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# **The dependency game: multiperson reciprocal sharing leads to stable cooperation which can evolve into group formation**

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## **Abstract**

In the standard model for reciprocal collaboration, the repeated Prisoner's Dilemma (PD), it has proved difficult to establish collaboration in larger groups, necessitating the introduction of additional mechanisms such as reputation or assortment. The problem is corroborated because current multiperson PDs model simultaneous player action, known as a common goods situation, whereas multiperson collaboration could be easier to obtain in a PD with alternate player action, a private goods situation. Here we present such a game, called a dependency game, and show that stable collaboration can be obtained in a 255-player simulation if only players are allowed to remember three previous benefactors, so they can play advanced tit-for-tat. Furthermore, we show that such a freely collaborating population is threatened by assorted strategies, which define groups that parasitize on independent tit-for-tat players. By excluding others, these groups engage in indirect reciprocal behaviour. Our model therefore combines many hitherto separate collaboration-enhancing concepts into one game, and suggests that group formation and collaboration are two separate social phenomena.

**Keywords**

Prisoner's dilemma, multiperson, alternate, sharing, dependency game, assortedness, group, competition, size, cohesion, tit-for-tat, evolution, competition, alternate, tag

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## Introduction

Survival of organisms through cooperation represents an evolutionary paradox, because it is counterintuitive that selfish Darwinian organisms can be brought to sacrificing individual wealth for the good of others. However, past research has shown that cooperation is possible if organisms invest now in return for more payoff in the future, and such a system of so-called reciprocal altruism has neatly been captured in the classic repeated Prisoner's Dilemma (PD) game (Trivers, 1971; Axelrod and Hamilton, 1981).

The repeated PD can lead to stable collaboration when population sizes are small (Boyd and Richerson, 1988). However, in larger group sizes, it has been more difficult to establish collaboration, requiring the introduction of extra features such as altruistic punishment, reputation building or assortment (collaboration with members of a similar group, also called clustering, Axelrod and Hamilton, 1981; Fehr and Fischbacher, 2003). In these mechanisms, collaboration goes further than direct interactions with a partner (direct reciprocity), hence they are called indirectly reciprocal (Nowak and Sigmund, 2005). However, in all these mechanisms players personally profit from their strategies.

In the classic interpretation of the PD, two players act simultaneously, after which a payoff follows, and this simultaneousness has been retained in multiperson PD games (Boyd and Richerson, 1988; Eriksson and Lindgren, 2005; and references therein). A good example of a simultaneous collaboration is a dyke building project, because all members make their contributions and harvest at the same time. This situation, in which a communal resource is exploited, is called a common goods situation (Taylor and Ward, 1982). However, many collaborative interactions are not simultaneous, but alternate. A

good example of an alternate interaction is when a successful hunter shares meat with his unsuccessful group members. Another example is when a healthy group member cares for an ill or wounded group member (see Trivers, 1971; Frean, 1991; Nowak and Sigmund, 1994 for more examples of alternate interactions). In fact, it can be argued that every form of specialization of labour leads to situations of mutual dependency and to the alternate exchange of goods. Thereby alternate interactions form the basis of the mercantile economy. A distinguishing characteristic of the alternate game is that goods or care are exchanged between two individuals, rather than pooled into a common cause, and this is called a private goods situation (Taylor and Ward, 1982; Trivers, 2006).

Because of the interest in alternate interactions, alternate forms of the PD game have been explored before for two players (Frean, 1991; Nowak and Sigmund, 1994), but never as a multiperson game. It could be that multiperson private goods collaboration is more stable than common goods collaboration, because the former does not depend on the simultaneous cooperation of  $n$  persons that can fall apart when even a single player defects (Boyd and Richerson, 1988; Trivers, 2006). In other words, the  $n$ -person alternate PD could be much better suited to generate large scale collaboration than the  $n$ -person simultaneous PD, and this is investigated in this work.

In our multiperson alternate repeated PD, called the dependency game, a player can share a harvest with other players, or keep it to herself, at the expense of some degradation in value. After a theoretical characterization, we present a multiperson simulation and show that stable collaboration is supported, if only players are allowed to memorize a limited list of previous benefactors. To take our model further, we subsequently show that such a collaborative network can be invaded by assorted

strategies, which by definition form groups. Then, we show that such assorted groups are threatened in turn by assorted groups that are larger or more cohesive.

### **The 3-player dependency game**

Imagine three players and a hare from which two persons can eat. The hare consists of two rations, each of value  $b$  (in line with earlier notation (Nowak and Sigmund, 1994)). and can be caught by one of the three players, the harvesting player. Which player is determined by chance. For convenience only one hare can be caught each round, and every player has an average chance of  $1/3$  of becoming the harvesting (hare-catching) player. We introduce a chance here to avoid artefactual strategies that could arise if we let players become active in turn.

Whenever a player harvests, she first will keep one ration for herself. Then she can opt to give the remainder to another player (the recipient), or to keep the remaining ration, but it will deteriorate to a value of  $\delta$ , so that a non-sharing harvesting player ends up with  $b + \delta = a$  rations. When sharing, the harvester can single out specific players (“friends”) to preferentially give shares to, but she cannot share more or less than one ration, or divide her ration over several players. In this way there is always at least one player who does not get a ration.

### **Relation to the Prisoner’s dilemma**

Although it might not be apparent from its description, the dependency game is related to the Prisoner’s Dilemma and its variations, such as the two person alternate PD (Nowak and Sigmund, 1994), the three person simultaneous PD (Eriksson and Lindgren,

2005), and the classic two person simultaneous PD (Axelrod and Hamilton, 1981). This can be shown by assessing the payoff structure.

First suppose that  $V(D|k)$  is the expected payoff (value) for a player that would defect (play D) if she were harvesting, when  $k$  other coplayers would cooperate (play C) if they were harvesting. The defecting player has a probability of  $1/3$  to harvest  $a$ , but does not get anything if his coplayers are all defectors:

$$V(D|0) = 1/3 \cdot a$$

If one coplayer is cooperator, we can assume that the player under consideration has a 50% probability of getting a share when the cooperator becomes the active player. (for calculating these *expected* payoffs, we let the recipient make the assumption that a cooperating harvester has no preference for either player. This is a ‘best’ guess when there is no information to the contrary.) Thus,

$$V(D|1) = 1/3 \cdot a + 1/3 \cdot 0.5 \cdot b + 1/3 \cdot 0 = 1/3 \cdot a + 1/6 \cdot b$$

If both fellow players are cooperators:

$$V(D|2) = 1/3 \cdot a + 1/3 \cdot 0.5 \cdot b + 1/3 \cdot 0.5 \cdot b = 1/3 \cdot a + 2/6 \cdot b$$

Thus the general yield with  $k$  cooperators becomes, for  $k \in \{0, 1, 2\}$ :

$$V(D|k) = 1/3 \cdot a + k/6 \cdot b = 1/3 \cdot (a + k/2 \cdot b)$$

Now, suppose that  $V(C|k)$  is the expected payoff for a cooperating player with  $k$  other cooperators. Since a cooperator has a probability of  $1/3$  to become active with payoff  $b$ :

$$V(C|0) = 1/3 \cdot b$$

$$V(C|1) = 1/3 \cdot b + 1/3 \cdot 0.5 \cdot b + 1/3 \cdot 0 = 2/6 \cdot b$$

$$V(C|2) = 1/3 \cdot b + 1/3 \cdot 0.5 \cdot b + 1/3 \cdot 0.5 \cdot b = 4/6 \cdot b$$

Generally,  $V(C|k) = 1/3 \cdot (1 + k/2) \cdot b$



These expressions for  $V(C|k)$  and  $V(D|k)$  are similar to expressions for the 3-person simultaneous PD game (Eriksson and Lindgren, 2005), demonstrating the relatedness of both games.

The dependency game is also related to a 2-person PD payoff matrix, which can be shown by simplifying it to a hypothetical game in which only two players can harvest, who can only share with each other.

$$V_{\text{twoperson}}(C|0) = \frac{1}{2} \cdot b, \quad V_{\text{twoperson}}(C|1) = \frac{1}{2} \cdot b + \frac{1}{2} \cdot b = b,$$

$$\text{therefore for } k \in \{0,1\}: V_{\text{twoperson}}(C|k) = \frac{1}{2} \cdot (1 + \frac{k}{2}) \cdot b$$

$$V_{\text{twoperson}}(D|0) = \frac{1}{2} \cdot a, \quad V_{\text{twoperson}}(D|1) = \frac{1}{2} \cdot a + \frac{1}{2} \cdot b,$$

$$\text{therefore for } k \in \{0,1\}: V_{\text{twoperson}}(D|k) = \frac{1}{2} \cdot (a + \frac{k}{2} \cdot b)$$

Comparing outcomes shows that  $V_{\text{twoperson}}$  is always  $\frac{3}{2}$  of the outcome of the 3-player game. This is because in both games, there are two rations to divide, but the three person game has  $\frac{3}{2}$  times more players. In earlier analyses, it was concluded that the final payoff matrix needs to be based on  $2V_{\text{twoperson}}$ , because a two person alternate game needs minimally two rounds for all players to participate (Nowak and Sigmund, 1994). This payoff is identical to  $3V_{\text{threeperson}}$ , which makes sense since the three-person game needs three rounds for full participation. The final expected payoff matrix (Table 1) represents a true PD payoff (Axelrod and Hamilton, 1981), since it satisfies the requirements for the classic parameters T, R, P and S. Indeed,  $T > R > P > S$  because  $a+b > 2b > a > b$ , and  $2R > T+S$  because  $4b > 2b+a$  (Table 1).

The result of Table 1 can be obtained in a much more direct way by imagining two players who alternately harvest over two rounds, who ignore the third player, but not each other. The two round payoffs are then identical to those of Table 1, as shown earlier

(Nowak and Sigmund, 1994). Both calculations demonstrate that the dependency game is an extended variant of the 2-person simultaneous PD game.

### **Nash equilibria in the dependency game**

Even though the expected payoff matrix in the dependency game can be simplified to a classic PD payoff (if we assume cooperators distributing randomly), the true payoff matrix becomes much more complex when all strategic options of all players are incorporated (Table 2). To do this, we need to extend our nomenclature. Imagine the players are in a circle. Every harvesting player then has a choice between defecting (D), sharing with the player on her left hand (CL), or on her right hand (CR). This is in contrast to other (multiperson) PDs, which only have options C or D (Eriksson and Lindgren, 2005). In the 3-person dependency game, this results in 27 different possible outcomes  $((X|Y|Z), \text{ with } X,Y,Z \in \{D,CL,CR\})$  (Table 2). For each interaction, an expected payoff can be defined as  $V(X|Y,Z)$ , which is the expected value for player 1 if she would opt X if she would harvest, and if players 2 and 3 would opt for Y and Z respectively if they would harvest.

The expected payoffs for all individual interactions (Table 2) reveal that there is only one Nash equilibrium, which is when nobody shares (D|D|D). This parallels the PD game, where all-defect is also the only Nash equilibrium (Gintis, 2000). However, two types of interaction pareto-dominate the Nash equilibrium payoff, which we call couple and team patterns (see below). When our game is played in repeated fashion, any combination of these interaction patterns is also a Nash equilibrium, as follows from the

folk theorem (Gintis, 2000). In conclusion, there are three interaction patterns that are relevant in the repeated dependency game:

1. *No sharing*: none of the players, when active, ever shares. The expected value for any player in this pattern is  $V(D|D,D) = V_{\text{solo}} = \frac{1}{3} \cdot a$ . This is equal to the payoff  $V(D|0)$  as defined above.
2. *Couple pattern*: if two players mutually share, and leave one player out, the expected yield of a member of the couple is  $V(CL|D,CR) = V(CR|CL,D) = V_{\text{couple}} = \frac{1}{3} \cdot b + \frac{1}{3} \cdot b = \frac{2}{3} \cdot b$ . The expected yield of the left-out player is  $V(D|CR,CL) = V_{\text{solo}}$ . Note that these yields are not equal to  $V(C|1)$  or  $V(D|2)$  as defined above, which is because the players don't share randomly but specifically target a partner for sharing. As it is a matter of chance who end up forming a couple, and who ends up as bystander, the average payoff for any random player in a situation with a couple is  $\langle V_{\text{couple}} \rangle = V_{\text{couple}} = \frac{2}{3} \cdot V_{\text{couple}} + \frac{1}{3} \cdot V_{\text{solo}} = \frac{4}{9} \cdot b + \frac{1}{9} \cdot a = \frac{1}{9} \cdot (4b + a)$ . The defining feature of this pattern is that two players mutually share and one defects.
3. *Team pattern*: when players all help their left or right neighbour, the payoff is  $V_{\text{team}} = V(CL|CL,CL) = V(CR|CR,CR) = \frac{1}{3} \cdot b + \frac{1}{3} \cdot b = \frac{2}{3} \cdot b$ . If played in a repeated fashion, this is a pattern of indirect reciprocity, because players share with partners that do not share with them (Fehr and Fischbacher, 2002). However, if all players choose alternately CL and CR, then the resulting interaction after many rounds is a succession of (CL,CL,CL) and (CR,CR,CR), again with payoff  $V_{\text{team}}$ , but this time in a pattern of direct reciprocity. The payoff for all players is identical, so the average payoff  $\langle V_{\text{team}} \rangle = V_{\text{team}}$ , which is higher than  $\langle V_{\text{couple}} \rangle$ . The defining feature of this pattern is that all players choose to share.

### **The tit for tat strategy and the requirement for memory**

In order to maximize payoff for all players in the dependency game, an all-sharing team pattern would be optimal. However simply playing all-cooperate makes players vulnerable to all-defecting players that will realize even higher payoff (Table 2). In repeated PD games, this free-rider problem is most efficiently countered by the tit-for-tat (TFT) strategy (Axelrod and Hamilton, 1981; Nowak and Sigmund, 1994), in which a player starts with cooperation, but defects as soon as the other defects. This strategy minimizes chances of being exploited as a sucker (sharing, but never receiving a share), but still benefits from repeated collaborations.

Because the repeated dependency game bears similarities to the repeated PD, it is expected that TFT is also an important strategy in our game. It can easily be seen how this will work: if a player remembers receiving a share from a player (a ‘friend’) during her harvest, she could share preferentially with this friend. On the other hand, if a player was passed-over during another player’s harvest, she could retaliate by declining to share with this player. The only thing that is needed to play TFT, is that each player remembers who her friends are.

The requirement of memory to play TFT is not unique to our game. A one-round memory is also required in the alternate PD game (Nowak and Sigmund, 1994), and the name tit-for-tat in itself suggests that the previous move of the partner is remembered (Axelrod and Hamilton, 1981). Moreover, in all multiperson PD games, additional memory mechanisms are needed to sustain collaboration, in the form of remembering players reputations, or remembering who deserves altruistic punishment (Fowler, 2005).

In our game, better memory will allow more complex collaborative patterns to be established: for a simple couple pattern, only one friend needs to be remembered, but for a team pattern the responses of two partners have to be remembered over two rounds. In fact, memorizing friends in our game can be viewed as a simple and natural way of keeping track of player's reputations.

### **Simulation of an n-player dependency game**

To assess the viability of TFT and other strategies in the dependency game, we built a 255-player simulation in Excel. Each round, a random fraction of players receives a harvest, which they can keep or share. Keeping results in a score of  $a$ , sharing in a score of  $b$  for both the harvester and the receiver.

For sharing, players can keep an individual *memory* of 'friends', who are defined as players from whom shares were received. The size of *memory* can vary from 1 to 5 and is a parameter that is constant for all players throughout the game. If strategy allows sharing to friends, the most recent friend is picked from the memory table, who is defined as the player from whom most recently a share was received, and this player is given a share. If strategy dictates sharing to a random friend, a player is picked from a worksheet with precalculated random player numbers.

Once sharing is sorted out, the player score is calculated. If players get more than 1 share, the share from the lowest player number is accepted. On the rare occasion that players share to themselves, their score is reset to  $a$ . The sharing score is added to the harvesting score and the previous-round score to result in a new total player score.

Each round, a fixed number of players with the lowest total scores are allowed to switch strategy, and their new strategies are randomly picked from a (different) fraction of strategies with the highest total score, again making use of a precalculated random number table. In our model, the function that picks new strategies from the set of successful strategies sometimes returns an error (4% of all picks), and in this case a strategy is picked randomly from all available strategies, which allows continuous seeding of low-frequency or extinct strategies into the game and thereby proper assessing of stability against all strategies present in the simulation.

Single standard simulations were run in Microsoft Excel 2003 (version 11.65) with 255 participants over 10,000 iterations, with 2-6 competing strategies. Unless otherwise stated, standard parameters are:  $a=1.1$ ,  $b=1.0$ ,  $memory=3$ ,  $\frac{1}{3}$  of players harvests, 25 players switch strategy (*refresh rate*=25), 25 strategies reproduce. Unless otherwise indicated, initial strategies are randomly and evenly allocated among players, and the starting memory is seeded with one round of random friends.

### **In the dependency game, collaborative strategies are dominant**

First we benchmarked our game by running an all-sharing and all-defecting strategy against each other.

**1:** always share with a random player

**2:** never share

As expected, strategy 2 quickly dominates because it exploits the collaborative strategy 1 (Axelrod and Hamilton, 1981) (not shown). Next we introduced two more strategies:

3: share with a ‘friend’, but if no friend can be remembered share with a random player

4: share with a friend, but if no friend can be remembered, do not share.

The collaborative strategies 3 and 4 both work with the concept of friends and are therefore capable of tit-for-tat (see above). Strategy 3 aims at establishing the *team* pattern, as it always collaborates, whereas strategy 4 aims at establishing the *couple* pattern, as it shares limitedly and excludes others.

First, strategy 3 was pitted against a pure population of strategy 2 players, and this clearly shows that strategy 3 can dominate ‘2’ (Fig. 1). Additional simulations show that strategy 3 can dominate even from a small initial population. The minimum size of this initial population depends on the excess payoff for defecting. For  $a=1.1$ , a starting population of 11% (28 out of 255, using *memory*=5) is sufficient to dominate the field (Fig. 1). For  $a=1.05$ , this fraction goes down to 5.1% (13 out of 255), and for  $a=1.01$ , 1.6% (4 out of 255) can grow out, but in this case the stability limit of the simulation is reached. These examples illustrate the general pattern that the initial fraction of ‘3’ players (defined as  $w$ ) needs to be larger than the amount  $a-b$ , thus  $w \geq (a-b)$ .

The required initial population of ‘3’ is related to  $a-b$  because of statistics. If players of ‘3’ need to share with a random player, they will only be rewarded if the random player follows strategy 3. If the chance of such an encounter lessens, the rewards have to increase to keep the strategy viable. In the past, it was derived that for stable collaboration in the 2-person repeated PD, the probability of continued interaction  $w'$  needs to satisfy  $w' \geq (T-R)/(T-P)$ , and  $w' \geq (T-R)/(T-P)$  (Axelrod and Hamilton, 1981). Using the definitions in Table 1, these equations in our nomenclature merge to  $w' \geq$

$(a-b)/b$ , which in our case for  $b=1$  becomes  $w' \geq (a-b)$ . In our game the probability of continued interaction for a player of '3' can be defined as picking a player of '3' when it comes to random pick (which is inevitable for all players once so often). This chance is equivalent to the fraction of players of strategy 3, so  $w = w'$ . In this way, the original equation  $w' \geq (a-b)$  for stability (Axelrod and Hamilton, 1981) also holds in our game. In the extreme case of  $w=1$ , when all players follow strategy 3, collaboration would only collapse if  $(a-b) > 1$ , at which point the game is not a prisoner's dilemma anymore (Table 1). So, when  $w' \geq (a-b)$  is satisfied, strategy 3 can both dominate strategy 2 and form a stable population.

#### **Generously sharing strategy 3 wins from the strict strategy 4**

To test strategy 4, we pitted it against a pure population of strategy 2 players. In all cases strategy 4 survives against strategy 2 (not shown). However, no collaboration is established as strategy 4 is always quickly led into continuous defection. In its all-defection mode, strategy 4 is identical to strategy 2. Strategy 4 is led to defection because it starts sharing with its initially chosen random friends, but not all of these friends play strategies that return shares. Even if we pre-align collaborations before starting the game, strategy 4 is eventually led into defection, as its original friends sometimes switch strategy and then do not share anymore. In general, the problem of strategy 4 is that it can only destroy partnerships, not form new ones.

Next, we ran a simulation of all competing four strategies, which shows that strategy 3 is the most viable (Fig. 2A). Strategy 3 dominates 2 because in its collaborations, it creates more value. At the same time, it is never exploited by strategy 2



because players of ‘2’ are never recognized as friends. Strategy 3 dominates 4 because on average throughout the game, ‘3’ makes more collaborative interactions. Thus, strategy 3 is more successful for the same reasons as  $\langle V_{\text{team}} \rangle$  is higher than  $\langle V_{\text{couple}} \rangle$  or  $V_{\text{solo}}$ .

Strategy 3 obtains more collaboration because it makes more new friends by occasionally sharing with non-friends. In this behaviour, strategy 3 resembles the ‘generous’ TFT strategy, which makes occasional openings to prevent quick decline into mutual defection (Nowak and Sigmund, 2005). Strategy 4, by never taking the initiative for collaboration, resembles the strict TFT strategy. In other multiperson PD games, generous TFT also wins from TFT (Nowak and Sigmund, 2005), and here our game shows again that, in a TFT setting, making openings to new players is essential for survival.

### **Collaboration only arises with sufficient memory**

In order to test the importance of memory, we varied this parameter in our 4-strategy simulations. (Fig. 2). As long as *memory* is  $\geq 3$ , then strategy 3 remains dominant (Fig. 2A). However, if *memory* is  $\leq 2$ , then selfish strategy 2 wins (Fig. 2B). If we switch to other values for *a* and *b* collaboration can be induced with other values for *memory* (as long as we ensure  $(a-b) \leq 0.25$  as we let all strategies start with a population fraction of 0.25). Thus indeed, player memory is an important condition for cooperation (Axelrod and Hamilton, 1981). In effect, memory increases the probability of a productive encounter.

In the same simulations, we also assessed the dynamics of the collaborative networks. It appears that strategies 3 and 4 form networks of reciprocity which are

similar to the *team* and *couple* networks discussed above. The participants in these networks change with a frequency depending on the rarity of the harvests. This is because in our simulation players respond to their latest friend, and if harvests are frequent there are relatively many new openings from new friends. However, if harvests are rare, sufficient memory is needed to remember a friend from many rounds ago, else collaboration breaks up. Collaborative networks are therefore most stable in our model when harvests are rare and memory is long.

### **The dependency game is a strong model for multiplayer collaboration**

In Figs. 1 and 2A, collaboration emerges as the dominant strategy. In the past, simple collaborative strategies were shown to be only evolutionary stable in small groups (Boyd and Richerson, 1988), whereas in larger groups mechanisms such as reputation building or altruistic punishment were needed for sustained collaboration (Fehr and Fischbacher; 2003). However, there is no theoretical reason why large groups cannot collaborate in a PD game (Trivers, 2006). In the dependency game, we observe for the first time that collaboration in a larger PD-playing population can emerge by nothing more complex than allowing strategies that maintain a memory of previous benefactors. This memory is merely the extension of a feature that already exists for one round in normal tit-for-tat strategies, as discussed above. Therefore, the dependency game is a particularly strong model for collaboration in n-player groups.

The reason why multiperson collaboration usually breaks down is ‘second order free riding’(Fowler, 2005), meaning that selfish players can exploit collaborators by participating in benefits, while they never contribute to the group. This problem is tackled

in two ways by our model. First, the list of friends is an implicit mechanism for reputation building, which can induce collaboration despite free riding (for a review see Fehr and Fischbacher, 2003). Second, the game is a model of private goods, not public goods.

In a public goods game, collaboration requires a one-round coordinated action of all group members, and it is statistically challenging to defend against defectors for that one round (Boyd and Richerson, 1988). It has been argued that collaboration is probably better described as a collection of dyadic interactions (private goods), as in our game (Trivers, 2006). In the dependency game, an ensemble of private interactions occurs that, when added up over multiple rounds, becomes equivalent to group collaboration (above we discussed a 2-round summation). In such a summation, the game is undistinguishable from a public goods game in terms of player's cost and value, but the core interaction remains dyadic which is a more robust basis (Trivers, 2006). In essence, the private game divides its net collaborative effect over more rounds, giving TFT more opportunity to expel defectors.

Despite its defenses, our game is not unexploitable. When players could mimic being a friend without sharing first, they could exploit strategy 3. Such exploitation would be exactly similar to the exploitation of all-C strategy 1 by all-D strategy 2 (see above). In answer, strategy 3 players need to evolve sophisticated mechanisms to make sure they can maximally detect false impersonations. Indeed, the human capacity for recognition of other humans seems extremely well developed (Bruce and Young, 2000).

### Assortedness can break up free collaboration

Given the parameter set under which strategy 3 is dominant, we next investigated which strategy is able to replace 3, to get more insight into the vulnerabilities of collaborative networks and thereby into the evolution of socialization. First we tried ‘jealous’ strategies, which never share with successful players, but those lost out. Next we tried assorted strategies, which preferentially share with players that adhere to the same strategy. It is known that assortedness is a strong mechanism to induce collaboration (Boyd and Richerson, 1988; Riolo, 2001), and here we wanted to see if it can threaten non-assorted collaboration. We defined the following strategies:

**5:** pick a partner in the same way as strategy 3, but if this partner does not follow strategy 5, pick a random partner.

**6:** pick a partner in the same way as strategy 3, but if this partner does not follow strategy 6, do not share.

Because strategy 5 still shares with ‘strangers’, it is less assorted than strategy 6, which exclusively shares with itself. In Fig. 3A it can be seen that strategy 5 dominates strategies 1-4, including 3. In Fig. 3B, it can be seen that in turn, strategy 6 dominates strategies 1-5. Additional calculations show that strategy 6 can overwhelm the others from a very small starting population (4 out of 255, 1.6%). The reason for the success of the assorted strategies is that they systematically exploit the others by accepting their openings but never return anything. Thus, a population of freely collaborating GTFT players is vulnerable to a population of assorted GTFT players, and less assorted strategies are vulnerable to more assorted strategies.

### **Assortedness leads to formation of groups**

Assorted strategies are interesting in our game because they define groups, which is an essential concept in collaboration research and human society (Fehr and Fischbacher, 2003). Our initial winning strategy 3 does not form a group, it represents a collection of individuals who freely share with whomever they trust. In contrast, the assorted strategies 5 and 6 recognize each other, and thus they must have an identification tag and therefore they are by definition a group. Such a tag is not similar to the ‘green beard’ mechanism (Dawkins, 1976; Jansen and van Baalen, 2006), in which a tag is associated with a gene with favourable survival characteristics. Assorted strategies only need an arbitrary tag, no further genetic associations (Riolo, 2001). Our data for the first time show that group formation is not necessary for collaboration, but that it has more evolutionary fitness than free collaboration.

Although assortedness is generally associated with collaboration (Riolo, 2001; Fehr and Fischbacher, 2003), the opposite appears from the dependency game. In our game, assortedness is anti-collaborative because it restricts interactions, and breaks down the stable collaboration shown in Figs. 1 and 2. If all other strategies have disappeared, the total average yield, and number of collaborative interactions, are similar between assorted strategy 6 and collaborative strategy 3. Thus, the survival benefit of being part of an assorted group is very complex; it mostly allows players to prey on other non-assorted players. Our model therefore states that the main reason for group membership is to exploit other groups, membership is a matter of eat or be eaten. To quote an example: in the case of two large armies making war (Fehr, 2004), assortedness is not needed to

explain the collaboration in both armies, but the fact that both armies don't manage to collaborate.

### **Assortedness introduces indirect reciprocity**

Another feature of assorted strategies is that they are indirectly reciprocal (for indirect reciprocity see Nowak and Sigmund, 2005). Whenever a player X of strategy 6 encounters a player of strategy 3, she has to decline sharing, which is not in her direct interest since it robs her of a chance to make friends. So in fact player X engages in altruistic punishment. However, she also participates in the group exploitation of the freely collaborating strategies, which can be seen as a communal benefit, since engaging by herself in such exploitation would be unfruitful (as shown by the decline of all-D strategy 2). By belonging to an assorted group, the individual player can have it both ways: profit from reciprocal interactions *and* exploit others. Introduction of assortedness therefore automatically introduces indirectly reciprocal features in our directly reciprocal game, and the success of assortedness shows that indirect reciprocity can have a sound evolutionary benefit over direct reciprocity, which might explain part of why indirect reciprocity is so widespread in human society (Nowak and Sigmund, 2005).

### **When equally assorted groups compete, the largest wins**

Taking into account that assorted strategies are successful because they prey on non-assorted (freely collaborating) strategies, we next investigated assortedness in the absence of free collaborators. For this, we simulated a combination of strategies 1-4 and two competing assorted strategies (Fig. 4):

6: pick a partner as strategy 3, but if this partner does not follow strategy 6, do not share.

7: pick a partner as strategy 3, but if this partner does not follow strategy 7, do not share.

As expected, strategies 1-4 are quickly reduced to insignificance until only 6 and 7 are left (Fig. 4). After that, dynamics are dependent on the starting population. If strategies 6 and 7 have about equal starting populations, both evolve to a final population of exactly 50% strategy 6 and 50% strategy 7 (Fig. 4A). The reason for this is that a group grows by addition of players with lower scores, so the smaller group has a relative overrepresentation of high-score players, and therefore grows relatively quicker as long as it is smaller. This leads to a final 50:50 balance in group size. However, if one strategy has substantial more starters than the other, this strategy will end up dominating (Fig. 4B). Also if the game is restricted from the start to strategies 6 and 7, the one with the largest initial group size wins (not shown). The reason for this ‘large group dominance’ is that a larger group can make more successful internal networks, so less often has to make the costly move of not-sharing.

### **Other threats to groups**

As shown above, an assorted strategy can be outcompeted by another assorted strategy, if the latter forms a larger group. Furthermore, more assorted strategies such as 6 can dominate less assorted ones such as 5. This leads to two general tactics in group competition: 1. aim to have the largest size, 2. aim to have the highest group cohesion. As the first tactic needs to convert other players, and the second needs to exclude others

more vehemently, both tactics are essentially contradictory. Therefore small well-bonded groups can co-exist with larger more loosely associated groups. In addition, tightening group cohesion might be an effective tactic when faced with a larger group. Superficially regarded, size and cohesiveness indeed seem essential survival strategies for human groups, as seen in religions and local cultures, but more investigation would be needed to confirm that these are indeed the dominant mechanisms.

Groups can also be threatened by exploitation of the group tag. For example players could be successful that mimic group membership but themselves share with any candidate. Another way of seeing those mimics is that they try to avoid the cost of altruistic punishment that is involved in refusing other groups. These hypothetical players can be called traitors (although they are in fact more collaborative – appeasers would be a more apt name) and are a serious threat to group cohesion. Indeed, human groups have a particular aversion for traitors, even more than for members of other groups, as witnessed by the more fanatic condemnation of heretics compared to heathen in religious history, and the fact that in old justice systems, treason rather than murder deserved the highest punishment (United Kingdom Treason Act, 1814).

In order to avoid traitor strategies, impersonation of group membership should be made as difficult as possible, and there will be evolutionary pressure on making the group tag difficult to forge, leading to complex and dynamic traits as group tags (Riolo, 2002), which could be similar to the fashions we see in human society. These and other predictions show that the dependency game can yield useful hypotheses about collaboration and group culture which could be tested in more experimental settings.



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## Figure captions

**Table 1.** Payoff matrix for a 2-person alternate PD game. The harvesting player can choose between cooperating (C), which involves giving shares to the recipient, or defecting (D) which involves not sharing. *A*: theoretical payoffs in the form of expressions for payoff in the 3-person game, in superscript the definitions of the classic PD payoff (Axelrod and Hamilton, 1981). *B*: payoff as derived from the expressions in panel A or by considering two rounds of a 2-person dependency game in which the players alternately harvest (as in Nowak and Sigmund, 1994). Notation example: **2:C** indicates that player 2 cooperates. Note that the condition  $b < a < 2b$  applies, because  $a$  is formed by 1 ration and a fraction of a ration.

**Table 2.** Expected payoffs in the 3-person single-round dependency game as function of the strategic choices before harvesting. Within each panel, strategic choices of players 1 and 2 are represented. With panels A, B, C the 3 strategic choices for player 3 are represented. Within one table cell, the top, middle and bottom payoffs are for players 1, 2 and 3 respectively. To reduce complexity, all payoffs were multiplied by 3. The shaded payoff is the Nash equilibrium for a single round of play. Payoffs in bold boxes are higher than the Nash equilibria for all players and therefore Pareto-superior.

**Fig. 1** The cooperative strategy 3 can take over a population of strategy 2 players. The simulation was started with 28 strategy 3 players and 227 strategy 2 players.. For definition of strategies, see text. The number of rounds is plotted on the x-axis, and the

number of participants following a particular strategy on the y-axis. Parameters values were:  $a=1.1$ ,  $b=1$ , *refresh rate*=25, *memory*=5, *fraction harvesting players*= $\frac{1}{3}$ .

**Fig. 2.** Cooperation depends on memory. In this simulation, strategies 1, 2, 3 and 4 (for definitions see text) compete. *A*: with a 3-round memory (*memory*=3), cooperative strategy 3 dominates the population. *B*: with a 2-round memory (*memory*=2), the all defecting strategy 2 dominates the population. In addition, the strategy 4 players that are left after 10,000 rounds in panel B, continuously play defection. Axis and strategy labels and other parameters as in Fig. 1.

**Fig. 3.** Assorted strategies can dominate non-assorted strategies. *A*: simulation with strategies 1-5 present (for definitions see text), showing that the mildly assorted strategy 5 dominates strategies 1-4. *B*: simulation with strategies 1-6 present, showing that the strictly assorted strategy 6 dominates strategies 1-5. Parameter *memory*=3. Axis and strategy labels and other parameters as in Fig. 1. For definitions of strategies, see text.

**Fig. 4.** Strictly assorted strategies that compete either dominate or co-exist, depending on starting population. In these simulations, strategies 1-4, 6 and 7 were present. Parameter *memory*=3. Axis and strategy labels and other parameters as in Fig. 1. Panel *A*: Evenly distributed initial populations (42-43 players per strategy) lead to coexistence of strategies 6 and 7. *B*: A dominating initial population for one assorted strategy (strategies 1-4: 42-43 players; strategy 6: 58 players; strategy 7: 28 players) leads to its final dominance.

Table 1

|             |                            |                            |
|-------------|----------------------------|----------------------------|
| <b>A</b>    | <b>2: C</b>                | <b>2: D</b>                |
| <b>1: C</b> | $3V(C 2), 3V(C 2)^{(R,R)}$ | $3V(C 0), 3V(D 2)^{(S,T)}$ |
| <b>1: D</b> | $3V(D 2), 3V(C 0)^{(T,S)}$ | $3V(D 0), 3V(D 0)^{(P,P)}$ |

|             |             |             |
|-------------|-------------|-------------|
| <b>B</b>    | <b>2: C</b> | <b>2: D</b> |
| <b>1: C</b> | $(2b, 2b)$  | $(b, a+b)$  |
| <b>1: D</b> | $(a+b, b)$  | $(a, a)$    |

Table 2

A

| 3:CL | 2:CL  | 2:CR | 2:D    |
|------|-------|------|--------|
| 1:CL | $2b$  | $b$  | $b$    |
|      | $2b$  | $2b$ | $b+a$  |
|      | $2b$  | $3b$ | $2b$   |
| 1:CR | $2b$  | $b$  | $b$    |
|      | $3b$  | $3b$ | $2b+a$ |
|      | $B$   | $2b$ | $b$    |
| 1:D  | $b+a$ | $a$  | $a$    |
|      | $2b$  | $2b$ | $a+b$  |
|      | $B$   | $2b$ | $b$    |

B

| 3:CR | 2:CL | 2:CR | 2:D   |
|------|------|------|-------|
| 1:CL | $3b$ | $2b$ | $2b$  |
|      | $b$  | $b$  | $a$   |
|      | $2b$ | $3b$ | $2b$  |
| 1:CR | $3b$ | $2b$ | $2b$  |
|      | $2b$ | $2b$ | $b+a$ |
|      | $B$  | $2b$ | $b$   |

|            |        |       |       |
|------------|--------|-------|-------|
| <b>1:D</b> | $2b+a$ | $a+b$ | $b+a$ |
|            | $b$    | $b$   | $a$   |
|            | $b$    | $2b$  | $b$   |

**C**

|             |             |             |            |
|-------------|-------------|-------------|------------|
| <b>3:D</b>  | <b>2:CL</b> | <b>2:CR</b> | <b>2:D</b> |
| <b>1:CL</b> | $2b$        | $b$         | $b$        |
|             | $b$         | $b$         | $a$        |
|             | $b+a$       | $2b+a$      | $b+a$      |
| <b>1:CR</b> | $2b$        | $b$         | $b$        |
|             | $2b$        | $2b$        | $b+a$      |
|             | $A$         | $b+a$       | $a$        |
| <b>1:D</b>  | $b+a$       | $a$         | $a$        |
|             | $b$         | $b$         | $a$        |
|             | $a$         | $b+a$       | $a$        |

Figure 1

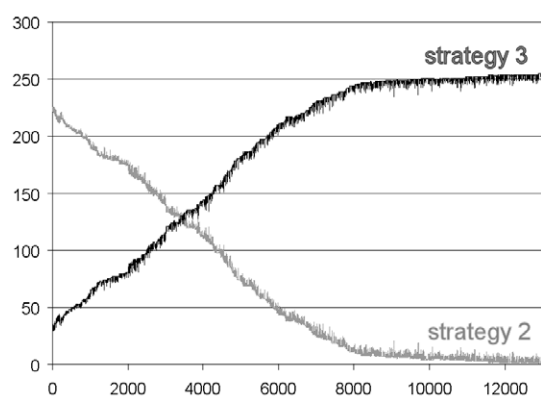


Figure 2

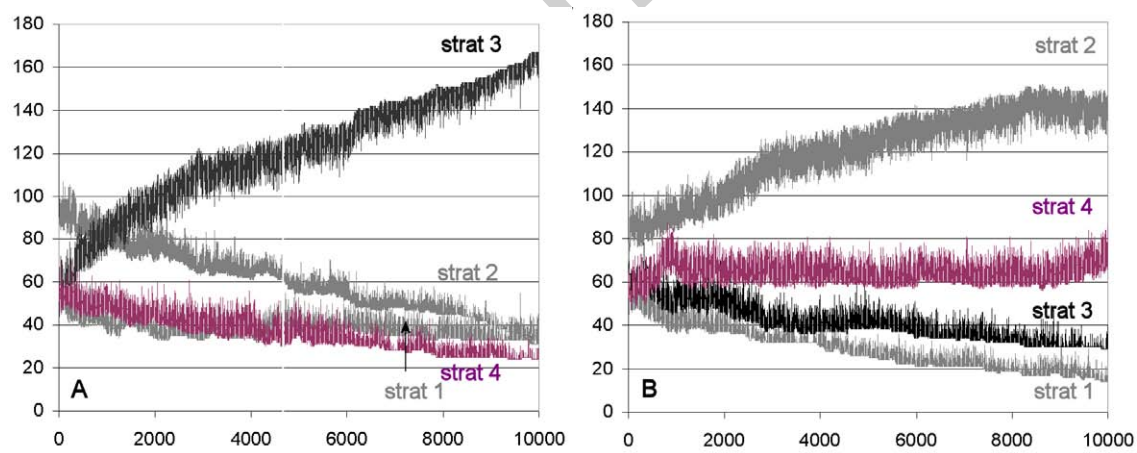




Figure 3

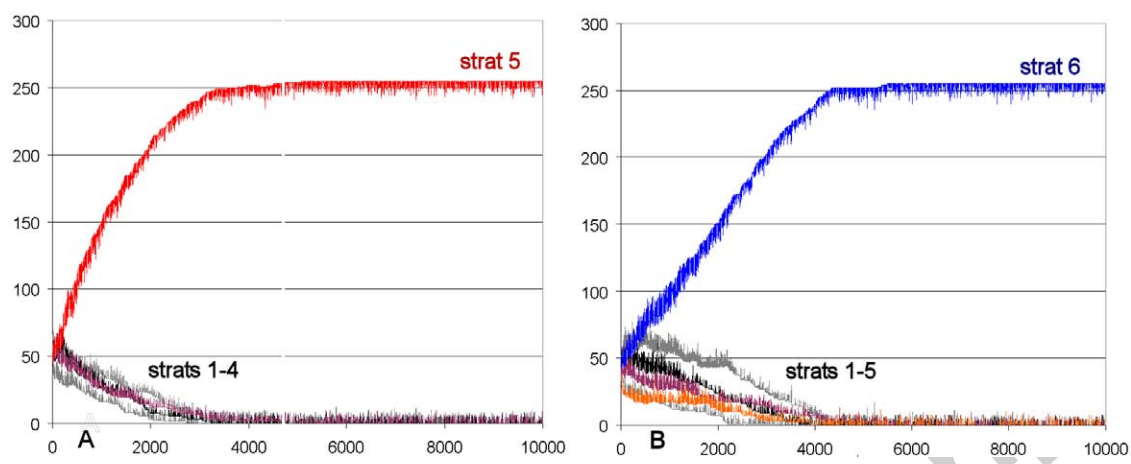


Figure 4

