Artificial Life & Complex Systems

Lecture 7

The Evolution of Cooperation

June 1, 2007

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Contents

- Evolution of cooperation: why is it surprising, and how does it evolve?
- Game Theory
- Iterated prisoner's dilemma
- Other games

Evolution

- **Evolution** is based on a fierce competition between individuals and should therefore reward only selfish behavior (winner-take-all)
- **Darwinian evolution** is based on three fundamental principles: reproduction, mutation and selection (of the fittest)

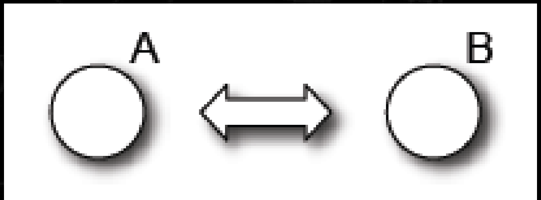
What is Cooperation?

"You scratch my back, I'll scratch yours."

Cooperation requires at least two individuals:

A: the one providing cooperation

B: the one benefiting from cooperation



Cooperation involves a cost c to A

Cooperation confers a benefit b to B

Cooperation (a form of altruistic behavior) means that selfish agents forgo some of their benefit to help one another (if both benefit that's mutualism)

What is Cooperation?

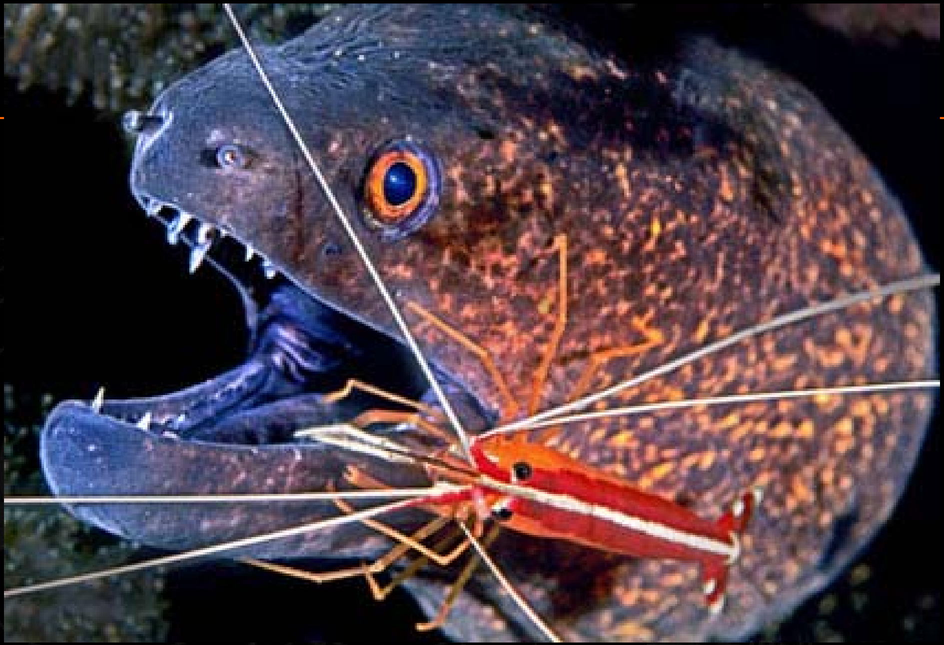
In the spite of all the "selfish genes", animals seem to altruistically help each other and cooperate!

Cooperation is a very general solution in biology and is essential for the evolution of reproductive entities (Nowak, 2006)

- Genes "cooperate" in genomes
- Chromosomes "cooperate" in eukaryotic cells
- Cells "cooperate" in multicellular organisms
- Symbiosis (e.g. fungus and alga that compose a lichen; fig wasps and fig trees; some birds or fish clean other animals)
- Hunter-gatherer societies

Cooperation is needed for evolution to construct new levels of organization

Odd Couples



Other Forms of Cooperation

Collective intelligence and cooperation

E.g. Didabot helping behavior, s-bots pushing a box

http://www.swarm-bots.org

Other Forms of Cooperation

E.g. Robocup

Other Forms of Cooperation

http://www.informatik.uni-freiburg.de/~nimbro/

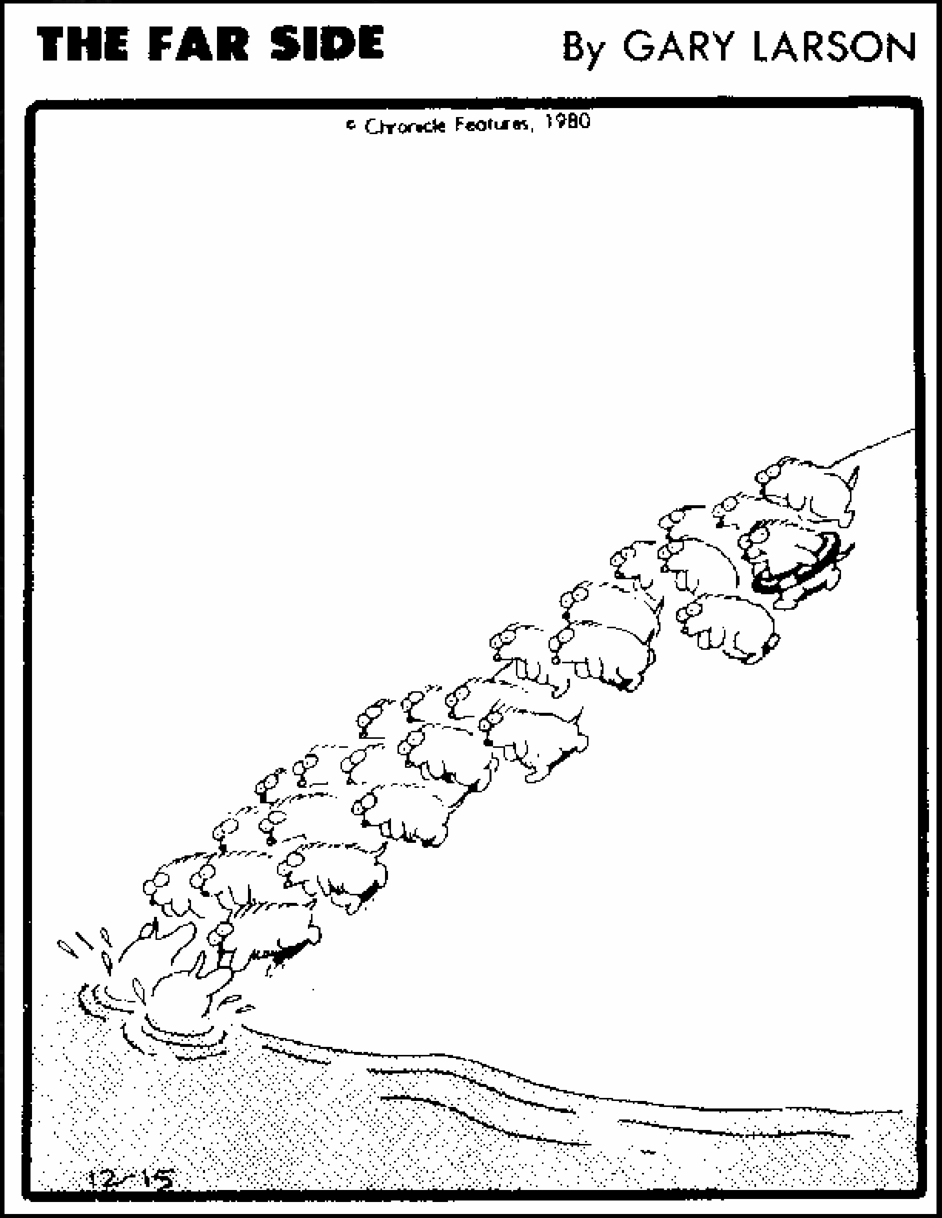
Other Forms of Cooperation

More on this next week ☺

What is Cooperation?

Social behavior (e.g. group living) is not cooperation!

Why don't individuals sacrifice themselves for the good of the group?



Questions and Tools

Understanding the evolution of cooperation remains a fundamental challenge, for scientists from fields like evolutionary biology, political science, anthropology, mathematics, etc.

Key questions are:

- How can cooperation emerge although living things are in a state of perpetual competition?
- How can mutual cooperation evolve?

Common tools:

- Mathematical framework: evolutionary game theory
- Evolution: replicator dynamics (set of diff. eq.)
- Metaphor: Prisoner's dilemma and other games

What is Game Theory? Cake Slicing Problem

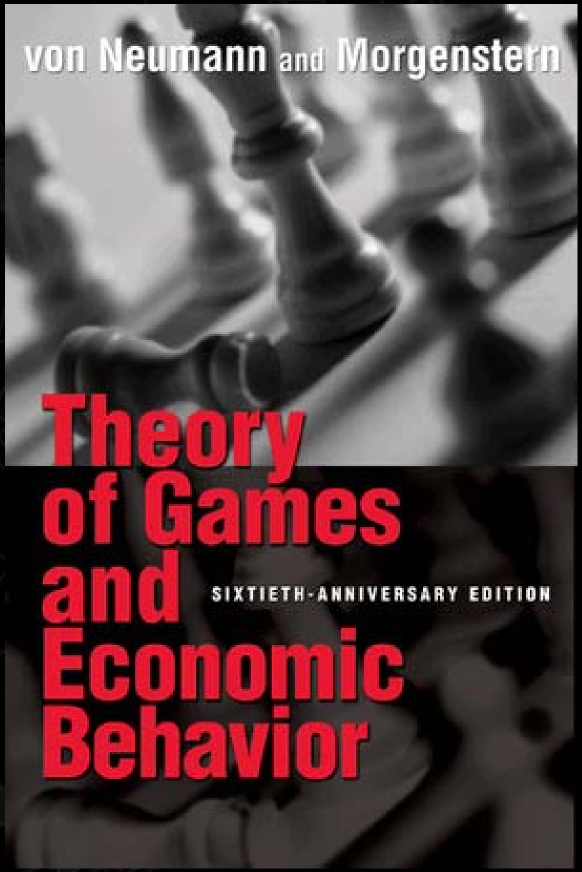
The “cutter-chooser dilemma”

Cake-Cutting Payoff Matrix

		Chooser's Strategies:	
		Choose Bigger Piece	Choose Smaller Piece
Cutter's Strategies:	Cut as Evenly as Possible	Chooser gets a *slightly* bigger piece.	Chooser gets a *slightly* smaller piece.
	Cut One Piece Bigger	Chooser gets a bigger piece.	Chooser gets a smaller piece.

What is Game Theory?

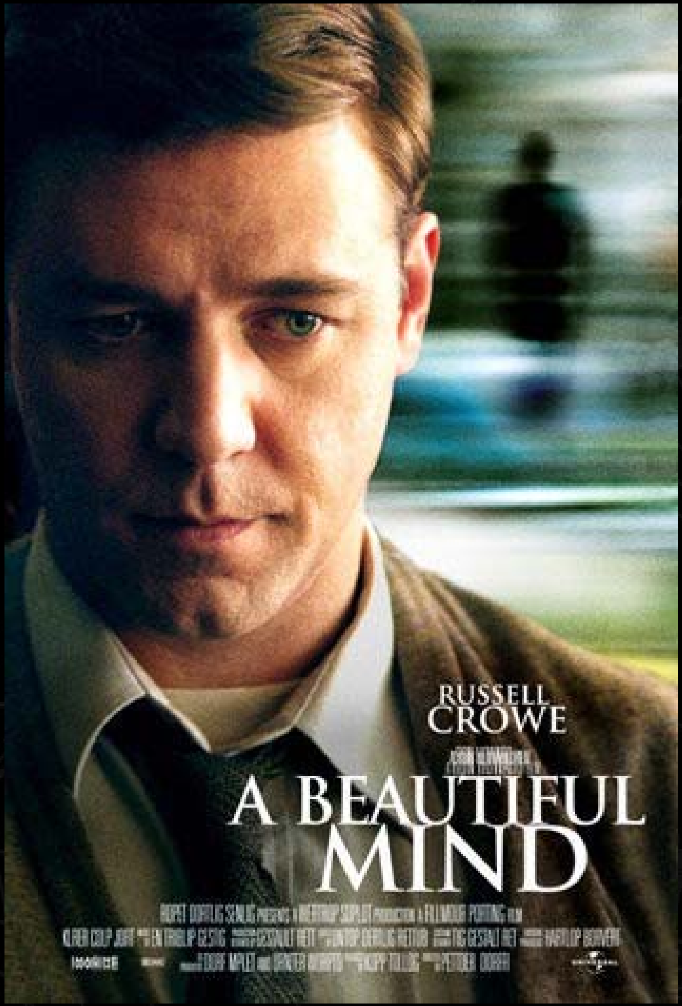
- Created and formalized by John von Neumann and Oskar Morgenstern (1944)
- Covers a wide range of situations, including both cooperative and non-cooperative situations
- Studies the ways in which <u>strategic interactions</u> among <u>rational players</u> produce outcomes with respect to the players' preferences (utilities, benefit)
- Rational players: <u>maximize</u> score/returns or <u>minimize</u> costs



What is Game Theory?

- Offers a formal way to analyse interactions between agents who behave strategically: mathematics of decision making in conflict situations
- Widely applied to the study of economics, warfare, politics, animal behaviour, sociology, business, ecology and evolutionary biology

Game Theory in Pop-Culture



Games, Strategies, and Payoffs

- A game consists of an interaction between two or more players according to a set of rules which state who can do what, and when they can do it
- A player's strategy is a plan for actions (set of decisions the player has to make) in each possible situation in the game
- A player has a dominant strategy if his best strategy doesn't depend on what other players do
- A player's payoff is the amount that the player wins and loses in a particular situation in a game

Zero-Sum Games

- Zero-sum describes a situation in which a participant's gain (or loss) is exactly balanced by the losses (or gains) of the other participant
- The total gains of the participants minus the total losses always equals 0
- Zero-sum games:
  - Poker (the money won = the money lost)
  - Cutting the cake (if my piece is bigger, yours is smaller)
  - The game of Go

Non-Zero-Sum Games

- Trade is a <u>non-zero-sum game</u>
  - If a country with an excess of bananas trades with another for their excess of apples, both benefit from the transaction (win-win situation)
- Non-zero sum games are more complex to analyze
- They permit win-win and lose-lose outcomes which adds a nice dose of realism (and leaving open the <u>possibility for cooperation</u>)
- We find more non-zero-sum games as the world becomes more complex, specialized, and interdependent

Note on Terminology

- A <u>cooperator</u> is someone who pays a <u>cost *c*</u> for another individual to receive a <u>benefit *b*</u>
- A <u>defector</u> has no (or reduced) cost and does not deal out benefits

Payoff Matrix for a Generic Two-Player Game

Player B's move

Player A's move

	Cooperate	Defect
Cooperate	(CC,CC) Reward for mutual cooperation	(CD,DC) Sucker's payoff, temptation to defect
Defect	(DC,CD) Temptation to defect, sucker's payoff	(DD,DD) Punishment for mutual defection

Number of Possible Orderings (Games)

Example: CC > CD > DC > DD

How many are there?

Number of Possible Orderings (Games)

Solution: 24

Catch: some of the orderings lead to a dilemma ("damned if you do, damned if you don't")

E.g. CC > CD > DC > DD does not lead to a dilemma (cooperation is always better than defection; for both players)

Conditions for Dilemma

You take one course of action, and then specify what you would prefer your opponent's action to be:

CC > CD: if you cooperate, then you will benefit more if the other player also cooperates

DC > DD: if you defect, then it is better if the other player cooperates

Conditions for Dilemma

The other player takes some course of action; then you specify what to do:

DC > CC: if the other player cooperates, then you'd better defect

DD > CD: if the other player defects, then you'd better defect

The Prisoner's Dilemma - DC>CC>DD>CD

- Discovered by Melvin Dresher and Merrill Flood in 1950
- Provides a framework for studying how cooperation can become established in a situation where short-range maximization of individual utility leads to a collective utility (welfare) minimum
- Typically two players who have same payoff matrix
- Players adopt dominant strategies, but they don't necessarily lead to best outcome
- Rational behavior leads to a situation where everyone is worse off

Bonnie and Clyde

Bonnie and Clyde are arrested by the police and charged with various crimes. They are questioned in separate cells, unable to communicate with each other. They know how it works:

- If they both resist interrogation (cooperating with each other) and proclaim their mutual innocence, they will get off with a 3 year sentence for robbery.

- If one of them confesses (defects) to the entire string of robberies and the other does not (cooperating), the confessor will be rewarded with a light, 1 year sentence and the other will get a severe 8 year sentence.

- If they both confess (defect), then the judge will sentence both to a moderate 4 years in prison.

What should Bonnie do? What should Clyde do?

The Prisoner's Dilemma: DC>CC>DD>CD

- Both cooperate (mutual cooperation: 3 years each)
- Both defect (mutual defection: 4 year each)
- Bonnie defects, Clyde cooperates ("temptation": 1 year)
- Bonnie cooperates, Clyde defects (sucker's payoff: 8 years)

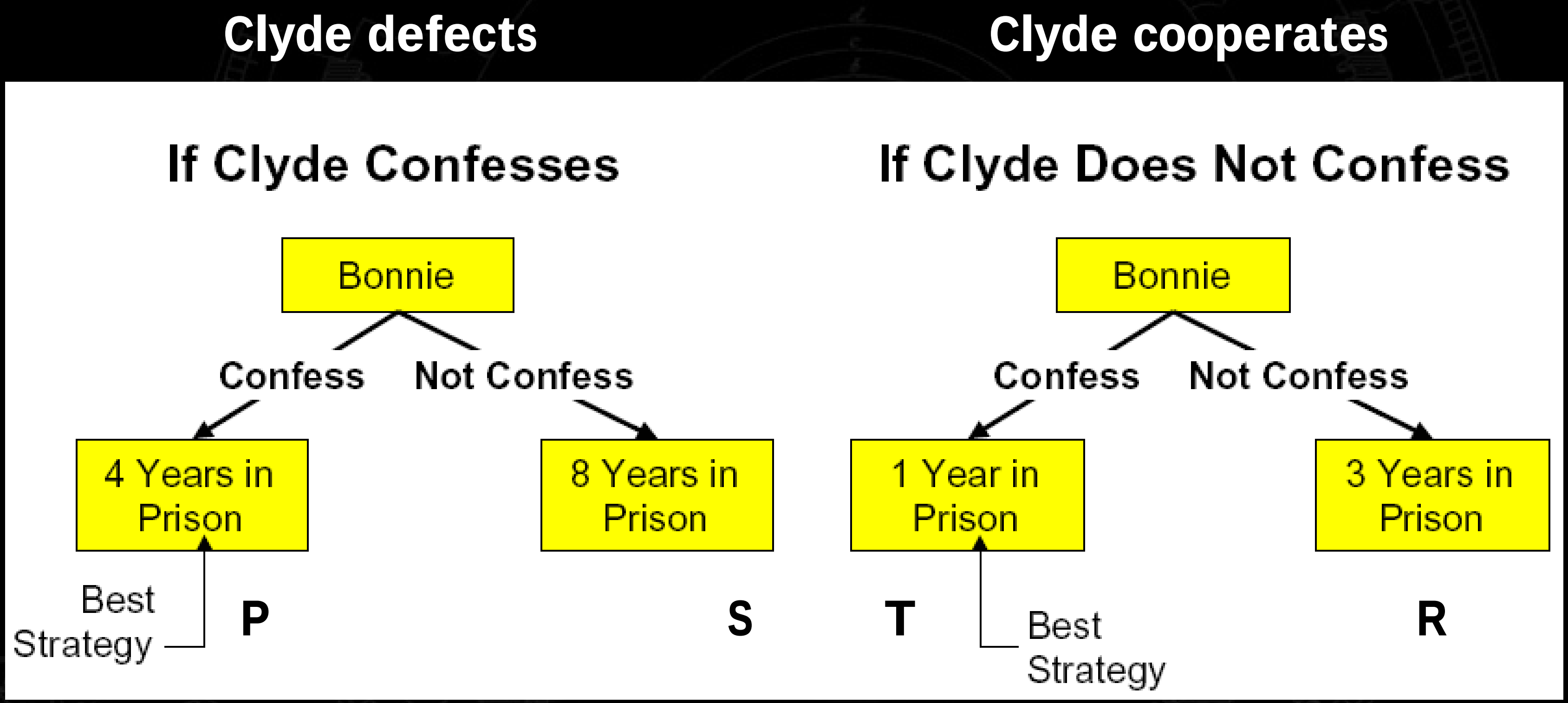
Payoff for Bonnie (C = cooperate; D = defect)

$$\text{Bonnie}\begin{cases} C \\ D \end{cases} \overbrace{\begin{array}{cc} C & D \end{array}}^{\text{Clyde}} \begin{pmatrix} R=3 & S=8 \\ T=1 & P=4 \end{pmatrix}$$

R (CC) is REWARD for mut. cooperation	= 3
S (CD) is SUCKER's payoff	= 8
T (DC) is TEMPTATION to defect	= 1
P (DD) is PUNISHMENT for mut. defection	= 4

Note: The game is defined by T<R<P<S or DC<CC<DD<CD (minimization)

Bonnie’s Decision Tree



The <u>dominant strategy</u> for Bonnie is to defect (confess) because no matter what Clyde does she is better off confessing. Dilemma: Rational choice leads to DD although CC would be better!

Some Games Have No Simple Solution

In the following payoff matrix, neither player has a dominant strategy. There is no non-cooperative solution. The solution depends on the other players decision.

		Player B	
		1	2
Player A	1	1, -1	-1, 1
	2	-1, 1	1, -1

What is Player A’s decision tree?

Summarizing the PD (Flood & Dresher, 1950)

1. **Standard game**
   - No communication between players
   - Only one play/iteration of the game
2. **Two strategies for each player**

   Cooperate or defect
3. **Dominant strategy for each player**

   Defect regardless of opponents move
4. **Equilibrium of the game**

   Defect-Defect (DD) (best outcome according to classical game theory)
5. **Dilemma**

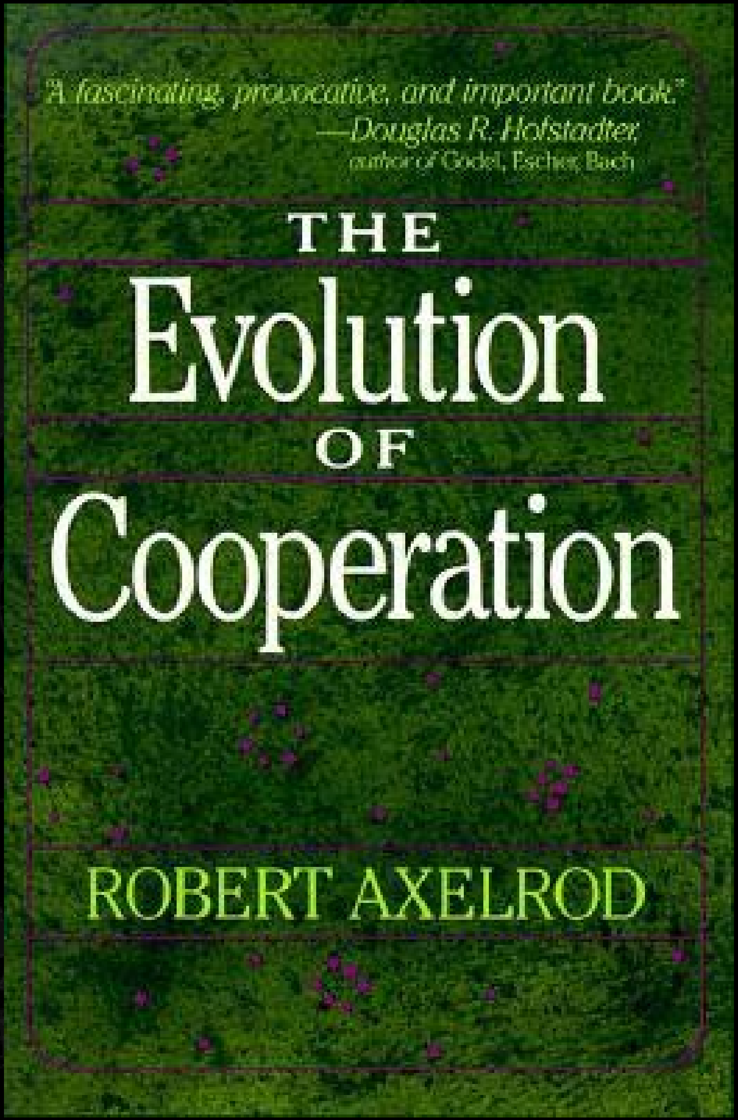
   Individual rationality leads to collectively inferior outcome (they'd do better by both cooperating)

Evolution of Cooperation

Questions addressed:

- *Under what conditions will cooperation emerge in a world of egoists without central authority?*
- Can a cooperative strategy gain a foothold in a population of rational egoists?
- How might cooperation emerge in anarchy?
- Can it survive better than its uncooperative rivals?
- Can it resist invasion and eventually dominate the system?
- Does it imply rationality?

Applies to Trade Wars, Arms Races, Trench Warfare



(1984)

Repeated/Iterated Games

- A repeated game is a game that the same players play more than once
- Repeated games differ from one-shot games because people's current actions can depend on the past behavior of other players
- Cooperation is encouraged
- Players have (at least, in theory) complete knowledge of the past games, including their choices and the other player's choices
- Your choice in future games when playing against a given player can be partially based on whether she has been cooperative in the past

The Iterated Prisoner's Dilemma

The Iterated Prisoner's Dilemma

PLAYER B

PLAYER A		COOPERATE	DEFECT
	COOPERATE	CC = +5 CC = +5	DC = +10 CD = -20
	DEFECT	CD = -20 DC = +10	DD = 0 DD = 0

	ITERATION	1 2 3	4 5 6	7 8 9	10	TOTALS
DEFECT STRATEGY (ALL-D):	PLAYER A:	D D D	D D D	D D D	D	+10
	PLAYER B:	C D D	D D D	D D D	D	- 20
COOPER. STRATEGY (ALL-C):	PLAYER A:	C C C	C C C	C C C	C	+50
	PLAYER B:	C C C	C C C	C C C	C	+50

The Iterated Prisoner's Dilemma

Strategies anyone?

The Iterated Prisoner’s Dilemma

Suppose that each player has a one-step memory (remembers the previous step only)

How many possible strategies are there?

One possible strategy

- If CC then C
- If CD then D
- If DC then C
- If DD then D

→ Encoding: CDCD = $(0101)_2$

The Iterated Prisoner's Dilemma

Suppose that each player remembers the outcome of three previous games (history of previous moves)

How many possible strategies are there?

One possible strategy

If CC CC CC then C

If CC CC CD then C

If CC CC DC then C

...

If DD DD DD then D

→ Encoding: CCC...D = $(000...1)_2$

The Iterated Prisoner's Dilemma

How many three-memory strategies are there?

The Iterated Prisoner's Dilemma (IPD)

- A simulation was first realized by Robert Axelrod (U. Michigan; 1980) in which he solicited a group of scholars to design and submit design strategies to play the iterated prisoner's dilemma
- The computer programs played the IPD in a round-robin tournament for 200 rounds (contestants did not know the length of the games)
- In each round of the game, each entry was matched against every other, itself, and a control (RANDOM)

http://www2.lifl.fr/IPD/applet-tournament.html

The Iterated Prisoner's Dilemma (IPD)

- Second tournament took place
- The first tournament lasted 200 rounds; the second varied probabilistically with an average of 151
- The first tournament had 14 entrants, including game theorists, mathematicians, psychologists, political scientists, and others
- Results were published and new entrants solicited. The second tournament included 62 entrants ...

IPD: Some Possible Strategies

- Always defect (ALL-D; suffers when playing against itself)
- Always cooperate (ALL-C; suffers when playing against ALL-D)
- Random strategy (RANDOM; flip a coin)
- Tit-for-Tat (TFT; “conditional strategy”; has memory)
  - Be nice, but punish any defections. Starts by cooperating and, after that, always does what the other player did on the previous round
- Joss
  - A sneaky TFT that defects 10% of the time

The Iterated Prisoner's Dilemma

- **Surprising result: TFT** won both tournaments!
- **Interestingly: TFT** was the simplest of all submitted programs (4 lines of code) and it turned out to be the best
- **Note:** In an idealized (noise free) environment, TFT is both a very simple and a very good strategy

Characteristics of Robust Strategies

Axelrod analyzed the various entries and identified the characteristics of a robust strategy (such as TFT)

- **Be nice** – never defect first; "mean" strategies perform more poorly
- **Reciprocate** – elicit cooperation by <u>punishing defection</u> and <u>rewarding cooperation</u>
- **Don't be envious** – seek for win-win situations and don't get greedy for higher payoffs; TFT can never beat another strategy, at best it can only tie
- **Be prompt** – respond to a defection by promptly defecting. "Being slow to anger" might be a good strategy, but can cause certain classes of programs to try even harder to take advantage
- **Don't be too clever** – TFT is perfectly transparent; you know exactly what to expect and what would or wouldn't work. Too many random number generators or bizarre strategies in a program, and the competing programs just sort of said the *"hell with it and began to generate all D"*

Back to the Evolution of Cooperation

Initial viability: How can cooperation get started in a world of unconditional defection?

Answer: an invasion by small clusters of cooperating organisms is enough to give cooperation a toehold

Back to the Evolution of Cooperation

Robustness: What type of strategy does well in unpredictable and shifting environment?

Answer: Strategies that possess five characteristic traits

Back to the Evolution of Cooperation

Stability: Can cooperation protect itself from invasion?

Answer: Although a world of all "meanies" (ALL-D strategies) can be penetrated by cooperators in clusters, a world of cooperators cannot be penetrated by meanies, even if they arrive in clusters of any size!

The gear wheels of social evolution have a ratchet! (Axelrod, 1981)

More on the Iterated Prisoner’s Dilemma

The Trouble with TFT

Noise in the form of random errors in implementing or perceiving an action is a common problem in real-world interactions. Such misunderstandings may lead “well-intentioned” cooperators into periods of alternating or mutual defection resulting in lower tournament scores.

Player A – TFT: C C C

Player B – TFT: C C C

The Trouble with TFT

Noise in the form of random errors in implementing or perceiving an action is a common problem in real-world interactions. Such misunderstandings may lead "well-intentioned" cooperators into periods of alternating or mutual defection resulting in lower tournament scores.

Player A – TFT:	C	C	C	C
Player B – TFT:	C	C	C	D

Error!

The Trouble with TFT

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Player A – TFT: C C C C D

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Player A – TFT:	C	C	C	C	D
Player B – TFT:	C	C	C	D	C

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Player A – TFT: C C C C D C

Player B – TFT: C C C D C D

The Trouble with TFT

Noise in the form of random errors in implementing or perceiving an action is a common problem in real-world interactions. Such misunderstandings may lead “well-intentioned” cooperators into periods of alternating or mutual defection resulting in lower tournament scores.

Player A – TFT: C C C C D C D C

Player B – TFT: C C C D C D C D

Lower average payoff

PAVLOV

Nowak and Sigmund (1993) ran an extensive series of computer-based experiments and found the simple learning rule PAVLOV outperformed TIT FOR TAT in the presence of noise

PAVLOV (win-stay, lose-switch): Cooperate after both cooperated or both defected; otherwise defect

PAVLOV: Features

PAVLOV cannot be invaded by a random C; PAVLOV is an exploiter (will “fleece a sucker” once it discovers it; no need to fear retaliation).

A mistake between a pair of PAVLOVs causes only a single round of mutual defection followed by a return to mutual cooperation.

Player A – PAV:	C	C	C	C
Player B – PAV:	C	C	C	D

Error!

PAVLOV

PAVLOV cannot be invaded by a random C; PAVLOV is an exploiter (will "fleece a sucker" once it discovers it; no need to fear retaliation).

A mistake between a pair of PAVLOVs causes only a <u>single round</u> of mutual defection followed by a return to mutual cooperation.

Player A – PAV:	C	C	C	C	D
Player B – PAV:	C	C	C	D	

PAVLOV

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Player A – PAV:	C	C	C	C	D
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PAVLOV

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A mistake between a pair of PAVLOVs causes only a single round of mutual defection followed by a return to mutual cooperation.

Player A – PAV:	C	C	C	C	D	C
Player B – PAV:	C	C	C	D	D	C

PAVLOV

PAVLOV cannot be invaded by random C; PAVLOV is an exploiter (will "fleece a sucker" once it discovers no need to fear retaliation).

A mistake between a pair of PAVLOVs causes only a single round of mutual defection followed by a return to mutual cooperation.

Player A – PAV: C C C C D C C

Player B – PAV: C C C D D C C

Lower average payoff

Iter. Prisoner's Dilemma: Variations

STANDARD PRISONER'S DILEMMA

1. DC -- +10
2. CC -- +5
3. DD -- 0
4. CD -- -20

VERY HARSH PRISONER'S DILEMMA

1. DC --+100
2. CC -- +5
3. DD -- 0
4. CD -- -200

VERY MILD PRISONER'S DILEMMA

1. DC -- +6
2. CC -- +5
3. DD -- 0
4. CD -- -1

Final Thoughts

- Nothing suggests that nature employs a pure TFT or PAVLOV strategy
- Remarkably, Axelrod and others have shown that a “live and let live” strategy similar to TFT was used by both German and Allied forces in trench warfare during World War I
- Key 1 to cooperation: <u>iteration</u>
- Key 2 to cooperation: number of iterations needs to be unknown
- Without iteration then defection is the better action from a game-theoretic point of view
- Mindless cooperation and defection are both bad strategies

Final Thought!

Mutual cooperation can emerge in a world of egoists without central control, by starting with a cluster of individuals who rely on reciprocity.

Spatial Games

Where is Artificial Life?

Example: artificial ecologies / understanding human society

Such ecologies have some degree of biological plausibility (abstractions)

Spatial Games: Towards Artificial Ecosystems

Example: lattice game

- Each lattice is occupied by a single strategy
- All sites are updated in the following manner:
  1) Score of site is calculated as sum of average scores obtained when strategy at site plays iterated game with neighbors
  2) Score is compared with neighbors and highest scoring strategy replaces site strategy

Spatial Games: Towards Artificial Ecosystems

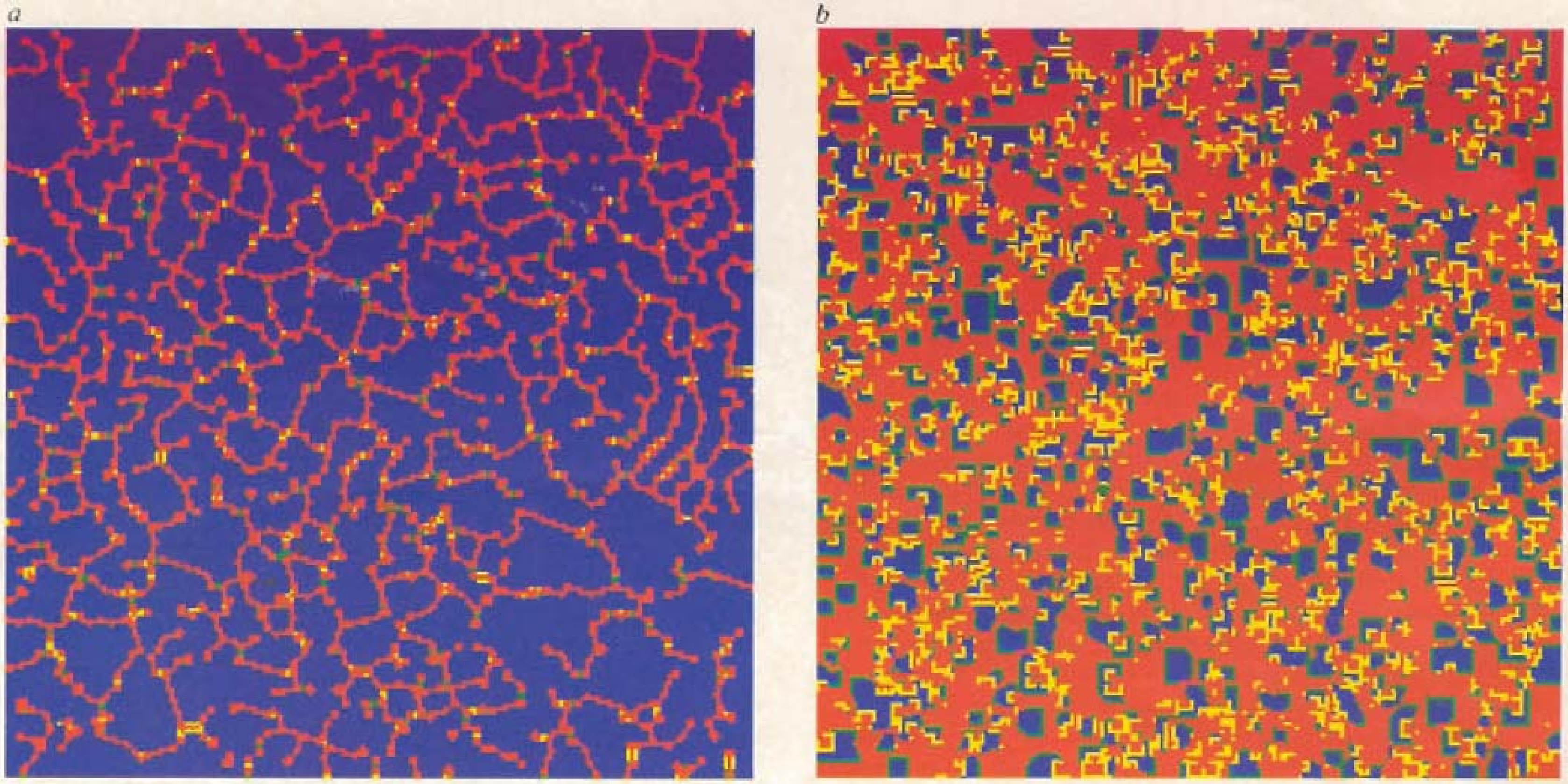


FIG. 1 The spatial Prisoners' Dilemma can generate a large variety of qualitatively different patterns, depending on the magnitude of the parameter, *b*, which represents the advantage for defectors. This figure shows two examples. Both simulations are performed on a 200×200 square lattice with fixed boundary conditions, and start with the same random initial configuration with 10% defectors (and 90% cooperators). The asymptotic pattern after 200 generations is shown. The colour coding is as follows: blue represents a cooperator (C) that was already a C in the preceding generation; red is a defector (D) following a D; yellow a D following a C; green a C following a D. *a*, An irregular, but static pattern (mainly of interlaced networks) emerges if $1.75 < b < 1.8$. The equilibrium frequency of C depends on the initial conditions, but is usually between 0.7 and 0.95. For lower *b* values (provided $b > \frac{9}{8}$), D persists as line fragments less connected than shown here, or as scattered small oscillators ('D-blinkers'). *b*, Spatial chaos characterizes the region $1.8 < b < 2$. The large proportion of yellow and green indicates many changes from one generation to the next. Here, as outlined in the text, 2×2 or bigger C clusters can invade D regions, and vice versa. C and D coexist indefinitely in a chaotically shifting balance, with the frequency of C being (almost) completely independent of the initial conditions at ~ 0.318.

Spatial Games: Towards Artificial Ecosystems

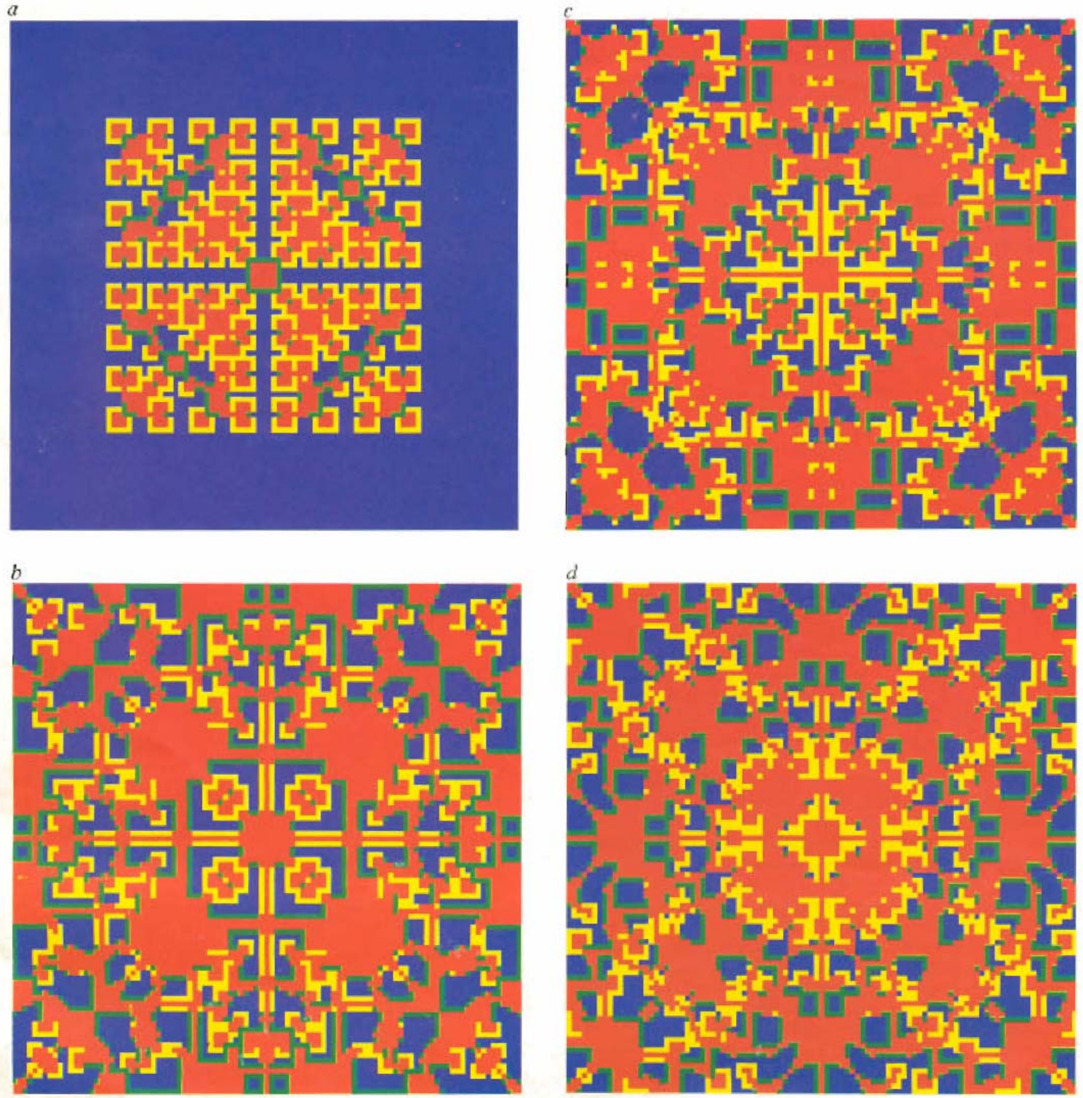


FIG. 3 Spatial games can generate an 'evolutionary kaleidoscope'. This simulation is started with a single D at the centre of a 99×99 square-lattice world of C with fixed boundary conditions. Again $1.8 < b < 2$. This generates an (almost) infinite sequence of different patterns. The initial symmetry is always maintained, because the rules of the game are symmetrical. The frequency of C oscillates (chaotically) around a time average of 12 log 2-8 (of course). *a*, Generation $t = 30$; *b*, $t = 217$; *c*, $t = 219$; *d*, $t = 221$.

Nowak and May, 1992

Other Dilemmas

PRISONER'S DILEMMA : DC>CC>DD>CD (or reverse)

CHICKEN (SNOWDRIFT) : DC>CC>CD>DD (T>R>S>P)

Two drivers, both headed for a single lane bridge from opposite directions. The first to swerve away yields the bridge to the other. If neither player swerves, the result is a potentially fatal head-on collision. It is presumed that the best thing for each driver is to stay straight while the other swerves (since the other is the "chicken" while a crash is avoided). Additionally, a crash is presumed to be the worst outcome for both players (DD). This yields a situation where each player, <u>in attempting to secure his best outcome (DC), risks the worse (DD)</u>.

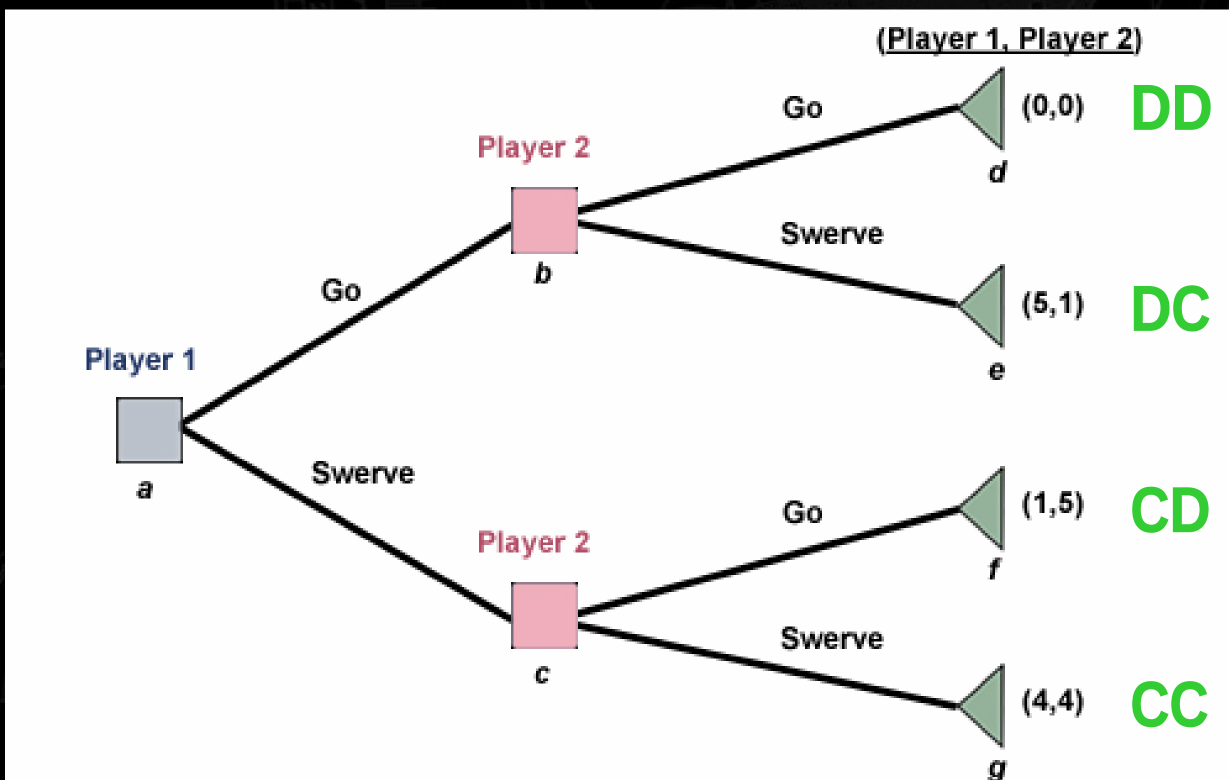
STAG HUNT : CC>DC>DD>CD (R>T>P>S)

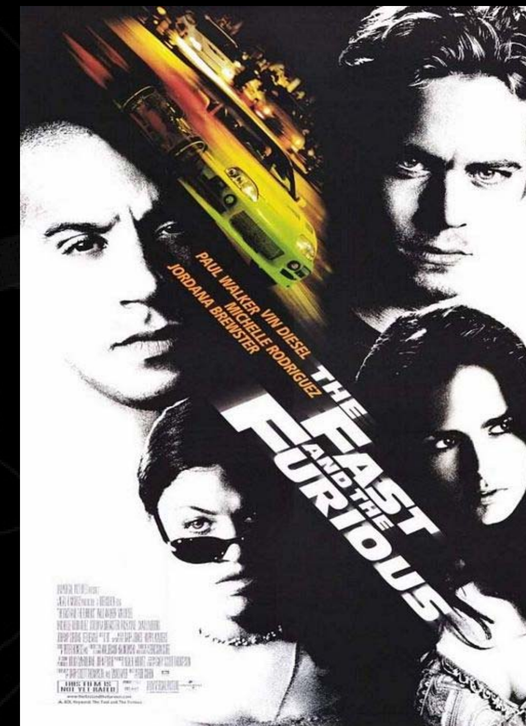
Two hunters can either jointly hunt a stag (an adult deer and rather large meal; CC) or individually hunt a rabbit (tasty, but substantially less filling; DC). Hunting stags is quite challenging and requires mutual cooperation. If either hunts a stag alone, the chance of success is minimal (CD). Hunting stags is most beneficial for society but requires a lot of trust among its members.

DEAD LOCK : DC>DD>CC>CD

Chicken Game

CHICKEN: DC>CC>CD>DD





Different Dilemmas → Different Tensions

	C	D
C	R	S
D	T	P

greed fear

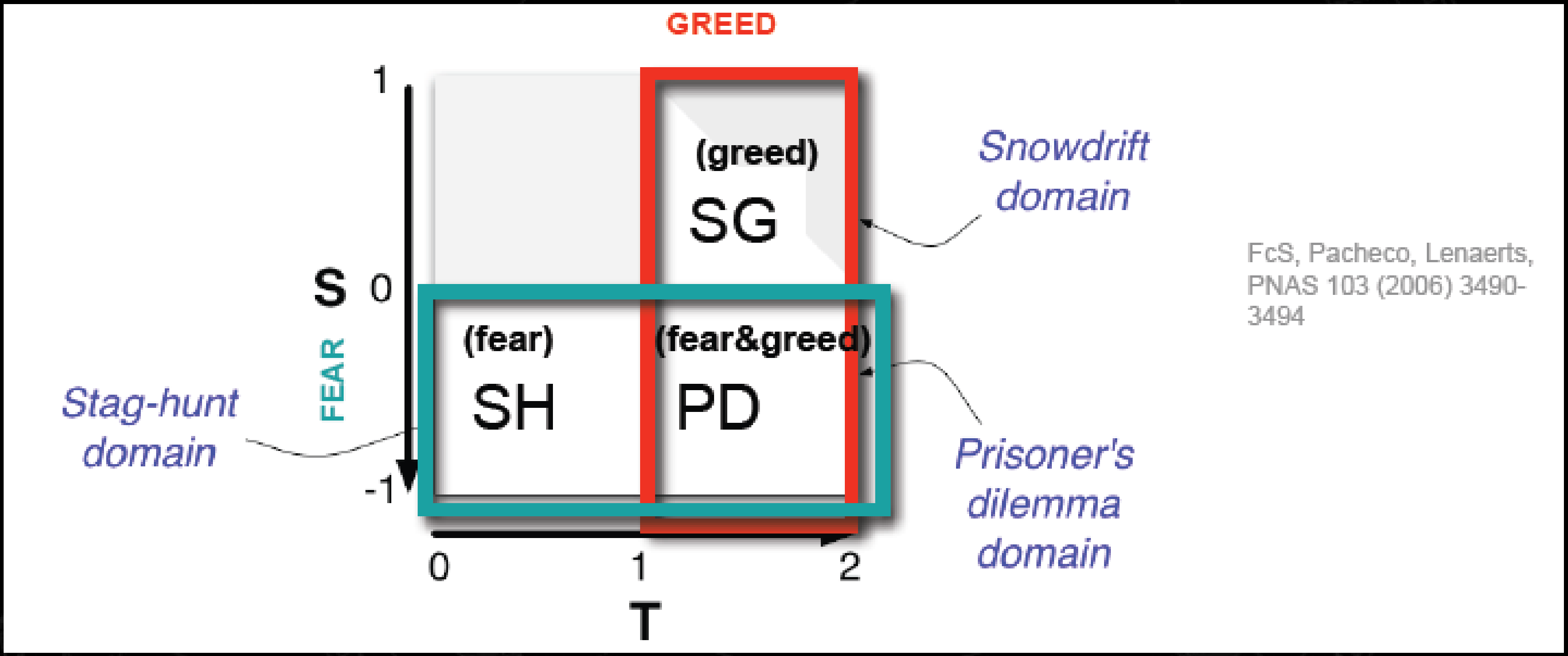
SG: snowdrift game : $T > R > S > P$

SH: stag-hunt game : $R > T > P > S$

PD: prisoner's dilemma : $T > R > P > S$

Without loss of generality one can normalize the difference between mutual cooperation (CC) and mutual defection (DD) by assuming $P=0$ and $R=1$, leaving two parameters $0<=T<=2$ and $-1<=S<1$

2D Parameter Space



Formally, these dilemmas span the parameter space of
T (temptation to defect = greed) AND
S (sucker's payoff = fear)