

Suspicion: Recognising and evaluating the effectiveness of extortion in the Iterated Prisoner's Dilemma

Vincent A. Knight

Nikoleta E. Glynatsi

Jonathan Gillard

October 23, 2018

Abstract

The Iterated Prisoner's Dilemma is a model for rational and evolutionary interactive behaviour. It has applications both in the study of human social behaviour as well as in biology. It is used to understand when and how a rational individual might accept an immediate cost to their own utility for the direct benefit of another.

Much attention has been given to a class of strategies called Zero Determinant strategies. It has been theoretically shown that these strategies can “extort” any player.

In this work, an approach to identify if observed strategies are playing in an extortionate way is described. This corresponds to a mathematical model of suspicion. Furthermore, experimental analysis of a large tournament with 204 strategies is considered. In this setting the most highly performing strategies do not play in an extortionate way against each other but do against lower performing strategies. This suggests that whilst the theory of Zero Determinant strategies indicates that memory is not of fundamental importance to the evolution of cooperative behaviour, this is incomplete.

1 Introduction

Agent based game theoretic models have become a stalwart of the underpinning mathematics of interactive behaviours. One of the major pieces of work in this area is the pair of original computer tournaments run by Robert Axelrod [1, 2]. These tournaments pitted submitted computer strategies against each other in plays of the Iterated Prisoner's Dilemma. A common game where agents can choose to pay a slight cost to their immediate utility in the hope of building a reputation. This has been used in economic and evolutionary game theory to understand the evolution of cooperative behaviour.

In [16] a class of strategies that can provably extort any given opponent was described. In [6, 10] some questions have already been asked about the true effectiveness of these strategies in an evolutionary setting. Here another question is asked: is it possible to recognise this extortionate behaviour? A mathematical procedure for suspicion is presented: this reflects the way that the continued actions of an extortionate individual might raise suspicion.

This work makes use of the Axelrod Python library [9, 11] with a large number of Prisoner Dilemma strategies available to give an extensive numerical example of the ideas presented. The approach is presented in Section 2. All of the code and data discussed in Section 3 is open sourced, archived and written according to best scientific principles [22]. The data archive can be found at [8].

2 Recognising Extortion

In [16], given a match between 2 memory one strategies, the concept of Zero Determinant (ZD) strategies is introduced. Memory one strategies are represented as elements of \mathbb{R}^4 mapping a state of $\{C, D\}^2$ to a probability of cooperating. A match between two such strategies creates a Markov chain with transient states $\{C, D\}^2$. The main result of [16] is that given two memory one players $p, q \in \mathbb{R}^4$, a linear relationship between the players' scores can be forced by one of the players.

Using the notation of [16], the utilities for player p are given by $S_x = (R, S, T, P)$ and for player q by $S_y = (R, T, S, P)$ and the stationary scores of each player are given by S_X and S_Y respectively. The main result of [16] is that if

$$\tilde{p} = \alpha S_x + \beta S_y + \gamma \tag{1}$$

or

$$\tilde{q} = \alpha S_x + \beta S_y + \gamma \tag{2}$$

where $\tilde{p} = (1 - p_1, 1 - p_2, p_3, p_4)$ and $\tilde{q} = (1 - q_1, 1 - q_2, q_3, q_4)$ then:

$$\alpha S_X + \beta S_Y + \gamma = 0 \quad (3)$$

In [16] a particular type of ZD strategy is defined: extortionate strategies. If:

$$\gamma = -P(\alpha + \beta) \quad (4)$$

then the player can ensure they get a score χ times larger than the opponent. This extortion coefficient is given by:

$$\chi = \frac{-\beta}{\alpha} \quad (5)$$

Thus, if (4) holds and $\chi > 1$ a player is said to extort their opponent. Here, the reverse problem is considered: given a $p \in \mathbb{R}^4$ how does one identify α, β if they exist and is the strategy in fact acting in an extortionate way?

In this case constraints (1) and (4) correspond to:

$$\tilde{p}_1 = \alpha R + \beta R - P(\alpha + \beta) \quad (6)$$

$$\tilde{p}_2 = \alpha S + \beta T - P(\alpha + \beta) \quad (7)$$

$$\tilde{p}_3 = \alpha T + \beta S - P(\alpha + \beta) \quad (8)$$

$$\tilde{p}_4 = \alpha P + \beta P - P(\alpha + \beta) \quad (9)$$

Equation (9) ensures that $p_4 = \tilde{p}_4 = 0$. Equations (6-8) can be used to eliminate α, β , giving:

$$\tilde{p}_1 = \frac{(R - P)(\tilde{p}_2 + \tilde{p}_3)}{S + T - 2P} \quad (10)$$

with:

$$\chi = \frac{\tilde{p}_2(P - T) + \tilde{p}_3(S - P)}{\tilde{p}_2(P - S) + \tilde{p}_3(T - P)} \quad (11)$$

Given a strategy $p \in \mathbb{R}^4$ equations (9-11) can be used to check if a strategy is extortionate. The conditions correspond to:

$$p_1 = \frac{(R - P)(p_2 + p_3) - R + T + S - P}{S + T - 2P} \quad (12)$$

$$p_4 = 0 \quad (13)$$

$$1 > p_2 + p_3 \quad (14)$$

The algebraic steps necessary to prove these results are available in the supporting materials.

All extortionate strategies reside on a triangular (14) plane (12) in 3 dimensions (13). Using this formulation it can be seen that a necessary (but not sufficient) condition for an extortionate strategy is that it cooperates on average less than 50% of the time when in a state of disagreement with the opponent.

As an example, consider the known extortionate strategy $p = (8/9, 1/2, 1/3, 0)$ from [19] which is referred to as **Extort-2**. In this case, for the standard values of (R, T, S, P) constraint (12) corresponds to:

$$p_1 = \frac{2(p_2 + p_3) + 1}{3} = \frac{2(1/2 + 1/3) + 1}{3} = \frac{8}{9} \quad (15)$$

It is clear that in this case all constraints hold.

This approach could in fact be used to confirm that a given strategy is acting in an extortionate manner even if it is not a memory one strategy. However, in practice, if a closed form for p is not known, then due to measurement and/or numerical error this would not work.

This problem can be written in the following linear algebraic form where $x = (\alpha, \beta)$ and $p^* = (\tilde{p}_1 - 1, \tilde{p}_2 - 1, \tilde{p}_3)$:

$$Cx = p^* \quad (16)$$

C corresponds to equations (6-8) and is given by:

$$C = \begin{bmatrix} R - P & R - P \\ S - P & T - P \\ T - P & S - P \end{bmatrix} \quad (17)$$

Note that in general, equation (16) will not necessarily have a solution. From the Rouché-Capelli theorem if there is a solution it is unique as $\text{rank}(C) = 2$ which is the dimension of the variable x . The best fitting x^* is defined by:

$$x^* = \underset{x}{\text{argmin}} \|Cx - p^*\|_2^2 \quad (18)$$

Known results [12, 18, 21] can now be applied:

$$x^* = (C^T C)^{-1} C^T p^* \quad (19)$$

The squared norm of the remaining error is referred to as SS_{error} :

$$\text{SS}_{\text{error}} = \|Cx^* - p^*\|_2^2 \quad (20)$$

This gives expressions for α, β as $\alpha = x_1^*$ and $\beta = x_2^*$ thus the conditions for a strategy to be acting extortionately become:

$$p_4^* = 0 \quad (21)$$

$$-x_2^* < x_1^* \quad (22)$$

A further known result [12, 18, 21] gives an expression for SS_{error} :

$$\text{SS}_{\text{error}} = p^{*T} p^* - p^* C (C^T C)^{-1} C^T p^* \quad (23)$$

By observing interactions (human or otherwise), their memory one representation can be inferred and if (21-22) hold then (23) can be used to identify if a strategy is acting extortionately. Suspicion of extortion then corresponds to a threshold on SS_{error} . Comparing theoretic and actual plays of the IPD is not novel, see for example [17].

In the next section, this idea will be illustrated by observing the interactions that take place in a large computer based tournament of the IPD.

3 Numerical experiments

In [19] results from a tournament with 19 strategies, was presented with specific consideration given to ZD strategies. This tournament is reproduced here using the Axelrod-Python library [9]. To obtain a good measure of the corresponding transition rates for each strategy all matches have been run for 2000 turns and every match has been repeated 60 times. All of this interaction data is available at [8]. Note that in the interest of open scientific practice, [8] also contains interaction data for noisy and probabilistic ending interactions which are not investigated here. A good match between the inferred Markov chain and the state distribution of the actual interactions has been verified. Data for this is presented in the supplementary materials.

Figure ?? shows the SS_{error} values for all the strategies in the tournament, as reported in [19] the extortionate strategy (which has an expected SS_{error} approximately 0) gains a large number of wins.

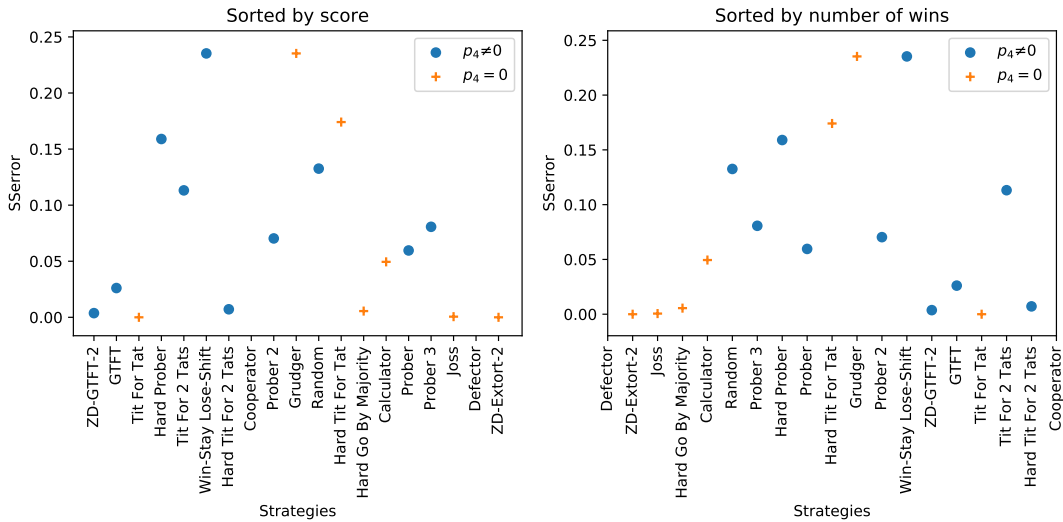


Figure 1: SS_{error} and state probabilities for the strategies of [19], ordered both by number of wins and overall score.

Here, the work of [19] is extended by investigating a tournament with 204 strategies. The results of this analysis are shown in Figure 2. The top ranking strategies by number of wins seem to be extortionate (but not against all strategies) and it can be seen that a small sub group of strategies achieve mutual defection. All the top ranking strategies according to score achieve mutual cooperation and do not extort each other, however they **do** exhibit extortionate behaviour towards a number of the lower ranking strategies.

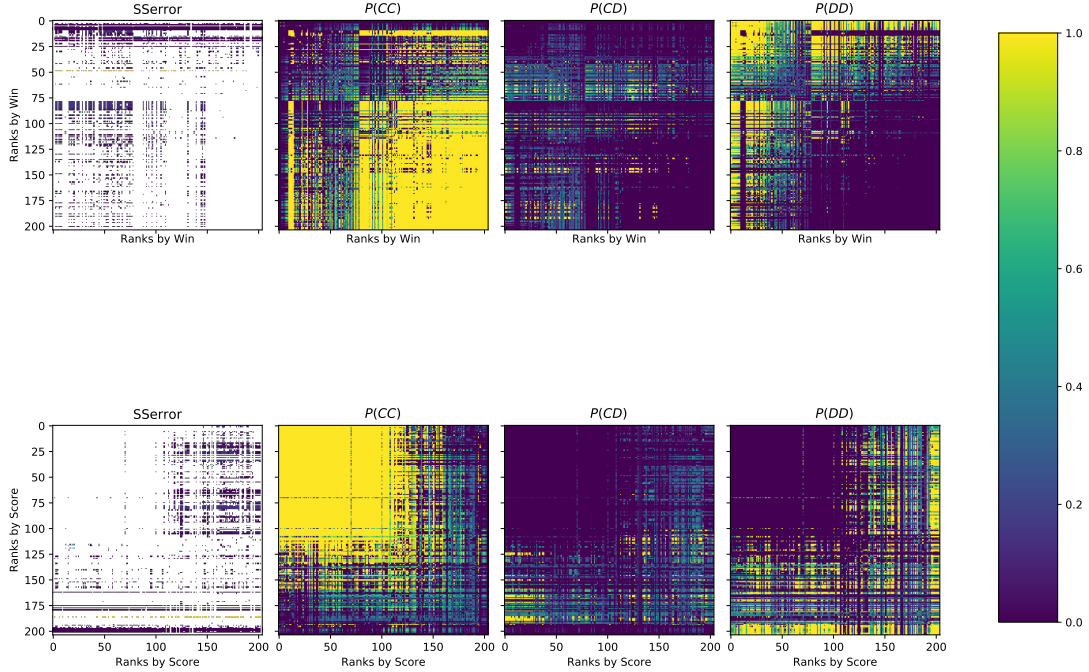


Figure 2: SS_{error} for the strategies for the full tournament. Only strategy interactions for which $p_4 = 0$ and $\chi > 1$ are displayed. Note that $P(DC)$ is not shown as it corresponds to the transpose of $P(CD)$.

A detailed look at selected strategies is given in Table 1. It can be seen that **Extort-2** wins many matches but does not achieve a high mean score or a high mutual cooperation rate ($P(CC)$) but it does win most of its matches.

Rank	Name	Score per turn	$P(\text{Win})$	$P(CC)$	$P(C CC)$	$P(C CD)$	$P(C DC)$	$P(C DD)$	SSError	α	β	χ
1	EvolvedLookerUp2.2.2	2.944	0.230	0.673	0.938	0.498	0.207	0.470	0.0095	0.038	-0.104	2.765
7	Evolved ANN 5	2.893	0.225	0.682	1.000	0.930	0.001	0.000	0.0011	1.001	-0.013	12.225
31	ZD-GTFT-2	2.721	0.000	0.806	1.000	0.125	1.000	0.250	0.0037	0.199	-0.176	0.889
45	ZD-GEN-2	2.689	0.016	0.801	1.000	0.562	0.500	0.125	0.0009	0.099	-0.088	0.889
69	Tit For Tat	2.638	0.000	0.723	1.000	0.000	1.000	0.000	0.0000	0.200	-0.200	1.000
88	Win-Stay Lose-Shift	2.616	0.099	0.649	1.000	0.000	0.000	1.000	0.2353	0.012	-0.188	16.000
200	ZD-Extort-2	1.821	0.851	0.179	0.889	0.500	0.334	0.000	0.0000	0.056	-0.111	1.998

Table 1: Summary of overall results for a selected list of strategies. The transition rates are computed as an average over all matches.

4 Conclusion

This work defines an approach to measure whether or not a player is playing a strategy that corresponds to an extortionate strategy as defined in [16]: a mathematical model for suspicion. All extortionate strategies have been classified as lying on a triangular plane. This rigorous classification fails to be robust to small measurement error, thus a statistical approach is proposed approximating the solution of a linear system. Using this, a large number of pairwise interactions is simulated and in fact very few strategies are found to act extortionately.

The work of [16], whilst showing that a clever approach to taking advantage of another memory one strategy exists: this is not the full story. Whilst the elegance of this result is very attractive, just as the simplicity of the victory of Tit For Tat in Axelrod's original tournaments was, it is incomplete. Extortionate strategies achieve a high number of wins but they do not achieve a high score which corresponds to the fitness landscape in an evolutionary sense. From the large number of interactions a payoff matrix S can be measured where S_{ij} denotes the score (using standard values of $(R, S, T, P) = (3, 0, 5, 1)$) of the i th strategy against the j th strategy. Using this, the replicator equation describes the evolution of the system based on a population density fitness function:

$$\frac{dx}{dt} = x(S - x^T Sx) \quad (24)$$

Equation (24) is solved numerically through an integration technique described in [15] and Figure 3 shows the evolution of the distribution of the system: the various strategies are ranked by scores. It is clear to see that only the high ranking strategies survive the evolutionary process (in fact, only 18 have a final distribution value greater than 10^{-2}). This confirms the findings of [10] in which sophisticated strategies resist evolutionary invasion of shorter memory strategies. Recalling Figure 2 this demonstrates that:

- Cooperation emerges through the evolutionary process: the high scoring strategies do not exhibit extortionate behaviour towards each other.
- Extortionate strategies do not survive the evolutionary process.

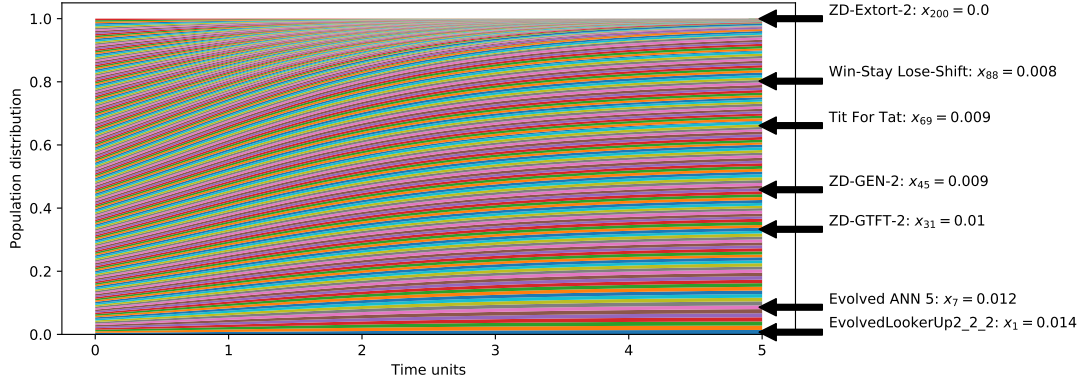


Figure 3: Numerical simulation of the replicator equation (24): strategies are ordered by score. Some selected strategies are highlighted with their long run population distribution.

Following Axelrod’s seminal work [1, 2], it was commonly thought that evolutionary cooperation required strategies that followed a simple set of rules. The discover/definition of extortionate strategies [16] seemingly showed that simple strategies could be taken advantage of. In this manuscript it has been shown that not only is it possible to be suspicious of extortionate strategies but that more complex strategies can be evolutionary stable. The complex strategies in question were obtained through reinforcement learning approaches [5, 10]. Thus, this work demonstrates the possibility for the evolution of cooperation through suspicion.

Acknowledgements

The following open source software libraries were used in this research:

- The Axelrod [9, 11] library (IPD strategies and tournaments).
- The sympy library [13] (verification of all symbolic calculations).
- The matplotlib [4] library (visualisation).
- The pandas [20], dask [3] and NumPy [14] libraries (data manipulation).
- The SciPy [7] library (numerical integration of the replicator equation).

This work was performed using the computational facilities of the Advanced Research Computing @ Cardiff (AR-CCA) Division, Cardiff University.

References

- [1] Robert Axelrod. “Effective Choice in the Prisoner’s Dilemma”. In: *Journal of Conflict Resolution* 24.1 (Mar. 1980), pp. 3–25. DOI: 10.1177/002200278002400101.
- [2] Robert Axelrod. “More Effective Choice in the Prisoner’s Dilemma”. In: *Journal of Conflict Resolution* 24.3 (Sept. 1980), pp. 379–403. DOI: 10.1177/002200278002400301.

- [3] Dask Development Team. *Dask: Library for dynamic task scheduling*. 2016. URL: <http://dask.pydata.org>.
- [4] Michael Droettboom et al. *Matplotlib/Matplotlib V2.2.2*. 2018. DOI: 10.5281/zenodo.1202077.
- [5] Marc Harper et al. “Reinforcement learning produces dominant strategies for the Iterated Prisoner’s Dilemma”. In: *PLOS ONE* 12.12 (Dec. 2017). Ed. by Yong Deng, e0188046. DOI: 10.1371/journal.pone.0188046.
- [6] C. Hilbe, M. A. Nowak, and K. Sigmund. “Evolution of extortion in Iterated Prisoner’s Dilemma games”. In: *Proceedings of the National Academy of Sciences* 110.17 (Apr. 2013), pp. 6913–6918. DOI: 10.1073/pnas.1214834110.
- [7] Eric Jones, Travis Oliphant, Pearu Peterson, et al. *SciPy: Open source scientific tools for Python*. [Online; accessed [today]]. 2001–. URL: <http://www.scipy.org/>.
- [8] Vincent Knight. *Raw data for: "Suspicion: Recognising and evaluating the effectiveness of extortion in the Iterated Prisoner’s Dilemma"*. June 2018. DOI: 10.5281/zenodo.1297075. URL: <https://doi.org/10.5281/zenodo.1297075>.
- [9] Vincent Knight et al. “An Open Framework for the Reproducible Study of the Iterated Prisoner’s Dilemma”. In: *Journal of Open Research Software* 4 (Aug. 2016). DOI: 10.5334/jors.125.
- [10] Vincent Knight et al. “Evolution Reinforces Cooperation with the Emergence of Self-Recognition Mechanisms: an empirical study of the Moran process for the iterated Prisoner’s dilemma”. In: 1707.
- [11] Vince Knight et al. *Axelrod-Python/Axelrod: V4.2.0*. 2018. DOI: 10.5281/zenodo.1252994.
- [12] Michael H Kutner, Chris Nachtsheim, and John Neter. *Applied linear regression models*. McGraw-Hill/Irwin, 2004.
- [13] Aaron Meurer et al. “SymPy: symbolic computing in Python”. In: *PeerJ Computer Science* 3 (Jan. 2017), e103. DOI: 10.7717/peerj-cs.103.
- [14] Travis E. Oliphant. *Guide to NumPy: 2nd Edition*. CreateSpace Independent Publishing Platform, 2015. ISBN: 9781517300074. URL: <https://www.amazon.com/Guide-NumPy-Travis-Oliphant-PhD/dp/151730007X?SubscriptionId=0JYN1NVW651KCA56C102&tag=techkie-20&linkCode=xm2&camp=2025&creative=165953&creativeASIN=151730007X>.
- [15] Linda Petzold. “Automatic Selection of Methods for Solving Stiff and Nonstiff Systems of Ordinary Differential Equations”. In: *SIAM Journal on Scientific and Statistical Computing* 4.1 (Mar. 1983), pp. 136–148. DOI: 10.1137/0904010.
- [16] W. H. Press and F. J. Dyson. “Iterated Prisoner’s Dilemma contains strategies that dominate any evolutionary opponent”. In: *Proceedings of the National Academy of Sciences* 109.26 (May 2012), pp. 10409–10413. DOI: 10.1073/pnas.1206569109.
- [17] David G. Rand and Martin A. Nowak. “Human cooperation”. In: *Trends in Cognitive Sciences* 17.8 (Aug. 2013), pp. 413–425. DOI: 10.1016/j.tics.2013.06.003.
- [18] Calyampudi Radhakrishna Rao. *Linear statistical inference and its applications*. Vol. 2. Wiley New York, 1973.
- [19] A. J. Stewart and J. B. Plotkin. “Extortion and cooperation in the Prisoner’s Dilemma”. In: *Proceedings of the National Academy of Sciences* 109.26 (June 2012), pp. 10134–10135. DOI: 10.1073/pnas.1208087109.
- [20] Data Structures et al. “PROC. OF THE 9th PYTHON IN SCIENCE CONF. (SCIPY 2010)”. In: 2010.
- [21] Jon Wakefield. *Bayesian and frequentist regression methods*. Springer Science & Business Media, 2013.
- [22] Greg Wilson et al. “Best Practices for Scientific Computing”. In: *PLoS Biology* 12.1 (Jan. 2014). Ed. by Jonathan A. Eisen, e1001745. DOI: 10.1371/journal.pbio.1001745.

Supplementary materials

Proof of algebraic condition for extortionate strategies

The defining equations for an extortionate strategy are:

$$\tilde{p}_1 = \alpha(R - P) + \beta(R - P) \quad (1)$$

$$\tilde{p}_2 = \alpha(S - P) + \beta(T - P) \quad (2)$$

$$\tilde{p}_3 = \alpha(T - P) + \beta(S - P) \quad (3)$$

$$\tilde{p}_4 = 0 \quad (4)$$

Using equation (2), α is isolated

$$\alpha = \frac{-\beta(P - T) - \tilde{p}_2}{P - S} \quad (5)$$

Substituting this value in to equation (3), β is isolated:

$$\beta = -\frac{P\tilde{p}_1 - P\tilde{p}_2 + S\tilde{p}_2 - T\tilde{p}_1}{(S - T)(2P - S - T)} \quad (6)$$

Substituting this back in to (5) gives:

$$\alpha = \frac{-\tilde{p}_2 + (P - T)(P\tilde{p}_1 - P\tilde{p}_2 + S\tilde{p}_2 - T\tilde{p}_1)}{(S - T)(2P - S - T)(P - S)} \quad (7)$$

Substituting equations (6-7) in to equation (1) gives the required expression for p_1 .

Taking the ratio of equations (6-7) gives the required expression for χ .

Finally, the condition $\chi > 1$ corresponds to:

$$\tilde{p}_2(P - T) + \tilde{p}_3(S - P) > \tilde{p}_2(P - S) + \tilde{p}_3(T - P) \quad (8)$$

which can be simplified to:

$$\tilde{p}_2 < -\tilde{p}_3 \quad (9)$$

recalling that $\tilde{p}_2 = p_2 - 1$ and $\tilde{p}_3 = p_3$ gives the required result.

Comparison of steady states

Using the pair wise interactions the transition rates p, q can be measured and the steady state probabilities inferred and compared to the actual probabilities of each state. This is done numerically by computing the singular eigenvector of the matrix A [1]:

$$A = \begin{bmatrix} p_1 q_1 & p_1(1 - q_1) & (1 - p_1)q_1 & (1 - p_1)(1 - q_1) \\ p_2 q_2 & p_2(1 - q_2) & (1 - p_2)q_2 & (1 - p_2)(1 - q_2) \\ p_3 q_3 & p_3(1 - q_3) & (1 - p_3)q_3 & (1 - p_3)(1 - q_3) \\ p_4 q_4 & p_4(1 - q_4) & (1 - p_4)q_4 & (1 - p_4)(1 - q_4) \end{bmatrix}$$

Figure 1 shows a regression line fitted to every pairwise interaction with a reported SSError value (pairwise interactions with missing states were omitted). This serves to validate the approach: a part from some edge cases the relationship is consistent.

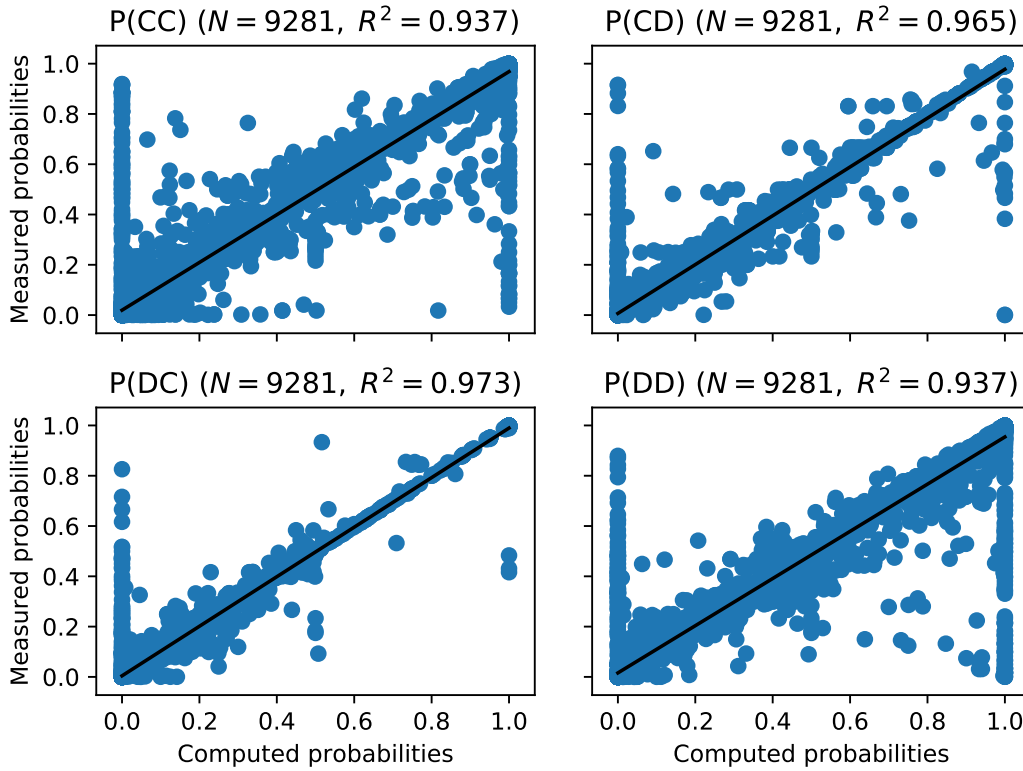


Figure 1: The relationship between the steady state probabilities inferred from the measured transitions and the actual steady state probabilities. A linear regression line is included validating the approach.

References

- [1] William J. Stewart. *Probability, Markov Chains, Queues, and Simulation*. Princeton Univers. Press, July 11, 2009. 760 pp. ISBN: 0691140626. URL: https://www.ebook.de/de/product/8052317/william_j_stewart_probability_markov_chains_queues_and_simulation.html.

List of all strategies used from [21]

1. Adaptive - Deterministic - Memory length: ∞ - [25]
2. Adaptive Tit For Tat: 0.5 - Deterministic - Memory length: ∞ - [39]
3. Aggravater - Deterministic - Memory length: ∞ - [21]
4. Alexei: (D,) - Deterministic - Memory length: ∞ - [43]
5. ALLCorALLD - Stochastic - Memory length: 1 - [2]
6. Alternator - Deterministic - Memory length: 1 - [31, 11]
7. Alternator Hunter - Deterministic - Memory length: ∞ - [21]
8. AntiCycler - Deterministic - Memory length: ∞ - [21]
9. Anti Tit For Tat - Deterministic - Memory length: 1 - [18]
10. AON2 - Deterministic - Memory length: 2 - [19]
11. Adaptive Pavlov 2006 - Deterministic - Memory length: ∞ - [24]
12. Adaptive Pavlov 2011 - Deterministic - Memory length: ∞ - [25]
13. Appeaser - Deterministic - Memory length: ∞ - [21]
14. Arrogant QLearner - Stochastic - Memory length: ∞ - [21]
15. Average Copier - Stochastic - Memory length: ∞ - [21]
16. BackStabber: (D, D) - Deterministic - Memory length: ∞ - [21]
17. Better and Better - Stochastic - Memory length: ∞ - [29]
18. Black - Stochastic - Memory length: 5 - [10]
19. Borufsen - Deterministic - Memory length: ∞ - [10]
20. Bully - Deterministic - Memory length: 1 - [32]
21. Bush Mosteller: 0.5, 0.5, 3.0, 0.5 - Stochastic - Memory length: ∞ - [20]
22. Calculator - Stochastic - Memory length: ∞ - [29]
23. Cautious QLearner - Stochastic - Memory length: ∞ - [21]
24. Cave - Stochastic - Memory length: ∞ - [10]
25. Champion - Stochastic - Memory length: ∞ - [10]
26. Colbert - Deterministic - Memory length: 4 - [10]
27. CollectiveStrategy - Deterministic - Memory length: ∞ - [26]
28. Contrite Tit For Tat - Deterministic - Memory length: 3 - [42]
29. Cooperator - Deterministic - Memory length: 0 - [34, 11, 31]
30. Cooperator Hunter - Deterministic - Memory length: ∞ - [21]
31. Cycle Hunter - Deterministic - Memory length: ∞ - [21]
32. Cycler CCCCCD - Deterministic - Memory length: 5 - [21]

33. Cycler CCCD - Deterministic - Memory length: 3 - [21]
34. Cycler CCD - Deterministic - Memory length: 2 - [31]
35. Cycler DC - Deterministic - Memory length: 1 - [21]
36. Cycler DDC - Deterministic - Memory length: 2 - [31]
37. Cycler CCCDCD - Deterministic - Memory length: 5 - [21]
38. Davis: 10 - Deterministic - Memory length: ∞ - [9]
39. Defector - Deterministic - Memory length: 0 - [34, 11, 31]
40. Defector Hunter - Deterministic - Memory length: ∞ - [21]
41. Desperate - Stochastic - Memory length: 1 - [41]
42. Delayed AON1 - Deterministic - Memory length: 2 - [19]
43. DoubleCrosser: (D, D) - Deterministic - Memory length: ∞ - [21]
44. Doubler - Deterministic - Memory length: ∞ - [29]
45. DoubleResurrection - Deterministic - Memory length: 5 - [15]
46. EasyGo - Deterministic - Memory length: ∞ - [29, 25]
47. Eatherley - Stochastic - Memory length: ∞ - [10]
48. EugeneNier: (D,) - Deterministic - Memory length: ∞ - [43]
49. Eventual Cycle Hunter - Deterministic - Memory length: ∞ - [21]
50. Evolved ANN - Deterministic - Memory length: ∞ - [21]
51. Evolved ANN 5 - Deterministic - Memory length: ∞ - [21]
52. Evolved ANN 5 Noise 05 - Deterministic - Memory length: ∞ - [21]
53. Evolved FSM 4 - Deterministic - Memory length: 4 - [21]
54. Evolved FSM 16 - Deterministic - Memory length: 16 - [21]
55. Evolved FSM 16 Noise 05 - Deterministic - Memory length: 16 - [21]
56. EvolvedLookerUp1_1_1 - Deterministic - Memory length: ∞ - [21]
57. EvolvedLookerUp2_2_2 - Deterministic - Memory length: ∞ - [21]
58. Evolved HMM 5 - Stochastic - Memory length: 5 - [21]
59. Feld: 1.0, 0.5, 200 - Stochastic - Memory length: 200 - [9]
60. Firm But Fair - Stochastic - Memory length: 1 - [16]
61. Fool Me Forever - Deterministic - Memory length: ∞ - [21]
62. Fool Me Once - Deterministic - Memory length: ∞ - [21]
63. Forgetful Fool Me Once: 0.05 - Stochastic - Memory length: ∞ - [21]
64. Forgetful Grudger - Deterministic - Memory length: 10 - [21]
65. Forgiver - Deterministic - Memory length: ∞ - [21]
66. Forgiving Tit For Tat - Deterministic - Memory length: ∞ - [21]
67. Fortress3 - Deterministic - Memory length: 3 - [7]
68. Fortress4 - Deterministic - Memory length: 4 - [7]
69. GTFT: 0.33 - Stochastic - Memory length: 1 - [33, 17]

70. General Soft Grudger: $n=1, d=4, c=2$ - Deterministic - Memory length: ∞ - [21]
71. Getzler - Stochastic - Memory length: ∞ - [10]
72. Gladstein - Deterministic - Memory length: ∞ - [10]
73. Soft Go By Majority - Deterministic - Memory length: ∞ - [10, 11, 31]
74. Soft Go By Majority: 10 - Deterministic - Memory length: 10 - [21]
75. Soft Go By Majority: 20 - Deterministic - Memory length: 20 - [21]
76. Soft Go By Majority: 40 - Deterministic - Memory length: 40 - [21]
77. Soft Go By Majority: 5 - Deterministic - Memory length: 5 - [21]
78. ϕ - Deterministic - Memory length: ∞ - [21]
79. GraaskampKatzen - Deterministic - Memory length: ∞ - [10]
80. Gradual - Deterministic - Memory length: ∞ - [13]
81. Gradual Killer: (D, D, D, D, D, C, C) - Deterministic - Memory length: ∞ - [29]
82. Grofman - Stochastic - Memory length: ∞ - [9]
83. Grudger - Deterministic - Memory length: 1 - [41, 9, 13, 12, 25]
84. GrudgerAlternator - Deterministic - Memory length: ∞ - [29]
85. Grumpy: Nice, 10, -10 - Deterministic - Memory length: ∞ - [21]
86. Handshake - Deterministic - Memory length: ∞ - [35]
87. Hard Go By Majority - Deterministic - Memory length: ∞ - [31]
88. Hard Go By Majority: 10 - Deterministic - Memory length: 10 - [21]
89. Hard Go By Majority: 20 - Deterministic - Memory length: 20 - [21]
90. Hard Go By Majority: 40 - Deterministic - Memory length: 40 - [21]
91. Hard Go By Majority: 5 - Deterministic - Memory length: 5 - [21]
92. Hard Prober - Deterministic - Memory length: ∞ - [29]
93. Hard Tit For 2 Tats - Deterministic - Memory length: 3 - [38]
94. Hard Tit For Tat - Deterministic - Memory length: 3 - [40]
95. Harrington - Stochastic - Memory length: ∞ - [10]
96. Hesitant QLearner - Stochastic - Memory length: ∞ - [21]
97. Hopeless - Stochastic - Memory length: 1 - [41]
98. Inverse - Stochastic - Memory length: ∞ - [21]
99. Inverse Punisher - Deterministic - Memory length: ∞ - [21]
100. Joss: 0.9 - Stochastic - Memory length: 1 - [38, 9]
101. Kluepfel - Stochastic - Memory length: ∞ - [10]
102. Knowledgeable Worse and Worse - Stochastic - Memory length: ∞ - [21]
103. Level Punisher - Deterministic - Memory length: ∞ - [15]
104. Leyvraz - Stochastic - Memory length: 3 - [10]
105. Limited Retaliate: 0.1, 20 - Deterministic - Memory length: ∞ - [21]
106. Limited Retaliate 2: 0.08, 15 - Deterministic - Memory length: ∞ - [21]

107. Limited Retaliate 3: 0.05, 20 - Deterministic - Memory length: ∞ - [21]
108. Math Constant Hunter - Deterministic - Memory length: ∞ - [21]
109. Naive Prober: 0.1 - Stochastic - Memory length: 1 - [25]
110. MEM2 - Deterministic - Memory length: ∞ - [27]
111. Michaelos: (D,) - Stochastic - Memory length: ∞ - [43]
112. Mikkelson - Deterministic - Memory length: ∞ - [10]
113. MoreGrofman - Deterministic - Memory length: 8 - [10]
114. More Tideman and Chieruzzi - Deterministic - Memory length: ∞ - [10]
115. Negation - Stochastic - Memory length: 1 - [40]
116. Nice Average Copier - Stochastic - Memory length: ∞ - [21]
117. N Tit(s) For M Tat(s): 3, 2 - Deterministic - Memory length: 3 - [21]
118. Nydegger - Deterministic - Memory length: 3 - [9]
119. Omega TFT: 3, 8 - Deterministic - Memory length: ∞ - [37]
120. Once Bitten - Deterministic - Memory length: 12 - [21]
121. Opposite Grudger - Deterministic - Memory length: ∞ - [21]
122. π - Deterministic - Memory length: ∞ - [21]
123. Predator - Deterministic - Memory length: 9 - [7]
124. Prober - Deterministic - Memory length: ∞ - [25]
125. Prober 2 - Deterministic - Memory length: ∞ - [29]
126. Prober 3 - Deterministic - Memory length: ∞ - [29]
127. Prober 4 - Deterministic - Memory length: ∞ - [29]
128. Pun1 - Deterministic - Memory length: 2 - [6]
129. PSO Gambler 1.1.1 - Stochastic - Memory length: ∞ - [21]
130. PSO Gambler 2.2.2 - Stochastic - Memory length: ∞ - [21]
131. PSO Gambler 2.2.2 Noise 05 - Stochastic - Memory length: ∞ - [21]
132. PSO Gambler Mem1 - Stochastic - Memory length: 1 - [21]
133. Punisher - Deterministic - Memory length: ∞ - [21]
134. Raider - Deterministic - Memory length: 3 - [8]
135. Random: 0.5 - Stochastic - Memory length: 0 - [39, 9]
136. Random Hunter - Deterministic - Memory length: ∞ - [21]
137. Random Tit for Tat: 0.5 - Stochastic - Memory length: 1 - [21]
138. Remorseful Prober: 0.1 - Stochastic - Memory length: 2 - [25]
139. Resurrection - Deterministic - Memory length: 5 - [15]
140. Retaliate: 0.1 - Deterministic - Memory length: ∞ - [21]
141. Retaliate 2: 0.08 - Deterministic - Memory length: ∞ - [21]
142. Retaliate 3: 0.05 - Deterministic - Memory length: ∞ - [21]
143. Revised Downing: True - Deterministic - Memory length: ∞ - [9]

144. RichardHufford - Deterministic - Memory length: ∞ - [10]
145. Ripoff - Deterministic - Memory length: 2 - [5]
146. Risky QLearner - Stochastic - Memory length: ∞ - [21]
147. SelfSteem - Stochastic - Memory length: ∞ - [14]
148. ShortMem - Deterministic - Memory length: 10 - [14]
149. Shubik - Deterministic - Memory length: ∞ - [9]
150. Slow Tit For Two Tats 2 - Deterministic - Memory length: 2 - [29]
151. Sneaky Tit For Tat - Deterministic - Memory length: ∞ - [21]
152. Soft Grudger - Deterministic - Memory length: 6 - [25]
153. Soft Joss: 0.9 - Stochastic - Memory length: 1 - [29]
154. SolutionB1 - Deterministic - Memory length: 3 - [4]
155. SolutionB5 - Deterministic - Memory length: 5 - [4]
156. Spiteful Tit For Tat - Deterministic - Memory length: ∞ - [29]
157. Stalker: (D,) - Stochastic - Memory length: ∞ - [14]
158. Stein and Rapoport: 0.05: (D, D) - Deterministic - Memory length: ∞ - [9]
159. Stochastic Cooperator - Stochastic - Memory length: 1 - [1]
160. Stochastic WSLs: 0.05 - Stochastic - Memory length: 1 - [3]
161. Suspicious Tit For Tat - Deterministic - Memory length: 1 - [13, 18]
162. Tester - Deterministic - Memory length: ∞ - [10]
163. TF1 - Deterministic - Memory length: ∞ - [21]
164. TF2 - Deterministic - Memory length: ∞ - [21]
165. TF3 - Deterministic - Memory length: ∞ - [21]
166. ThueMorse - Deterministic - Memory length: ∞ - [21]
167. ThueMorseInverse - Deterministic - Memory length: ∞ - [21]
168. Thumper - Deterministic - Memory length: 2 - [5]
169. Tideman and Chieruzzi - Deterministic - Memory length: ∞ - [9]
170. Tit For Tat - Deterministic - Memory length: 1 - [9]
171. Tit For 2 Tats - Deterministic - Memory length: 2 - [11]
172. Tranquilizer - Stochastic - Memory length: ∞ - [9]
173. Tricky Cooperator - Deterministic - Memory length: 10 - [21]
174. Tricky Defector - Deterministic - Memory length: ∞ - [21]
175. Tricky Level Punisher - Deterministic - Memory length: ∞ - [15]
176. Tullock: 11 - Stochastic - Memory length: 11 - [9]
177. Two Tits For Tat - Deterministic - Memory length: 2 - [11]
178. VeryBad - Deterministic - Memory length: ∞ - [14]
179. Weiner - Deterministic - Memory length: ∞ - [10]
180. White - Deterministic - Memory length: ∞ - [10]

181. Willing - Stochastic - Memory length: 1 - [41]
182. Winner12 - Deterministic - Memory length: 2 - [30]
183. Winner21 - Deterministic - Memory length: 2 - [30]
184. Win-Shift Lose-Stay: D - Deterministic - Memory length: 1 - [25]
185. Win-Stay Lose-Shift: C - Deterministic - Memory length: 1 - [22, 33, 38]
186. WmAdams - Stochastic - Memory length: ∞ - [10]
187. Worse and Worse - Stochastic - Memory length: ∞ - [29]
188. Worse and Worse 2 - Stochastic - Memory length: ∞ - [29]
189. Worse and Worse 3 - Stochastic - Memory length: ∞ - [29]
190. Yamachi - Deterministic - Memory length: ∞ - [10]
191. ZD-Extortion: 0.2, 0.1, 1 - Stochastic - Memory length: 1 - [36]
192. ZD-Extort-2: 0.1111111111111111, 0.5 - Stochastic - Memory length: 1 - [38]
193. ZD-Extort3: 0.11538461538461539, 0.3333333333333333, 1 - Stochastic - Memory length: 1 - [34]
194. ZD-Extort-2 v2: 0.125, 0.5, 1 - Stochastic - Memory length: 1 - [23]
195. ZD-Extort-4: 0.23529411764705882, 0.25, 1 - Stochastic - Memory length: 1 - [21]
196. ZD-GTFT-2: 0.25, 0.5 - Stochastic - Memory length: 1 - [38]
197. ZD-GEN-2: 0.125, 0.5, 3 - Stochastic - Memory length: 1 - [23]
198. ZD-Mem2 - Stochastic - Memory length: 2 - [28]
199. ZD-Mischief: 0.1, 0.0, 1 - Stochastic - Memory length: 1 - [36]
200. ZD-SET-2: 0.25, 0.0, 2 - Stochastic - Memory length: 1 - [23]
201. e - Deterministic - Memory length: ∞ - [21]
202. Dynamic Two Tits For Tat - Stochastic - Memory length: ∞ - [21]
203. Meta Hunter: 6 players - Deterministic - Memory length: ∞ - [21]
204. Meta Hunter Aggressive: 7 players - Deterministic - Memory length: ∞ - [21]

References

- [1] Christoph Adami and Arend Hintze. “Evolutionary instability of zero-determinant strategies demonstrates that winning is not everything.” In: *Nature communications* 4.1 (2013), p. 2193. ISSN: 2041-1723. DOI: 10.1038/ncomms3193. arXiv: arXiv:1208.2666v4. URL: <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3741637&7B%5C%7Dtool=pmcentrez%7B%5C%7Drendertype=abstract>.
- [2] Ethan Akin. “What you gotta know to play good in the iterated prisoners dilemma”. In: *Games* 6.3 (2015), pp. 175–190.
- [3] Marco A Amaral et al. “Stochastic win-stay-lose-shift strategy with dynamic aspirations in evolutionary social dilemmas”. In: *Physical Review E* 94.3 (2016), p. 032317.
- [4] Daniel Ashlock, Joseph Alexander Brown, and Philip Hingston. “Multiple Opponent Optimization of Prisoners Dilemma Playing Agents”. In: *IEEE Transactions on Computational Intelligence and AI in Games* 7.1 (2015), pp. 53–65.
- [5] Daniel Ashlock and Eun-Youn Kim. “Fingerprinting: Visualization and automatic analysis of prisoner’s dilemma strategies”. In: *IEEE Transactions on Evolutionary Computation* 12.5 (2008), pp. 647–659.
- [6] Daniel Ashlock, Eun-Youn Kim, and Nicole Leahy. “Understanding representational sensitivity in the iterated prisoner’s dilemma with fingerprints”. In: *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)* 36.4 (2006), pp. 464–475.

- [7] Wendy Ashlock and Daniel Ashlock. “Changes in prisoners dilemma strategies over evolutionary time with different population sizes”. In: *Evolutionary Computation, 2006. CEC 2006. IEEE Congress on*. IEEE. 2006, pp. 297–304.
- [8] Wendy Ashlock, Jeffrey Tsang, and Daniel Ashlock. “The evolution of exploitation”. In: *Foundations of Computational Intelligence (FOCI), 2014 IEEE Symposium on*. IEEE. 2014, pp. 135–142.
- [9] Robert Axelrod. “Effective choice in the prisoner’s dilemma”. In: *Journal of conflict resolution* 24.1 (1980), pp. 3–25.
- [10] Robert Axelrod. “More Effective Choice in the Prisoner’s Dilemma”. In: *Journal of Conflict Resolution* 24.3 (1980), pp. 379–403. ISSN: 0022-0027. DOI: 10.1177/002200278002400301.
- [11] Robert Axelrod. *The Evolution of Cooperation*. Basic Books, 1985. ISBN: 0-465-02121-2. URL: <https://www.amazon.com/Evolution-Cooperation-Robert-Axelrod/dp/0465021212?SubscriptionId=AKIAIOBINVZYXZQZ2U3A&tag=chimbori05-20&linkCode=sm2&camp=2025&creative=165953&creativeASIN=0465021212>.
- [12] Jeffrey S Banks and Rangarajan K Sundaram. “Repeated games, finite automata, and complexity”. In: *Games and Economic Behavior* 2.2 (1990), pp. 97–117.
- [13] Bruno Beaufils, Jean-Paul Delahaye, and Philippe Mathieu. “Our meeting with gradual, a good strategy for the iterated prisoners dilemma”. In: *Proceedings of the Fifth International Workshop on the Synthesis and Simulation of Living Systems*. 1997, pp. 202–209.
- [14] Andre LC Carvalho et al. “Iterated Prisoners Dilemma-An extended analysis”. In: (2013), pp. 1–6. DOI: 10.21528/CBIC2013-202.
- [15] Arnold Eckhart. *CoopSim v0.9.9 beta 6*. <https://github.com/jecki/CoopSim/>. 2015.
- [16] Marcus R Frean. “The prisoner’s dilemma without synchrony”. In: *Proceedings of the Royal Society of London B: Biological Sciences* 257.1348 (1994), pp. 75–79.
- [17] Marco Gaudesi et al. “Exploiting evolutionary modeling to prevail in iterated prisoners dilemma tournaments”. In: *IEEE Transactions on Computational Intelligence and AI in Games* 8.3 (2016), pp. 288–300.
- [18] C. Hilbe, M. A. Nowak, and K. Sigmund. “Evolution of extortion in Iterated Prisoner’s Dilemma games”. In: *Proceedings of the National Academy of Sciences* 110.17 (Apr. 2013), pp. 6913–6918. DOI: 10.1073/pnas.1214834110.
- [19] Christian Hilbe et al. “Memory-n strategies of direct reciprocity”. In: *Proceedings of the National Academy of Sciences* 114.18 (2017), pp. 4715–4720.
- [20] Luis R Izquierdo and Segismundo S Izquierdo. “Dynamics of the Bush-Mosteller learning algorithm in 2x2 games”. In: *Reinforcement Learning*. InTech, 2008.
- [21] Vince Knight et al. *Axelrod-Python/Axelrod: V4.2.0*. 2018. DOI: 10.5281/zenodo.1252994.
- [22] David Kraines and Vivian Kraines. “Pavlov and the prisoner’s dilemma”. In: *Theory and decision* 26.1 (1989), pp. 47–79. ISSN: 00405833. DOI: 10.1007/BF00134056.
- [23] Steven Kuhn. “Prisoner’s Dilemma”. In: *The Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Spring 2017. Metaphysics Research Lab, Stanford University, 2017.
- [24] Jiawei Li et al. “How to design a strategy to win an IPD tournament”. In: *The iterated prisoners dilemma* 20 (2007), pp. 89–104.
- [25] Jiawei Li, Philip Hingston, and Graham Kendall. “Engineering design of strategies for winning iterated prisoner’s dilemma competitions”. In: *IEEE Transactions on Computational Intelligence and AI in Games* 3.4 (2011), pp. 348–360.
- [26] Jiawei Li and Graham Kendall. “A strategy with novel evolutionary features for the iterated prisoner’s dilemma.” In: *Evolutionary Computation* 17.2 (2009), pp. 257–274. ISSN: 1063-6560. DOI: 10.1162/evco.2009.17.2.257. URL: <http://www.ncbi.nlm.nih.gov/pubmed/19413490>.
- [27] Jiawei Li and Graham Kendall. “The effect of memory size on the evolutionary stability of strategies in iterated prisoner’s dilemma”. In: *IEEE Transactions on Evolutionary Computation* 18.6 (2014), pp. 819–826. DOI: 10.1109/TEVC.2013.2286492.
- [28] Siwei Li. *Strategies in the Stochastic Iterated Prisoner’s Dilemma*. <http://math.uchicago.edu/~may/REU2014/REUPapers/2014>.
- [29] LIFL. *PRISON*. <http://www.lifl.fr/IPD/ipd.frame.html>. 2008.
- [30] Philippe Mathieu and Jean-Paul Delahaye. “New Winning Strategies for the Iterated Prisoner’s Dilemma (Extended Abstract)”. In: *14th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2015)* (2015), pp. 1665–1666. ISSN: 15582914.

- [31] Shashi Mittal and Kalyanmoy Deb. “Optimal strategies of the iterated prisoner’s dilemma problem for multiple conflicting objectives”. In: *IEEE Transactions on Evolutionary Computation* 13.3 (2009), pp. 554–565.
- [32] John H Nachbar. “Evolution in the finitely repeated prisoner’s dilemma”. In: *Journal of Economic Behavior & Organization* 19.3 (1992), pp. 307–326.
- [33] Martin A Nowak and Karl Sigmund. “A strategy of win-stay, lose-shift that outperforms tit-for-tat in the Prisoner’s Dilemma game.” In: *Nature* 364.6432 (1993), pp. 56–58. ISSN: 0028-0836. DOI: 10.1038/364056a0.
- [34] W. H. Press and F. J. Dyson. “Iterated Prisoner’s Dilemma contains strategies that dominate any evolutionary opponent”. In: *Proceedings of the National Academy of Sciences* 109.26 (May 2012), pp. 10409–10413. DOI: 10.1073/pnas.1206569109.
- [35] Arthur J Robson. “Efficiency in evolutionary games: Darwin, Nash and the secret handshake”. In: *Journal of theoretical Biology* 144.3 (1990), pp. 379–396.
- [36] Lars Roemheld. “Evolutionary Extortion and Mischief: Zero Determinant strategies in iterated 2x2 games”. In: *arXiv preprint arXiv:1308.2576* (2013).
- [37] Wolfgang Slany, Wolfgang Kienreich, et al. “On some winning strategies for the Iterated Prisoners Dilemma, or, Mr. Nice Guy and the Cosa Nostra”. In: *The iterated prisoners dilemma* 20 (2007), p. 171.
- [38] A. J. Stewart and J. B. Plotkin. “Extortion and cooperation in the Prisoner’s Dilemma”. In: *Proceedings of the National Academy of Sciences* 109.26 (June 2012), pp. 10134–10135. DOI: 10.1073/pnas.1208087109.
- [39] Elpida Tzafestas. “Toward adaptive cooperative behavior”. In: *Proceedings of the Simulation of Adaptive Behavior Conference*. Citeseer. 2000, pp. 334–340.
- [40] Unkwown. *www.prisoners-dilemma.com*. <http://www.prisoners-dilemma.com/>. 2017.
- [41] Pieter Van den Berg and Franz J Weissing. “The importance of mechanisms for the evolution of cooperation”. In: *Proc. R. Soc. B*. Vol. 282. 1813. The Royal Society. 2015, p. 20151382.
- [42] Jianzhong Wu and Robert Axelrod. “How to cope with noise in the iterated prisoner’s dilemma”. In: *Journal of Conflict resolution* 39.1 (1995), pp. 183–189.
- [43] *Zoo of strategies*. 2011. URL: http://lesswrong.com/lw/7f2/prisoners_dilemma_tournament_results/.