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THE SUCCESS OF COOPERATIVE STRATEGIES IN THE ITERATED PRISONER'S DILEMMA AND THE CHICKEN GAME

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Abstract. The prisoner's dilemma has evolved into a standard game for analyzing the success of cooperative strategies in repeated games. With the aim of investigating the behavior of strategies in some alternative games we analyzed the outcome of iterated games for both the prisoner's dilemma and the chicken game. In the chicken game, mutual defection is punished more strongly than in the prisoner's dilemma, and yields the lowest fitness. We also ran our analyses under different levels of noise. The results reveal a striking difference in the outcome between the games. Iterated chicken game needed more generations to find a winning strategy. It also favored nice, forgiving strategies able to forgive a defection from an opponent. In particular the well-known strategy tit-for-tat has a poor successrate under noisy conditions. The chicken game conditions may be relatively common in other sciences, and therefore we suggest that this game should receive more interest as a cooperative game from researchers within computer science.

Key words. Game theory, prisoner's dilemma, chicken game, noise, tit-for-tat

1. Introduction. Within computer science, biology, social and economic sciences the issue of cooperation between individuals in an evolutionary context is widely discussed. An evolutionary context means some conflict of interest between the participants preferrably modeled in a game theoretical context using conflicting games. A simple, but frequently used, game model is between two participants each with two choices, either to cooperate or to defect (a $2*2$ matrix game) played once or repeated. In multi agent systems iterated games have become a popular tool for analyzing social behavior and cooperation based on reciprocity ([3, 5, 4, 9]). By allowing games to be played several times and against several other strategies a "shadow of the future", i. e. a non-zero probability for the agents to meet again in the future, is created for the current game. This increases the opportunity for cooperative behavior to evolve (e.g., [4]). A collection of different models of cooperation and altruism was discussed in Lehmann and Keller [14].

Most iterative analyses on cooperation have focused on the payoff environment defined as the prisoner's dilemma (PD) ([5, 9, 13, 20]). In terms of payoffs, a PD is defined when $T > R > P > S$, where R = reward, S = sucker, T = temptation and P = punishment. It should also hold that $2R > T + S$ according to table 1.1a. The second condition means that the value of the payoff, when shared in cooperation, must be greater than it is when shared by a cooperator and a defector. Because it pays more to defect, no matter how the opponent chooses to act, an agent is bound to defect, if the agents are not deriving advantage from repeating the game. If $2R < T + S$ is allowed there will be no upper limit for the value of the temptation. However, there is no definite reason for excluding this possibility. Carlsson and Johansson [11] argued that Rapoport and Chammah [23] introduced this constraint for practical more than theoretical reasons. PD belongs to a class of games where each player has a dominating strategy of playing defect in the single play PD.

Chicken game (CG) is a similar but much less studied game than PD, but see Tutzauer et al. [26] for a recent study. CG is defined when $T > R > S > P$, i. e. mutual defection is punished more in the CG than in the PD. In the single-play form, the CG has no dominant strategy (although it has two Nash equilibria in pure strategies, and one mixed equilibrium), and thus no expected outcome as in the PD [16]. Together with the generous chicken game (GCG), also called the battle of sexes [17] or coordination game, CG belongs to a class of games where neither player has a dominating strategy. For a GCG, playing defect increases the payoff for both of them, unless the other agent also plays defect ($T > S > R > P$).

In table 1.1b, R and P are assumed to be fixed to 1 and 0 respectively. This can be obtained through a two steps reduction where all variables are first subtracted by P and then divided by $R - P$. This makes it possible to describe the games with only two parameters $S' = (S - P)/(R - P)$ and $T' = (T - P)/(R - P)$. In fact we can capture all possible $2x2$ games in a two-dimensional plane.

In figure 1.1 the parameter space for PD, CG and GCG defined by S' and T', is shown. $T' = 1$ marks a dividing line between conflict and cooperation. $S' = 0$ marks the line between CG and PD. $T' < 1$ means that playing cooperate (R) is favored over playing defect (T) when the other agent cooperates. This prevents an

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Table 1.1

Pay-off matrices for 2∗2 games where R = reward, S = sucker, T = temptation and P = punishment. In b the four variables R, S, T and P are reduced to two variables $S' = (S - P)/(R - P)$ and $T' = (T - P)/(R - P)$

a	Cooperate	Defect	b	Cooperate	Defect
Cooperate	R	S	Cooperate	1	$(S-P)/(R-P)$
Defect	T	P	Defect	$(T-P)/(R-P)$	0

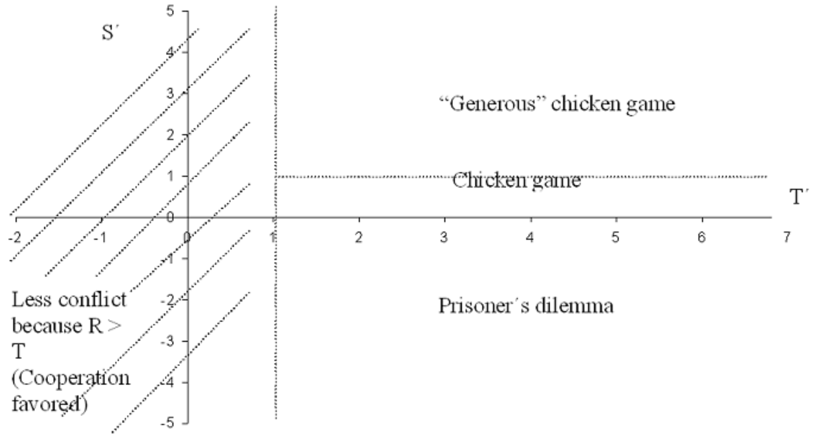

Fig. 1.1. *The areas covered by three kinds of conflicting games in a two-dimensional plane: prisoner's dilemma, chicken game and generous chicken game*

agent from being "selfish" in a surrounding of cooperation. Conflicting games are expected when $T' > 1$ because of better outcome playing temptation (T).

In an evolutionary context, the payoff obtained from a particular game represents the change in fitness (reproductive success) of a player. Maynard Smith [18] describes an evolutionary resource allocation within a $2x2$ game as a hawk and dove game. In the matrices of table 1.1 a hawk constitutes playing D, and a dove constitutes playing C. A hawk gets all the resources playing against a dove. Two doves share the resource whereas two hawks escalate a fight about the resource. If the cost of obtaining the resource for the hawks is greater than the resource there is a CG, otherwise there is a PD. In a generous CG (not a hawk and dove game) more resources are obtained for both agents when one agent defects compared to both playing cooperate or defect.

Recent analyses have focused on the effects of mistakes in the implementation of strategies. In particular, such mistakes, usually called noise, may allow evolutionary stability of pure strategies in iterated games [9]. Two separate cases are generally considered: the trembling hand noise and misinterpretations. Within the trembling hand noise ([24, 4]) a perfect strategy would take into account that agents occasionally do not perform the intended action[1]. In the misinterpretations case an agent may not have chosen the "wrong" action. Instead it is interpreted as such by at least one of its opponents, resulting in agents keeping different opinions about what happened in the game. This introduction of mistakes represents an important step, as real biological systems as well as computer systems will usually involve uncertainty at some level.

Here, we study the behavior of strategies in iterated games within the prisoner's dilemma and chicken game payoff structures, under different levels of noise. We first give a background to our simulations, including a round robin tournament and a characterization of the strategies that we use. We then present the outcome of iterated population tournaments, and discuss the implications of our results for game theoretical studies on the evolution of cooperation.

[1]In this metaphor an agent chooses between two buttons. The trembling hand may, by mistake, cause the agent to press the wrong button

2. Games, Strategies, and Simulation Procedures.

2.1. Games. A game can be modeled as a strategic or an extensive game. A strategic game is a model of a situation in which each agent chooses his plan of action once and for all, and all agents' decisions are made simultaneously while an extensive game specifies the possible orders of events. The strategic agent is not informed of the plan of action chosen by any other agent while an extensive agent can consider its plan of action whenever a decision has to be made. All the agents in our analyses are strategic. All strategies may affect the moves of the other agent, i. e. to play C or D, but not the payoff value, so the latter does not influence the strategy. The kind of games that we simulate here have been called ecological simulations, as distinguished from evolutionary simulations in which new strategies may arise in the course of the game by mutation ([3]). However, ecological simulations include all components necessary for the mimicking of an evolutionary process: variation in types (strategies), selection of these types resulting from the differential payoffs obtained in the contests, and differential propagation of strategies over generations. Consequently, we find the distinction between ecological and evolutionary simulations based on the criteria of mutation rather misleading.

The PDs and CGs that we analyze are repeated games with memory, usually called iterated games. In iterated games some background information is known about what happened in the game up to now. In our simulation the strategies know the previous moves of their antagonist[2]. In all our simulations, interactions among players are pair-wise, i. e. a player interacts with only one player at a time

2.2. Nice and Mean Strategies. Axelrod ([1, 5, 2, 3]) categorized strategies as nice or mean. A nice strategy never plays defection before the other player defects, whereas a mean strategy never plays cooperation before the opponent cooperates. Thus the nice and mean terminology describes an agent's next move.

According to the categorization of Axelrod Tit-for-tat, TfT, is a nice strategy, but it could as well be regarded as a repeating strategy. Another category of strategies is a group of forgiving strategies consisting of Simpleton, Grofman, and Fair. They can, unlike TfT, avoid getting into mutual defection by playing cooperate. If the opponent does not respond to this forgiving behavior they start to play defect again. Finally we separate a group of revenging strategies, which retaliate a defection at some point of the game with defection for the rest of the game. Friedman and Davis belong to this group of strategies.

The principle for the categorization of strategies into nice and forgiving against defecting strategies, which use threats and punishments, is unclear. For instance, why is TfT not just treated as a strategy repeating the action of the other strategy instead?

2.3. Generous and Greedy Strategies. One alternative way of categorizing strategies is to group them together as being generous, even-matched, or greedy ([11, 10]). If a strategy more often plays as a sucker, n_S, than playing temptation, n_T, then it is a generous strategy $n_S > n_T$. An even-matched strategy has $n_S \approx n_T$ and a greedy strategy has $n_S < n_T$ where n_S and n_T are the proportion an agent plays sucker and temptation, respectively.

Boerlijst, et al [8] uses a similar categorization into good or bad standings. An agent is in good standing if it has cooperated in the previous round or if it has defected while provoked, i. e., if the agent is in good standing it should not be greedy unless the other agent was greedy the round before. In every other case of defection the agent is in bad standing, i. e. it tries to be greedy. The generous and greedy categorization uses a stable approach, a once and for all categorization[3], contrary to the more dynamic good and bad standing dealing with what happened in the previous move.

The stable approach of the generous and greedy categorization makes it easier to analyze this model. The basis of the partition is that it is a zero-sum game at the meta-level in that the sum of proportions of the strategies n_S must equal the sum of the strategies n_T. In other words, if there is a generous strategy, then there must also be a greedy strategy.

The classification of a strategy can change depending on the surrounding strategies. Let us assume we have the following four strategies:

- Always Cooperate (AllC) has 100 per cent co-operate $n_R + n_S$ when meeting another strategy. AllC will never act as a greedy strategy.
- Always Defect (AllD) has 100 percent defect $n_T + n_P$ when meeting another strategy. AllD will never act as a generous strategy.

[2]One of the strategies, Fair, also remembers its own previous moves
[3]For a certain set of strategies

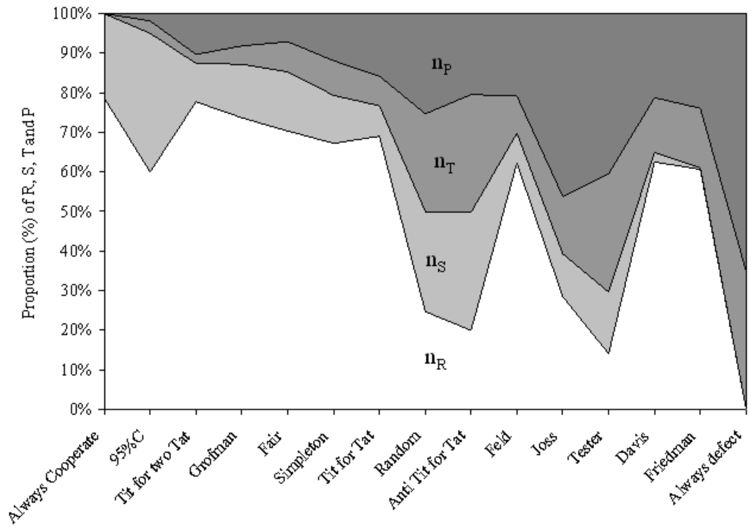

Fig. 2.1. *Proportions of R, S, T and P for different strategies. There is a generous strategy if $n_S > n_T$ and a greedy strategy if $n_S < n_T$*

- Tit-for-tat (TfT) always repeats the move of the other contestant, making it a repeating strategy. TfT naturally entails that $n_S \approx n_T$.
- Random plays cooperate and defect approximately half of the time each. The proportions of n_S and n_T will be determined by the surrounding strategies.

Random will be a greedy strategy in a surrounding of AllC and Random, and a generous strategy in a surrounding of AllD and Random. Both TfT and Random will behave as an even-matched strategy in the presence of only these two strategies as well as in a surrounding of all four strategies, with AllC and AllD participating in the same proportions. All strategies are even-matched when there is only a single strategy left.

The strategies used in our iterated prisoner's dilemma (IPD) and iterated chicken game (ICG), in all 14 different strategies plus playing Random, are presented in table 2.1. AllC, AllD and Random do not need any memory function at all because they always do the same thing (which for Random means always randomize). TfT and ATfT need to look back one move because they repeat or reverse the move of its opponent. Most of the other strategies also need to look back one move but may respond to defection or show forgiveness.

AllC definitely belongs to a group of generous strategies and so do 95% Cooperate (95%C), tit-for-two-tats (Tf2T), Grofman, Fair, and Simpleton, in this specific environment.

The even-matched group of strategies includes TfT, Random, and Anti-tit-for-tat (ATfT).

Within the group of greedy strategies, Feld, Davis, and Friedman belong to a smaller family of strategies doing more co-operation moves than Random, i. e. having significantly more than 50 % R or S. An analogous family consists of Joss, Tester, and AllD. These strategies co-operate less frequently than does Random.

What will happen to a particular strategy depends both on the surrounding strategies and on the characteristics of the strategy. For example, AllC will always be generous while 95%C will change to a greedy strategy when these two are the only strategies left. The described relation between strategies is independent of what kind of game is played, but the actual outcome of the game is related to the payoff matrix.

2.4. Simulation Procedures. The set of strategies used in our first simulation includes some of Axelrod's original strategies and a few, later reported, successful strategies. Of course, these strategies represent only a very limited number of all possible strategies. However, the emphasis in our work is on differences between IPD and ICG. Whether there exists a single "‘best of the game"’ strategy is outside the scope of our analyses.

Mistakes in the implementation of strategies (noise) were incorporated by attaching a certain probability p between 0.02 and 20% to play the alternative action (C or D), and a corresponding probability $(1 - p)$ to play the original action.

TABLE 2.1
Description of the different strategies used in the first simulation (see section 3.1)

Strategy	*First move*	*Description*
AllC	C	Cooperates all the time
95%C	C	Cooperates 95% of the time
Tf2T	C	tit-for-two-tats, Cooperates until its opponent defects twice, and then defects until its opponent starts to cooperate again
Grofman	C	Cooperates if R or P was played, otherwise it cooperates with a probability of 2/7
Fair	C	A strategy with three possible states, - 'satisfied' (C), 'apologizing' (C) and 'angry' (D). It starts in the satisfied state and cooperates until its opponent defects; then it switches to its angry state, and defects until its opponent cooperates, before returning to the satisfied state. If Fair accidentally defects, the apologizing state is entered and it stays cooperating until its opponent forgives the mistake and starts to cooperate again
Simpleton	C	Like Grofman, it cooperates whenever the previous moves were the same, but it always defects when the moves differed (e.g.S)
TfT	C	Tit-for-tat. Repeats the moves of the opponent
Feld	C	Basically a tit-for-tat, but with a linearly increasing (from 0 with 0.25% per iteration up to iteration 200) probability of playing D instead of C
Davis	C	Cooperates on the first 10 moves, and then, if there is a defection, it defects until the end of the game
Friedman	C	Cooperates as long as its opponent does so. Once the opponent defects, Friedman defects for the rest of the game
ATfT	D	Anti-tit-for-tat. Plays the complementary move of the opponent
Joss	C	A TfT-variant that cooperates with a probability of 90%, when opponent cooperated and defects when opponent defected
Tester	D	Alters D and C until its opponent defects, then it plays a C and TfT
All D	D	Defects all the time

Our population tournament involves two sets of analyses. In the first set, the strategies are allowed to compete within a round robin tournament with the aim of obtaining a general evaluation of the tendency of different strategies to play cooperate and defect. In a round robin tournament, each strategy is paired once with all other strategies plus its twin. The results from the round robin tournament are used within the population tournament but will not be presented here (for the results see [10]). In the second set, the competitive abilities of strategies in iterated population tournaments were studies within the IPD and the ICG. We also conducted a second simulation of the IPD and the ICG where two sets of strategies were used. We used the strategies in figure 2.2 represented by finite automata [15]. The play between two automata is a stochastic process where all finite memory strategies can be represented by increasingly complicated finite automata. Memory-0 strategies, like AllC and AllD, do not involve any memory capacity at all. If the strategy in use only has to look back at one draw, there is a memory-1 strategy (a choice between two circles dependent of the other agent's move). All the strategies in figure 2.2 belong to memory-0 or memory-1 strategies.

Both sets of strategies include AllD, AllC, TfT, ATfT and Random. In the first set of strategies, the cooperative-set five AllC variants (100, 99.99, 99.9, 99 and 90% probability of playing C) are added. In the second set of strategies, the defective-set the corresponding five AllD variants (100, 99.99, 99.9, 99 and 90%

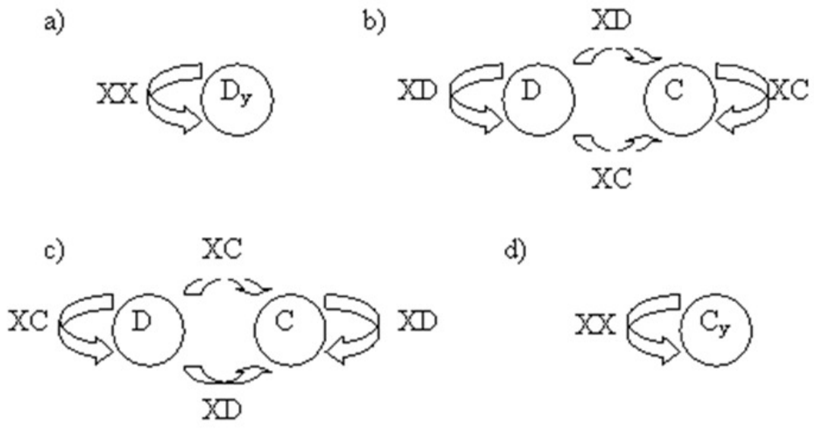

Fig. 2.2. *a) AllD (and variants) b) TfT c) ATfT d) AllC (and variants). On the transition edges, the left symbol correspond to an action done by a strategy against an opponent performing the right symbol, where an X denotes an arbitrary action. Y in Cy and Dy denotes a probability factor for playing C and D respectively*

probability of playing D) are added. C_y and D_y in figure 2.2 show a probability factor y 100, 99.99, 99.9, 99, 90% or for the Random strategy 50% for playing C and D respectively.

3. Population Tournament With Noise.

3.1. First Simulation. We evaluated the strategies in table 2.1 by allowing them to compete within a round robin tournament.

To obtain a more general treatment of IPD and ICG, we used several variants of payoff matrices within these games, based on the general matrix of table 3.1. In this matrix, C stands for cooperate; D for defect and q is a cost variable.

Table 3.1
Payoff values used in our simulation. q is a cost parameter. $0 < q < 0.5$ defines a prisoner's dilemma game, while $q > 0.5$ defines a chicken game

	Player 2	
Player 1	C	D
C	1.5	1
D	2	1.5 - q

The payoff for a D agent playing against a C agent is 2, while the corresponding payoff for a C agent playing against a D agent is 1, etc. Two C agents share the resource and get 1.5 each.

The outcome of a contest with two D agents depends on q. For $0 < q < 0.5$, a PD game is defined, and for $q > 0.5$ we have a CG. Simulations were run with the values for $(1.5 - q)$ set to 1.4 and 1.1 for PD, and to 0.9, 0.6, and 0.0 for the CG (these values are chosen with the purpose to span a wide range of the games but are otherwise arbitrarily chosen). We also included Axelrod's original matrix Ax ($R = 3, S = 0, T = 5$ and $P = 1$) and a compromise dilemma game CD ($R = 2, S = 2, T = 3$ and $P = 1$). A CD is located on the borderline between the CG area and the generous CG area. In the discussion part we also compare the mentioned strategies with a coordination game CoG ($R = 2, S = 0, T = 0$ and $P = 1$), the only game with $T' < 1$. CoG is included as a reference game and does not belong to the conflicting games. In figure 3.1 all these games are shown within the two-dimensional plane. The CD is closely related to the chicken game and CoG is a game with two Nash equilibria, playing (C,C) or playing (D,D) (see also Johansson et

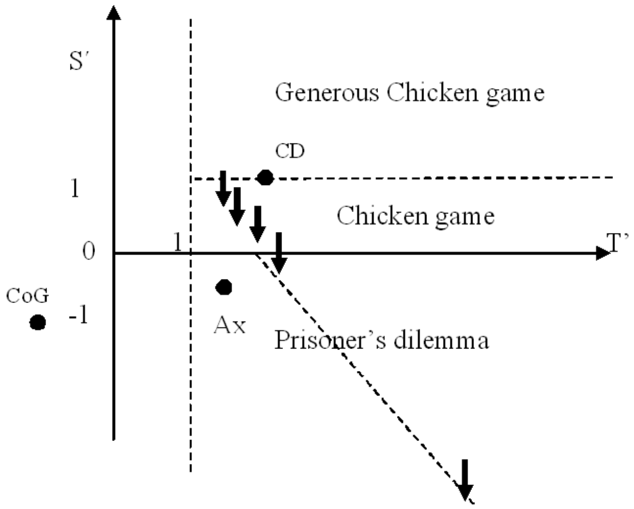

Fig. 3.1. *The different game matrices represented as dots in a 2-dimensional diagram. CoG is the coordination game, CD the compromise dilemma and Ax is the original Axelrod game. The unmarked dots represent 0.0, 0.6, 0.9, 1.1 and 1.4 from upper left to lower right*

al. [12]). Each game in the tournament was played on average 100 times (randomly stopped)[4] and repeated 5000 times.

In the second part of the simulation, strategies were allowed to compete within a population tournament for the iterated games. These simulations were based on the same payoff matrices for IPD and ICG as in the initial round robin tournament. Based on the success in the single round-robin tournaments, strategies were allowed to reproduce copies into the next round robin tournament, creating a population tournament, i. e. a quality competition in the round-robin tournament (make a good score) is transformed to an increased number of copies in the population tournament. Each of the fifteen strategies starts with 100 copies resulting in a total population of 1500. The number of copies for each strategy changes, but the total of 1500 copies remains constant. The proportions of the different strategies propagated into a new generation were based on the payoff scores obtained in the preceding round-robin tournament. A given strategy interacts with the other strategies in the proportions that they occur in their global population. The games were allowed to continue until a single winning strategy was identified, i. e. the whole population consists of the same strategy, or until the number of generations reached 10,000. In most of the simulations, a winning strategy was found before reaching this limit.

Also, if a pure population of agents with the random strategy are allowed to compete with each other in a population game, a single winning strategy will be found after a number of generations, i. e. there are small simulation variations between different agents in their actual play of C and D moves. As seen in figure 3.2, with increased total population size of agents the number of generations for finding a winning strategy increases. This almost linear increase ($r = 0.99$) is only marginally dependent of what game is played.

Randomized strategies with 100 individuals are according to figure 3.2 supposed to halt, i. e. all 1500 individuals belong to the same initial strategy, after approximately 2800 generations in a population game. Which strategy that wins will vary between the games. There are two possible kinds of winning strategies: pure strategies that halt, and mixed strategies (two or more pure strategies) that do not halt. If there is an active choice of a pure strategy it should halt before 2800 generations, because otherwise playing random could be treated as a winning pure strategy. There is no reason to believe that a single strategy winner should be found by extending the simulation beyond 10000 generations. If there exists a pure solution, this solution should turn up much earlier.

The effect of uncertainty (noise) in the choice of actions (C or D) by the agents within the tournaments was analyzed by repeating the tournaments in environments of varying levels of noise. Tournaments were run

[4]If an agent knows exactly or with a certain probability when a game will end, it may use such information to improve its behavior. Because of this, the length of the games was determined probabilistic, with an equal chance of ending the game with each given move (see also [1])

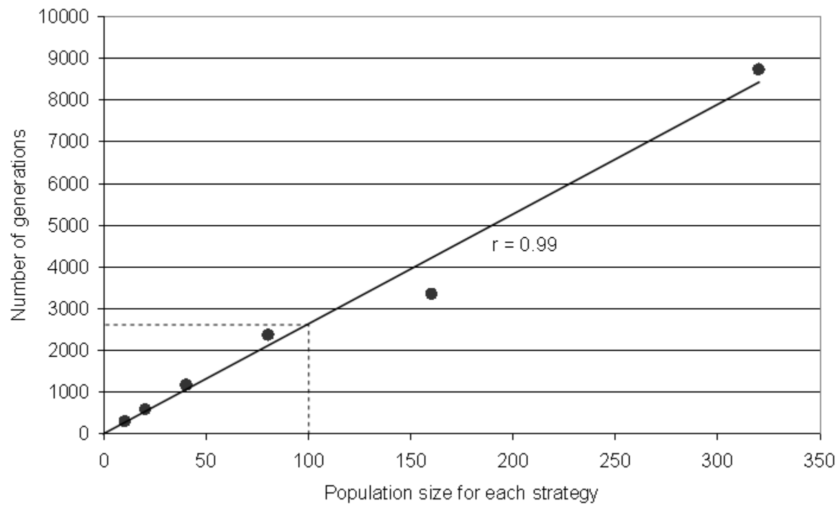

FIG. 3.2. *Number of generations for finding a winning strategy among 15 random strategies with a varying population size*

at 0, 0.02, 0.2, 2, and 20% noise. The probability of making a mistake was neither dependent on the sequence of behaviors up to a certain generation, nor on the identity of the player. Noise will affect the implementation of all strategies except for the strategy Random. We focused on three different aspects when comparing the IPDs and ICGs, which will be further analyzed in the discussion part:

1. The number of generations for finding a winning strategy.
2. Differences in robustness for the investigated strategies.
3. The behavior of the, generally regarded, cooperative strategy TfT in IPD and ICG.

3.2. Second Simulation. To obtain a more general treatment of IPD and ICG, we used several variants of payoff matrices within these games, based on the general matrix of table 3.2.

TABLE 3.2
A payoff matrix for PD and CG. C stands for cooperate, D for defect, and s_1 and s_2 are cost variables. If $s_1 > 1$ it is a PD. If $s_1 < 1$ it is a CG

	Cooperate (C)	Defect (D)
Cooperate (C)	1	1-s_1
Defect (D)	1+s_2	0

In the first set of simulations we investigated the successfulness of the agents using different strategies (one strategy per agent) in a round-robin tournament. Since this is independent of the actual payoff value, the same round-robin tournament can be used for both IPD and ICG. Every agent was paired with all the other agents plus a copy of itself. Every meeting between agents in the tournament was repeated on average 100 times (randomly stopped) and played for 5000 times.

The result from the two-by-two meetings between agents using different strategies in the round robin tournament was used in a population tournament. The tournament starts with a population of 100 agents for each strategy, making a total population of 900. The simulation halts when there is a winning strategy (all 900 agents use the same strategy) or when the number of generations exceeds 10.000. Agents are allowed to change strategy and the population size remains the same during the whole contest. For the IPD the following parameters were used: $s_1 \in \{1.1, 1.2 \ldots 2.0\}$ and $s_2 \in \{0.1, 0.2 \ldots 1.0, 2.0\}$, making a total of 110 different games. For the ICG games with parameter settings $s_1 \in \{0.1, 0.2 \ldots 0.9\}$ and $s_2 \in \{0.1, 0.2 \ldots 1.0, 2.0\}$ a total of 99 different games were run. Each game is repeated during 100 plays and the average success is calculated for each strategy. For each kind of game there is both the cooperative set and the defective set explained in section 2.4.

4. Results.

4.1. First Simulation. In figure 4.1 and figure 4.2 the success of individual strategies in IPD, ICG and CD population games at no noise and 0.2% of noise are shown. The repeating strategy TfT is represented by a solid line, the generous strategies Simpleton, Grofman, and Fair by dashed lines, and the greedy strategies Friedman and Davis by dotted lines.

In the IPD games TfT, Friedman and Davis are the most successful with no noise (figure 4.1), while TfT, Grofman, Fair and Friedman are the most successful with 0.2% noise (figure 4.2). For the other levels of noise (not shown in figures) TfT, and for Axelrod's matrix also Tf2T, is dominating with 0.02%. With 2% noise Davis and TfT dominates, and finally AllD and Friedman are the dominating strategies with 20% noise.

At no noise all three groups of strategies are approximately equally successful in ICG (figure 4.1), with a minor advantage for the generous strategies Simpleton, Grofman, and Fair. This advantage increases with increasing noise. The greedy strategies Friedman and Davis disappear at 0.02% noise and TfT at 0.2% noise (figure 4.2) leaving the generous strategies alone at 0.2% and 2% noise. At 20% noise AllD supplements the set of successful strategies.

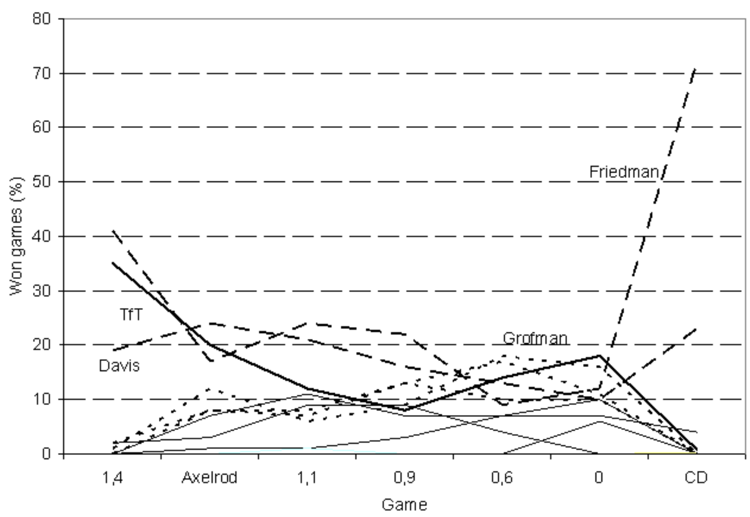

Fig. 4.1. *Percentage of runs won by strategies in the population games for different chicken games (0.9, 0.6, 0), prisoners' dilemmas (1.4, Ax, 1.1) and the compromise dilemma with 0% noise*

The greedy strategies Friedman and Davis completely outperform Simpleton, Grofman, Fair and TfT strategies in CD. With increasing noise ATfT (0.2-20% noise) and AllD (20% noise) become more successful as part of a mixed set of strategies, because CD does not find a single winner (Figure 10).

Finally, in CoG Tf2T and TfT are dominating with 0% noise. Tf2T together with AllC and Grofman constitute all the winning strategies with 0.02%, 0.2% and 2% noise. 95%C is the only winner with 20% noise.

With increased noise the group of Simpleton, Grofman, and Fair become more and more successful in ICG up to and including 2% noise. When noise is introduced, IPDs favor the repeated TfT. With increased noise the greedy Friedman and Davis disappears for both ICG and IPD. Finally, with 20% noise AllD is the dominating strategy. More and more defecting strategies will dominate with increasing noise in IPD. Finally in CD the greedy strategies Friedman and Davis dominates. In contrast to IPD and CD cooperating and generous strategies dominate in ICG which makes the ICG the best candidate for finding robust strategies.

On average there was 80% accordance (for all levels of noise) between winning strategies in different ICG, i. e. four out of five strategies being the same. In the IPD there was a discrepancy with only on average 35% of the winning strategies being the same. The performance of the 0.4 and Ax matrices are similar within the ICG. This was especially notable for both matrices without noise (on average 75%) and for the 0.4 matrices with 2 and 20% noise (on average 55%).

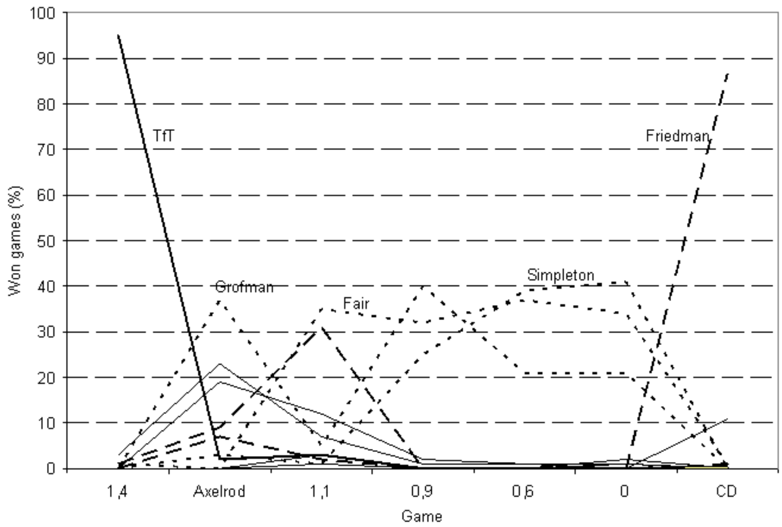

Fig. 4.2. *Percentage of runs won by strategies in the population games for different chicken games (0.9, 0.6, 0), prisonerś dilemmas (1.4, Ax, 1.1) and the compromise dilemma with 0.2% noise*

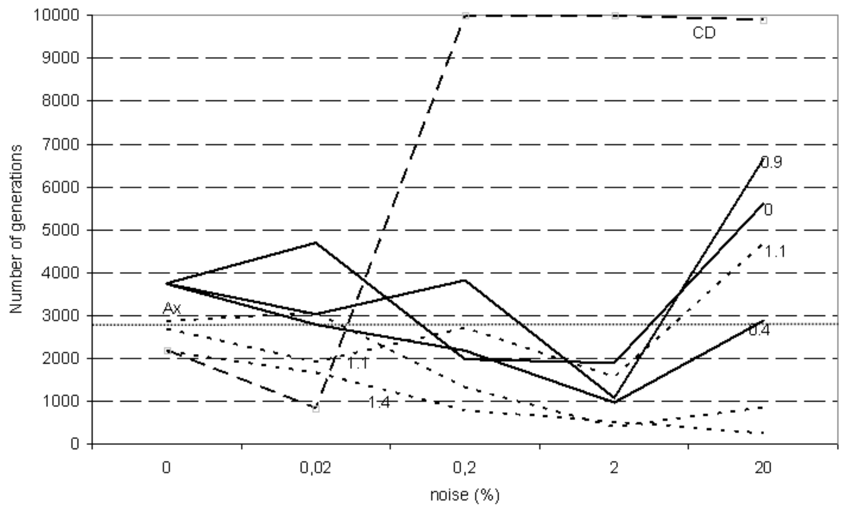

Fig. 4.3. *Number of generations for finding a winning strategy in chicken games, prisonerś dilemmas and compromise dilemma at different levels of noise*

In figure 4.3, the number of generations needed to find a winning strategy is plotted for different level of noise. The dotted line shows the expected generations (2800) for competing Random strategies mentioned earlier. At 0 or low levels of noise more generations are needed in the ICG for finding a winner than in IPD. The lowest numbers of generations are needed with 2% of noise and the highest with 0% and 20% noise. There is no single strategy winner for the CD game with 0.2% noise and above

In summary; coordination games give mutual cooperation the highest results, which favors nice, but to a less extent too forgiving, strategies. Compared to the ICG, IPD is less punishing towards mutual defection,

Table 4.1
The difference between pure and mixed-strategies in IPD and ICG. For details see text

	IPD		ICG	
	Cooperative set	Defective set	Cooperative set	Defective set
Pure strategies	TfT 78% AllD 20%	TfT 75% AllD 20%	TfT 3%	TfT 2%
Mixed strategies	none	none	2-strat 61% 3-strat 33%	2-strat 69% 3-strat 24%

which allows repeating and greedy strategies to become more successful. Finally in the compromise dilemma, where playing the opposite to the opponent is favored, greedy and/or a mixture of different strategies are favored. With increased noise (2% or below), generous strategies become more and more successful in ICG while repeating and greedy strategies are more successful in IPD.

4.2. Second Simulation. In a surrounding of a cooperative or a defective set of strategies a major difference between pure and mixed strategies for IPD and ICG are shown in table 4.1. IPD has no successful mixed strategies at all, while ICG favors mixed-strategies for an overwhelming majority of the games. Some details not shown in table 4.1 are discussed below.

For the cooperative set there is a single strategy winner after on average 167 generations. TfT wins 78% of the plays and is dominating in 91 out of 110 games[5]. AllD is dominating in the rest of the games and wins 20% of the plays.

For the defective-set there is a single strategy winning in 47 generations on average. TfT is dominating 84 games, AllD 21 games and 99.99D, playing D 99.99% of the time, 5 games out of 110 games in all. TfT wins 75% of the plays, AllD 20% and 99.99D 4%.

In the cooperative-set there are two formations of mixed strategies winning most of the games; one with two strategies and the other with three strategies involved. This means that when the play was finished after 10000 generations not a single play could separate these strategies finding a single winner. The two-strategy set ATfT and AllD wins 61% of the plays and the three-strategy set ATfT, AllD and AllCtot wins 33% of the plays. AllCtot means that one and just one of the strategies AllC, 99.99C, 99.9C, 99C or 90C is the winning strategy. For 3% of the games there was a single TfT winner within relatively few generations (on average 754 generations).

In the defective-set there is the same two formations winning most of the games. ATfT + AllDtot wins 69% of the plays and ATfT + AllC + AllDtot wins 24% of the plays. AllDtot means that one and just one of the strategies AllD, 99.99D, 99.9D, 99D or 90D is the winning strategy. TfT is a single winning strategy in 2% of the plays, which needs on average 573 generations before winning a play.

In the C-variant set all AllC variants are generous and TfT is even matched. AllD, ATfT and Random are all greedy strategies. In the D-variant set all AllD variants are greedy and TfT is still even-matched. AllC, ATfT and Random are now representing generous strategies.

In the IPD the even-matched TfT is a dominating strategy in both the C- and D-variant set with the greedy AllD as the only primary alternative. So the IPD will end up being a fully cooperative game (TfT) or a fully defecting game (AllD) after relatively few generations. This is the case both for the C-variant set and, within even fewer generations, for the D-variant set.

In ICG there is instead a mixed solution between two or three strategies. In the C-variant ATfT and AllD form a greedy two-strategy set[6]. In the three-strategy variant the generous AllCtot join the other two. In all, generous strategies only constitute about 10% of the mixed strategies. In the D-variant the generous ATfT forms various strategy sets with the greedy AllDtot.

5. DISCUSSION. In our investigation we found ICG to be a strong candidate for being the major cooperate game. ICG seems to facilitate cooperation as much as or even more than IPD, especially under noisy conditions. Axelrod regarded TfT to be a leading cooperative strategy, but in our investigation we found TfT

[5]A game is dominated by a certain strategy if it wins more than 50 out of 100 plays

[6]With just ATfT and AllD left ATfT will behave as a generous strategy even though it starts off as a greedy strategy in the C-variant environment

to have poor success under noisy conditions within ICG. These statements will be further addressed in the discussion below.

If it is true that more cooperating strategies are favored in ICG, we should also expect nice and forgiving strategies to be successful in this game. In the ICG, both players that play defect are faring the worst, which should favor generous strategies. Both ICG and coordination game favors nice, non-revenging, strategies, but unlike coordination game ICG may forgive a defection from the opponent. This makes ICG a primary candidate for being the main cooperative game, favoring both niceness and forgivingness.

Most studies today consider the IPD as a cooperative game where nice and forgiving strategies are successful. A typical winning strategy, like TfT, ends up as an agent playing cooperate all the time. There are contradictory arguments about cooperation within chicken games. The advantage of cooperation may be expected to be stronger, because the cost of defection is higher than in the prisoner's dilemma. Lipman [16] suggests that in ICG, mutual cooperation is less clearly the best outcome because there is no dominant strategy. Each agent prefers the equilibrium in which it defects and the other cooperates, but has no way to force the other agent to cooperate. A mixed strategy or a set of strategies, unlike a single dominant strategy, may favor mutual cooperation. With pure and mixed strategies we here refer to the set of strategies (played by individuals) winning the population tournament. A mixed strategy is a combination of two or more strategies from the given set of strategies i. e. an extended strategy set could include the former mixed strategy as a pure strategy.

In the normalized matrices stochastic memory-0 and memory-1 strategies are used. The main difference between IPD and ICG is best shown by the two strategies TfT and ATfT. TfT does the same as its opponent. This is a successful way of behaving if there is a pure-strategy solution because it forces the winning strategy to cooperate or defect, but not doing both. ATfT is doing very badly in IPD because it tries to jump between playing cooperate and defect.

In ICG we have a totally different assumption because a mixed-strategy solution is favored (at least in the present simulation). ATfT does the opposite as its opponent but cannot by itself form a mixed-strategy solution. It has to rely on other cooperative or defect strategies. In all different ICG ATfT is one of the remaining strategies, while TfT is only occasionally winning a play.

For a simple strategy setting like the cooperative and defective-set, ICG will not find a pure strategy winner at all but a mixture between two or more strategies, while IPD quickly finds a single winner.

Unlike the single play PD, which always favors defect, the IPD will favor playing cooperate. In CG the advantage of cooperation should be even stronger, because it costs more to defect compared to the PD, but in our simulation greedier strategies were favored with memory-0 and memory-1 strategies. We think this new paradox can be explained by a greater robustness of the chicken game. This robustness may be present if more strategies, like the strategies in the two other simulations, are allowed and/or noise is introduced. Robustness is expressed by two or more strategies winning the game instead of a single winner or by a more sophisticated single winner. Such a winner could be cTfT, Pavlov, or Fair in the presence of noise, instead of TfT. Also, with minor exceptions this is also true for noise between 0.02% and 20%.

An interesting exception to the higher success of cooperating strategies within ICG is the poor success under noisy conditions of TfT. The vulnerability of TfT to errors in the implementation of actions within the IPD is well known and has been discussed extensively ([3, 19, 4, 27, 7, 21, 22]). The even poorer ability of TfT to handle noise within the ICG, is however a novel finding. The classical description by Axelrod [3] of a successful strategy in a deterministic (non-noisy) environment is that it should be nice (not be the first to defect), provocable (immediately punish defection), forgiving (immediately reciprocate cooperation), and simple (easily recognizable). Obviously, under noisy conditions TfT either behaves less nice, provocable, forgiving, and simple, or these characteristics are of less value in the ICG. Axelrod and Dion [4] suggested that the difficulty for TfT to handle noise is an inherent consequence of generosity: vulnerability to exploitation. Errors in the implementation of strategies give rise to unconditional cooperation, which undercuts the effectiveness of simple and reciprocating strategies. It also introduces mutual defection among TfT players, reducing their obtained payoffs [22]. In the long run, the average payoffs of two interacting TfT players in a noisy environment converge to that of two interacting Random players [19]. Thus, the main problem for TfT in a noisy environment may be to cope with copies of itself.

A solution to the problem of noise for a strategy is to punish defection in the other player less readily than does TfT. This can be done either by not immediately responding to an opponent's defection or by avoidance of responding to the other player's defection after one has made an unintended defection [19]; see also [27]. Thus, some modified versions of TfT, Contrite tit-for-tat (CTfT) and generous tit-for-tat (GTfT) have proved to cope much better with noise than the original TfT ([27, 9]). Bendor [6] concludes that uncertainty sometimes affects nice strategies negatively but he also proposes that reciprocating but untrustworthy strategies may start to cooperate because of unintended actions.

Several attempts have been made to classify strategies according to their willingness to play cooperate and defect, respectively, the classical being Axelrod's [1] distinction between nice and mean strategies based on whether a strategy's first draw is cooperate or defect, respectively. Under noisy conditions, the static description of a strategy based on its behavior under non-noisy becomes more or less meaningless. Naturally, a nice strategy then becomes meaner, and a mean strategy becomes nicer, but the actual behavior is difficult to evaluate.

6. CONCLUSION. In our opinion, the discussion about the evolution of cooperative behavior has relied too heavily on analyses within the prisoner's dilemma context. The differences in the outcome of IPD and ICG shown in our study suggest that future game theoretical analyses on cooperation should explore alternative payoff environments. The chicken game was discussed as a special case within the general hawk and dove context by Maynard Smith [18], but for some reason subsequent game theoretical studies has almost exclusively focused on the prisoner's dilemma. This is unfortunate, since the chicken game appears to us to be a very interesting game in explaining the evolution of cooperative behavior. If we give the involved agents the ability to establish trust the difference between the two kinds of games are easier to understand. In the PD establishing credibility between the agents means establishing trust, whereas in CG, it involves creating fear, i. e. avoiding situations where there is too much to lose [25]. This makes ICG a strong candidate for being a major cooperate game together with IPD. We therefore hope that in future studies, more attention will be paid to the role of chicken games in the evolution of agents with cooperative behavior within multi agent systems.

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