Literature review paper for the iterated prisoner's dilemma.

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1 Introduction

The emergence of cooperation is a topic of continuing and public interest for social [23, 29], biological [30] and ecological sciences [31, 37, 46, 69]. Cooperation is essential for evolution but according to Darwins theory it is not always easy to achieve. The game called the prisoner's dilemma offers a theoretical framework for studying the emergence of altruist behaviour. Collecting data from 5 sources shows that more than 1150 papers related to the prisoner's dilemma have been published since it's origin.

In this work an extensive literature review will be presented. In addition, an introduction to the prisoner's dilemma is given in Section 2 and some major pieces of work will be discussed in Section 3. In Section 4 a comprehensive data set of literature regarding the prisoner's dilemma will be presented and analysed.

2 The Prisoner's Dilemma

The prisoner's dilemma a two player no-cooperative game where the decisions of the players are made simultaneously and independently. Both players can choose between cooperation (**C**) or defection (**D**).

The fitness of each player is influenced by its own behaviour, and the behaviour of the opponent. If both players choose to cooperate, both do better than if both defect. However, a player has the temptation to deviate. If a player was to defect while the other cooperates, the defector receives more than if both had cooperated. The reward for mutual cooperation is R units, for a mutual defection they receive P, and for cooperation-defection, the cooperator receives S where the defector receives T. Thus, the game's payoffs are given by,

$$\begin{pmatrix} R & S \\ T & P \end{pmatrix} \tag{1}$$

where $T > R > P > S$ and $2R > T + S$ are the conditions for a dilemma to exist. Due to rational behaviour and the knowledge that an individual is tempted to defect the game's equilibrium lies at a mutual defection and both players receive a payoff of P. Thus, the unbeatable strategy for the prisoner's dilemma is **D**.

However, when the game is studied in a manner where prior outcomes matter, the defecting choice is no longer necessarily the unbeatable choice. The repeated form of the game is called the iterated prisoner's dilemma and now players interact more than just once.

In Section 3 it will be discussed how it was proven that the iterated prisoner's dilemma leaves room for cooperation. The prisoner's dilemma has attracted much attention and that's shown in Figure 1, which illustrates the number of publications on the prisoner's dilemma per year from the following sources:

- arXiv;
- PLOS;
- IEEE;
- Nature;
- Springer.

The choice of sources is due to the fact that they have an open access Api, the process of collecting the data and the analysis will be described more comprehensively in Section 4. Each point of Figure 1 marks the starting year of a time period. Each of these time periods is discussed later in Section 3.

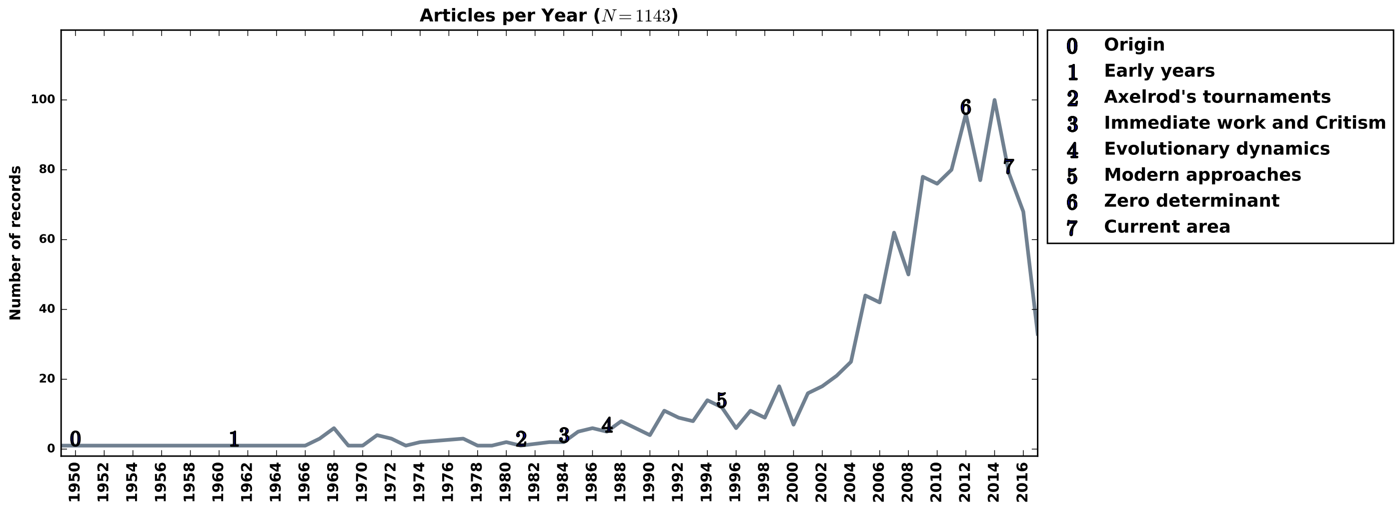


Figure 1: A timeline of the prisoner's dilemma research.

3 Timeline

3.1 Origin and (1961-1972)

The origin of the prisoner's dilemma goes back to the 1950s in early experiments conducted in RAND [25] to test the applicability of games described in [68]. Though in [25] the two player game was introduced the name behind the game was given later the same year. A. W. Tucker, the PhD advisor of J. Nash, in an attempt to delivery the game with a story during a talk used prisoners as players and the game is known as the prisoner's dilemma ever since [64].

The study of the prisoner's dilemma has attracted people from various fields across the years. An early figure within the field is Prof A. Rapoport, a mathematical psychologist, whose work focused on peacekeeping. In his early work [56] Rapoport conducted experiments using humans to simulate a play of the prisoner's dilemma. Experimental groups were not been used only by Rapoport but it was a common mean of studying the game [24, 27, 43, 44, 60] and are still being used to date.

Those experiments explored the conditions under which altruist behaviour emerges in human societies. Conditions such as, the gender [24, 43, 44] of individuals, the representation of the game [24], the distance between players [60], the start effect [63] and whether the experimenter was biased [27].

Even though, several of these experiments were held and continuous research on the topic was undergoing game theorists were still arguing with each other about the best way to play the game [56]. Inspired by the work of Rapoport and intrigued by the very same question the political scientist R. Axelrod took upon him to identify the dominant strategy of the prisoners dilemma.

The main difference on Axelrod's approach was that machines were going to be used instead of humans. The issues with using humans, according to Axelrod [16], was the fact that humans can act very randomly even though the aim of the game is cleared to them. Thus, Axelrod was the first researcher, to the author's knowledge, to perform a computer tournament of the iterated prisoner's dilemma. The work of Axelrod is considered one of the greatest milestones within the field. The tournaments and their results are discussed in the next session.

3.2 Axelrod's Tournaments (1981-1984)

This section serves as a follow up from the earlier years of the topic and as an introduction to the modern ways of studying the prisoner's dilemma. It is dedicated to the computer tournaments of Axelrod from 1981 to 1984.

The first computer tournament was performed in 1980 [13]. Several scientists were invited to submit their strategies, written in the programming languages Fortran or Basic. There was a total number 13 submissions made by the following researchers,

1. T Nicolaus Tideman and Paula Chieruzz;
2. Rudy Nydegger;
3. Bernard Grofman;
4. Martin Shubik;
5. Stein and Anatol Rapoport;
6. James W Friedman;
7. Morton Davis;
8. Jim Graaskamp;
9. Leslie Downing;
10. Scott Feld;
11. Johann Joss;
12. Gordon Tullock;
13. Name not given.

Each strategy competed against all the 13 opponents, itself and a player that played randomly a match of 200 turns. This topology is called round robin and is the equivalent of a complete graph. The tournament was repeated 5 times to reduce variation in the results. Each participant knew the exact length of the matches and had access to the full history of each match. Furthermore, Axelrod performed an preliminary tournament and the results were known to the participants. The payoff values used where $R = 3, P = 1, T = 5$ and $S = 0$. These values are commonly used in the literature and unless specified will be the values used in the rest of the work described here.

The winner of the tournament was determined by the total average score and not by the number of matches won. The strategy that was announced the winner was submitted by Rapoport and was called **Tit For Tat**. Tit for Tat, is a strategy that always cooperates on the first round and then mimics the opponent's previous move.

Examples of Tit for Tat interacting with deterministic opponents are given by Tables 1, 2, 3. The opponents are, **Cooperator** a strategy that always cooperates, **Defector** an opponent that always defects and **Altenator** a player who alternates between cooperating and defecting.

Turns	Tit for Tat	Cooperator
1	C	C
2	C	C
3	C	C
⋮	⋮	⋮
200	C	C

Table 1: Tit for Tat example match against Cooperator

The results of the first tournament were filled with surprises. Tit for Tat the simplest strategy of all had won and had managed to defeat even entrants that tried to improve on Tit for Tat after the preliminary tournament results. Axelrod justified the success of the strategy saying that the strategy was 'nice' and 'forgiving'.

The top eight ranked strategies have been strategies that never defected on the first round, thus they were described as 'nice' strategies. Compared to the rest nice strategies Tit for Tat had also another property. That property was

Turns	Tit for Tat	Defector
1	C	D
2	D	D
3	D	D
⋮	⋮	⋮
200	D	D

Table 2: Tit for Tat example match against Defector

Turns	Tit for Tat	Altenator
1	C	C
2	C	D
3	D	C
⋮	⋮	⋮
200	C	D

Table 3: Tit for Tat example match against Altenator

‘forgiveness’. Tit for Tat punished it’s opponent for a defection but just once and then it would try to cooperate again.

These two properties were described to be the secret of success in a prisoner’s dilemma tournament. In order to further test the robustness of the results Axelrod performed a second tournament [14]. This time a total of 63 participants submitted strategies for the second tournament, their names were the following,

1. Gail Grisell;
2. Harold Rabbie;
3. James W Friedman;
4. Abraham Getzler;
5. Roger Hotz;
6. George Lefevre;
7. Nelson Weiderman;
8. Tom Almy;
9. Robert Adams;
10. Herb Weiner;
11. Otto Borufsen;
12. R D Anderson;
13. William Adams;
14. Michael F McGurrin;
15. Graham J Eatherley;
16. Richard Hufford;
17. George Hufford;
18. Rob Cave;
19. Rik Smoody;
20. John Willaim Colbert;
21. David A Smith;
22. Henry Nussbacher;
23. William H Robertson;
24. Steve Newman;
25. Stanley F Quayle;
26. Rudy Nydegger;
27. Glen Rowsam;
28. Leslie Downing;
29. Jim Graaskamp and Ken Katzen;
30. Danny C Champion;
31. Howard R Hollander;
32. George Duisman;
33. Brian Yamachi;
34. Mark F Batell;
35. Ray Mikkelson;
36. Craig Feathers;
37. Fransois Leyvraz;
38. Johann Joss;
39. Robert Pebly;
40. James E Hall;
41. Edward C White Jr;
42. George Zimmerman;
43. Edward Friedland;
44. X Edward Friedland;
45. Paul D Harrington;
46. David Gladstein;
47. Scott Feld;
48. Fred Mauk;
49. Dennis Ambuehl and Kevin Hickey;
50. Robyn M Dawes and Mark Batell;

51. Martyn Jones;
52. Robert A Leyland;
53. Paul E Black;
54. T Nicolaus Tideman and Paula Chieruzz;
55. Robert B Falk and James M Langsted;
56. Bernard Grofman;
57. E E H Schurmann;
58. Scott Appold;
59. Gene Snodgrass;
60. John Maynard Smith;
61. Jonathan Pinkley;
62. Anatol Rapoport.

All the participants knew the results of the previous tournament. The rules were similar to those of the first tournament with only one exception; the number of turns was not specified instead a probabilistic ending tournament was meant to be used. In a probabilistic ending tournament each match has probability of ending after each turn. This is also refereed as 'shadow of the future' [17].

However, the tournament was not a probabilistic ending one. A fixed probability of 0.0036 was chosen as a chance of ending a match with each given move. The value was chosen so that the expected median length of a match would be 200 turns. The topology was of a round robin and each pair of players was matched 5 times. The length of the matches was determined once by drawing a random sample. Each of the five matches had a length of 63, 77, 151 and 308.

The results of the tournament once again came as a surprise. Tit for Tat was the simplest submission in the second tournament and won the second tournament as well. Tit for Tat provided proof that reciprocity behaviour can allow cooperation to emerge in the iterated prisoner's dilemma game. In [13] the main conclusions indicating strong performance was:

- that it start of by cooperating
- it would forgive it's opponent after a defection
- after opponents identified that they were playing Tit for Tat choose to cooperate for the rest of the game.

Another successful strategy from Axelrod's tournament that can been seen in literature to date is **Grudger**. Grudger is a strategy that will cooperate as long as the opponent does not defect. The name Grudger was give to the strategy in [41]. Though the strategy goes by many names in the literature such as, Spite [20], Grim Trigger [19] and Grim [67].

As for the rest of the strategies, though a full explanation of all 14 strategies is given in [13] the same does not hold for all 63 strategies of the second tournament [14]. The author mainly focuses on the high ranked participants and several details for the rest strategies are left unknown.

However, the source code of the 63 strategies be found on Axelrod's personal website [1]. The source code was written by Axelrod and several other contributors. The strategies written in Basic were translated to Fortran before the tournament. The source code includes the code only for the strategies and not for creating and performing the tournament.Figure 2 serves as an example of the source code giving the code for the the winning strategy Tit for Tat. Unfortunately, the source code of the first 13 strategies is not available, as stated in Axelrod's personal website [1].

So far it was discussed how the performance of the strategy was tested through tournament against other strategies. But is the overall success of a strategy based only on it's performance in a round robin tournament or should it be checked through other ways as well?

Following his initial tournaments Axelrod performed an 'ecological' tournament in 1981 [18]. In [18], the set of strategies from Axelrod's second tournament was used to perform the ecological tournament. The 63 strategies interacted generation after generation to a round robin competition where their frequencies were proportional to their payoff in the previous round. The ecological approach is based on the payoff matrix of the tournament. The highest performing strategies are adapted by lower scoring individuals within a fixed population. Over time a strategy takes over the population. Figure 3 demonstrates an example of the natural selection proceeder. Four different strategies are being used by the population, Defector, Alternator, TitForTat and Grudger. In [18], the results showed that in a homogeneous population of Tit for Tat invasion by mutant strategies was not successful.

```
   FUNCTION K92R(J,M,K,L,R, JA)
C BY ANATOL RAPOPORT
C TYPED BY AX 3/27/79 (SAME AS ROUND ONE TIT FOR TAT)
c replaced by actual code, Ax 7/27/93
c  T=0
c   K92R=ITFTR(J,M,K,L,T,R)
      k92r=0
      k92r = j
c test 7/30
c   write(6,77) j, k92r
c77   format(' test k92r. j,k92r: ', 2i3)
      RETURN
      END
```

Figure 2: Source code for Tit for Tat in Fortran. Provided by [1].

The ability of strategies to be favoured under natural selection and their ability to withstand invasion from other strategies soon became an new measure of performance; refereed to as the stability of a strategy.

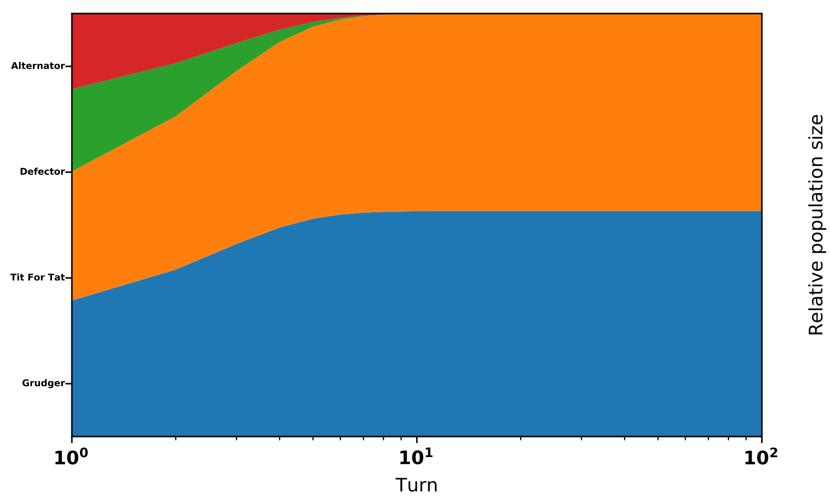


Figure 3: System evolving over time based on natural selection using [6].

3.2.1 Immediate work and Criticism on Computer Tournaments (1984-1993)

The pioneer work of computer tournaments and the results on the reciprocal behaviour of the prisoner's dilemma spread the knowledge of the game not only worldwide but also across different scientific principles. The study of cooperation was once again a critical issue. This section focuses on the immediate research that was spawn after the initial computer tournaments and on the criticism these tournaments received from 1984 to 1993.

Ecological studies that made use of Axelrod's results include the works of [31, 46, 69]. In[46] an experiment was conducted using sticklebacks to test the robustness of the strategy Tit for Tat in the interactions of fish. Fish usually travel in pairs and monitor their hunters to gain information on the enemy. The works of [31, 69] looked upon food sharing between vampire bats.

Nevertheless success often comes with criticism. Axelrod's tournaments assumed that each player has perfect information of the opponent's actions. In real life situations this is not always the case. Colleagues' interactions often suffer from measures of uncertainty. In the original tournaments there was no possibility of mis implementation or misunderstanding. These stochastic variations are refereed to as **noise** and **mis perception**. Noise is the concept of flipping one's move based on a given probability. On the contrary, mis perception is the probability that the opponent's current move is flipped before being recorded. Noise will flip a player's action and it will be recorded correctly in the history where mis perception will not have an effect on the player's move but it will be recorded wrong [35].

The performance of Tit for Tat was proven to suffer from such stochasticity in the tournament environment, especially against itself [5, 31, 48, 49]. If two strategies playing Tit for Tat were to compete against each other in a noisy environment the strategies will get a series of unwanted defections. In a non noisy environment the two strategies would have been cooperating for the entire match. An interesting result was introduced by [48]. Molander stated that if two strategies playing Tit for Tat meet in a noisy match the average payoff that a strategy will receive will be the same as that of a Random player (with probability 0.5 of cooperating).

In [5] a similar tournament to that of Axelrod's was performed but this time noise was used. Bendor invited academics to submit strategies to participate in his tournament. A total of thirteen strategies were used including already existed strategies such as Tit for Tat and **Tit for Two Tats**. The results showed that Tit for Tat performed purely placing eight in the tournament. Bendor stated that a more forgiving strategy was needed, in his tournament a strategy called **Nice and Forgiving** ranked first.

The work of [49] following a similar approach agreed with the result. In [49], the space of re-active strategies was explored in a noisy environment. The strategy that was performing the best in that environment was the re-active strategy known as **Generous Tit for Tat**. Reactive strategies are a subset of memory one strategies introduced in 1989 [50]. Reactive strategies are denoted by the probabilities to cooperate after a **C** and a **D** of the opponent. Thus, a reactive strategy only considers the previous turn of the opponent. Strategies such as, Tit for Tat and Generous Tit for Tat are reactive.

The author published yet another paper a years later [52] introducing another interesting player. The new strategy had the tolerance of Generous Tit for Tat but also the capability of resisting and invading an all-out cooperators population was. The strategy is called **Pavlov**, and is based on the fundamental behavioural mechanism win-stay, lose-shift. The strategy starts off with a **C**, then Pavlov will repeat it's last move it was awarder with by R or T but will shift if punished by P or S. Palvov is a memory one strategy.

Memory one strategies, are a set of strategies that consider only the last turn of the game to decide on the next action [51]. They are represented by the four conditional probabilities p_1, p_2, p_3 and p_4 to cooperate after CC, CD, DC and DD respectively (the four possible states a player can be in if only the last turn of the game was to be considered). Reactive strategies are just a constrained version where $p_1 = p_3$ and $p_2 = p_1$. The first action of the strategy (when the history does not exist yet) is assumed to be **C** unless is stated otherwise. For example, a reactive strategy called **Suspicious Tit for Tat**, studied in [49].

Other strategies that made an impact have been **Tit for Two Tats** [17], **Handshake** [58] and **Gradual** [20]. Presented in 1988, 1989 and 1997 respectively. Tit for Two Tats, is a variant of the classic strategy which defects only if the other player defected on the two preceding moves. Handshake is a strategy that starts with cooperation, defection. If the opponent plays in a similar way then it will cooperate forever, otherwise it will defect forever.Gradual starts off by cooperating, then after the first defection of the other player, it defects one time and cooperates twice. After the second defection of the opponent, it defects two times and cooperates twice. After the n^{th} defection it reacts with n consecutive defections and then two cooperations.

3.3 Evolutionary Dynamics (1987-1999)

The results of the round robin tournaments were not the only ones to receive criticism. Similarly, the ecological tournament and the statements for the stability of Tit for Tat were also delved into by other researchers. The results of [22] argued that no pure strategy is evolutionary stable in the iterated prisoner's dilemma. This was not proven analytically, instead a series of examples using strategies such as Tit for Tat, Suspicious Tit for Tat and Defector where explored.

The results were questioned by [45], stating that much was still no fully explored and more research had to be put into the results. Another attempt to explore stability of strategies in the prisoner's dilemma was done in [21]. This time exploring the results in a noisy environment, but similarly a analytical proof was not achieved.

An extension to the natural selection was introduced in the 1992 [53], recommending a different type of topology. A population of two deterministic strategies, Defector and Cooperator, were placed on a a two dimensional square array where the individuals could interact only with the immediate neighbours. The number of immediate neighbours could be either, fourth, six or eight. As shown in Figure 4. The authors claimed that the essential results remain true of all topologies; the results also hold whether self interactions are taken into account.

Thus each cell of the lattice is occupied by a **C** or a **D** and in each generation step each cell owner interacts with its immediate neighbours and play the game. The score of each player is the sum of the overall games the player competed in. At the start of the next generation, each lattice cell is occupied by the player with the highest score among the previous owner and the immediate neighbours. Nowak and all created this model where the model parameter has been the temptation payoff denoted as b. Thus $T = b$. For different values of the parameter b it was shown that cooperators and defectors can persist together indefinitely. This topology is refereed to as spatial topology.

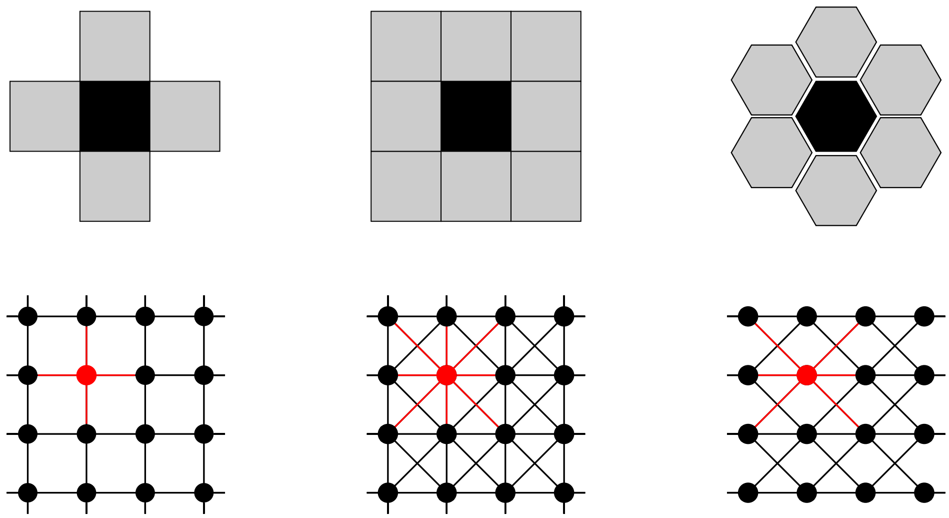


Figure 4: Spatial neighbourhoods

Evolutionary dynamics have been highly useful in the research of the prisoner's dilemma. In [15], an evolutionary process, called the genetic algorithm, was used to discover effective strategies. The author introduced lookup tables as a mean of representing a strategy in a gene format. A lookup table is a set of deterministic responses based on the opponents m last moves; [15] considered $m = 3$.

3.4 Modern approaches (1995-2015)

This section covers several pieces of work from 1995 to 2015. During this time period several aspects discussed in the previous sections are now being applied continuously and are considered standard means of researching the iterated prisoners dilemma.

Several computer tournaments are performed, and new strategic rules surface. The performance of these strategic rules is being measured by round robin tournaments and evolutionary tournaments.

A number of Tit for Tat variants make an appearance and are introduced as more as more dominant than Tit for Tat. These include, **Contrite Tit for Tat** [70] and **Adaptive Tit for Tat** [66]. On the other hand, defector variants have also been studied [34]. **Anti Tit for Tat**, is a strategy that plays the opposite of the opponents previous move. Another limitation of the strategy was discussed in [61]. Tit for Tat was proven to hit a deadlock. Deadlock meaning a loop between cooperation and defection. **Omega Tit For Tat** was introduced and was a strategy capable of avoiding the deadlock [61].

In 2011 the authors of [40] performed their own tournament where several interesting strategies made an appearance.

- **Periodic player CCD**, plays **C**, **C**, **D** periodically. Note that variations of a period player also make appearance in the article but will not be listed here.

- **Prober**, starts with the pattern **D**, **C**, **C** and then defects if the opponent has cooperated in the second and third move; otherwise, it play as Tit for Tat.
- **Reverse Pavlov**, a strategy that does the reverse of Pavlov.

In earlier work the same author introduced a strategy called **APavlov**, which stands for adaptive Pavlov [39]. The strategy attempts to classify the opponent as one of the following strategies, All Cooperator, All Defector, Pavlov, Random or **PavlovD**. PavlovD, is just Pavlov but it starts the game with a **D**. Once Adaptive Pavlov has classified the opponent plays to maximize it's payoff.

Evolutionary dynamics and optimization methods are used with different representation methods in order to discover new optimized strategies. Include lookup tables [15, 42], artificial neural networks [33, 38] and finite state machines [47, 59].

Strategies based on finite state machines are described by the number of states. The strategy selects the next action in each round based on the current state and the opponent's last move, transitioning to a new state each time. Figure 5, illustrates the finite state representation of Tit For Tat.

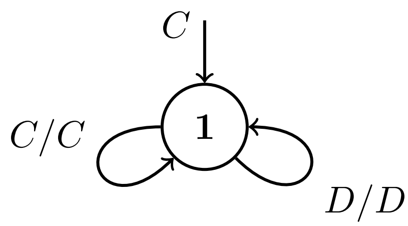


Figure 5: Finite state machine representation of Tit for Tat.

In [12] the author presented two new strategies that have been trained using a finite state machine representation. They are called, **Fortress3** and **Fortress4**. Figure 6 illustrates their diagrammatic representation where the transition arrows are labelled *O/P* where *O* is the opponent's last action and *P* is the player's response.

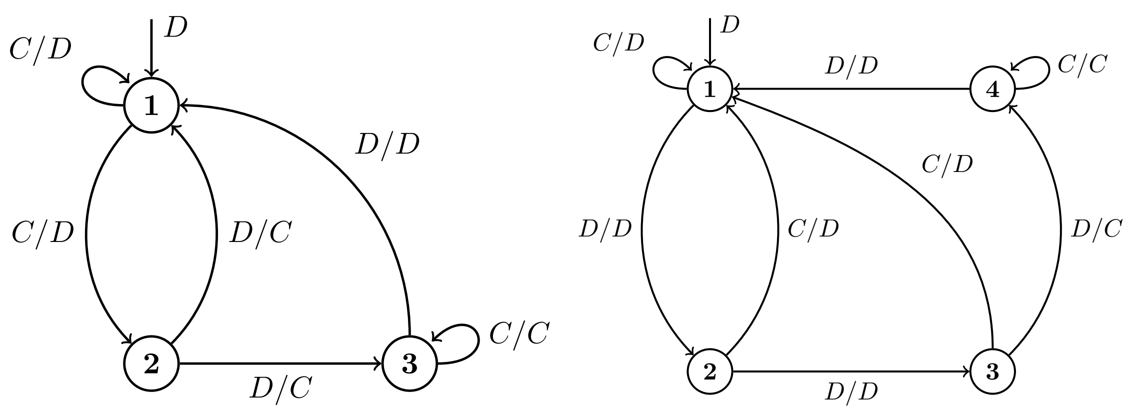


Figure 6: Representations of Fortress 3 and Fortress 4. Note that the strategy's first move, enters state 1, is defection for both strategies.

Optimisation methods will return a spectrum of strategies. In order to distinguish the strategies and assuring that they are indeed different [7] introduced a method called fingerprinting.

The method of fingerprinting is a technique for generating a functional signature for a strategy [8]. This is achieved by computing the score of a strategy against a spectrum of opponents. The basic method is to play the strategy against a probe strategy with varying noise parameters. In [7] Tit for Tat is used as the probe strategy. Fingerprint functions can then be compared to allow for easier identification of similar strategies. In Figure 7 an example of Pavlov's fingerprint is given. Fingerprinting has been studied in depth in [8, 9, 10, 11].

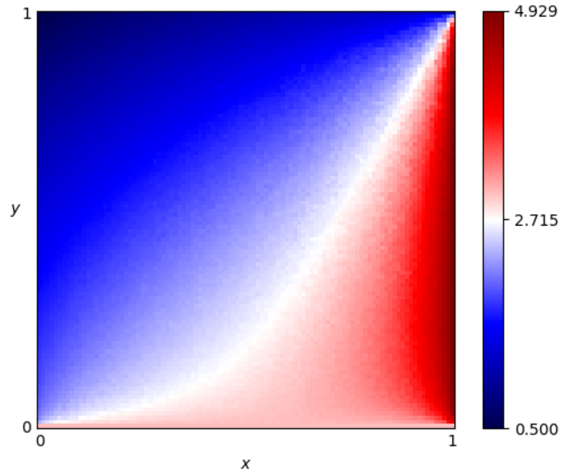


Figure 7: Pavlov fingerprinting with Tit for Tat used as the probe strategy. Figure was generated using [6].

Due the nature of the research several pieces of software are starting to appear, this includes a library called PRISON [4]. PRISON is written in the programming language Java and it has been used by it's authors in several publications. The project includes a good number of strategies from the literature but unfortunately the last update of the project dates back in 2004.

3.5 Zero determinant (2012 - 2015)

Following Section 3.4, this section is a review of an important set of strategies, the zero determinant.

In [55], a new set of memory one strategies were introduced, called **zero determinant (ZD)** strategies. The ZD strategies, manage to force a linear relationship between the score of the strategy and the opponent. Press and Dyson, prove their concept of the ZD strategies and claim that a ZD strategy can outperform any given opponent.

The ZD strategies have attracted a lot of attention. It was stated that "Press and Dyson have fundamentally changed the viewpoint on the Prisoner's Dilemma" [62]. In [62], a new tournament was performed including ZD strategies and a new set of ZD strategies the **Generous ZD**. Even so, ZD and memory one strategies have also received criticism. In [38], the 'memory of a strategy does not matter' statement was questioned. A set of more complex strategies, strategies that take in account the entire history set of the game, were trained and proven to be more stable than ZD strategies.

3.6 Current area (2015 - 2017)

Following a discussion on research of short memory strategies this section reviews recent work done in complex strategies. As well as a discussion of new software and how modern approaches allows us to now revisit several pieces of work produced in the past.

Modern approaches of artificial neural networks and machine learning are now used in the field. A number of strategies based on artificial neural networks are introduced by [32]. Artificial neural networks provide a mapping function to an action based on a selection of features computed from the history of play.

These strategies are refereed to as **EvovlvedANN** strategies and are based on a pre-trained neural network with the following features,

- Opponent's first move is C
- Opponent's first move is D
- Opponent's second move is C
- Opponent's second move is D
- Player's previous move is C
- Player's previous move is D
- Player's second previous move is C
- Player's second previous move is D
- Opponent's previous move is C
- Opponent's previous move is D
- Opponent's second previous move is C
- Opponent's second previous move is D
- Total opponent cooperations
- Total opponent defections
- Total player cooperations
- Total player defections
- Round number

A representation of **EvovlvedANN 5** is given in Figure 8. The inputs of the neural network are the 17 features as listed above. Number 5 reefers to the size of the hidden layer.

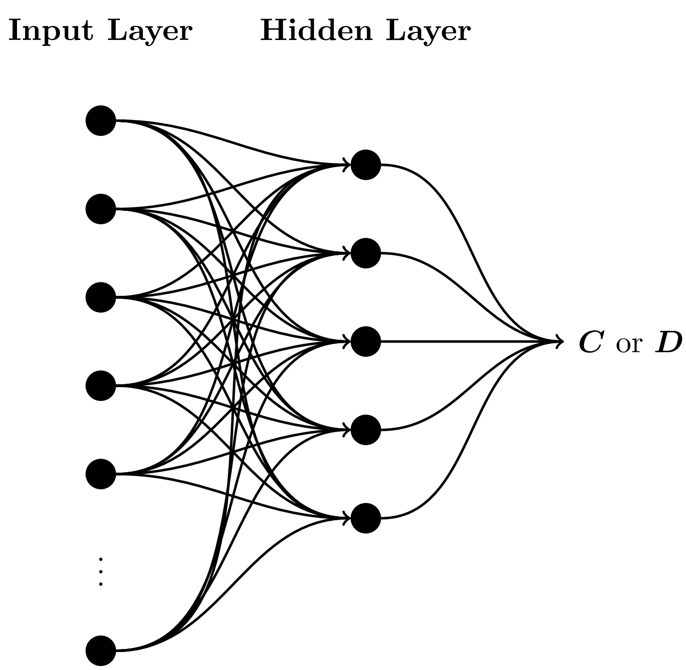


Figure 8: Neural network representation of EvovlvedANN 5.

In [32], these representing methods are refereed to as archetypes. Finite state machines and artificial neural networks are included in the work but also new archetypes are introduced, such as hidden Markov models. A variant of a finite state machine that use probabilistic transitions based on the prior round of play to other states and cooperate or defect with various probabilities at each state. Finite state machines and hidden Markov models based strategies are characterized by the number of states. Similarly, artificial neural networks based players are characterized by the size of the hidden layer and number of input features.

Additionally a variant of a look up table is also presented called the lookerup archetype. The lookerup archetype responses based on the opponent's first n_1 moves, the opponent's last m_1 moves, and the players last m_2 moves. Taking into account the initial move of the opponent can give many insights. For it is the only move a strategy is truly itself without being affected by the other player. As a reminder, Axelrod in his work highlighted the importance of the initial move and believed that it was one of the secrets of success of the strategy Tit for Tat.

Finally, a new archetype called the Gambler is also introduced, which is a stochastic variant of the lookerup archetype.

Archetypes are used with evolutionary algorithms to train set of new strategies. The evolutionary algorithm used in both [15, 28] is called genetic algorithm. Other algorithms including particle swarm optimization have been used in research of the most dominant strategy [26].

In [32] the approach in used to introduce as stated by the authors the best performing strategies for the iterated prisoner's dilemma. These strategies will be refereed as **Evolved** strategies. Several successful new strategies are,

- **EvolvedLookerUp2_2_2** a looker up strategy trained with a genetic algorithm; EvolvedLookerUp2_2_2 responses based on the opponent's 2 first and last moves and the player's 2 last moves. Thus $n_1 = 2, m_1 = 2$ and $m_2 = 2$.
- **Evolved HMM 5** a 5 states hidden markov model trained with a genetic algorithm;
- **Evolved FSM 16** a 16 state machine trained with a genetic algorithm;
- Finally **PSO Gambler 2 2 2** a looker up strategy trained with a particle swarm algorithm, where $n_1 = 2, m_1 = 2$ and $m_2 = 2$.

Though several papers have claimed before to have discovered the dominant strategies for the game the work of [32] is promising. This is due the fact that the introduced strategies have been trained using different types of evolutionary algorithms in a pool of 176 well known strategies for the literature. Including all the strategies that have been discussed in this section.

This was made possible due an open source library, called the Axelrod project [6]. The project is written in the programming language Python, it is accessible and open source. To date the list of strategies implemented within the library exceed the 200. The project has been used in several publications including [32] and a paper describing it and it's capabilities was published in 2016 [36]. The source code for Tit for Tat as implement within the library is shown in Figure 9. Furthermore, performing a tournament with a selection of strategies is possible in five lines of code, shown in Figure 10.

```python
def strategy(self, opponent: Player) -> Action:
    """This is the actual strategy"""
    # First move
    if not self.history:
        return C
    # React to the opponent's last move
    if opponent.history[-1] == D:
        return D
    return C
```

Figure 9: Source code for Tit for Tat in Python as implemented in Axelrod Python library [6]

.

```python
>>> import axelrod as axl
>>> players = (axl.Cooperator(), axl.Defector(), axl.TitForTat(), axl.Grudger())
>>> tournament = axl.Tournament(players)
>>> results = tournament.play()
>>> results.ranked_names
['Defector', 'Tit For Tat', 'Grudger', 'Cooperator']
```

Figure 10: Performing a computer tournament using [6].

Software has a crucial role in research. Well written and maintained software allows the reproducibility of prior work and can accelerate findings within the field. The field of the iterated prisoner's dilemma has suffered the consequences of poor research software. As stated above the source code of the initial computer tournament is not retrievable. Several of the strategies that competed in the tournament are not given a full explanation of how the decided on their next move. In terms of best practice and reproducibility the Axelrod library is the lead software in the field.

Other recent projects include [2, 3], both are education platforms and not research tools. In [2], several concepts such as the iterated game, computer tournaments and evolutionary dynamics are introduced through a user interface game. Project [3] offers a big collection of strategies and allows the user to try several match and tournaments configurations. Such as noise.

In [57], the authors claim that they have managed to re-run the first tournament that Axelrod performed. They tried to push his work further by altering aspects such as, the format of the tournament, the objective and the population. One of the authors claimed to have been a contributor to the first tournaments, which would explain how it was managed to reproduce the tournament.

3.6.1 Biological Applications

- [65] uses evolutionary game theory to study the spread of virus.
- [30] a shout for his work, using tit for tat to study cells.

4 Analysis

This section follows a circumstantial review of the prisoner's dilemma timeline conducted by the authors. The section focuses on the analysis of the prisoner's dilemma timeline using a large dataset of prisoner's dilemma articles' metadata. Using various machine learning techniques the number and topics that have been researched over the years within the field are discussed. Moreover, we explore the connections of the authors that have work on the game using network theory.

4.1 Data Collection

Academic articles are accessible through scholarly databases and collections of journals. Several databases and collections today offer access through an open Api. An Api is an application protocol interface that allows users to talk directly the database, skipping the user interface side of a journal. Interacting with the Api has two phases:

- requesting;
- receiving;

The requesting phase includes composing a url with the requesting message. The head of the url includes the address of the Api and the tail the search argument, such as the word 'prisoner' to exists within the title. The address of the Api and the search arguments themselves differ from journal to journal, thus different journals can generate complete different requesting urls.

The second phase of the receiving includes receiving a number of raw metadata of articles that satisfied the request. The answer is commonly received in an xml format but similarly the number of features and the syntax of the xml file differs from journal to journal.

Data collection is a crucial proceeder. We wanted to include a large number of articles from various journal for the analysis to be objective. Moreover, we wanted the data to be collected within a short period of time. For these reasons an open source library was developed for the purpose of this work. The library is called Arcas and though the package it self will not be analysed here the source code can be found here, `https://github.com/Nikoleta-v3/Arcas`.

Arcas serves as a translator between us and various Apis. More specifically it works in coordinate with five different journal. For Arcas to collect data a series of keywords had to be specified. Each keyword individually is checked weather it exists within the title or the abstract of an article. Only if this check is satisfied an article is collected. A list of the keywords that were used in this work are given by Table 4.

1. arXiv;
2. PLOS;
3. IEEE;
4. Nature;
5. Springer.

	Keywords
1	prisoner's dilemma
2	prisoners dilemma
3	prisoners evolution
4	prisoner game theory
5	R Axelrod
6	memory one strategy
7	tit-for-tat
8	tit for tata
9	zero determinant strategies

Table 4: Keywords used in searching for articles.

Each entry retrieved by Arcas is constituted of various features which are listed on Table 5. In the following section only a number are considered. These are listed on Table 6.

	Result name	Explanation
1	Abstract	The abstract of the article.
2	Author	A single entity of an author from the list of authors of the respective article.
3	Date	Year of publication.
4	Journal	Journal of publication.
5	Key	A generated key containing an authors name and publication year (ex. Glynatsi2017).
6	Keyword	A single entity of a keyword assigned to the article by the given journal.
7	Labels	A single entity of labels assigned to the article manual by us.
8	Pages	Pages of publication.
9	Provenance	Scholarly database for where the article was collected.
10	Score	Score given to article by the given journal.
11	Title	Title of article.
12	Unique key	A unique key.

Table 5: Metadata for each entry/article.

	Result name	Explanation
1	Abstract	The abstract of the article.
2	Author	A single entity of an author from the list of authors of the respective article.
3	Date	Year of publication.
4	Journal	Journal of publication.
5	Provenance	Scholarly database for where the article was collected.
6	Title	Title of article.

Table 6: Structure of data set. Contained results.

4.2 Preliminary Analysis

The data set is consisted by a total of 1150 articles, although only 1145 are unique titles. This is because a total of 5 articles have been collected from more than just one Api. All 5 duplicates are from the pre print server arXiv and will be dropped for the analysis, thus hereupon we consider 1145 entries. The full data set has been archived and is available online.

Though Arcas was used as an automated data collection in progress of writing the literature review of Section 3 the authors have discussed a number of articles that were not retrieved by Arcas. This is only because these articles were not published by the 5 journals considered in the analysis. Even so, the meta data of those article have been manually included, more specifically 41 entries. The provenance of the articles are given by Table 7.

More specifically, a total number of 470 articles have been collected from arXiv, 312 from Springer and 241 from IEEE. A smaller number of entries were contributed by Nature and PLOS.

provenance	Number of articles
IEEE	241
Manual	41
Nature	25
PLOS	63
Springer	312
arXiv	470

Table 7: Keywords used in searching for articles.

The eldest entry was published in 1944 and the most recent one in 2017. Note that the last time data were collected was on December 2017. The provenance of articles can also be viewed over the year of publication. This is illustrated in Figure 11. This allow us to view the significance of each journal's contribution to the field over the years as well as when the prisoner's dilemma fitted the scope of each journal.

Springer and IEEE are the two journals that have been publishing papers on the topic for the longest time. Even so, it can been seen that IEEE contributed more than 10 articles per year after 2002. Similarly, arXiv contributes with a big number of papers with an increasing trend after the 2000s. Both arXiv and IEEE are associated with computer engineering and allied disciplines. As a reminder from Section 3, the 'Modern Area' started near the 2000s where now the study of the prisoner's dilemma is associated with computer science. PLOS journal was launched on 2000 and it can been seen that accepted it's first publication on the topic on 2006 and Nature has a few publications over the years. Nature began it's publications after the work of Axelord in 1980s and some of it's first publications include the work of Martin Nowak done in the 1990's.

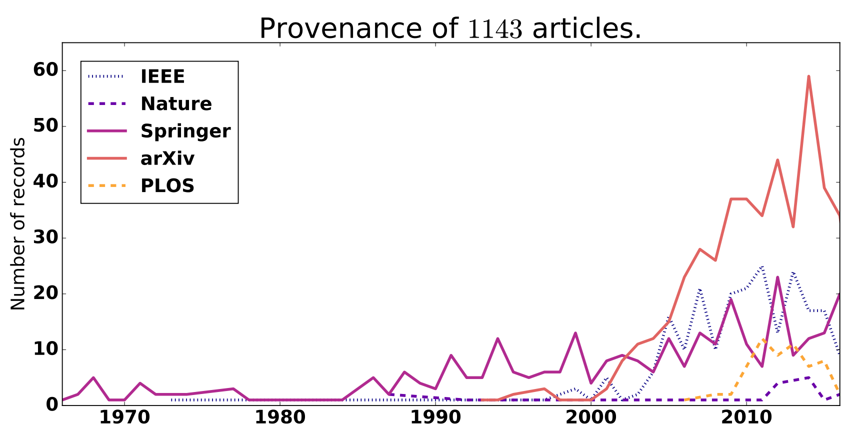


Figure 11: Provenance of articles

Now that the number and the years over when publications have been made on the prisoner's dilemma have been discussed on the following section the people that have written about the game and their connections are explored.

4.3 Authors Analysis

4.3.1 Co authors network

Number of authors varies per paper. Some fields are more collaborative than others. In this section the connectivity of the authors within the prisoner's dilemma field is examined. Over the 1145 articles within the data set the total number of unique authors is 2104 .

Note that the authors names had to be cleaned before the analysis could be held. Several journals use different methods of writing an author's name. For this reason the Levenshtein Distance was used to calculated the difference between name entries. A manual check was performed before replacing the flagged entries by the Levenshtein Distance.

The authors will be represented in a network. The network, shown in Figure 12, has sets of vertices V and edges E. The 2104 vertices represent each of the unique authors. The vertices are connected with an edge if and only if two authors have written together. Weights have been applied to both the vertices and the edges. Vertices' weight corresponds to the number of papers the author has within the data set and the edge weight to the number of times the authors wrote together. The weighted network can be seen in Figure 13.

In Figure 12 it can bee seen that overall the authors network is disjoint. Several researchers on the outer circle seem to have written alone or have a single connection to another researcher. On the other hand, in the inner circle of the network some connectivity of the vertices does seem to exists, with a single large cluster located in the middle of the network.

More insights can be gained by observing Figure 13 as well. The authors that cover the outer space, that seem to be less collaborative, are not authors that have single contributions to the field. On the other hand authors that have repeatedly published on the topic are located in both the outer and inner circles of the network.

Let's identify the authors with the maximum number of publication in the data set. The 10 most published authors of the data set are given by Table 8. Authors such as M. Nowak and D. Ashlock, that have previously been discussed in Section 3, appear on the list. Though other authors such as R. Axelrod do not. On the other hand, several people whose work was not discussed in the previous section appear here for example Matjaz Perc with a total of 34 articles.

The number of publications is not the only measure examined here. The centrality of the authors is explored in a similar manner. Several measures of centrality are used in network theory. For the purpose of this work the measure examined is the betweenness centrality. The results are given by Table 9.

	Number of publications
Martin A. Nowak	11
Hisao Ishibuchi	13
Yamir Moreno	13
Zhen Wang	13
Angel Snchez	16
Long Wang	16
Gyorgy Szabo	19
Daniel Ashlock	21
Attila Szolnoki	29
Matjaz Perc	34

Table 8: Top 10 most published authors.

The co authors networks can also be evaluated over the time period used as sections in Section 1. Initially, lets us look at the four first time periods illustrated in Figure 14. It can be seen that over the early years a small number of authors existed with several collaborations between them. This seems to be changing the closer we get to 2000, Figures 15, 16. Now a larger of author appear but no much collaboration between them is visible. Again the trend chances as time progress, Figure 17, we see that in recent year the network is more joint.

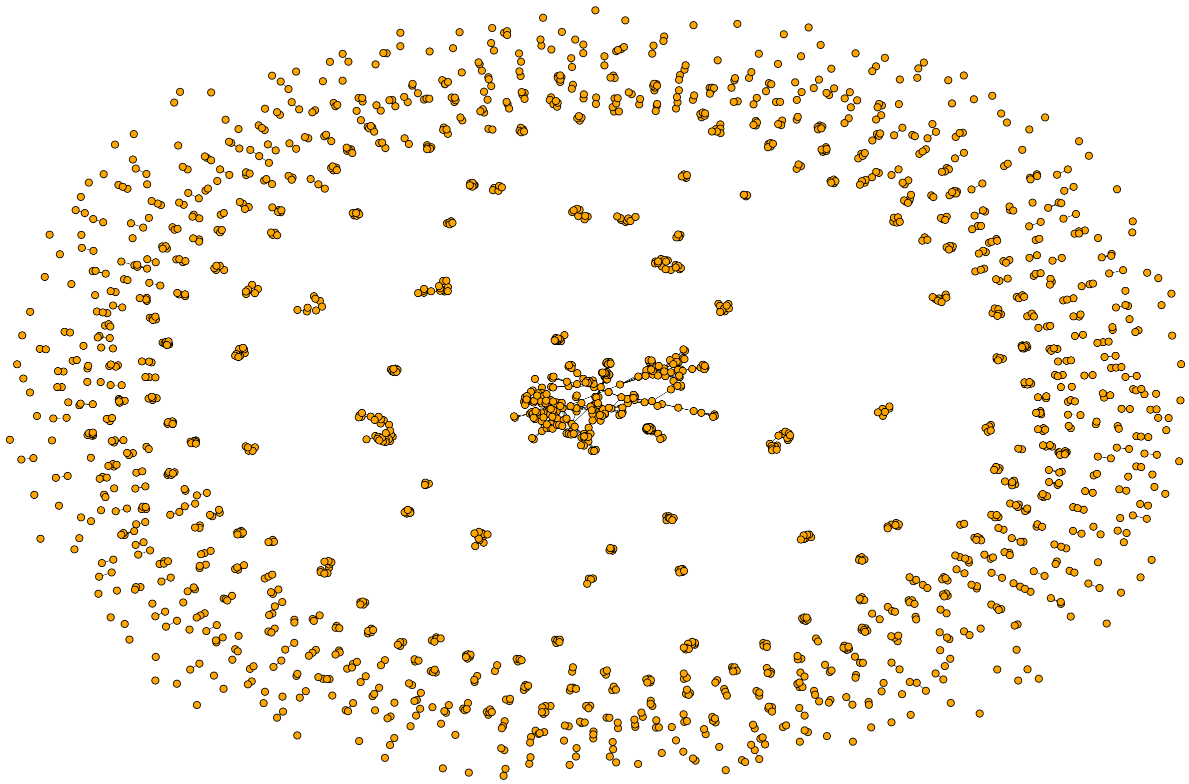


Figure 12: Co authors network.

	Author name	Centrality
1	Matjaz Perc	0.010551
2	Yamir Moreno	0.008759
3	Luo-luo Jiang	0.004306
4	Arne Traulsen	0.003908
5	Martin A. Nowak	0.003821
6	V. Latora	0.003425
7	Krishnendu Chatterjee	0.002602
8	Angel Snchez	0.002533
9	Han-xin Yang	0.002056
10	Zhihai Rong	0.001930

Table 9: Central authors.

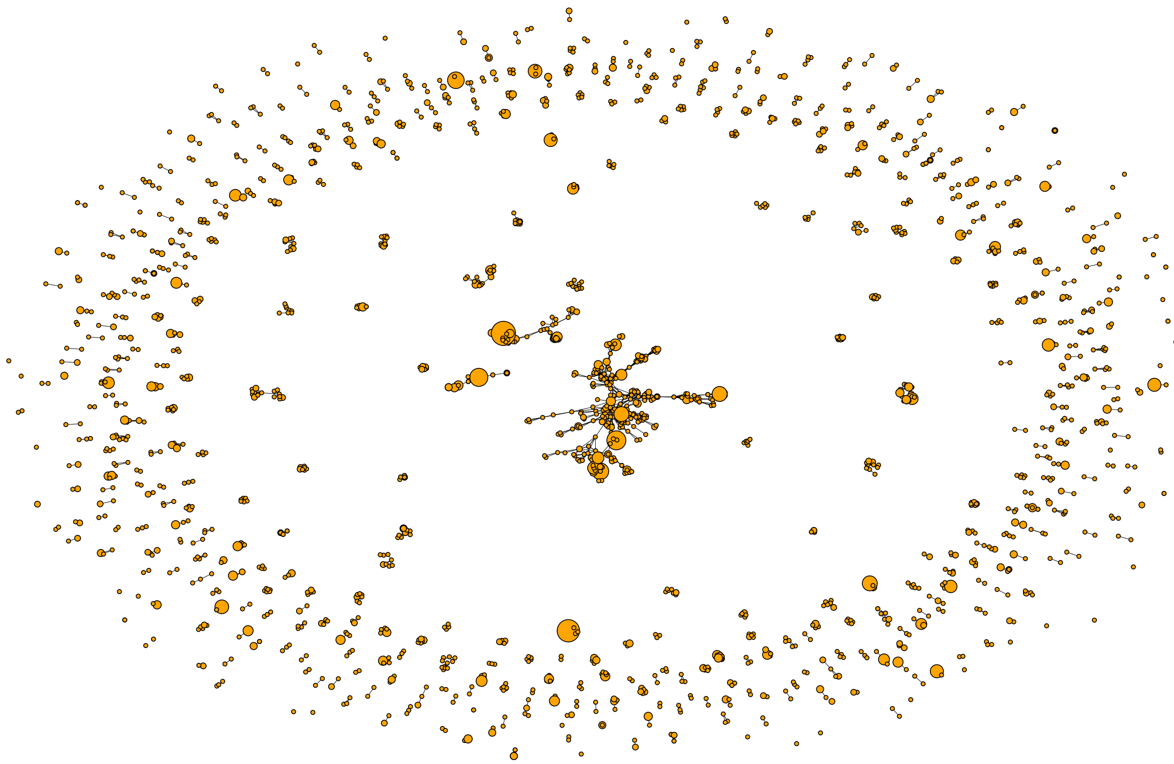
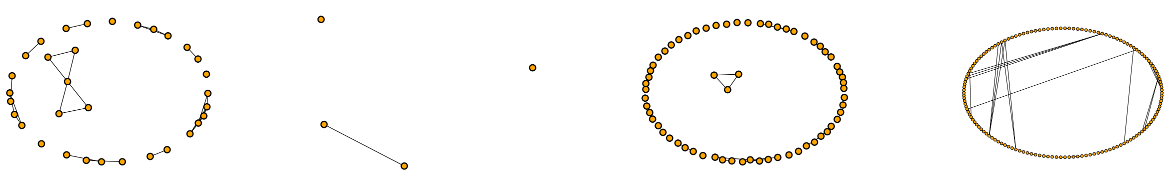


Figure 13: Co authors network with vertices' weight.



(a) 1961 to 1972

(b) 1981 to 1984

(c) 1984 to 1993

(d) 1987 to 1999

Figure 14: Co authors networks over time periods.

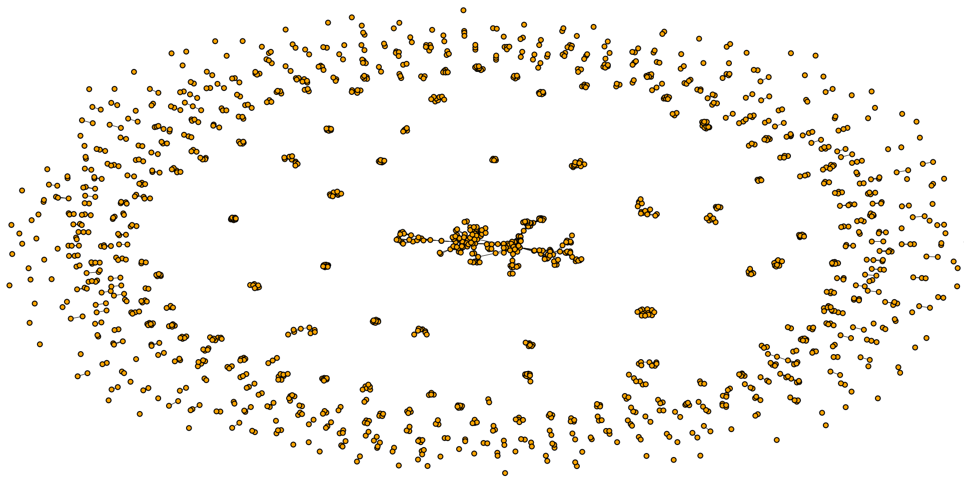


Figure 15: Co authors network over 1995 to 2015.

However, what is the number of people that collaborate? Table 10 gives the frequency of each size of co authorships. It can be seen that the size of co-authors varies from 1 to 12 and an outlier of size 21 exists within the data set as well. The most frequented sizes are those of 3 and 1 authors. Thus within the field collaboration do exist, but most of them are between 2-3 people.

4.3.2 Collaborations

The immediate step is to evaluate these collaborations and understand why authors tend to collaborate. This is achieved by studying the cliques of the network. Cliques are subsets of vertices, all adjacent to each other, also called complete subgraphs. Cliques can be looked at is a group of individuals who interact with one another and have worked on the same projects within the research of the prisoner's dilemma.

A total of 728 cliques exists within the network and the max node number of a clique is 21. Visualising the subgraphs that exist within the network allow us to look at the type of collaborations that exist within the field. The following sub graphs have been generated by looking at cliques with a minimum of 5 vertices that are not just co-authors for a single paper.

The first formulation of a clique that was identified is that of Figure 18. Figure 18 illustrates how two clusters of several people are connected through a single, or in one case two authors. A very common collaborations structure. More interesting cases arise, shown in Figure 19. These can be viewed as cases that people worked on the same topic and almost everyone in the clique has collaborated with each other, generating almost a complete graph.

The most interesting cases are those that appear in Figure 20. It is shown that clusters of authors have been brought together by few connecting vertices. The connecting vertices are authors such as Long Wang, Martjaz Perc, Yamir Moreno

Figure 16: Co authors network over 2012 to 2015.

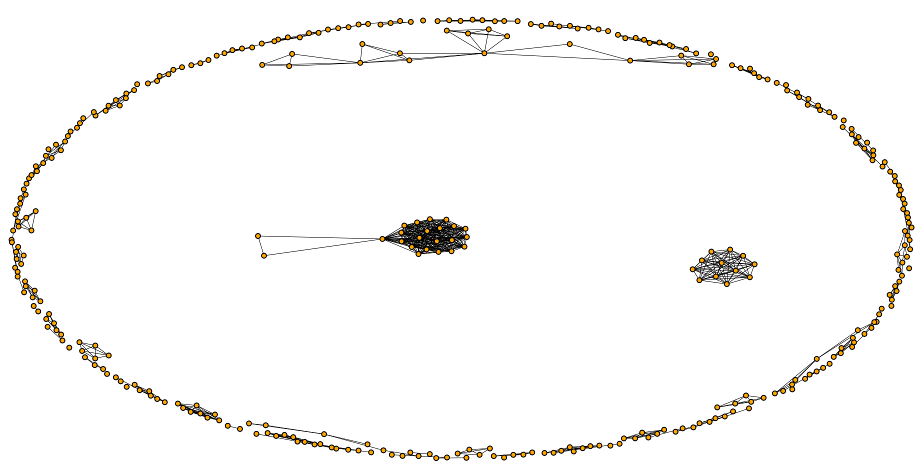


Figure 17: Co authors network over 2015 to 2017.

Size of co authorships	Frequency
1	262
2	139
3	373
4	272
5	26
6	55
7	2
8	4
9	1
10	3
11	4
12	1
21	1

Table 10: Co-authors size frequency.

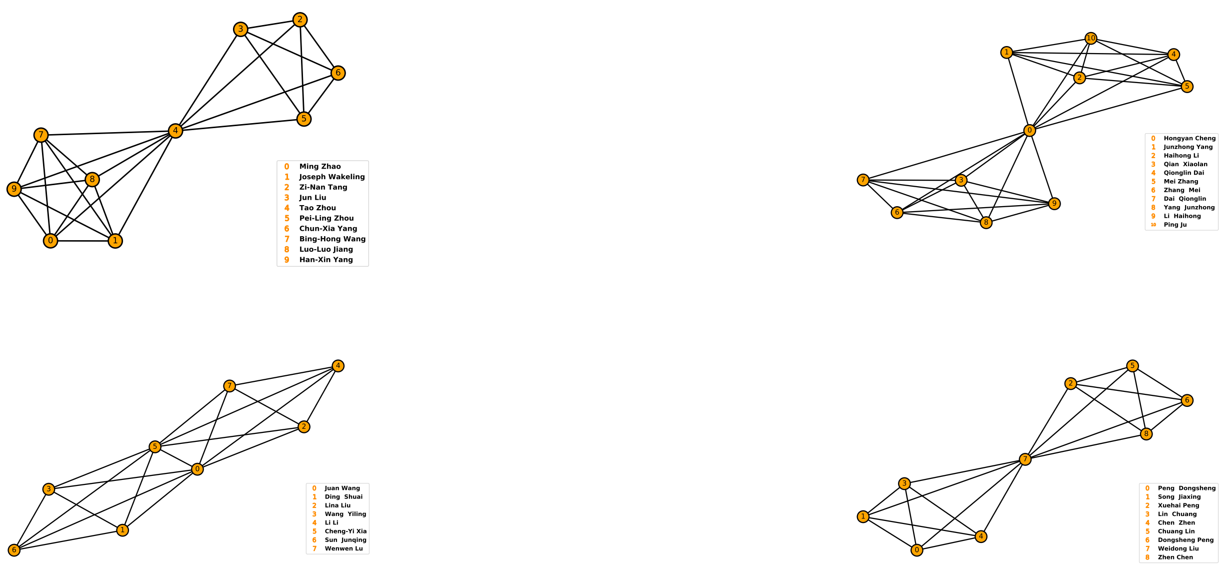


Figure 18: Cliques with 1 or 2 central authors.

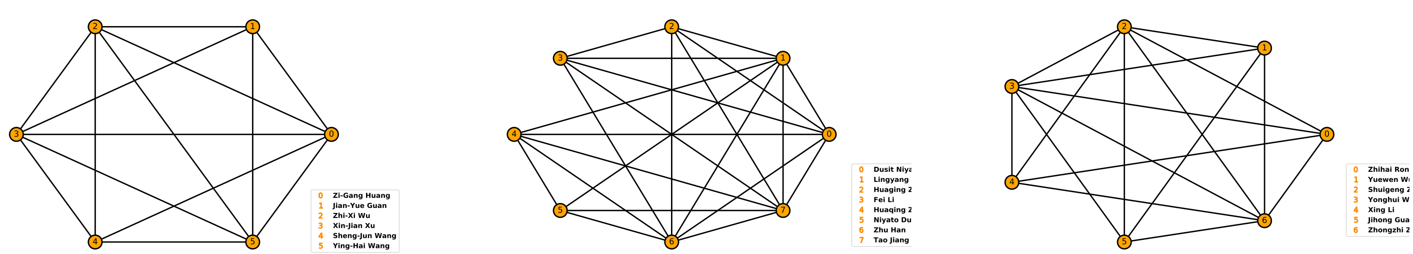


Figure 19: Cliques of several connecting authors.

and Alex Doud. Investigating the reasons these authors appear as connecting nodes will be discussed later on using natural language techniques.

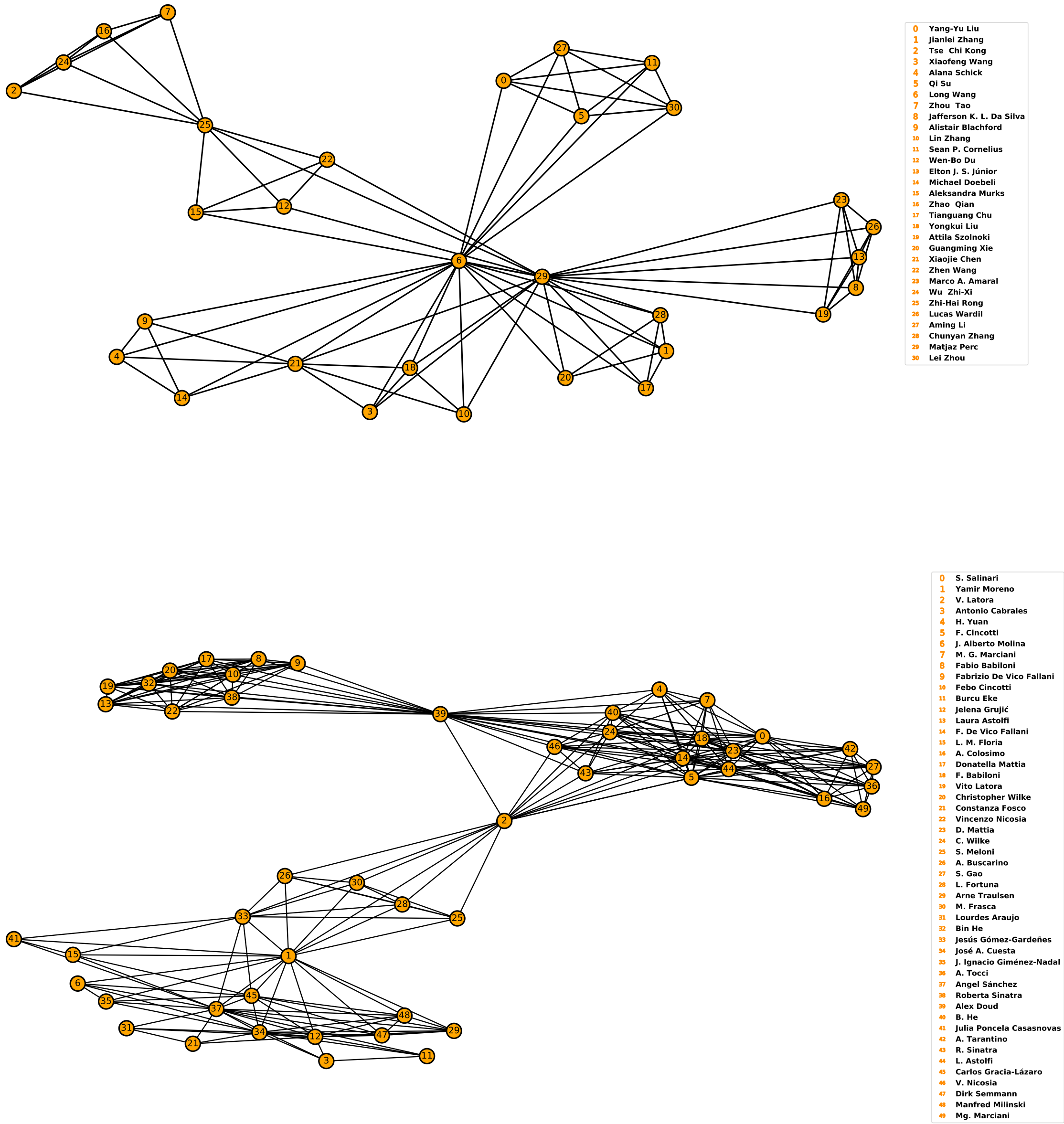


Figure 20: Complicated clique networks.

However noticeable authors such as Nowak, Ashlock, Plotkin and Axelord did not appear on these networks. Plotkin and Axelrod are authors that have not many collaborations during their work. On the other hand, Nowak's clique can be visualised by looking at cliques with minimum 4 vertices. Similarly for Ashlock, however this time the network with cliques of minimum 3 vertices is shown.

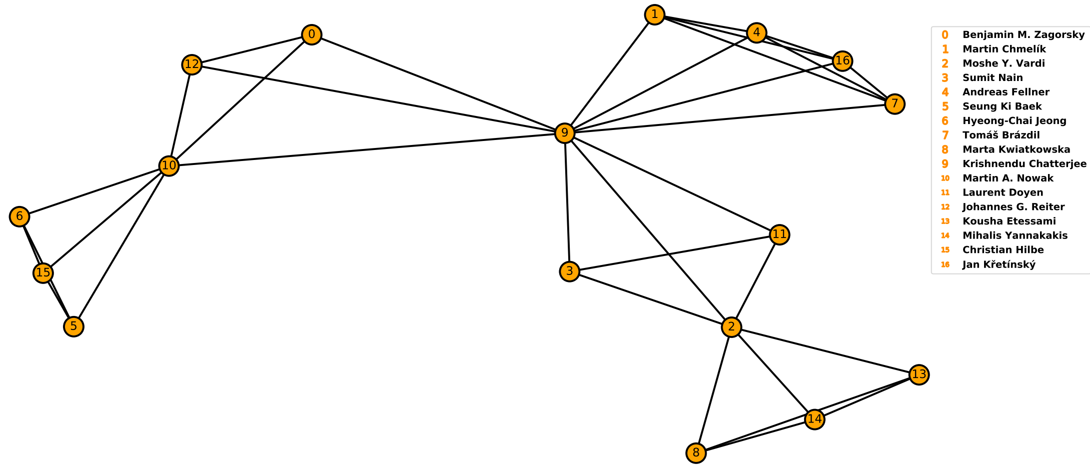


Figure 21: Martin Nowak clique network.

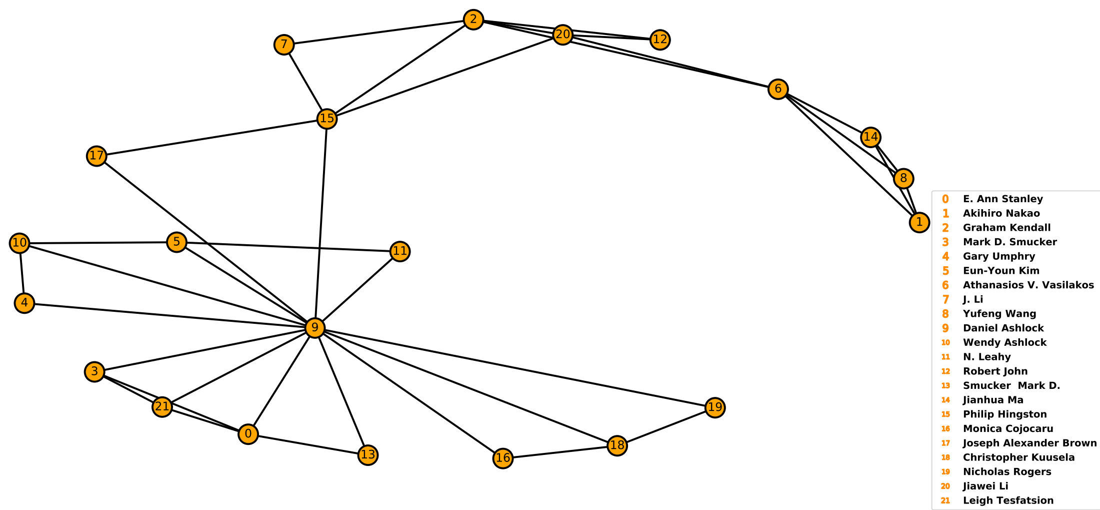


Figure 22: Daniel Ashlock clique network.

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