Effective Choice in the Prisoner's Dilemma

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This is a "primer" on how to play the iterated Prisoner's Dilemma game effectively. Existing research approaches offer the participant limited help in understanding how to cope effectively with such interactions. To gain a deeper understanding of how to be effective in such a partially competitive and partially cooperative environment, a computer tournament was conducted for the iterated Prisoner's Dilemma. Decision rules were submitted by entrants who were recruited primarily from experts in game theory from a variety of disciplines: psychology, political science, economics, sociology, and mathematics. The results of the tournament demonstrate that there are subtle reasons for an individualistic pragmatist to cooperate as long as the other side does, to be somewhat forgiving, and to be optimistic about the other side's responsiveness.

INTRODUCTION

ITERATED PRISONER'S DILEMMA

This article is a "primer" on how to play the Prisoner's Dilemma game effectively.

International politics is just one of the arenas which offer numerous occasions of the Prisoner's Dilemma iterated for many moves. For example, between the United States and the Soviet Union there are aspects of the Prisoner's Dilemma in such sequences of events as arma-

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ments budgets, trade concessions, deployment of troops, and escalation in limited or proxy wars (see, for example, Snyder, 1971).

The distinguishing feature of the Prisoner's Dilemma is that in the short run, neither side can benefit itself with a selfish choice enough to make up for the harm done to it from a selfish choice by the other. Thus, if both cooperate, both do fairly well. But if one defects while the other cooperates, the defecting side gets its highest payoff, and the cooperating side is the sucker and gets its lowest payoff. This gives both sides an incentive to defect. The catch is that if both do defect, both do poorly. Therefore the Prisoner's Dilemma embodies the tension between individual rationality (reflected in the incentive of both sides to be selfish) and group rationality (reflected in the higher payoff to both sides for mutual cooperation over mutual defection). The payoff structure of each move in a typical Prisoner's Dilemma is given in Table 1.

The fact that interactions are repeated is very important to the dynamics of the situation. If the two sides knew that there would be only a single choice, there would be every incentive to defect, since no matter what the other player chooses, defection yields a higher payoff than cooperation. But actors often have ongoing relationships with both an informative history and an important future. Making effective choices in such an ongoing relationship requires insight into the structural implications of strategic interaction.

Suppose, for example, that in an interaction between the United States and the Soviet Union, both sides are following a strategy of TIT FOR TAT: cooperate initially, and thereafter cooperate if the other side cooperated last time and defect if the other side defected last time. This pair of strategies would lead to an unending series of mutual cooperation. But now suppose that one side or the other decided to make a minor change in its strategy to seek a slightly greater measure of success. One such change would be to cooperate 90% rather than 100% of the time after the other side has just cooperated. This change in strategy may seem promising, because it occasionally yields the highest possible payoff, while still punishing the other side for any defections it might undertake. In fact, as we shall see, this slight and seemingly advantageous variation on TIT FOR TAT actually performs much worse than the TIT FOR TAT strategy in a variety of settings, and it frequently leads to an uninterrupted series of unrewarding mutual defections.

Of course, the elegant formulation of an interaction as a Prisoner's Dilemma puts aside many vital features which make any actual event

TABLE 1
Payoff Matrix for Each Move of the Prisoner's Dilemma

		Column Player	
		Cooperate	Defect
Row Player	Cooperate	3,3	0,5
	Defect	5,0	1,1

(The payoff to the row player is given first in each pair of numbers.)

unique. Examples of what is left out by this formal abstraction include the possibility of messages to go along with the choices, the presence of third parties, the problems of implementing a choice, and uncertainty about the actual prior choice of the other side. The list could be extended indefinitely. Of course, no intelligent actor should make a choice without taking such complicating factors into account. The value of an analysis without them is that it can help the decision maker see some subtle features of the interaction, features which might otherwise be lost in the maze of complexities of the highly particular circumstances in which choice must actually be made. It is the very complexity of reality which makes the analysis of an abstract interaction so helpful as an aid to perception.

The Study of Effective Choice

Psychologists using experimental subjects have found that in the iterated Prisoner's Dilemma, the amount of cooperation attained and the specific pattern for attaining it depend on a wide variety of factors relating to the context of the game, the attributes of the individual players, and the relationship between the players. Since behavior in the game reflects so many important factors about people, it has become a standard way to explore questions in social psychology from the effects of Westernization in Central Africa (Bethlehem, 1975) to the existence (or nonexistence) of aggression in career-oriented women (Baefsky and Berger, 1974) and the differential consequences of abstract vs. concrete thinking styles (Nydegger, 1974). Just in the last 10 years, there have been over 350 articles on the Prisoner's Dilemma cited in

Psychological Abstracts. The iterated Prisoner's Dilemma has become the *E. coli.* of social psychology.[1]

Equally important as its use as an experimental test bed is its use as the conceptual foundation for models of important social processes. Richardson's model of the arms race is based on an interaction which is essentially a Prisoner's Dilemma played once a year with the budgets of the competing nations (Richardson, 1960; Zinnes, 1976: 33-440). Oligopolistic competition can also be modeled as Prisoner's Dilemma (Samuelson, 1973: 503-505). The ubiquitous problems of collective action to produce a collective good are analyzable as an n-person Prisoner's Dilemma (Hardin, 1971). Even vote trading has been modeled as a Prisoner's Dilemma (Riker and Brams, 1973). In fact, many of the best developed models of important political, social, and economic processes have the Prisoner's Dilemma as their foundation.

There is yet a third literature about the Prisoner's Dilemma. This is the literature which goes beyond the empirical questions of the laboratory or the real world, and instead uses the abstract game to analyze the features of some fundamental strategic issues, such as the meaning of rationality (Luce and Raiffa, 1957), choices which have externalities (Schelling, 1973), and cooperation with enforcement (Taylor, 1976).

Unfortunately, none of these three literatures on the Prisoner's Dilemma tells us much about how to play the game well. The experimental literature is not much help, because virtually all of it is based on analyzing the choices made by inexperienced players who are seeing the game for the first time. Their appreciation of the strategic subtleties is bound to be restricted. The choices of experienced economic and political elites are studied in some of the applied literature of Prisoner's Dilemma, but the evidence is of limited help, because of the relatively slow pace of most high level interactions and the difficulty of controlling for changing circumstances. All together, no more than a few dozen choices have been identified and analyzed this way. Finally, the abstract literature of strategic interaction usually studies variants of the iterated Prisoner's Dilemma designed to eliminate the dilemma itself by introducing changes in the game such as allowing interdependent choices (Howard, 1966; Rapoport, 1967) or putting a tax on defection (Tideman and Tullock, 1976; Clarke, 1978).

To learn more about how to choose effectively in an iterated Prisoner's Dilemma, a new approach is needed. Such an approach would have to draw on people who had a rich understanding of the strategic possi-

1. A helpful article reviewing the effects of programmed strategies is Oskamp (1971).

bilities. It would also have to take into account two important facts about strategic interaction in a non-zero sum setting. First, what is effective is likely to depend not only upon the characteristics of a particular strategy, but also upon the nature of the other strategies with which it must interact. The second point follows directly from the first. An effective strategy must be able at any point to take into account the history of the interaction as it has developed so far.

A computer tournament for the study of effective choice in the iterated Prisoner's Dilemma meets these needs. In a computer tournament, each entrant writes a program which embodies a decision rule to select the cooperative or noncooperative choice on each move. The program has available to it the history of the game so far, and may use this history in making a choice. Because the participants are recruited primarily from those who have written on game theory and especially the Prisoner's Dilemma, the entrants are assured that their decision rule will be facing rules of other experts. Such recruitment also guarantees that the state of the art is represented in the tournament.

Just such a tournament was conducted. The results contain some real surprises. These surprises in turn offer new insights into the questions of how to understand and how to cope with an environment which contains aspects of the Prisoner's Dilemma.

THE TOURNAMENT

The Winner

TIT FOR TAT, submitted by Professor Anatol Rapoport of the University of Toronto, won the Computer Tournament for the Iterated Prisoner's Dilemma. This simplest of all submitted programs turned out to be the best of the fourteen entries from economists, mathematicians, political scientists, psychologists, and a sociologist.

TIT FOR TAT starts with a cooperative choice, and thereafter does what the other player did on the previous move. This decision rule is probably the most widely known and most discussed rule for playing the Prisoner's Dilemma. It is easily understood and easily programmed. It is known to elicit a good degree of cooperation when played with humans (Oskamp, 1971). As an entry to a computer tournament, it has the desirable properties that it is not very exploitable and that it does well with its own twin. It has the disadvantage that it is too generous with the RANDOM rule, which was known by the participants to be entered in the tournament.

In addition, TIT FOR TAT was known to be a powerful competitor. In a preliminary tournament, TIT FOR TAT scored second place, and in a variant of that preliminary tournament, TIT FOR TAT won first place. All of these properties were known to most of the people designing programs for the Computer Prisoner's Dilemma Tournament, because they were sent copies of the description of a preliminary tournament. And not surprisingly, many of them used the TIT FOR TAT principle and tried to improve upon it.

The striking fact is that *none* of the more complex programs submitted were able to perform as well as the original, simple TIT FOR TAT.

This result contrasts with computer chess tournaments where complexity is obviously needed. For example, in the Second World Computer Chess Championships, the least complex program came in last (Jennings, 1978). It was submitted by Johann Joss of the Eidgenossishe Technische Hochschule of Zurich, Switzerland, who also submitted an entry to the Computer Prisoner's Dilemma Tournament. His entry to the Prisoner's Dilemma Tournament was the small modification of TIT FOR TAT which has already been mentioned. But his modification, like the others, just lowered the performance of the decision rule.

The Form of the Tournament

The tournament was run as a round robin so that each entry was paired with each other entry. As announced in the rules of the tournament, each entry was also paired with its own twin and with RANDOM, a program that randomly cooperates and defects with equal probability.

Each game consisted of exactly 200 moves. The payoff matrix for each move awards both players 3 points for mutual cooperation, and 1 point for mutual defection. If one player defects while the other player cooperates, the defecting player receives 5 points and the cooperating player receives 0 points (see Table 1).

No entry was disqualified for exceeding the allotted time. In fact, the entire round robin tournament was run five times to get a more stable estimate of the scores for each pair of players. In all, there were 120,000 moves, making for 240,000 separate choices.

The Contestants

The fourteen submitted entries came from three countries and five disciplines. The Appendix lists the names and affiliations of the sixteen people who submitted these entries, and it gives the rank and score of their entries.

One remarkable aspect of the tournament is that it allowed people from different disciplines to interact with each other in a common format and language. Most of the entrants were recruited from those who had published articles on game theory in general or the Prisoner's Dilemma in particular.

Analysis of the results shows that neither the discipline of the author, the brevity of the program, nor its length accounts for a rule's relative success. What does?

Before answering this question, a remark on the interpretation of numerical scores is in order. A useful benchmark for very good performance is 600 points, which is equivalent to the score attained by a player when both sides always cooperate with each other. A useful benchmark for very poor performance is 200 points, which is equivalent to the score attained by a player when both sides never cooperate with each other. As we shall see, most scores range between 200 and 600 points, although scores from 0 to 1000 points are possible. The winner, TIT FOR TAT, averaged 504 points per game.

PROPERTIES OF SUCCESSFUL RULES

Niceness

Surprisingly, there is a single property which distinguishes the relatively high scoring entries from the relatively low scoring entries. I will call this the property of being nice. A decision rule is *nice* if it will not be the first to defect, or if at least it will not be the first to defect before the last few moves (say before move 199).

Each of the top eight ranking entries are nice. None of the other entries are nice. There is even a substantial gap in the score between the nice entries and the others. The nice entries received tournament averages between 472 and 504, while the best of the entries that were not nice received only 401 points. Thus, not being the first to defect, at least until virtually the end of the game, was a property which all by itself separated the more successful rules from the less successful rules in this Computer Prisoner's Dilemma Tournament.

Each of the nice rules got about 600 points with each of the 7 other nice rules and with its own twin. This is because when 2 nice rules play, they are sure to cooperate with each other until virtually the end of the game. Actually the minor variations in end-game tactics did not account for much variation in the scores.

The scores of each player with each of the others are displayed in Table 2. Notice that the numbers in the upper left are all near 600, due to the fact that the top ranking entries are all nice and therefore cooperate with each other.

The bottom left section of Table 2 shows that the rules which are not nice rarely got more than 400 points with any of the nice rules. Therefore, the nice rules had a tremendous advantage in that they cooperated with each other, but were not very cooperative with the rules which were the first to defect.

So far we have seen that niceness accounts for which rules are in the top eight ranks and which rules are below. But what accounts for the relative ranking among the top eight?

Effectiveness with the Kingmaker

Since the nice rules all got within a few points of 600 with each other, the thing which distinguishes the relative rankings among the nice rules is their scores with the rules which are not nice. This much is obvious.

What is not obvious is that the relative ranking of the eight top rules was largely determined by just two of the other seven rules. These two rules are *kingmakers* because they do not do so well for themselves, but they largely determine the rankings among the top contenders. The two kingmakers are GRAASKAMP and DOWNING. (Entries are indicated by capital letters. All entries except the familiar TIT FOR TAT are named after their authors.)

DOWNING is the most important kingmaker because the range of scores achieved with it by the nice rules was the largest of any rule. The scores of the nice rules playing DOWNING ranged from a high of 601 by TIDEMAN AND CHIERUZZI to a low of 158 by NYDEGGER.

DOWNING is a particularly interesting rule in its own right, because, unlike most of the others, its logic is not based on a variant of TIT FOR

TABLE 2

Tournament Scores

Player / Other Players	TIT FOR TAT	TIDEMAN AND CHIERUZZI	NYDEGGER	GROFMAN	SHUBIK	STEIN AND RAPOPORT	FRIEDMAN	DAVIS	GRAASKAMP	DOWNING	FELD	JOSS	TULLOCK	(Name Withheld)	RANDOM	Average Score
1. TIT FOR TAT (Anatol Rapoport)	600	595	600	600	600	595	600	600	597	597	280	225	279	359	441	504
2. TIDEMAN AND CHIERUZZI	600	596	600	601	600	596	600	600	310	601	271	213	291	455	573	500
3. NYDEGGER	600	595	600	600	600	595	600	600	433	158	354	374	347	368	464	486
4. GROFMAN	600	595	600	600	600	594	600	600	376	309	280	236	305	426	507	482
5. SHUBIK	600	595	600	600	600	595	600	600	348	271	274	272	265	448	543	481
6. STEIN AND RAPOPORT	600	596	600	602	600	596	600	600	319	200	252	249	280	480	592	478
7. FRIEDMAN	600	595	600	600	600	595	600	600	307	207	235	213	263	489	598	473
8. DAVIS	600	595	600	600	600	595	600	600	307	194	238	247	253	450	598	472
9. GRAASKAMP	597	305	462	375	348	314	302	302	588	625	268	238	274	466	548	401
10. DOWNING	597	591	398	289	261	215	202	239	555	202	436	540	243	487	604	391
11. FELD	285	272	426	286	297	255	235	239	274	704	246	236	272	420	467	328
12. JOSS	230	214	409	237	286	254	213	252	244	634	236	224	273	390	469	304
13. TULLOCK	284	287	415	293	318	271	243	229	278	193	271	260	273	416	478	301
14. (Name Withheld)	362	231	397	273	230	149	133	173	187	133	317	366	345	413	526	282
15. RANDOM	442	142	407	313	219	141	108	137	189	102	360	416	419	300	450	276

TAT. DOWNING assumes that the other side bases its choice on DOWNING's own previous choice. DOWNING estimates the probability that the other player cooperates after it (DOWNING) cooperates, and also the probability that the other player cooperates after DOWNING defects. Each move, it updates its estimate of these two conditional probabilities and then selects the choice which will maximize its own long-term payoff under the assumption that it has correctly modeled the other player. The decision rule is based on "an outcome maximization" principle originally developed as a possible interpretation of what human subjects do in Prisoner's Dilemma laboratory experiments (Downing, 1975). If the two conditional probabilities have similar values, DOWNING determines that it pays to defect, since the other player seems to be doing the same thing whether DOWNING cooperates or not. Conversely, if the other player tends to cooperate after a cooperation but not after a defection by DOWNING, then the other player seems responsive, and DOWNING will calculate that the best thing to do with a responsive player is to cooperate. Under certain circumstances, DOWNING will even determine that the best strategy is to alternate cooperation and defection.

At the start of a game, DOWNING does not know the values of these conditional probabilities for the other players. It assumes that they are both .5, but gives no weight to this estimate when information actually does come in during the play of the game.

This is a fairly sophisticated decision rule, but its implementation does have one flaw. By initially assuming that the other player is unresponsive, DOWNING is doomed to defect on the first two moves. These first two defections led many other rules to punish DOWNING, so things usually got off to a bad start. But this is precisely why DOWNING served so well as a kingmaker. First ranking TIT FOR TAT and second ranking TIDEMAN AND CHIERUZZI both reacted in such a way that DOWNING learned to expect that defection does not pay but that cooperation does. All of the other nice rules went downhill with DOWNING.

The other kingmaker is GRAASKAMP. This is a very clever program. It plays tit for tat for 50 moves, defects once, plays tit for tat for another 5 moves, and then examines the history of the game so far. Its defection on move 51 allows it to recognize its own twin and be cooperative with it. Similarly, it can check to see if the other player seems to be TIT FOR TAT or another program it recognizes. If so, it plays the rest of the game in an appropriate way. If its score is not very good, it suspects (perhaps incorrectly) that it is playing RANDOM and defects for the rest of the game. Otherwise it continues to play tit for tat, but throws in a defection every five to fifteen moves. Not being nice, GRAASKAMP itself did not do very well in the tournament, but it was one of the two kingmakers. TIT FOR TAT did well with GRAASKAMP, getting 597 points. Third ranking NYDEGGER also got a boost by doing next best among the nice programs when playing with GRAASKAMP.

The importance of the kingmakers is that they largely determined the rank order of the top programs. TIT FOR TAT did very well with both, thereby winning the tournament. TIDEMAN AND CHIERUZZI did very well with one of them and came in second. In fact, the rank order of the nice programs in the tournament exactly matched their rank order of scores with just the two kingmakers, with only a single exception. The exception was NYDEGGER, which moved up to third in the tournament ranking because it not only did moderately well with the two kingmakers, but also did about a hundred points better than the other nice programs with both FELD and JOSS.

It is noteworthy that RANDOM was not a kingmaker since all entrants knew that RANDOM would be in the tournament. The range of scores achieved by the nice programs with RANDOM was only 157, compared to a range of 443 achieved with DOWNING and 290 achieved with GRAASKAMP. In fact, among the nice programs, there is actually a negative relationship between how well they did with RANDOM and how well they did in the full tournament. The reason is not hard to find and it carries an important lesson. To do well with RANDOM requires giving up on it early. But being too ready to give up on a seemingly random player will mean often mistakenly giving up on a potentially responsive player.

FRIEDMAN provides an extreme example of this. FRIEDMAN is never the first to defect, but once the other player defects even once, FRIEDMAN defects from then on. FRIEDMAN did very well with RANDOM, and since it is nice, it did well with all the other nice rules. But it did not do well with the kingmakers, because it did not let them recover from the consequences of their first defection. This brings us to the important property of forgiveness of a decision rule.

Forgiveness

We have seen that the nice rules did well in the tournament largely because they did so well with each other, and because there were enough of them to substantially raise each other's average score. As long as the other player did not defect, each of the nice rules was certain to continue cooperating until virtually the end of the game.

But what happened if there was a defection? As we shall see, different rules responded quite differently, and their response was important in determining their overall success. A key concept in this regard is the forgiveness of a decision rule. *Forgiveness* of a rule is its propensity to cooperate in the moves after the other player has defected.

The least forgiving rule is also a nice one. This is FRIEDMAN, which as we have just seen is cooperative until the other player defects; then it never cooperates again. TIT FOR TAT is unforgiving for one move, but then is totally forgiving of an isolated defection. SHUBIK, on the other hand, gets progressively less forgiving: It punishes the first defection with one defection, then punishes the next with two defections, and so on.

One of the main reasons why the rules which are not nice did not do well in the tournament is that most of the rules in the tournament were not very forgiving. A concrete illustration will help. Consider the case of JOSS. This decision rule is a variation of TIT FOR TAT. Like TIT FOR TAT, it always defects immediately after the other player defects. But instead of always cooperating after the other player cooperates, 10% of the time it defects after the other player cooperates. Thus it tries to get away with an occasional exploitation of the other player.

This decision rule seems like a fairly small variation of TIT FOR TAT, but in fact its overall performance was much worse, and it is interesting to see exactly why. Table 3 shows the move-by-move history of a game between JOSS and TIT FOR TAT. At first both players cooperated, but on the sixth move, JOSS selected one of its probabilistic defections. On the next move JOSS cooperated again, but TIT FOR TAT defected in response to JOSS's previous move. Then JOSS defected in response to TIT FOR TAT's defection. In effect, the single defection of JOSS on the sixth move created an *echo* back and forth between JOSS and TIT FOR TAT. This echo resulted in JOSS defecting on all the subsequent even numbered moves and TIT FOR TAT defecting on all the subsequent odd numbered moves.

During this alternation of cooperation and defection by the two players, each was getting an average of 2.5 points per turn (5 when the

TABLE 3
Illustrative Game Between TIT FOR TAT and JOSS

moves	1- 20	11111	23232	32323	23232
moves	21- 40	32324	44444	44444	44444
moves	41- 60	44444	44444	44444	44444
moves	61- 80	44444	44444	44444	44444
moves	81-100	44444	44444	44444	44444
moves	101-120	44444	44444	44444	44444
moves	121-140	44444	44444	44444	44444
moves	141-160	44444	44444	44444	44444
moves	161-180	44444	44444	44444	44444
moves	181-200	44444	44444	44444	44444

Score in this game: TIT FOR TAT 236, JOSS 241

Legend: 1 both cooperated
2 TIT FOR TAT only cooperated
3 JOSS only cooperated
4 neither cooperated

other cooperated and 0 when the other defected). This is not too much below the average of 3 points per turn when both were cooperating. However, worse was to come. JOSS was still cooperating on moves 7, 9, 11, 13, and so on. But on the twenty-fifth move, JOSS selected another of its probabilistic defections. Of course TIT FOR TAT defected on move 26 and another reverberating echo began. This echo had JOSS defecting on the odd numbered moves and TIT FOR TAT defecting on the even numbered moves. Together these two echoes resulted in both players defecting on every move after move 25. This meant that for the next 175 moves they both got only one point per turn. The final score of this game was 236 for TIT FOR TAT and 241 for JOSS. Notice that while JOSS did a little better than TIT FOR TAT, both did poorly.[2]

The problem was a combination of an occasional defection after the other's cooperation by JOSS, combined with a short-term lack of forgiveness by both sides. The moral is that if both sides are unforgiving in the way that JOSS and TIT FOR TAT were, it does not pay to be as greedy as JOSS was.

2. In the five games between them, the average scores were 225 for TIT FOR TAT and 230 for JOSS.

In the tournament as a whole, TIT FOR TAT won with an average of 504 points, but JOSS came in twelfth with an average of only 304 points. They did about the same with the rules which were not nice. The difference was that JOSS did much worse than TIT FOR TAT with the rules which were nice. The reason is simply that when playing with a nice rule JOSS would sooner or later throw in a defection, and then the other player would punish it, setting off mutual recriminations. Without sufficient forgiveness by either side, these recriminations echoed throughout the game, often being magnified by the specific pattern of retaliation of the other player.

A similar story could be told for FELD. FELD is a rule which also defects after the other player defects, but does not always cooperate after the other player cooperates. In FELD's case, the probability of cooperation after the other player cooperates is not a constant 90% as it was for JOSS. Instead it starts at 100% and declines steadily so that it is 50% by the end of the game at move 200. FELD ran into the same problem of having its defections echoed back to it, and overall FELD ranked eleventh with an average score of 328.

FELD does, however, reveal how maximization rules, like DOWNING, are subject to exploitation. In their 5 games together, FELD averaged 704 points (including the highest single score in the entire tournament), while DOWNING attained a middling score of 436. Recall that DOWNING is the rule which estimates what the other player does after its own cooperation, and what the other player does after its own defection, and then selects the strategy which gives it the maximum long-term gains if these estimates are accurate. What happened in these games was that DOWNING defected on the first move, and FELD defected on the second move in response. Then DOWNING drew the conclusion that if it ever defected, the other player was sure to defect. So DOWNING cooperated on move 3. DOWNING's cooperations were usually met with cooperations from FELD, so DOWNING determined that the best thing would be to cooperate. Then when FELD threw in an occasional defection, DOWNING was totally forgiving because DOWNING (correctly) estimated that the other player would be sure to defect if DOWNING defected but would be likely to cooperate if DOWNING cooperated. FELD's tactic of increasing its probability of defection following the other side's cooperation was sufficiently gradual so that from DOWNING's point of view the best thing to do was always to cooperate. Thus FELD got away with about 25% defections, while DOWNING sat still for it and never defected after the second move. This gave FELD an exceptionally high score when paired with DOWNING.

Actually, no other rule was very successful at exploiting DOWNING's reactive maximization approach. DOWNING's main problem in the tournament was simply that its initial beliefs led it to defect on the very first move. As we have seen, its initial expectations were that the other side would defect with equal probability whether DOWNING defected or not. This proved to be an inaccurate estimate. In actual play, a cooperation by one player on the first move of the game was followed by a cooperation by the other player on the second move 83% of the time. Conversely, a defection by one player on the first move was followed by a cooperation by the other player on the second move only 29% of the time. So DOWNING's initial belief in the unresponsiveness of the other players was not well-founded and led to its own downfall.

The very best rules were not only nice, but they were relatively forgiving. TIT FOR TAT, for example, has a very short memory. It punishes each defection once, but then it is willing to let bygones be bygones. This is why it did so well with the two kingmakers.

Second place TIDEMAN AND CHIERUZZI was also forgiving, but in its own special way. Like SHUBIK, it punishes the other player's first defection with one defection, punishes the second defection with two defections, and so on. But it does not give up entirely on an uncooperative player. Under certain conditions, it gives the other player a fresh start. When a fresh start is decided upon, TIDEMAN AND CHIERUZZI cooperates twice and then plays as if the game had just started. TIDEMAN AND CHIERUZZI is no pushover: It only forgives the other player if five separate conditions are simultaneously met. These conditions even include a statistical test to check the hypothesis that the other player is not RANDOM. Another test is that TIDEMAN AND CHIERUZZI is more than ten points ahead. But even this controlled degree of forgiveness was enough to get the program out of some ruts of mutual defection and thereby achieve second place in the tournament.[3]

Much of the reason why NYDEGGER achieved third place in the tournament was the fact that after three mutual defections, it was willing

3. As might be expected, the results could depend on the payoff matrix. For example, if P is changed from 1 to 2, then TIDEMAN AND CHIERUZZI would have come in first, followed by STEIN AND RAPOPORT, FRIEDMAN, and TIT FOR TAT. Of course, the entrants knew the actual payoff matrix. Had the announced payoff matrix been different, some of them might have submitted different programs, and this would have affected everyone's score.

to try a cooperation. This direct kind of forgiveness was especially helpful in getting out of mutual recriminations when playing the variations of the tit for tat principle used by FELD and JOSS. And among the nice rules, the least forgiving (FRIEDMAN and DAVIS) did the least well.

In contrast to the successful forgiveness of the top entries, TULLOCK demonstrates the costs of being not nice and deliberately mean. TULLOCK cooperates for the first eleven moves, but from then on, it has a probability of cooperation which is 10% *less* than the level of cooperation shown by the other side in the preceding ten moves. Other players tended to echo TULLOCK's defections, and then TULLOCK would amplify the echo. Often games with TULLOCK would end with a long string of mutual defection. This lack of forgiveness along with the willingness to be the first to defect was largely to blame for TULLOCK's relatively low score of 301 points and thirteenth rank.[4]

THE SURPRISES AND THEIR IMPLICATIONS

Many surprises were produced by the Computer Tournament for the Iterated Prisoner's Dilemma. Here is a review of these surprises, with some remarks on their implications.

(1) TIT FOR TAT won the tournament. This was the simplest rule submitted: Cooperate on the first move and then do whatever the other player did on the previous move. One implication is that reciprocity is not only a social norm, but can also be an extremely successful operating rule for an individualistic pragmatist.

(2) Despite the fact that most entrants tried to improve on TIT FOR TAT, none of the submitted attempts actually performed as well. As the British would say, "they were too clever by half." It seems that the main thing overlooked by many of these entries was the significance of echo effects. While many of the rules would work well with a player who tolerated their occasional exploitative moves, they did less well in an environment in which their defections were usually echoed back at them. In many games, even two unprovoked defections were enough to set up echoes leading to a pattern of unending mutual punishment.

4. TULLOCK was also involved in a cycle of scores. TULLOCK did about fifty points better than SHUBIK in their games together. And SHUBIK did about ten points better than DOWNING in *their* games together. But DOWNING did fifty points better

Perhaps the primary lesson of the tournament is the importance of minimizing echo effects in an environment of mutual power. A sophisticated analysis must go at least three levels deep. First is the direct effect of a choice. This is easy, since a defection always earns more than a cooperation. Second are the indirect effects, taking into account that the other side may or may not punish a defection. This much was certainly appreciated by many of the entrants. But third is the fact that in responding to the defections of the other side, one may be repeating or even amplifying one's own previous exploitative choice. Thus a single occasional defection may be successful when analyzed for its direct effects, and perhaps even when its secondary effects are taken into account. But the real costs may be in the tertiary effects when one's own isolated defections turn into unending mutual recriminations. Without realizing it, many of these rules actually wound up punishing themselves. With the other player serving as a mechanism to delay the self-punishment by a few moves, this aspect of self-punishment was not perceived by the decision rules.

(3) The clearest pattern in the tournament data was certainly a surprise: A single attribute, "niceness," accounted completely for which rules were in the top eight ranks and which were in the bottom seven ranks. Niceness is the property of never being the first to defect, at least until the last few moves. Every rule which had it did much better than any rule which did not. Each of the nice rules did well with each of the other nice rules, but in addition few of the rules which were not nice did very well with any of the nice rules. It is remarkable that a single property would so clearly separate the successful rules from the unsuccessful rules. At least in this first tournament, it paid to be nice.

(4) It also paid to be forgiving. TIT FOR TAT did so well because it punished each defection by the other side once, but only once. Therefore its forgiveness prevented it from amplifying the echoes of the other player's defections. Just as the presence or absence of niceness accounted for whether a program was in the top or bottom half of the tournament, the degree of forgiveness largely accounted for how a nice program ranked within the top half. The more forgiving, the better the performance.

(5) The very existence of two kingmakers is surprising. The relative ranking among the top rules was almost totally accounted for by their performance with just two of the fifteen rules. Given that there were kingmakers at all, the fact that RANDOM was not one of them is also surprising since there was a lot to be gained from discriminating promptly

against RANDOM. In retrospect, we can see that giving up quickly on RANDOM was only done at the cost of being too uncooperative with some other rules which may appear to be either RANDOM or untrainable. Thus another lesson of the tournament is that it pays to be wary of regarding the other side's seemingly inexplicable behavior as hopelessly unresponsive.

(6) Despite the fact that none of the attempts at more or less sophisticated decision rules were improvements on TIT FOR TAT, it was easy to find several rules which performed substantially better than TIT FOR TAT in the environment of the tournament. This should serve as a warning against the facile belief than an eye for an eye is necessarily the best strategy. Here are three rules that would have won the tournament if submitted.

(a) The sample program sent to prospective contestants to show them how to make a submission would in fact have won the tournament if anyone had simply clipped it and mailed it in! But no one did. This rule is to defect only if the other player defected on the previous two moves. It is a more forgiving version of TIT FOR TAT in that it does not punish isolated defections. The excellent performance of the TIT FOR TWO TATS rule highlights the fact that a common error of the contestants was to expect that gains could be made from being relatively less forgiving than TIT FOR TAT, whereas in fact there were big gains to be made from being even more forgiving. The implication of this finding is striking, since it suggests that expert strategists do not give sufficient weight to the importance of forgiveness.

(b) Another rule which would have won the tournament was also available to most of the contestants. This was the rule which won the preliminary tournament, a report of which was used in recruiting the contestants (Axelrod, 1978). Called LOOK AHEAD, it was inspired by the tree searching techniques used in the artificial intelligence programs to play chess. It is interesting that artificial intelligence techniques could have inspired a rule which was in fact better than any of the rules designed by game theorists specifically for the Prisoner's Dilemma.

(c) A third rule which would have won the tournament was a slight modification of DOWNING. If DOWNING had started with initial beliefs that the other players would be responsive rather than unresponsive, it too would have won and won by a large margin.[5] A kingmaker could have been king. DOWNING's initial beliefs about the other players were pessimistic. It turned out that optimism about their responsiveness would not only have been more accurate but would also have led to more successful performance. It would have resulted in first place rather than tenth place.

5. In the environment of the 15 rules of the tournament, REVISED DOWNING averages 542 points. This compares to TIT FOR TAT which won with 504 points. TIT FOR TWO TATS averages 532 in the same environment, and LOOK AHEAD averages 520 points.

These results from supplementary rules reinforce a theme from the analysis of the tournament entries themselves: The entries were too competitive for their own good. In the first place, many of them defected early in the game without provocation, a characteristic which was very costly in the long run. In the second place, the optimal amount of forgiveness was considerably greater than displayed by any of the entries (except possibly DOWNING). And in the third place, the entry which was most different from the others, DOWNING, floundered on its own misplaced pessimism regarding the initial responsiveness of the others.

(7) Finally, the most impressively, the sheer number of surprises was itself a surprise. What this indicates is that there is a lot to be learned about coping with an environment of mutual power. Even expert strategists from political science, sociology, economics, psychology, and mathematics made the systematic errors of being too competitive for their own good, not forgiving enough, and too pessimistic about the responsiveness of the other side.

The effectiveness of a particular strategy depends not only on its own characteristics, but also on the nature of the other strategies with which it must interact. For this reason, the results of a single tournament are not definitive. What this tournament does provide are concepts and examples which allow a deeper appreciation of some of the subtle consequences of choice in an environment which contains aspects of the iterated Prisoner's Dilemma.

The application of these concepts and examples can be widespread since the Prisoner's Dilemma is so common. The discovery of subtle reasons for the individualistic pragmatist to be nice, forgiving, and optimistic is an unexpected bonus.

Appendix

THE DECISION RULES

First Place with 504.5 points is TIT FOR TAT submitted by Anatol Rapoport of the Department of Psychology, University of Toronto. This rule is only four lines long in FORTRAN. It cooperates on the first move, and then does whatever the other player did on the previous move. It has a long history, since it can be identified with the ancient *lex talionis* or an eye for an eye. A recent mathematical treatment of its strategic properties is given in Taylor (1976). Discussions of its successful performance with human subjects include Oskamp (1971) and Wilson (1971).

Second Place with 500.4 points is a program of 41 lines by T. Nicolas TIDEMAN and Paula CHIERUZZI of the Department of Economics, Virginia Polytechnic Institute and State University. This rule begins with cooperation and tit for tat. However, when the other player finishes his second run of defections, an extra punishment is instituted, and the number of punishing defections is increased by one with each run of the other's defections. The other player is given a fresh start if he is 10 or more points behind, if he has not just started a run of defections, if it has been at least 20 moves since a fresh start, if there are at least 10 moves remaining, and if the number of defections differs from a 50-50 random generator by at least 3.0 standard deviations. A fresh start involves two cooperations and then play as if the game had just started. The program defects automatically on the last two moves.

Third Place with 485.5 points is a 23-line program by Rudy NYDEGGER of the Department of Psychology, Union College, Schenectady, New York. The program begins with tit for tat for the first three moves, except that if it was the only one to cooperate on the first move and the only one to defect on the second move, it defects on the third move. After the third move, its choice is determined from the 3 preceding outcomes in the following manner. Let A be the sum formed by counting the other's defection as 2 points and one's own as 1 point, and giving weights of 16, 4, and 1 to the preceding three moves in chronological order. The choice can be described as defecting only when A equals 1, 6, 7, 17, 22, 23, 26, 29, 30, 31, 33, 38, 39, 45, 49, 54, 55, 58, or 61. Thus if all three preceding moves are mutual defection, A = 63 and the rule cooperates. This rule was designed for use in laboratory experiments as a stooge which had a memory and appeared to be trustworthy, potentially cooperative, but not gullible (Nydegger, 1978).

Fourth Place with 481.9 points is an eight-line program by Bernard GROFMAN of the Public Policy Research Organization, University of California, Irvine. If the players did different things on the previous move, this rule cooperates with probability 2/7. Otherwise this rule always cooperates.

Fifth Place with 480.7 points is a sixteen-line program by Martin SHUBIK of the Department of Economics, Yale University. This rule cooperates until the other defects, and then defects once. If the other defects again after the rule's cooperation is resumed, the rule defects twice. In general, the length of retaliation is increased by one for each departure from mutual cooperation. This rule is described with its strategic implications in Shubik (1970). Further treatment of its is given in Taylor (1976).

Sixth Place with 477.8 is a fifty-line program by William STEIN of the Mathematics Department, Texas Christian University and Amnon RAPOPORT of the Department of Psychology, University of North Carolina. This rule plays tit for tat except that it cooperates on the first four moves, it defects on the last two moves, and every fifteen moves it checks to see if the opponent seems to be playing randomly. This check uses a chi-squared test of the other's transition probabilities and also checks for alternating moves of CD and DC.

Seventh Place with 473.4 points is a thirteen-line program by James W. FRIEDMAN of the Department of Economics, University of Rochester. This rule cooperates until the other player defects, and then defects until the end of the game. This strategy was described in the context of the Prisoner's Dilemma by Harris (1969). Its properties in a broader class of games have been developed by Friedman (1971).

Eighth Place with 471.8 points is a six-line program by Morton DAVIS of the Department of Mathematics, City College, CUNY. This rule cooperates on the first ten moves, and then if there is a defection it defects until the end of the game.

Ninth Place with 400.7 points is a 63-line program by James GRAASKAMP, an undergraduate at Beloit College. This rule plays tit for tat for 50 moves, defects on move 51, and then plays 5 more moves of tit for tat. A check is then made to see if the player seems to be RANDOM, in which case it defects from then on. A check is also made to see if the other is TIT FOR TAT, ANALOGY (a program from the preliminary tournament), and its own twin, in which case it plays tit for tat. Otherwise it randomly defects every 5 to 15 moves, hoping that enough trust has been built up so that the other player will not notice these defections.

Tenth Place with 390.6 points is a 33-line program based on an idea submitted by Leslie DOWNING of the Department of Psychology, Union College, Schenectady, New York. This rule selects its choice to maximize its own long-term expected payoff on the assumption that the other rule cooperates with a fixed probability which depends only on whether the other player cooperated or defected on the previous move. These two probabilities estimates are continuously updated as the game progresses. Initially, they are both assumed to be .5, which amounts to the pessimistic assumption that the other player is not responsive. This rule is based on an outcome maximization interpretation of human performances proposed by Downing (1975).

Eleventh Place with 327.6 points is a six-line program by Scott FELD of the Department of Sociology, University of California, Riverside. This rule starts with tit for tat and gradually lowers its probability of cooperation following the other's cooperation to .5 by the two hundredth move. It always defects after a defection by the other.

Twelfth Place with 304.4 points is a five-line program by Johann JOSS of the Eidgenossishe Technische Hochschule, Zurich. This rule cooperates 90% of the time after a cooperation by the other. It always defects after a defection by the other.

Thirteenth Place with 300.5 points is an eighteen-line program entered by Gordon TULLOCK of the Center for Study of Public Choice, Virginia Polytechnic Institute and State University. This rule cooperates on the first eleven moves. It then cooperates 10% less than the other player has cooperated on the preceding ten moves. This rule is based on an idea developed in Overcast and Tullock (1971). Professor Tullock was invited to specify how the idea could be implemented, and he did so out of scientific interest rather than an expectation that it would be a likely winner.

Fourteenth Place with 282.2 points is a 77-line program by a graduate student of political science whose dissertation is in game theory. This rule has a probability of cooperating, P, which is initially 30% and is updated every 10 moves. P is adjusted if the other player seems random, very cooperative, or very uncooperative. P is also adjusted after move 130 if the rule has a lower score than the other player. Unfortunately, the complex process of adjustment frequently left the probability of cooperation in the 30% to 70% range, and therefore the rule appeared random to many other players.

Fifteenth Place with 276.3 points was the five-line RANDOM program which cooperates and defects with equal probability.

Postscript: A second round of the Computer Tournament for the Iterated Prisoner's Dilemma has now been conducted. The results will be reported in this journal later this year.

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