$ for all $r \in [r_{\min}, r^*)$, and thus the proportion of reciprocators r in the population will grow over time. If, on the other hand, $T < T_{\min}(r^*)$, then $E\pi_r - E\pi_o < 0$ for all $r \in [r_{\min}, r^*)$, and therefore r will decline over time.*

[9] Recall that, in the evolutionary analysis, what determines the spread or disappearance of a type is the type's material payoff, not the type's utility.

[10] $T_{\min}$, as defined by (11), will decline as r increases (given that $\phi < 1$). Thus if $T > T_{\min}(r)$ at $r = r_{\min}$, then, *a fortiori*, $T > T_{\min}(r)$ for higher values of r; therefore r will increase over the interval $[r_{\min}, r^*)$. There is also the possibility, however, that $T < T_{\min}(r)$ for relatively low values of $r \in [r_{\min}, r^*)$, but, due to the decline of $T_{\min}(r)$ as r increases, $T > T_{\min}(r)$ for higher values of r. In this case, r would again increase over the higher values of r, as long as the latter are still less than r^*. Figure 7, below, illustrates this case. For the sake of expositional simplicity, $T_{\min}(r)$, in the second part of Proposition 7, is parameterized at $r = r^*$.

Proof. See Appendix. □

The intuition underlying Proposition 7 is that the evolutionary disadvantage of the reciprocators in the last stage of their careers, when they are cheated by opportunists who exhibit X, is countered by the fact that they are more likely to have trading partners. Due to the 'assortative matching' permitted by the positive correlation of the signal X with the reciprocator type, the second factor dominates when T is large.

3.3 Case 3: $r \geq r^*$

As shown above, in this case the community will consist of two trading groups, one composed of agents who exhibit X and one composed of agents who do not exhibit X. In both groups, by Proposition 5, the opportunists will defect, in equilibrium, only at stage T, while the reciprocators will cooperate throughout their careers. Given the fact that the reciprocators are not 'over-represented' among those agents who have trading partners, the cause of the increase in r over the range $[r_{\min}, r^*)$ is now absent. Thus, r will decrease for all $r \geq r^*$, and (if $T > T_{\min}$), r^* will be the unique evolutionary equilibrium point (EEP).[11] This result is formalised in the following proposition.

Proposition 8 *If $T > T_{\min}(r_{\min})$, then the unique EEP is at r^*. If $T < T_{\min}(r_{\min})$, then there is an evolutionary equilibrium region at $r \in [0, r_{\min})$.*

Proof. See Appendix. □

Figure 7 shows the evolutionary dynamics resulting from the model, for both $T > T_{\min}$ and $T < T_{\min}$. The arrows show the change in r from one generation to the next. The lack of arrows in the region $r < r_{\min}$ reflects the fact that this a region of critical points (as stated by Proposition 6). When $T < T_{\min}(r_{\min})$, this becomes an 'evolutionary equilibrium region' [Martinez Coll and Hirshleifer (1991)] since, for $r \gtrsim r_{\min}$, r will decline over time—i.e., the region has a 'basin of attraction'.

[11] See Martinez Coll and Hirshleifer (1991) for a definition and discussion of the concepts of EEP and evolutionary equilibrium region. Strictly speaking, since r decreases over time when r exactly equals r^*, we would obtain an r that oscillates, in equilibrium, between r^* and a value infinitesimally smaller than r^*.

4 Related Theoretical Work

As noted in the Introduction, several recent models have introduced preferences for reciprocity, in order to explain real-world and laboratory observations of non-opportunistic behaviour. The models making the smallest departure from 'standard' assumptions, such as Bolton and Ockenfels (2000) and Fehr and Schmidt (forthcoming), assume that agents care about their own payoffs relative to the payoffs of others. In other words, agents in these models are 'averse to inequity'. The present model, like most previous work in the 'indirect evolutionary' tradition, is an attempt to explain the emergence of such preferences.[12]

The present model differs from previous work by combining the 'indirect' evolutionary approach with a finitely repeated game, thus obtaining the result that *both* the reciprocator and the opportunist type will optimally cooperate over most of the stages of their careers. The model thus explains why agreements will be self-enforcing even if the equilibrium proportion of reciprocators r is small, particularly if the number of stages in the game T is sufficiently large. An additional implication of the model which accords well with experimental results [e.g., Andreoni and Miller (1993)] is that the equilibrium population is a *mixture* of the opportunistic and reciprocator types, and is not monomorphic.

One (or both) of two fundamental assumptions have been introduced by previous work, in order to explain the survival of the reciprocator type: (a) direct observability of the opponent's type, not only of the population mixture of the two types (i.e., the assumption of complete information), and (b) the existence of a 'punishment' stage following the basic interaction of the players. The complete information assumption was introduced by Güth and Yaari (1992), for example, and has been adopted by a number of other studies, despite its lack of appeal to many economists. Güth (1995) proved that even if there is only a positive *probability* that players identify each other's type, the reciprocator type is still evolutionarily stable. However, Güth (1995) also incorporated assumption (b), that a cheated player can punish his or her opponent in an additional stage of the game, and that the

[12] The idea of using an evolutionary process to determine the preferences of individuals seems to have been suggested first by Michael and Becker (1973) and Becker (1976). Formal models adopting this approach include Frank (1987, 1988), Hansson and Stuart (1990), Güth and Yaari (1992), Güth (1995), Bester and Güth (1998), Fershtman and Weiss (1998), Huck and Oechssler (1999), and Guttman (2000).

act of punishment affords direct utility to the punisher which exceeds the cost of punishing. (It is this direct utility of 'getting even' that *defines* the reciprocator type, in such models.)

Huck and Oechssler (1999) and Guttman (2000) dispense with the complete information assumption. But these models, like those of Güth and Yaari (1992) and Güth (1995), reach tis result by introducing a punishment stage [in Huck and Oechssler (1999)] or a stage in which a cheated player can, at a cost, retract his or her initial cooperative move [in Guttman (2000)].

The question arises, however, as to the empirical applicability of the assumed punishment stage without assuming a legal system that allows cheated agents to sue those who have cheated them (or various forms of 'vigilante justice'), when milder forms of punishment are insufficient deterrents. Thus, in effect, models incorporating a punishment stage implicitly assume an appropriate institutional framework in which the interaction of the agents is embedded. It should be recalled that if punishing is costly, it is itself subject to a free-rider problem (i.e., a higher-level PD), since the act of punishment discourages defections, and thus confers benefits on the entire community. Previous models have therefore tended to introduce spitefulness (or a taste for punishing) as part of their *definition* of preferences for reciprocity.

In contrast, the present model assumes that the moves of the players in each stage are simultaneous; cheated agents do not have the 'last word' [cf. Hirshleifer (1977)]. The repeated interaction provides a natural means of punishing defectors (though cheated players simply avoid playing with known defectors, and do not purposely punish them). In the last stage of the game, however, there is no further possibility of punishment.

Bester and Güth (1998) justify the complete information assumption by arguing that such models are relevant to situations in which individuals are well acquainted with each other, such as in small, stable communities. Indeed, over most of human history, individuals typically interacted in such communities. The present model directly models this important aspect of the real world by introducing repeated interaction, rather than introducing complete information by assumption.

We have found, however, that some signal, however noisy, of the agent's type is still required to explain the evolutionary stability of preferences for reciprocity, given that the game is finitely repeated. Note that Güth's (1995) weakening of the complete information assumption assumed that agents correctly identify each other's type with some positive probability. In Güth's (1995) model, agents either identify their opponent's type correctly or do not identify it at all; the possibility of an agent's making the *wrong* 'guess', and acting on it, is neglected. In contrast, the present model assumes that agents observe a signal that has some arbitrarily small correlation with the opponent's type, and optimally revise their prior beliefs, conditional on their observations, in accordance with Bayes' Theorem. Agents in the present model therefore do not assign more informational content to the observed signal than the signal objectively carries. Moreover, given the imperfect correlation of the signal with the reciprocator type, agents assign positive probability to the agent being the 'wrong' type, which is what occurs in reality.

An alternative, better-known evolutionary tradition stems from the work of Axelrod (1981, 1984), whose Prisoner's Dilemma tournaments established the potential of reciprocity [in the form of the Tit-for-Tat (TFT) strategy)] as an evolutionarily stable strategy. In this tradition, however, behaviour is directly determined by the evolutionary process; agents *do not optimise*,

r_0 would a reciprocator cooperate at stage T, while the opportunists would always defect at this stage.

A further extension of the model would introduce a (unimodal) probability distribution of end-points of the game, rather than a common, known end-point. As the mode of this distribution is approached, the probability of termination of the game before stage $t+1$ will increase with t. If this probability distribution has sufficiently small variance, the termination probability will eventually become sufficiently high that cooperation over the whole game will not be an equilibrium outcome, without the mixture of types and incomplete information endogenised in this model. In other words, if agents' probability distribution of endpoints is sufficiently 'peaked', the results of the theory would be unchanged.

The theory presented here implies that, if market and non-market interactions in a community are sufficiently long-lived (i.e., T is sufficiently large), then in the unique evolutionary equilibrium, there is a positive proportion of reciprocators, and this proportion will induce the remaining 'opportunistic' types to cooperate as well for nearly all of their careers in the community. The theory differs from conventional evolutionary models in its modeling of all players as rational, Bayesian maximisers, rather than as automota who play fixed, 'wired-in' strategies.

In the present theory, as in other work using the 'indirect' evolutionary approach, agent types are defined not by their strategies, but by their preferences. But the theory developed here, unlike previous indirect evolutionary work, models the interactions of the two types as a repeated game, thus explaining why opportunistic types cooperate as well, in order to maintain reputations for being reciprocators. This modeling of a repeated game also avoids the twin assumptions of previous indirect evolutionary models, (a) complete information and/or (b) a punishment stage following the basic interaction of the agents. The present model is therefore particularly relevant to stable communities in less developed societies, in which the interaction of agents is repeated many times, while the institutional framework required to support a punishment stage (apart from the repeated interaction itself) is lacking or overly costly to utilise.[13]

[13] For evidence that informal reciprocity norms are relatively strong in less-developed countries and in areas where geographical mobility is relatively low (as the model leads us to expect), see Putnam (1995a, 1995b), Guttman (forthcoming, *a*) and the references therein, and Guttman and Götte (1999).

Appendix

PROOF OF PROPOSITION 3:

Assume the opposite of the Proposition, that there was a pure strategy PBE in which the opportunists switched over to defection before t^*. Since $E\pi(wait) > E\pi(SS)$ for all $t < t^*$, each opportunist would have an incentive to deviate and cooperate. This proves that no such PBE exists. In contrast, at stage t^*, each opportunist's best response to a simultaneous switch by the other opportunists is to defect at t as well, since, at T, $E\pi(SS)$ has the highest expected payoff of the three possible pure strategies. (Strictly speaking, the Wait strategy is meaningless at stage T.) This implies that a simultaneous switch would occur, in equilibrium, at T.

Now consider a non-trivially mixed strategy in which the probability of defections, which we denote p_t, is positive at some stage $t < T$. Let $\underline{t}$ be the earliest defection stage played with positive probability in this mixed strategy. The expected payoff of $s_{\underline{t}}$ would be $\underline{t}-1+(1-p_{\underline{t}})(1+b)$, since, with probability $(1- p_{\underline{t}})$, the agent playing $s_{\underline{t}}$ would preempt his or her opponent, yielding a payoff of $1 + b$ at stage $\underline{t}$ and, in addition, he or she would have $\underline{t}$ -1 stages of cooperation with any opponent, yielding a payoff of unity in each stage. For any $p_{\underline{t}} > 0$, this expected payoff is less than the payoff of the Preempt strategy at stage $\underline{t}$, which is $\underline{t}-1 + (1 + b) = \underline{t} + b$. [Note that the expression for $E\pi(preempt)$ in equation (4) of the text is expressed as a function of the expected defection stage t of the *other* opportunists, which is one stage later than the planned preemption stage of the preemptor. Here, the expected payoff of the Preempt strategy is expressed in terms of the preemption stage $\underline{t}$ of the preemptor.] But we have found that

$$E\pi[preempt(\underline{t})] < E\pi[SS(\underline{t} + 1)] < E\pi(wait) \qquad \text{(A1)}$$

for all $\underline{t}$ $+1 < T$. Since $E\pi(wait)$ is invariant to the stage(s) at which the agent playing Wait is preempted, $E\pi(wait) = E\pi(s_T)$. Thus, by transitivity, $E\pi(s_{\underline{t}}) < E\pi(s_T)$, so that $s_{\underline{t}}$ would not be included in any such mixed strategy given that s_T is an alternative, available pure strategy.

Note, however, that the above argument assumed that $\underline{t}$ is less than $T-1$. If $\underline{t} = T - 1$, a simultaneous switch with the other opportunists defecting at stage T would give a higher expected payoff than $E\pi[preempt(\underline{t})]$ [by the left-hand inequality in (A1)] and thus a strictly higher expected payoff than $E\pi(s_{\underline{t}})$, implying again that $s_{\underline{t}}$ would not be played in equilibrium. □

PROOF OF PROPOSITION 7:

Using (8) of the text, equations (9) and (10) of the text can be rewritten as

$$E\pi_r = \frac{p(X\,|R)}{r+(1-r)\phi}\left[rT+(1-r)\phi(T-1-b)\right] \tag{A2}$$

and

$$E\pi_o = \frac{p(X\,|O)}{r+(1-r)\phi}\left[r(T+b)+(1-r)\phi(T-1)\right]. \tag{A2$'$}$$

Subtracting (A2′) from (A2),

$$\begin{aligned}(E\pi_r - E\pi_o)[r+(1-r)\phi] &= [p(X\,|R)-p(X\,|O)]\,[rT+(1-r)\phi(T-1)] \\ &\quad -p(X\,|O)\,br-(1-r)\phi p(X\,|R)\,b. \qquad \text{(A3)}\end{aligned}$$

By the definition of ϕ, $p(X\,|O) = \phi p(X\,|R)$. Substituting $\phi p(X\,|R)$ for $p(X\,|O)$ in (A3) and simplifying,

$$\frac{(E\pi_r - E\pi_o)[r+(1-r)\phi]}{p(X\,|R)} = (1-\phi)\left\{T[r+(1-r)\phi]-\phi(1-r)\right\}-\phi b. \text{(A4)}$$

Note that the l.h.s. of (A4) has the same sign as $(E\pi_r - E\pi_o)$. The r.h.s. of (A4) is positive, zero, or negative as

$$T \gtreqless \frac{\frac{\phi b}{1-\phi}+\phi(1-r)}{r+\phi(1-r)}. \tag{A5}$$

Thus the r.h.s. of (A5) is the desired $T_{\min}$. □

PROOF OF PROPOSITION 8:

In Case 3, agents exhibiting X and agents not exhibiting X both have trading partners. Thus the expected payoff of the reciprocators is

$$\begin{aligned}E\pi_r &= p(X\,|R)\,\{p(R\,|X)\,T+[1-p(R\,|X)]\,(T-1-b)\}+ \\ &\quad p(X'\,|R)\,\{p(R\,|X')T+[1-p(R\,|X')]\,(T-1-b)\}. \qquad \text{(A6)}\end{aligned}$$

The first term is the expected payoff of reciprocators exhibiting X, while the second term is that of reciprocators not exhibiting X. Using (8) and (8′) of the text, (A6) can be rewritten as

$$E\pi_r = T-(1+b)\left[\frac{(1-r)\phi p(X\,|R)}{r+(1-r)\phi}+\frac{(1-r)\psi[1-p(X\,|R)]}{r+(1-r)\psi}\right].$$

Recall that, by the definitions of ϕ and ψ, $p(X\,|O) = \phi p(X\,|R)$ and $[1 - p(X\,|O)] = \psi[1 - p(X\,|R)]$. We can therefore simplify this further to

$$E\pi_r = T - (1+b)\left[\frac{(1-r)p(X\,|O)}{r+(1-r)\phi} + \frac{(1-r)[1-p(X\,|O)]}{r+(1-r)\psi}\right]. \tag{A6$'$}$$

Similarly, we have

$$\begin{aligned} E\pi_o \;=\;& p(X\,|O)\,[p(R\,|X)\,(T+b) + (1-p(R\,|X))(T-1)] + \\ & p(X'\,|O)\,\{p(R\,|X')\,(T+b) + [1-p(R\,|X')](T-1)\}. \end{aligned} \tag{A7}$$

Again, using (8) and (8′) of the text, this can be rewritten as

$$E\pi_o = T - 1 + (1+b)\left[\frac{p(X\,|O)\,r}{r+(1-r)\phi} + \frac{[1-p(X\,|O)]r}{r+(1-r)\psi}\right]. \tag{A7$'$}$$

Subtracting (A7′) from (A6′),

$$E\pi_r - E\pi_o = 1 - (1+b)\left[\frac{p(X\,|O)}{r+(1-r)\phi} + \frac{[1-p(X\,|O)]}{r+(1-r)\psi}\right]. \tag{A8}$$

Note that both of the terms within the brackets are positive.

Define $\Delta \equiv p(X\,|R) - p(X\,|O) > 0$. Then, using the definitions of ϕ and ψ, we can rewrite the two fractions within the square brackets of (A8) as follows:

$$\frac{p(X\,|O)}{r+(1-r)\phi} = \frac{p(X\,|O)\,p(X\,|R)}{p(X\,|O)\,+ r\Delta} \tag{A9}$$

and

$$\frac{[1-p(X\,|O)]}{r+(1-r)\psi} = \frac{[1-p(X\,|O)]\,[1-p(X\,|R)]}{1-p(X\,|O)\,-r\Delta}. \tag{A10}$$

Substituting (A9) and (A10) into (A8) and simplifying,

$$E\pi_r - E\pi_o = 1 - (1+b)\left[\frac{\Omega + p(X\,|R)\,r\Delta}{\Omega + p(X\,|O)\,r\Delta + (r\Delta)^2}\right], \tag{A11}$$

where $\Omega \equiv -p(X\,|O)]\,(1-r\Delta) - r\Delta + p(X\,|O)^2$. Dividing both the numerator and the denominator of the bracketed expression in (A11) by $p(X\,|O)\,r\Delta$ and simplifying,

$$E\pi_r - E\pi_o = 1 - (1+b)\left[\frac{\dfrac{\Omega}{p(X\,|O)\,r\Delta} + \dfrac{p(X\,|R)}{p(X\,|O)}}{\dfrac{\Omega}{p(X\,|O)\,r\Delta} + \dfrac{p(X)}{p(X\,|O)}}\right]. \tag{A11$'$}$$

Since $p(X\,|R) > p(X)$, the bracketed term is greater than unity. (Both the numerator and denominator of the bracketed term in (A11′) are positive, since the bracketed term in (A11′) equals the bracketed term in (A8), which, as noted above, is composed of two positive fractions.) Thus, for any $b > 0$, $E\pi_r - E\pi_o < 0$. This implies that, for any $r \geq r^*$, $E\pi_r < E\pi_o$. Combining this result with Proposition 7, we obtain Proposition 8. □

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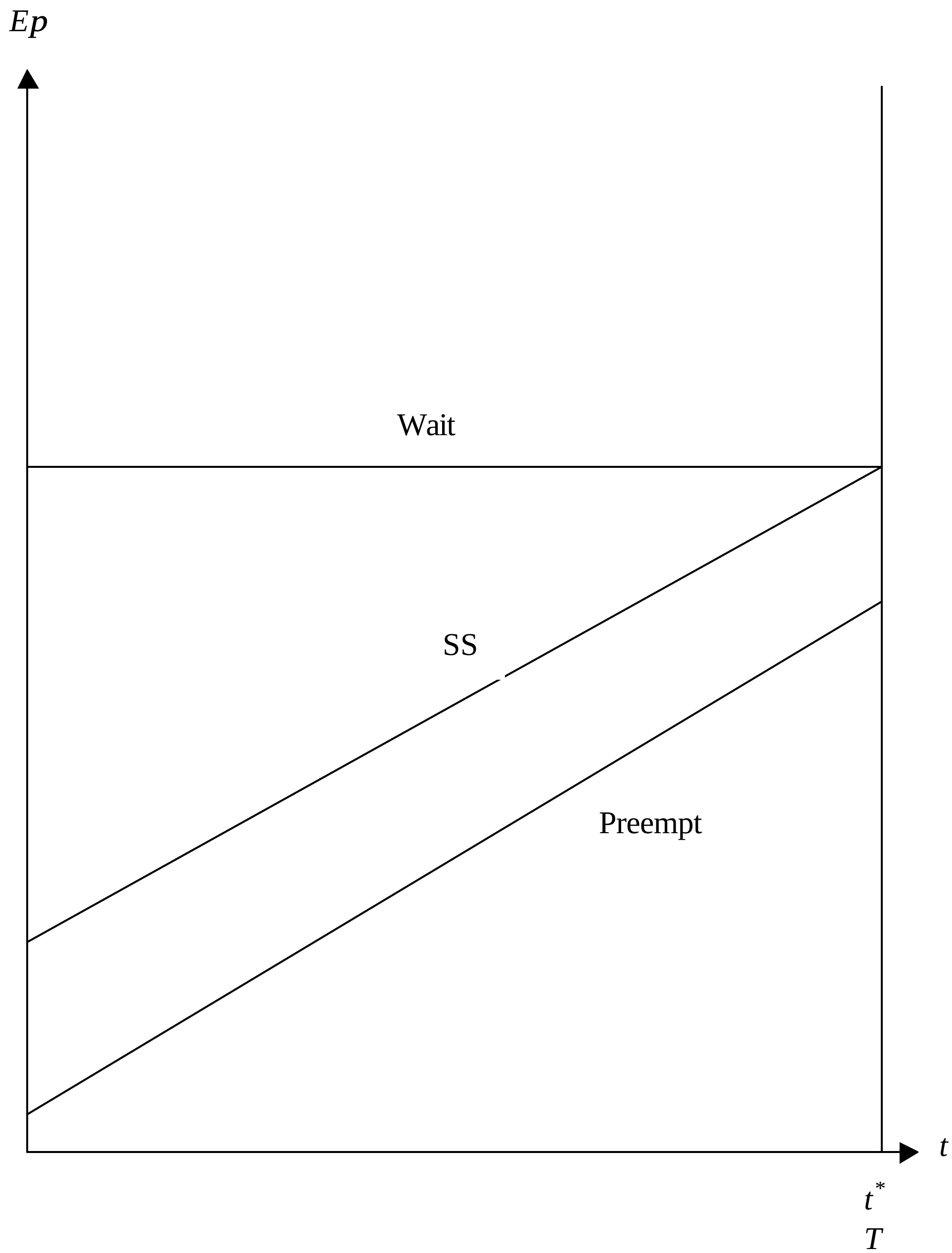

Figure 5. Optimal Preemption Stage

$\tilde{r}$

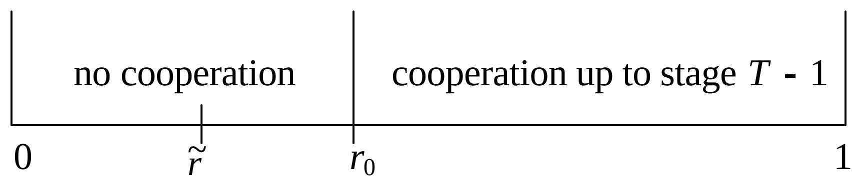

Figure 5. Regions Supporting and Not Supporting Cooperation in PBE

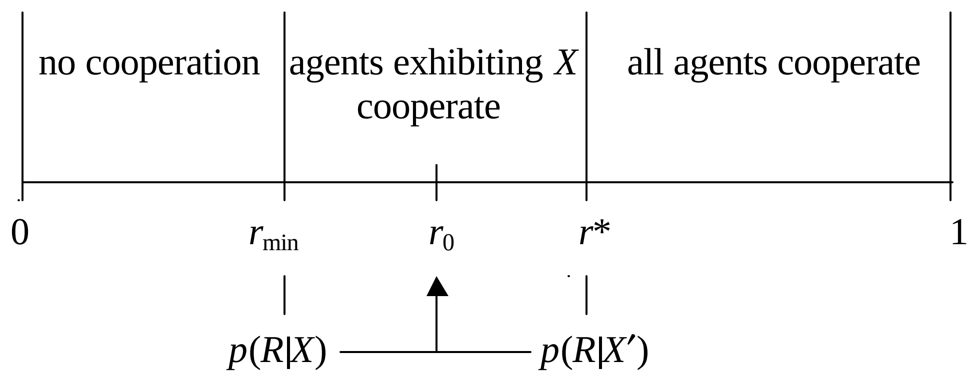

Figure 6. Regions Supporting Cooperation in PBE, with Specific Information

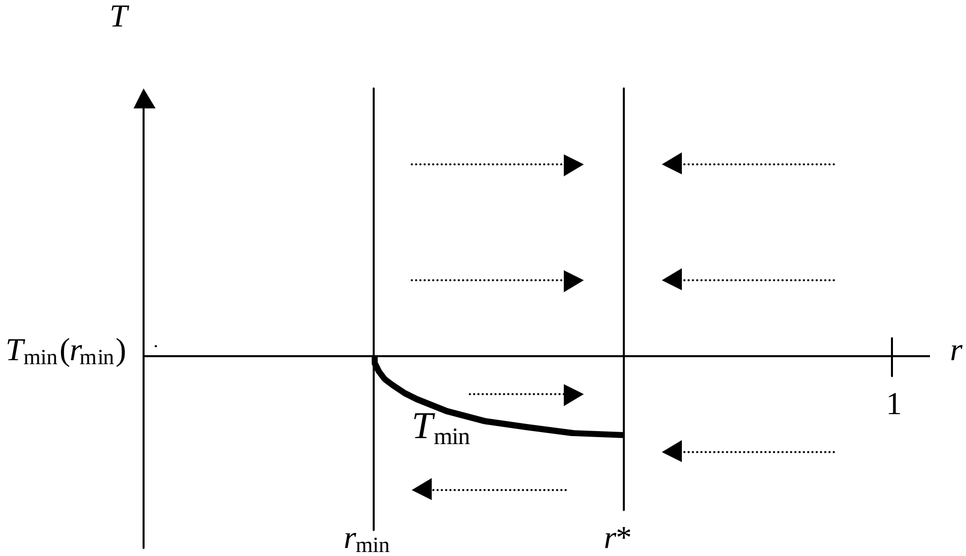

Figure 7. Evolutionary Dynamics for High and Low *T*