More Effective Choice in the Prisoner's Dilemma

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This study reports and analyzes the results of the second round of the computer tournament for the iterated Prisoner's Dilemma. The object is to gain a deeper understanding of how to perform well in such a setting. The 62 entrants were able to draw lessons from the results of the first round and were able to design their entries to take these lessons into account. The results of the second round demonstrate a number of subtle pitfalls which specific types of decision rules can encounter. The winning rule was once again TIT FOR TAT, the rule which cooperates on the first move and then does what the other player did on the previous move. The analysis of the results shows the value of not being the first to defect, of being somewhat forgiving, but also the importance of being provocable. An analysis of hypothetical alternative tournaments demonstrates the robustness of the results.

THE TOURNAMENT APPROACH

This article reports and analyzes the results of the second round of the Computer Tournament for the Prisoner's Dilemma. The object of the study is to gain a deeper understanding of how to perform well in such a Prisoner's Dilemma setting.

The Prisoner's Dilemma game is justifiably famous as an elegant embodiment of 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). A typical

AUTHOR'S NOTE: I would like to thank all the people whose entries made this tournament possible. Their names are given in Table 2. I would also like to thank John Chamberlin, Michael Cohen, and William Keech for their helpful suggestions concerning the design and analysis of the tournament and John Meyer for his help in getting the submissions in machine-readable form. For its support of this research, I owe thanks to the Institute of Public Policy Studies.

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payoff structure is illustrated in Table 1. When the interaction between the two players is iterated, the defecting choice is no longer necessarily the best choice. With iteration, both sides have an ongoing relationship with an informative history and an important future. This makes possible sophisticated strategies which use this history.

The best way to play an iterated Prisoner's Dilemma of uncertain duration depends on what decision rule the other player is using. In other words, there is no one rule which is optimal independent of the other player's rule. To see why this is so, suppose a rule is nice (i.e., is never the first to defect). Then unconditional defection would do better if the other player is using unconditional cooperation. Alternatively, suppose a rule is not nice. Then unconditional cooperation would do better if the other player is using the following rule: cooperate until the other defects, and then always defect.[1]

Given that the strategy of the other player is important, a good way to study effective choice is to arrange a situation in which each player is trying to do well for himself and each player knows in advance that the other players are intelligent and are also trying to do well for themselves. This is the tournament approach.

In the first round of the tournament, game theorists were invited to submit strategies for playing the iterated Prisoner's Dilemma. These strategies were coded as computer programs which had as input the history of the pairwise interaction and had as output the choice to be made on the current move. Each of the 14 entries 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. The winner of the first round of the tournament was TIT FOR TAT, submitted by Professor Anatol Rapoport by the Department of Psychology of the University of Toronto. TIT FOR TAT is the strategy which cooperates on the first move, and then does whatever the other player did on the previous move. This first round of the computer tournament for the iterated Prisoner's Dilemma led not only to a number of insights into the characteristics of successful rules but also highlighted a variety of subtle things that can go wrong when two sophisticated strategies interact. The rationale for the tournament approach and a detailed analysis of the first round is given in Axelrod (1980).

1. To be precise, this requires that the length of the game is sufficiently great relative to the specific payoff matrix. This condition is met for the tournament. For details see Axelrod (1979).

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

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

NOTE: The payoff to the row player is given first in each pair of numbers.

A second round of the tournament has now been conducted. The results of the second round provide much better insight into the nature of effective choice in the Prisoner's Dilemma because the entrants to the second round were all given the detailed analysis of the first round. This analysis included discussion of a variety of supplemental rules that would have done very well in the environment of the first round. This means that they were aware of the outcome of the first round, the concepts used to analyze success, and the pitfalls that were discovered. Moreover, they each knew that the others knew these things. Therefore the second round presumably began at a much higher level of sophistication than the first round, and its results should therefore be that much more valuable as a guide to effective choice in the Prisoner's Dilemma.

The second round is also a dramatic improvement over the first round in sheer size of the tournament. The response was far greater than anticipated. There were 62 entries from six countries. The contestants were largely recruited through announcements in journals for users of small computers. The game theorists who participated in the first round of the tournament were also invited to try again. The contestants ranged from a 10-year-old computer hobbyist to professors of computer science, economics, psychology, mathematics, sociology, political science, and evolutionary biology. The countries represented were the United States, Canada, Great Britain, Norway, Switzerland, and New Zealand.

The second round provides a chance both to test the validity of the themes developed in the analyisis of the first round and to develop additional new concepts to explain successes and failures. The entrants also drew their own lessons from the experience of the first round. But different people drew different lessons. What is particularly illuminating in the second round is the way the entries based on different lessons actually interact.

Finally, this report is able to evaluate the robustness of the results through the construction of alternative hypothetical tournaments. The evidence strongly supports the conclusion that, under a wide variety of environments, TIT FOR TAT is a highly successful decision rule.

THE WINNER

TIT FOR TAT was the simplest program submitted in the first round, and it won the first round. It was the simplest submission in the second round, and it won the second round. Even though all the entrants to the second round knew that TIT FOR TAT had won the first round, no one was able to design an entry that did any better.

TIT FOR TAT starts with a cooperative choice, and thereafter does what the other player did on the previous move. This decision rule was known to all of the entrants to the second round because they all had the report of the earlier round showing that TIT FOR TAT was the most successful rule so far. They had read the arguments about how it was known to elicit a good degree of cooperation when played with humans, how it is not very exploitable, how it did well in the preliminary tournament, and how it won the first round. The report on the first round also explained some of the reasons for its success, pointing in particular to its property of never being the first to defect ("niceness") and its propensity to cooperate after the other player defected ("forgiveness" with the exception of a single punishment).

The second round attracted over 60 entries, but only one person submitted TIT FOR TAT. This was Anatol Rapoport, who submitted it the first time, even though an explicit tournament rule allowed anyone to submit any program, even one authored by someone else.

THE FORM OF THE TOURNAMENT

The second round of tournament was conducted as a round robin so that each entry was paired with each other entry. As in the first round, each entry was also paired with its own twin and with RANDOM. As before, the payoff matrix was the one given in Table 1. Once again no entry was disqualified for exceeding the allotted time.

As announced in the rules, the length of the games was determined probabilistically with a .00346 chance of ending with each given move. This parameter was chosen so that the expected median length of a game would be 200 moves. In practice, each pair of players was matched five times, and the lengths of these five games were determined once and for all by drawing a random sample. The resulting random sample from the implied distribution specified that the five games for each pair of players would be of lengths 63, 77, 151, and 308 moves. Thus the average length of a game turned out to be somewhat shorter than expected at 151 moves. Since no one knew exactly when the last move would come, end-game effects were successfully avoided in the second round.

THE CONTESTANTS

None of the personal attributes of the contestants correlated significantly with the performance of the rules. The professors did not do significantly better than the others, nor did the Americans. Those who wrote in FORTRAN rather than BASIC did not do significantly better either, even though the use of FORTRAN would usually indicate access to something more than a bottom-of-the-line microcomputer. The ranking of the entries is shown in Table 2 along with some information about the contestants and the programs.

On average, short programs did not do significantly better than long programs, despite the victory of TIT FOR TAT. But on the other hand, neither did long programs (with their greater complexity) do any better than short programs.

So just as happened in round one, the features of the entries which do not directly relate to their mode of performance do not account for their relative success or failure.

The determination of just what does account for success is no easy task because there are over a million moves in the tournament.

THE REPRESENTATIVES

Since there are 63 rules in the tournament and 3969 ways the rules can be paired, the round robin tournament matrix has almost 20 times as

TABLE 2
The Contestants

Rank	*Name*	*Country (if not U.S.)*	*Discipline (if faculty)*	*Language (FORTRAN or BASIC)*	*Length of Program**
1	Anatol Rapoport	Canada	Psychology	F	5
2	Danny C. Champion			F	16
3	Otto Börufsen	Norway		F	77
4	Rob Cave			F	20
5	William Adams			B	22
6	Jim Graaskamp & Ken Katzen			F	23
7	Herb Weiner			F	31
8	Paul D. Harrington			F	112
9	T. Nicolaus Tideman & P. Chieruzzi		Economics	F	38
10	Charles Kluepfel			B	59
11	Abraham Getzler			F	9
12	Francois Leyvraz	Switzerland		B	29
13	Edward White, Jr.			F	16
14	Graham Eatherley	Canada		F	12
15	Paul E. Black			F	22
16	Richard Hufford			F	45
17	Brian Yamauchi			B	32
18	John W. Colbert			F	63
19	Fred Mauk			F	63
20	Ray Mikkelson		Physics	B	27
21	Glenn Rowsam			F	36
22	Scott Appold			F	41
23	Gail Grisell			B	10
24	J. Maynard Smith	United Kingdom	Biology	F	9
25	Tom Almy			F	142
26	D. Ambuelh & K. Kickey			F	23
27	Craig Feathers			B	48
28	Bernard Grofman		Pol. Science	F	27
29	Johann Joss	Switzerland	Mathematics	B	74
30	Jonathan Pinkley			F	64
31	Rudy Nydegger		Psychology	F	23
32	Robert Pebley			B	13
33	Roger Falk & James Langsted			B	117
34	Nelson Weiderman		Computer Sci.	F	18
35	Robert Adams			B	43
36	Robyn M. Dawes & Mark Batell		Psychology	F	29
37	George Lefevre			B	10
38	Stanley F. Quayle			F	44

Table 2 (Continued)

Rank	Name	Country (if not U.S.)	Discipline (if faculty)	Language (FORTRAN or BASIC)	Length of Program*
39	R. D. Anderson			F	44
40	Leslie Downing		Psychology	F	33
41	George Zimmerman			F	36
42	Steve Newman			F	51
43	Martyn Jones	New Zealand		B	152
44	E.E.H. Shurmann			B	32
45	Henry Nussbacher			B	52
46	David Gladstein			F	28
47	Mark F. Batell			F	30
48	David A. Smith			B	23
49	Robert Leyland	New Zealand		B	52
50	Micharl F. McGurrin			F	78
51	Howard R. Hollander			F	16
52	James W. Friedman		Economics	F	9
53	George Hufford			F	41
54	Rik Smoody			F	6
55	Scott Feld		Sociology	F	50
56	Gene Snodgrass			F	90
57	George Duisman			B	6
58	W. H. Robertson			F	54
59	Harold Rabbie			F	52
60	James E. Hall			F	31
61	Edward Friedland			F	84
62	RANDOM			F	(4)
63	Roger Hotz			B	14

*Length is given in terms of the number of internal statements in the FORTRAN version of the program. A conditional instruction is counted as two internal statements here, although it was counted as only one instruction in the report of the first round.

many numbers to report as in the first round which had only 15 rules. To compress the tournament matrix, the average score of each rule with each other rule is shown in Table 3 as a single digit according to the following code:

1: less than 100 points
2: 100-199.9 points (151 points is total mutual defection)
3: 200-299.9 points
4: 300-399.9 points
5: 400-452.9 points
6: exactly 453 points (total mutual cooperation)
7: 453.1-499.9 points
8: 500-599.9 points
9: 600 or more points.

While Table 3 can give some idea of why a given rule scored as it did, the amount of detail is overwhelming. Therefore, a more parsimonious method is needed to make sense of the results. Fortunately, stepwise regression provides such a method. It turns out that just five of the rules can be used to account very well for how well a given rule did with the entire set of 63. These five rules can thus be thought of as *representatives* of the full set in the sense that the scores a given rule sets with them can be used to predict the average score the rule gets over the full set.

The formula for the predicted tournament score is:

$$T = 120.0 + (.202)\ S_6 + (.198)\ S_{30} + (.110)\ S_{35} + (.072)\ S_{46} + (.086)\ S_{27}$$

where T is the predicted tournament score of a rule, and S_j is the score which that rule gets with the j^{th} rule.

This estimate of the tournament scores correlated with the actual tournament scores at $r = .979$. This means that 96% of the variance in the tournament scores is explained by a rule's performance with just the five representatives.

TIT FOR TAT's victory in the tournament can be explained by its good scores with all five of the representatives. Recall that 453 points is what is attained from unending mutual cooperation. TIT FOR TAT got the following scores with the five representatives: $S_6 = 453$; $S_{30} = 453$; $S_{35} = 453$; $S_{46} = 452$; and $S_{27} = 446$. Using these as the standard of comparison we can see how other rules did in the tournament by seeing how much worse (or better) they did with the five representatives compared to how TIT FOR TAT did with them. This display is provided in Table 4 and will form the basis of the rest of the analysis of this round.

Also provided in Table 4 are actual tournament scores for each rule and the residual which is the difference between the actual tournament score and the predicted tournament score. Notice that while the tournament scores cover a range of several hundred points, the residuals are usually smaller than 10 points, indicating again how well the five representatives account for the overall performance of the rules. Another interesting feature of the residuals is that the top-ranking rules tend to have the largest positive residuals indicating that they do better than most of the rules on the limited aspects of the tournament which are not accounted for by the five representatives.

We are now ready to use the representatives to help answer the central questions of what worked and why.

TABLE 3
Tournament Scores
(See text for legend)

Other Players / *Player*	*1*		*11*		*21*		*31*		*41*		*51*		*61*
1	66666	66566	66666	56556	66665	65656	66666	66656	66666	56555	56554	44452	442
2	66666	66566	66666	56556	66665	65656	66666	66656	66666	56555	56554	44552	442
3	66666	66566	66666	56556	66665	65656	66666	66656	66666	56555	56554	44443	452
4	66666	66566	66666	56556	66665	65656	66666	66656	66666	56555	56553	45542	352
5	66666	66566	66666	56546	66665	65656	66666	66656	66666	56545	36494	44542	442
6	66666	66566	66666	56556	66665	65656	66666	66656	66666	56555	46583	35232	353
7	66666	66566	66666	56546	66665	65656	66666	66656	66666	56555	56553	35272	253
8	55577	55555	55777	58558	75887	85455	45485	54888	58443	53758	53574	44543	452
9	66666	66566	66666	56556	66665	65656	66666	66656	66666	56455	56554	45232	272
10	66666	56566	66666	56546	66665	65656	66666	66656	66666	56554	56554	45342	352
11	66666	66566	66666	56536	66665	65656	66666	66656	66666	46534	56553	44552	342
12	66666	66566	66666	36546	66665	65646	66666	66656	66666	56555	56554	44553	242
13	66666	56466	66666	46556	66664	64656	66666	66646	66666	56544	56354	44552	442
14	66666	66566	66666	56556	66664	64656	66666	66646	66666	56538	56453	43533	432
15	66666	66566	66666	46556	66664	64656	66666	66646	66666	56544	56354	43532	232
16	55575	55555	54777	57557	75775	77757	43375	77777	47443	34757	42484	44222	452
17	66666	66466	66666	46556	66664	64656	66666	66646	66666	56534	56253	45533	253
18	57557	55555	55777	57547	75777	77557	35577	77777	77743	57558	51572	44553	442
19	55674	54564	35777	57557	75777	77757	43473	77777	47443	55757	53573	44572	453
20	66666	66466	66666	46556	66664	64656	66666	66646	66666	56534	56253	35532	252
21	66666	66566	66666	46556	66664	64646	66666	66646	66666	56534	56353	35332	252
22	66666	66566	66666	56556	66664	65646	66666	66656	66666	36538	56353	44422	242
23	66666	66466	66666	46556	66663	64656	66666	66646	66666	56538	56252	33533	443
24	66666	66466	66666	46556	66663	64656	66666	66646	66666	36554	56454	43433	332
25	55575	55555	55878	58558	75885	85255	55384	58848	28433	52745	52583	45243	242
26	66666	66466	66666	46556	66664	64656	66666	66646	66666	56538	56353	34252	243
27	55575	55555	55777	57558	75874	75557	54373	75878	58434	53737	52353	44442	342
28	66666	66366	66666	46556	66663	65656	66666	66646	66666	56534	56353	35232	252
29	55575	55555	54777	57557	54775	75757	43473	77777	37347	53757	52474	55532	252
30	66666	66566	66666	46556	66664	64656	66666	66646	66666	46524	56352	34233	242
31	66666	66466	66666	36546	66667	67626	66666	66676	56666	46534	56773	44242	242
32	66666	66566	66666	36536	66665	64636	66666	66646	66666	26433	26573	45242	252
33	66666	66566	66666	36536	66663	63646	66666	66636	66666	36453	46394	35222	252
34	66666	66466	66666	46556	66663	65656	66666	66646	66666	36534	56253	33233	253
35	66666	66566	66666	56536	66664	63636	66666	66656	66666	26432	26493	45252	252
36	66666	66466	66666	46556	66663	64656	66666	66646	66666	26534	56253	35232	253
37	66666	66466	66666	46556	66664	64656	66666	66646	56666	26532	56353	35222	273
38	66666	66466	66666	46556	66663	64656	66666	66646	66666	36524	56272	33233	273
39	55555	55455	55778	48558	55883	84855	54384	44958	38335	52738	72372	35232	252
40	66666	66466	66666	46556	66663	64656	66666	66646	66666	36534	56272	33233	253
41	66666	66566	66666	46546	66663	65646	66666	66646	66666	26433	36573	45252	242
42	66666	66466	66666	46556	66663	64646	66666	66646	56666	36524	56252	33223	252
43	66666	66466	66666	46546	66664	64636	66666	66636	66666	26433	46383	44222	242
44	66666	66566	66666	36546	66663	63626	66666	66626	66666	46434	46393	45222	242
45	66666	66566	66666	36536	66664	65636	66666	66676	66666	26433	36377	35232	252
46	57557	55555	45757	56757	54597	55754	42392	22959	29233	52758	52574	44252	442
47	66666	66366	66666	46546	66663	63636	66666	66636	66666	26333	36393	35232	253
48	55575	55545	55777	57557	75774	74757	43373	77744	44433	53555	52454	43433	332
49	55554	55555	35785	54553	45575	34358	43533	43848	38343	53557	53593	45572	352
50	55575	55454	55757	47557	75575	54757	43372	72747	37343	54745	72354	43232	442
51	55573	45555	55777	47557	75775	75757	32372	77744	35433	54555	52454	43432	332
52	66666	66366	66666	36536	66663	63636	66666	66636	66666	26332	26392	35222	253
53	55564	55555	55375	33543	35385	34243	55324	32333	24332	52758	72593	44532	242
54	55552	35455	55777	37557	75774	75757	44171	77444	57314	52525	51152	23413	131
55	44434	33544	35575	43533	44454	33347	43433	33737	38343	43535	42494	45342	353
56	55555	22544	45575	43542	34477	35348	44322	22424	45333	42725	52392	44233	442
57	44524	22712	44577	52442	24992	45114	42192	21929	39322	41829	81382	34923	442
58	45377	22433	55775	35647	35753	25247	42222	22222	23233	22542	52783	33533	253
59	55234	24532	55577	22552	24282	55224	43222	22222	33232	52838	82292	35853	252
60	22432	22742	27343	37522	33998	22235	42292	22828	28233	22722	32382	55982	542
61	44734	22734	34473	52742	23483	23222	42222	22222	23333	42724	72293	44223	253
62	44224	12212	45477	22422	24473	44212	32222	21123	32322	41724	51382	34223	142
63	33323	22533	34333	22522	23233	22233	42322	22222	23333	22333	32392	35232	252

TABLE 4
Performance of the Rules

Rank	Tournament Score	Performance with Representatives (Points lost relative to TIT FOR TAT): Rule 6	Rev. State Transition (30)	Rule 35	Tester (46)	Tranquilizer (27)	Residual
1	434.73	0	0	0	0	0	13.3
2	433.88	0	0	0	12.0	2.0	13.4
3	431.77	0	0	0	0	6.6	10.9
4	427.76	0	0	0	1.2	25.0	8.5
5	427.10	0	0	0	15.0	16.6	8.1
6	425.60	0	0	0	0	1.0	4.2
7	425.48	0	0	0	0	3.6	4.3
8	425.46	1.0	37.2	16.6	1.0	1.6	13.6
9	425.07	0	0	0	0	11.2	4.5
10	424.94	0	0	0	26.4	10.6	6.3
11	422.83	0	0	0	84.8	10.2	8.3
12	422.66	0	0	0	5.8	−1.2	1.5
13	419.67	0	0	0	27.0	61.4	5.4
14	418.77	0	0	0	0	50.4	1.6
15	414.11	0	0	0	9.4	52.0	−2.2
16	411.75	3.6	−26.8	41.2	3.4	−22.4	−11.5
17	411.59	0	0	0	4.0	61.4	−4.3
18	411.08	1.0	−2.0	−.8	7.0	−7.8	−10.9
19	410.45	3.0	−19.6	171.8	3.0	−14.2	3.5
20	410.31	0	0	0	18.0	68.0	−4.0
21	410.28	0	0	0	20.0	57.2	−4.9
22	408.55	0	0	0	154.6	31.8	.9
23	408.11	0	0	0	0	67.4	−7.6
24	407.79	0	0	0	224.6	56.0	7.2
25	407.01	1.0	2.2	113.4	15.0	33.6	2.5
26	406.95	0	0	0	0	59.6	−9.4
27	405.90	8.0	−18.6	227.8	5.6	14.0	8.9
28	403.97	0	0	0	3.0	1.4	−17.2
29	403.13	4.0	−24.8	245.0	4.0	−3.0	4.4
30	402.90	0	0	0	74.0	54.4	−8.6
31	402.16	0	0	0	147.4	−10.0	−9.6
32	400.75	0	0	0	264.2	52.4	2.7
33	400.52	0	0	0	183.6	157.4	5.7
34	399.98	0	0	0	224.6	41.6	−1.9
35	399.60	0	0	0	291.0	204.8	16.5
36	399.31	0	0	0	288.0	61.4	3.7
37	398.13	0	0	0	294.0	58.4	2.7
38	397.70	0	0	0	224.6	84.8	−.4
39	397.66	1.0	2.6	54.4	2.0	46.6	−13.0
40	397.13	0	0	0	224.6	72.8	−2.0

Table 4 (Continued)

		Performance with Representatives (Points lost relative to TIT FOR TAT)					
Rank	*Tournament Score*	*Rule 6*	*Rev. State Transition (30)*	*Rule 35*	*Tester (46)*	*Tran-quilizer (27)*	*Residual*
41	395.33	0	0	0	289.0	–5.6	–6.0
42	394.02	0	0	0	224.6	74.0	–5.0
43	393.01	0	0	0	282.0	55.8	–3.5
44	392.54	0	0	0	151.4	159.2	–4.4
45	392.41	0	0	0	252.6	44.6	–7.2
46	390.89	1.0	73.0	292.0	1.0	–.4	16.1
47	389.44	0	0	0	291.0	156.8	2.2
48	388.92	7.8	–15.6	216.0	29.8	55.2	–3.5
49	385.00	2.0	–90.0	189.0	2.8	101.0	–24.3
50	383.17	1.0	–38.4	278.0	1.0	61.8	–9.9
51	380.95	135.6	–22.0	265.4	26.8	29.8	16.1
52	380.49	0	0	0	294.0	205.2	–2.3
53	344.17	1.0	199.4	117.2	3.0	88.4	–17.0
54	342.89	167.6	–30.8	385.0	42.4	29.4	–3.1
55	327.64	241.0	–32.6	230.2	102.2	181.6	–3.4
56	326.94	305.0	–74.4	285.2	73.4	42.0	–7.5
56	309.03	334.8	74.0	270.2	73.0	42.2	8.4
58	304.62	274.0	–6.4	290.4	294.0	6.0	–9.3
59	303.52	302.0	142.2	271.4	13.0	–1.0	1.8
60	296.89	293.0	34.2	292.2	291.0	286.0	18.8
61	277.70	277.0	262.4	293.0	76.0	178.8	17.0
62	237.22	359.2	261.8	286.0	114.4	90.2	–12.6
63	220.50	311.6	249.0	293.6	259.0	254.0	–16.2

PROPERTIES OF SUCCESSFUL RULES

NICENESS

As in the first round, it paid to be nice. A "nice" rule is one which will never be the first to defect. Being the first to defect was usually quite costly.

More than half of the entries were nice, so obviously most of the contestants got the message from the first round that it did not seem to pay to be the first to defect.

In the second round, there was once again a substantial correlation between whether a rule was nice and how well it did. Of the top 15 rules, all but one were nice (and that one ranked eighth). Of the bottom 15 rules, all but one were not nice. And the overall correlation between whether a rule was nice and its tournament score was a substantial .58.

Table 4 shows the pattern very clearly in the scores with the five representatives. The first three representatives are themselves nice. All of the nice rules got 453 points with each of these three, so the nice rules lost no points compared to how first-placed TIT FOR TAT did with them. The rules which were not nice generally did not do as well as TIT FOR TAT did with these first three representatives, as shown by the predominance of positive over negative numbers in these three columns of Table 4.

To give an example, the best of the rules which was not nice was submitted by Paul Harrington and ranked eighth. This rule is a variant of TIT FOR TAT which has a check for RANDOM, and a way of getting out of alternating defections (echo effects), and also a method of seeing what it can get away with. It always defects on move 37 and with increasing probability after that unless the other player defects immediately after one of these defections, in which case it no longer defects randomly. It did not do as well as TIT FOR TAT with any of the five representatives, but it suffered most from the second representative. With that entry it got 37.2 points less than TIT FOR TAT did. This second representative is REVISED STATE TRANSITION, modified from the supplementary rule of round one and submitted in round two by Jonathan Pinkley. REVISED STATE TRANSITION models the other player as a one-step Markov process. It makes its own choice so as to maximize its own long-term payoff on the assumption that this model is correct. As Harrington's rule defected more and more, the REVISED STATE TRANSITION rule kept a running estimate of the probability that the other would cooperate after each of the four possible outcomes. Eventually REVISED STATE TRANSITION determined that it did not pay to cooperate after the other exploited it, and soon thereafter it also determined that it did not even pay to cooperate after a mutual cooperation.

So even if the other rule is willing to accept some defections, once the limit of its tolerance is reached, it is hard to convince it that one's ways have been mended. While some of the other rules which were not nice did in fact manage to do better than TIT FOR TAT with REVISED STATE TRANSITION, these rules tended to do much worse with some of the other representatives.

PROVOCABILITY

As we have seen, it paid to be nice. But what distinguishes among the majority of the rules which were nice?

To answer this we can examine the performance of the nice rules with the two representatives which were not nice. The analysis of the nice rules can be narrowed down to their performance with these two representatives since the other three representatives are themselves nice, and all nice rules do equally well with other nice rules.[2] The two representatives which were not nice, I shall call TESTER and TRANQUILIZER.

TESTER was submitted by David Gladstein and came in 46th in the tournament. The rule is unusual in that it defects on the very first move in order to test the other's response. If the other player ever defects, it apologizes by cooperating and playing tit-for-tat for the rest of the game. Otherwise, it defects as much as possible subject to the constraint that the ratio of its defections to moves remains under .5, not counting the first defection. This means that until the other player defects, TESTER defects on the first move, the fourth move, and every second move after that. TESTER did a good job of exploiting several supplementary rules which would have done quite well in the environment of the first round of the tournament. For example, TIT FOR TWO TATS is the rule which defects only after the other player defects on the preceding two moves. But TESTER never does defect twice in a row. So TIT FOR TWO TATS always cooperates with TESTER, and gets badly exploited for its generosity. Notice that TESTER itself did not do particularly well in the tournament, averaging only 391 points to come in 46th. It did, however, provide low scores for some of the more easy-going rules.

As another example of how TESTER causes problems for some rules which have done well in the first round, consider the three variants of Leslie Downing's outcome maximization principle. There were two separate submissions of the REVISED DOWNING program which looked so promising in round one. These came from Stanley F. Quayle and Leslie Downing himself. A slightly modified version came from a youthful competitor, 11-year-old Steve Newman. But all three were exploited by TESTER since they all calculated that the best thing to do

2. Unlike the first round, there are no end-game effects in the second round. For this reason we no longer have to worry about the possibility of minor fluctuations in the scores due to these end-game effects.

with a program that cooperated just over half the time after one's own cooperation was to keep on cooperating. Actually they would have been better off doing what TIT FOR TAT and many other high-ranking programs did, which is to defect immediately on the second move in response to TESTER's defection on the first move. This would have elicited TESTER's apology and things would have gone better thereafter.

The other nonnice representative, TRANQUILIZER, illustrates a different way of taking advantage of many rules. TRANQUILIZER was submitted by Craig Feathers and came in 27th in the tournament. The rule normally cooperates but is ready to defect if the other player defects too often. Thus the rule tends to cooperate for the first dozen or two moves if the other player is cooperating, but then it throws in a defection. If the other player continues to cooperate, then defections become more frequent. But as long as TRANQUILIZER is maintaining an average payoff of at least 2.25 points per move, it will never defect twice in succession and it will not defect more than one-quarter of the time.

An example of how a rule can suffer from TRANQUILIZER is provided by the submission of Graham Eatherley which came in 14th. Eatherley's rule is particularly elegant. It keeps track of how many times in the game the other player defected. After the other player defects, it defects with a probability equal to the ratio of the other's total defections to the total moves to that point. Eatherley reported that he was fascinated by the results of the first round and he immediately coded most of the round one entries and the supplementary rules in order to provide a suitable "proving ground" for his own routines. He even sent in a tournament matrix of 20 rules playing each other to show how well his own selected submission did. He experimented with many rules and took into account his expectation that there would be a mix of cooperative and competitive rules. The fact that so much work led to such an elegant rule was especially pleasing.

In the actual environment of round two, Eatherley's rule did exactly as well as TIT FOR TAT with four of the five representatives. But with TRANQUILIZER it averaged 50.4 points worse that TIT FOR TAT did. The reason is that by the time TRANQUILIZER started defecting, it had already established a good record of cooperation. This meant that Eatherley's rule was unlikely to defect after the first or even the second or third defection of TRANQUILIZER. So the defections came more and more often, until an occasional response from EATHERLEY was generated which in turn helped keep the proportion of defections under control. But since EATHERLEY would only respond to a defection in proportion to the other's percentage of defection in the entire game so far, it usually did not respond.

Table 5 shows the sequence of moves in one of the five games played between EATHERLEY and TRANQUILIZER. In this game TRANQUILIZER first defected on move 23, but EATHERLEY then had only a small chance of responding. It was not until after TRANQUILIZER's eighth defection on move 58 that EATHERLEY first defected. But TRANQUILIZER continued to throw in well-spaced defections which were only occasionally met by a response of a defection from EATHERLEY. The result was that EATHERLEY was successfully exploited, getting only 387 points, while TRANQUILIZER got an impressive 492 points in this game.

What it takes to do well with TESTER and TRANQUILIZER can be put in a single word: *provocability.* A rule is provocable if it immediately defects after an "uncalled for" defection from the other. Now just what is an "uncalled for" defection is not very precise. But surely what TESTER and TRANQUILIZER do is uncalled for. The first one defects on the very first move, and the second defects after a dozen or two mutual cooperations. If the other rule is not provoked to an immediate response, these rules (and many others like them) will simply take more and more advantage of such an easy-going player. So while it pays to be nice (by not being the first to defect), it also pays to be provocable (by being ready to defect immediately after an uncalled for defection by the other).

How does this fit in with the observation from the first round of the tournament that it paid to be forgiving of the other's defections? First, forgiveness was defined in terms of propensity to cooperate after the other player defected—and this propensity was taken to be either long-term or short-term propensity.[3] To be provocable is to have a short-term propensity not to forgive a defection which is uncalled for. Presumably it still pays to be forgiving when you are in a rut of mutual defection, or a sequence of alternating exploitation from an echo of a single defection. But at least in the second round where there were a number of rules which were looking for others who might be too easy-going, it also paid to be provocable so as not to be exploited.

3. This is a broader definition of forgiveness than the one used by Rapoport and Chammah (1965: 72-73), which is the probability of cooperation on the move after receiving the sucker's payoff, S.

TABLE 5
Illustrative Game Between EATHERLEY and TRANQUILIZER

moves 1- 20	11111	11111	11111	11111
moves 21- 40	11212	11121	11111	11211
moves 41- 60	11211	11112	11112	11232
moves 61- 80	11121	21121	11111	12111
moves 81-100	21121	11111	23111	11112
moves 101-120	11111	11111	21112	11111
moves 121-140	23111	12121	11111	21111
moves 141-151	12111	11111	1	

Score in this game: EATHERLEY 387, TRANQUILIZER 492

Legend: 1 both cooperated
2 EATHERLEY only cooperated
3 TRANQUILIZER only cooperated
4 neither cooperated

THE TOP THREE RULES

Niceness, forgiveness, and provocability are all well-illustrated by the winning rule, TIT FOR TAT. It is never the first to defect, it forgives an isolated defection after a single response, but it is always provoked by a defection no matter how good the interaction has been so far.

The rule which came in second was submitted by Danny Champion of Las Cruces, New Mexico. This rule cooperates on the first 10 moves and plays tit-for-tat for 15 more moves. After 25 moves, the program cooperates unless all of the following are true: the other player defected on the previous move, the other player has cooperated less than 60% of the time, and the random number between 0 and 1 is greater than the other player's cooperation rate.

Like the other top-ranking entries, this rule was nice and therefore did just as well as TIT FOR TAT with the three representatives which were themselves nice. Champion's rule was provoked by TRANQUILIZER's late defections, and so did well with it. With TESTER, however, Champion's rule did 12 points worse than TIT FOR TAT because, while CHAMPION was giving its unconditional cooperation on the first 10 moves, it was exploited five times by TESTER. But this did not get out of hand, because once CHAMPION defected on move 11, TESTER apologized and they cooperated thereafter.

The third place rule was submitted by Otto Börufsen of Underöy, Norway. The rule plays tit-for-tat except that it has a check for echo effects, for RANDOM, and for a very uncooperative other player. The check for an echo effect is actually too weak. It tests for three moves of alternating exploitation, and if this is found, it substitutes cooperation for its next defection no matter how many moves later this defection occurs. The trouble is that when playing TRANQUILIZER, TRANQUILIZER sometimes defects on move n and n+2 thereby setting up an apparent echo effect. Then whenever TRANQUILIZER next defects, Börufsen's rule will not be provoked. This unnecessary type of cooperation not only costs two points each time it happens but also slightly increases TRANQUILIZER's propensity to defect in the future.

THE ROLE OF THE ENVIRONMENT

THE LESSONS DRAWN FROM ROUND ONE

The report on the first round of the Prisoner's Dilemma computer tournament (Axelrod, 1980) concluded that it paid to be not only nice but also forgiving. To illustrate that point, it was shown that such forgiving decision rules as TIT FOR TWO TATS and REVISED DOWNING would have done even better than TIT FOR TAT in the environment of the first round.

In the second round, many contestants apparently hoped that these conclusions would still be relevant. Of the entries, 39 were nice, and nearly all of them were at least somewhat forgiving. TIT FOR TWO TATS itself was submitted by an evolutionary biologist from the United Kingdom, John Maynard Smith. But it came in only 24th. As we have seen, REVISED DOWNING was submitted twice. But in the second round, it was in the bottom half of the tournament.

What seems to have happened is an interesting interaction between people who drew one lesson and people who drew another from the first round. Lesson One was "be nice and forgiving." Lesson Two was "if others are going to be nice and forgiving, it pays to try to take advantage of them." The people who drew Lesson One suffered in the second round from those who drew Lesson Two. As we have seen, rules like TRANQUILIZER and TESTER were effective at exploiting rules which were too easy-going. But the people who drew Lesson Two did not themselves do very well either. The reason is that in trying to exploit other rules, they often eventually got punished enough to make the whole game less rewarding for *both* players than pure mutual cooperation would have been. For example, TRANQUILIZER and TESTER themselves came in only 27th and 46th place, respectively. They each did better than TIT FOR TAT with fewer than one-third of the rules. None of the other entries which tried to apply Lesson Two ranked at the top either.

While the use of Lesson Two tended to invalidate Lesson One, no one was able to benefit more than they were hurt in the tournament by his attempt to exploit the easy-going rules. The most successful entries tended to be relatively small variations on TIT FOR TAT which were designed to recognize and give up on a seemingly RANDOM player or a very uncooperative player. But even the implementations of these ideas did not do better than the pure form of TIT FOR TAT. So TIT FOR TAT, which got along with almost everyone, won the second round of the tournament just as it had won the first round.

ROBUSTNESS OF THE TOURNAMENT RESULTS

Would the results of the second round have been much different if the distribution of entries had been substantially different? Put another way, how *robust* are the results?

A good way to examine this question is to construct a series of hypothetical tournaments each with a different relative weighting of the types of rules participating. The five representatives can serve us again, since each can be thought of as having a large constituency. Together with the unrepresented constituency of the residuals, these five constituencies fully account for the performance of each rule in the tournament. This allows us to see what would have happened if one of the constituencies had been much larger than it actually was. To be specific, we will construct the hypothetical tournaments which would have resulted if a given constituency had been five times as large as it actually was. Since there are six constituencies, this gives us six hypothetical tournaments. Each of these hypothetical tournaments represents a substantial variation on the original tournament because it quintuples the size of one or another of the six constituencies. And each represents a different kind of variation since each is based on magnifying the effect of a given aspect of the tournament.[4]

4. Here is how the hypothetical tournament scores are calculated. To make the constituency of a given representative five times as large as it actually was, let $T' = T + 4cs$

In fact, the scores in these hypothetical tournaments correlate fairly well with the scores in the original tournament. If the residuals were five times as large as they actually were, the tournament scores would still have a correlation of .82 with the scores in the actual tournament. And if the constituency of any of the five representatives were made five times as large as it actually was, the tournament scores would still be correlated from .90 to .96 with the tournament scores of the actual second round. This means that the overall results would have been fairly stable even if the distribution of entries by types of program had been quite different from what it actually was. Thus the overall results of the second round are quite robust.

But moving from the tournament as a whole to the identity of the winner, we can also ask how TIT FOR TAT would have done in these six hypothetical tournaments. The answer is that it would still have come in first place in five of the six hypothetical tournaments. This is a very strong result since it shows that TIT FOR TAT would still have been the best rule of those submitted under very wide variations in the environment it had to face.

The one exception to TIT FOR TAT's success in the hypothetical tournaments is a very interesting one. Had the constituency of the REVISED STATE TRANSITION rule been five times as large as it actually was, TIT FOR TAT would have come in second. First place would have been won by a rule which ranked only 49th in the actual tournament. Ths rule was submitted by Robert Leyland of Auckland, New Zealand. Its motivation is similar to TRANQUILIZER's in that it starts off cooperatively but then sees how much it can get away with. As can be seen from Table 4, Leyland's rule came in 49th largely because it did so poorly with the third representative and with TRANQUILIZER. But it did do 90 points better than TIT FOR TAT with REVISED STATE TRANSITION, since that rule was quite well taken in by the early cooperations. If the constituency of the REVISED STATE TRANSITION representative had been five times as large as it actually was, Leyland's rule would actually have done better than TIT FOR TAT or any other submitted rule in the tournament as a whole.

where T′ is the new tournament score. T is the original tournament score, c is the coefficient in the regression equation of the representative whose effect is to be magnified, and s is the score of the given rule with that representative. It should be noted that the idea of a "constituency" of a representative is defined in this way, and that a typical rule is part of the constituency of several representatives. The hypothetical tournament in which the residuals are given added weight is constructed in an analogous manner with T′ = T + 4r, where r is the residual in the regression equation for the score of a given rule.

The fact that TIT FOR TAT won five of the six major variants of the tournament and came in second in the sixth, shows just how robust TIT FOR TAT's victory really was.

SURVIVAL OF THE FITTEST

THE ECOLOGICAL PERSPECTIVE

Another way to examine the robustness of the results is to construct a whole sequence of hypothetical rounds of the tournament. Some of the rules are so unsuccessful that they are unlikely to be tried again in future tournaments, while others are successful enough so that their continued presence in later tournaments would be more likely. For this reason, it would be helpful to analyze what would happen over a series of tournaments if the more successful rules became a larger part of the environment for each rule, and the less successful rules were met less often.

Evolutionary biology provides a useful way to think about this problem (Trivers, 1971; Dawkins, 1976: 197-202; Maynard Smith, 1978). Imagine that there are a very large number of animals of a single species, which interact with each other quite often. Suppose the interactions take the form of a Prisoner's Dilemma: When two animals meet, they can cooperate with each other, not cooperate with each other, or one animal could exploit the other. Suppose further that each animal can recognize individuals it has already interacted with and can remember salient aspects of their interaction such as whether the other has usually cooperated. The tournament can then be regarded as a simulation of a single generation of such animals with each decision rule being employed by large and equal numbers of individuals. One convenient implication of this interpretation is that a given animal is just about as likely to interact with an animal using its own decision rule as it is to run into an animal with any other rule.

The interesting part of this analogy is that it allows us to simulate future generations of a tournament. We simply have to interpret the average payoff received by an individual as proportional to that individual's expected number of offspring. For example, if one rule gets twice as high a tournament score in the initial round as another rule, then it will be twice as well-represented in the next round. This creates a simulated second generation of the tournament in which the average score achieved by a rule is the *weighted* average of its score with each of the rules, where the weights are proportional to the success of the other rules in the initial generation. Thus RANDOM, for example, will be less important in the second generation while TIT FOR TAT and the other high-ranking rules will be more important.

THE DYNAMICS OF THE ECOLOGY

The simulation of this process for the Prisoner's Dilemma tournament is actually quite straightforward. The tournament matrix (which is displayed in abbreviated form in Table 3) provides the expected payoff when an individual of one type interacts with an individual of another type. Starting with proportions of each type in a given generation, it is only necessary to calculate the proportions which will exist in the next generation. This is done by calculating the weighted average of the scores of a given rule with all other rules where the weights are the numbers of the other rules which exist in the current generation. The numbers of a given rule in the next generation is then taken to be proportional to the product of its numbers in the current generation and its score in the current generation.

The results provide an interesting story. The first thing that happens is that the lowest ranking 11 entries fall to half their initial size by the fifth generation while the middle-ranking entries tend to hold their own and the top-ranking entries slowly grow in size. By the 50th generation, the rules which ranked in the bottom third of the tournament have virtually disappeared, while most of those in the middle third have started to shrink, and those in the top third are continuing to grow (see Figure 1).

This simulates survival of the fittest. A rule which is successful on average with the current distribution of rules in the population will become an even larger proportion of the environment of the other rules in the next generation. At first a rule which is successful with all sorts of rules will proliferate, but later as the unsuccessful rules disappear, success requires good performance with other successful rules.

This is an ecological perspective rather than a strictly evolutionary perspective. There are no new rules of behavior introduced so there is no mutation to drive evolution.[5] But there is a changing distribution of given types of rules. The less successful rules become less common and the more successful rules proliferate. The statistical distribution of types

5. For an evolutionary perspective on the iterated Prisoner's Dilemma, see Axelrod (1979).

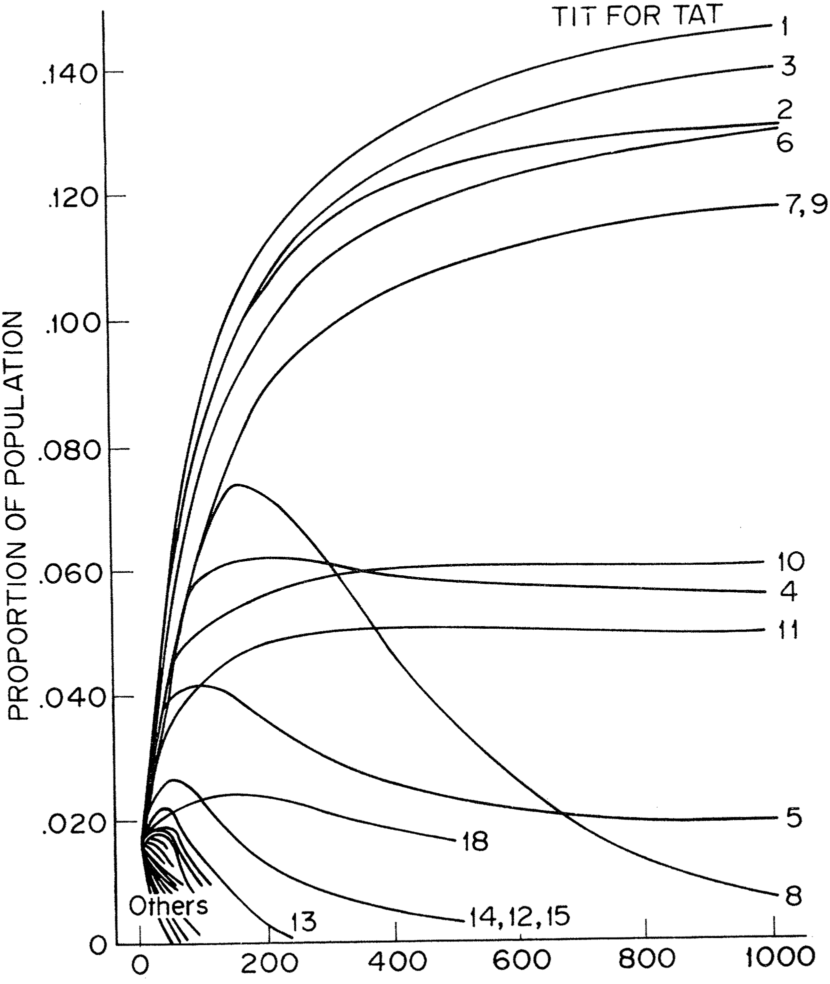

Figure 1: Simulated Ecological Success of the Decision Rules

of individuals changes in each generation, and this changes the environment with which each of the individual types has to interact.

The process of change slows as the remaining rules tend to achieve averages which are similar to each other. By the 500th generation only

11 rules are larger than their initial size in the population, and these happen to be the rules which originally ranked in the top 11. Together these 11 rules formed 96% of the population at that time. The rule which ranked fifth in the tournament grew to three times its original size in the population and then began to sink after generation 100. The rule which ranked eighth, and was the only nonnice rule in the top 15, grew to four times its original size but began to shrink after generation 150 to reach only a third of its original size by the 1000th generation.

The results show that the entries which ranked at the top in the tournament actually do quite well with other successful entries, and thus did not rely for their success merely on their ability to get high scores with unsuccessful rules. While there are a few exceptions, such as rules 5 and 8, most of the top-ranking entries continued to do quite well for very long periods.

The results also provide yet another victory for TIT FOR TAT. TIT FOR TAT had a very slight lead in the original tournament, and never lost this lead in simulated generations. By the 1000th generation it was 14.5% of the whole population, followed by the third place rule at 13.9% and then the second place rue at 13.1%. And TIT FOR TAT was still growing at .05% per generation which was a faster rate than any other rule.

IS TIT FOR TAT THE BEST DECISION RULE?

We have seen that in the second round, TIT FOR TAT achieved the highest average score of the 63 rules in the tournament. It also achieved the highest score in five of the six hypothetical tournaments which were constructed by magnifying the effects of different types of rules. And in the sixth hypothetical tournament it came in second. Finally, TIT FOR TAT never lost its first-place standing in a simulation of future generations of the tournament.

Added to its victory in the first round of the tournament, and its fairly good performance with human subjects (Oskamp, 1971; Wilson, 1971), one might well ask whether TIT FOR TAT is *the* best decision rule for the Prisoner's Dilemma. I think not, and here are my three reasons.

First, TIT FOR TAT could have been beaten in the second round by any rule which was able to identify and never cooperate with RAN-

DOM, while not mistaking other rules for RANDOM. Such a rule would be hard to design, but presumably it would be possible.[6]

Second, had only the entries which actually ranked in the top half been present, then TIT FOR TAT would have come in fourth after the ones which actually came in 25th, 16th, and 8th.[7] While the simulation of future tournaments is a more meaningful way of altering the environment to take account of the differential survival of the fittest, the fact remains that in a tournament among just the top half, TIT FOR TAT comes in only fourth.

Third, the most powerful argument against absolute superiority of TIT FOR TAT is the one demonstrated at the start of this article: There is no best rule independent of the environment.

Since there is no absolutely best rule, what we can say for TIT FOR TAT's successes is that it is a very robust rule; it does very well over a wide range of environments. Part of its success might be that other rules anticipate its presence and are designed to do well with it. Doing well with TIT FOR TAT requires cooperating with it, and this in turn helps TIT FOR TAT. As we have seen, even rules like TESTER which were designed to see what they can get away with, quickly apologize to TIT FOR TAT. Any rule which tries to take advantage of TIT FOR TAT will simply hurt itself. Since this is so well-understood, and the possibility of meeting TIT FOR TAT is so salient, and TIT FOR TAT is so easy to recognize, it reaps the benefits of its own nonexploitability.

On the other hand, TIT FOR TAT foregoes the possibility of exploiting other rules. While such exploitation is occasionally fruitful, there are serious problems in trying to turn it into an effective strategy over a wide range of environments. We have seen, for example, that if exploitable rules like REVISED STATE TRANSITION were a much larger part of the tournament than they actually were, then an otherwise low-ranking rule would have been able to win the tournament. But the problems with trying to exploit others are manifold. In the first place, if

6. Even knowing the rules which were submitted does not make the task easy. I tried to design such a rule. It played TIT FOR TAT except that it would always defect after move 100 if its score then was less than 2.75 per move. This rule averaged 431.3 points with the 63 rules in the tournament, which is a score exceeded by three of the rules that were actually submitted. The problem was that there were still four rules which this one gave up on, but which TIT FOR TAT did better with.

7. These three rules do well with the same ones as do TESTER and TRANQUILIZER, and for the same reasons. Not being nice, they are able to exploit rules which are too forgiving for their own good. But in the tournament as a whole these rules did not do as well as TIT FOR TAT because of the frequency of less-forgiving rules in the bottom half of the overall ranking.

a rule defects to see what it can get away with, it risks retaliation from the rules which are provocable. In the second place, once mutual recriminations set in, it can be difficult to extract oneself from them. And, finally, the attempt to identify and give up on unresponsive rules (such as RANDOM or excessively uncooperative rules) seems to have often mistakenly led to giving up on rules which were in fact salvageable by a more patient rule like TIT FOR TAT. Being able to exploit the exploitable without paying too high a cost with the others is a task which was not successfully accomplished by any of the entries in round two of the tournament.

What accounts for TIT FOR TAT's robust success is its combination of niceness, provocability, and forgiveness. Its niceness prevents it from getting into unnecessary trouble. Its provocability discourages the other side from persisting whenever defection is tried. And its forgiveness helps restore mutual cooperation.

REFERENCES

AXELROD, R. (1980) "Effective Choice in the Prisoner's Dilemma." J. of Conflict Resolution 24: 3-25.

——— (1979) "The Evolution of Cooperation in the Prisoner's Dilemma." Institute of Public Policy Studies, University of Michigan, Discussion Paper 143.

DAWKINS, R. (1977) *The Selfish Gene.* New York: Oxford Univ. Press.

MAYNARD SMITH, J. (1978) "The Evolution of Behavior." Scientific Amer. 239: 176-192.

OSKAMP, S. (1971) "Effects of Programmed Strategies on Cooperation in the Prisoner's Dilemma and Other Mixed-Motive Games." J. of Conflict Resolution 15: 225-259.

RAPOPORT, A. and A. M. CHAMMAH (1965) *Prisoner's Dilemma.* Ann Arbor: Univ. of Michigan Press.

TRIVERS, R. T. (1971) "The Evolution of Reciprocal Altruism." Q. Rev. of Biology 46: 35-57.

WILSON, W. (1971) "Reciprocation and Other Techniques for Inducing Cooperation in the Prisoner's Dilemma Game." J. of Conflict Resolution 15: 167-195.