

A brief history of modeling direct and indirect reciprocity

Christian Hilbe

Max Planck Research Group *Dynamics of Social Behavior*
MPI for Evolutionary Biology, Plön



Today's menu.

- Part 1: Intro
Overview of our research agenda
- Part 2: A brief history of direct reciprocity
Repeated prisoner's dilemma / Extortion / Reciprocity in complex environments
- Part 3: A brief history of indirect reciprocity
Image scoring / Leading eight / Private information
- Part 4: How to merge direct and indirect reciprocity
A first modest approach by Schmid et al (2021)

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Disclaimer: My view of the field is (necessarily) biased.

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Mark Oliver Everett

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A bibliometric study of research topics,
collaboration, and centrality in the iterated
prisoner's dilemma

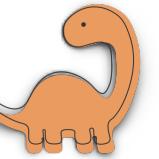
Nikoleta E. Glynatsi^{1,2✉} & Vincent A. Knight¹

1. Intro: RG Dynamics of Social Behavior

Overview

- Group started in October 2019
- Group leader, 3 PhD students, 1 Post-Doc, 1 visiting scientist

Max Planck Research Group
Dynamics of Social Behavior



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Where to find more information:
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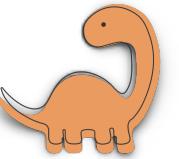
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How do traits or (strategic) behaviors spread in a population?
- **Understanding social behavior**
How do humans cooperate / signal / coordinate?

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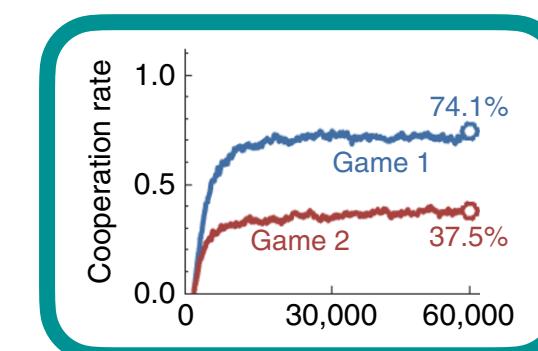
Our toolbox



Modelling

Theorem 1:
Suppose player 1 uses the memory-one strategy
 $p_{CC} = 1 - \phi(1-s)(b-c-l)$
 $p_{CD} = 1 - \phi(1-s)(c-l) + b + c$
 $p_{DC} = \phi(1-s)(l-b) + b + c$
 $p_{DD} = \phi(1-s)l$,
for some constants s, l, ϕ with $\phi \neq 0$. Then, no matter what player 2 does, payoffs satisfy $\pi_2 = s\pi_1 + (1-s)l$.

Mathematical analysis



Individual-based simulations

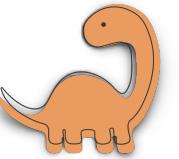


Behavioural experiments



Analysis of online data

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1. Intro: Evolution of cooperation

Basic question: Why do individuals cooperate?

That is, why would we pay a cost to the benefit of someone else?

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NATURE VOL. 325 29 JANUARY 1987

LETTERS

TIT FOR TAT in sticklebacks and the evolution of cooperation

Manfred Milinski

Arbeitsgruppe für Verhaltensforschung
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Reciprocal food sharing in the vampire bat

Gerald S. Wilkinson

Department of Biology, C-016, University of California,
San Diego, La Jolla, California 92093,



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- Social norms: We follow tacit rules.
- Institutions: Some cooperation is enforced by law.

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An ultimate explanation: Reciprocity

- Direct reciprocity: I help you, you help me later
- Indirect reciprocity: I help you, someone else helps me later

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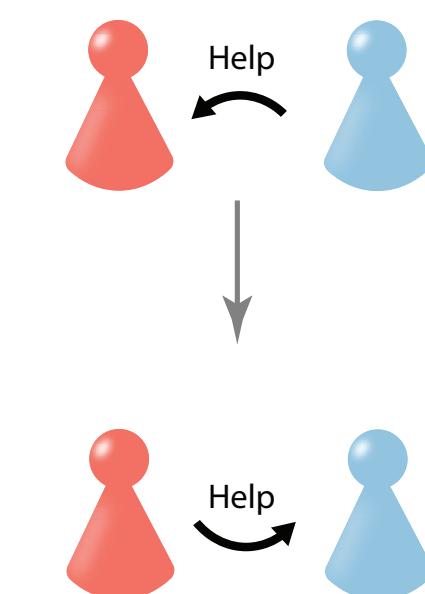
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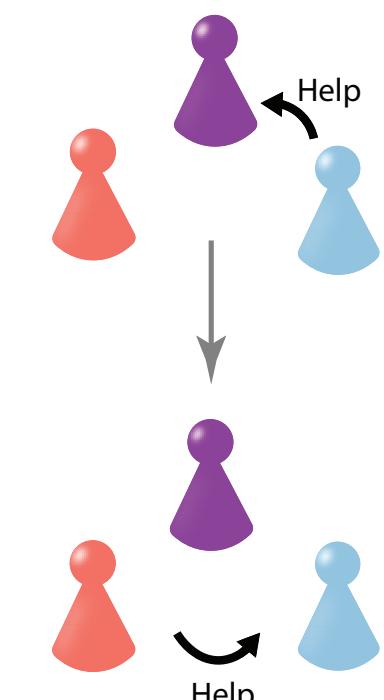
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Direct reciprocity



Indirect reciprocity



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A Non-cooperative Equilibrium for Supergames^{1,2}

JAMES W. FRIEDMAN
University of Rochester

The Evolution of Cooperation

Robert Axelrod and William D. Hamilton

Tit for tat in heterogeneous populations

Martin A. Nowak* & Karl Sigmund†

My (selective) historical timeline:

Aumann (60's)
Friedmann (1978)

Nowak and
Sigmund (1992)

Press & Dyson
(2012)

Axelrod and
Hamilton (1981)

Nowak and
Sigmund (1993)

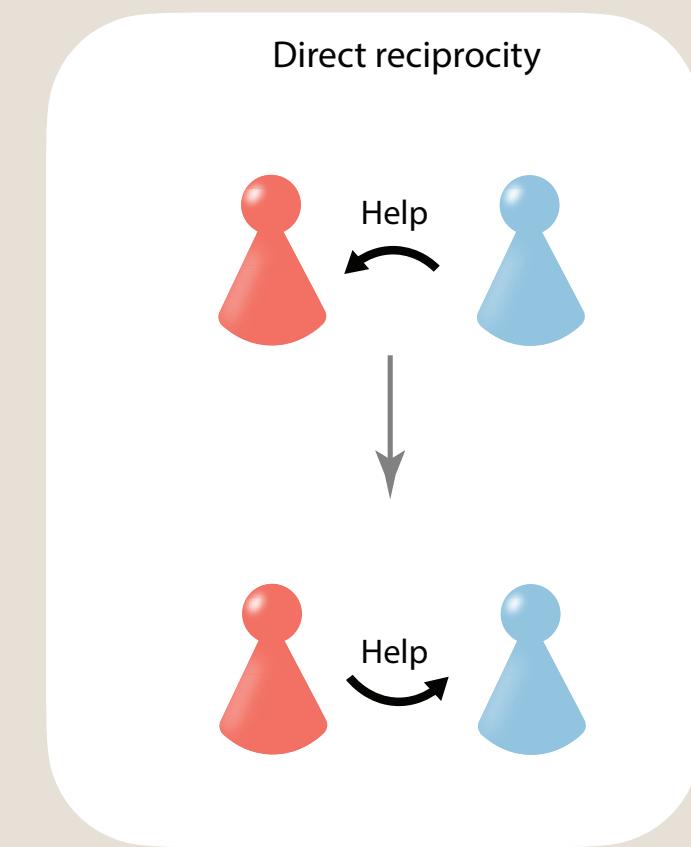
Some of my
own work

PNAS
Iterated Prisoner's Dilemma contains strategies that dominate any evolutionary opponent

William H. Press^{a,1} and Freeman J. Dyson^b
^aDepartment of Computer Science and School of Biological Sciences, University of Texas at Austin, Austin, TX 78712; and ^bSchool of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540
Contributed by William H. Press, April 19, 2012 (sent for review March 14, 2012)
The two-player Iterated Prisoner's Dilemma game is a model for both sentient and evolutionary behaviors, especially including the four outcomes of the previous move are labeled 1,...,4 for the

2. Direct reciprocity: Repeated prisoner's dilemma

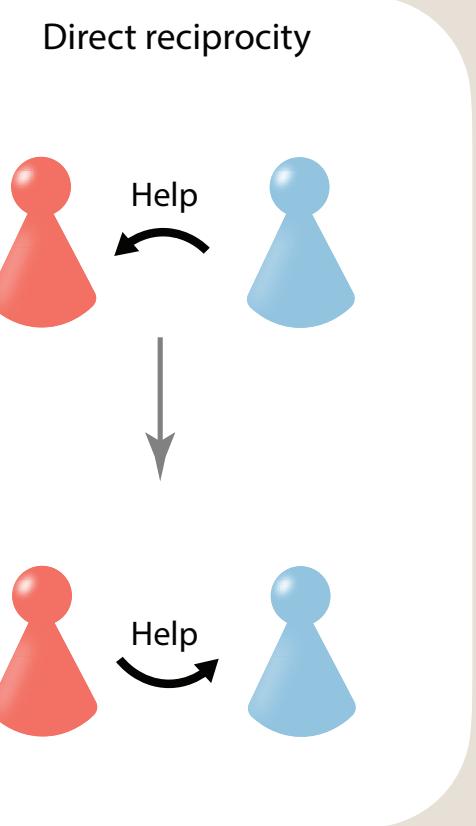
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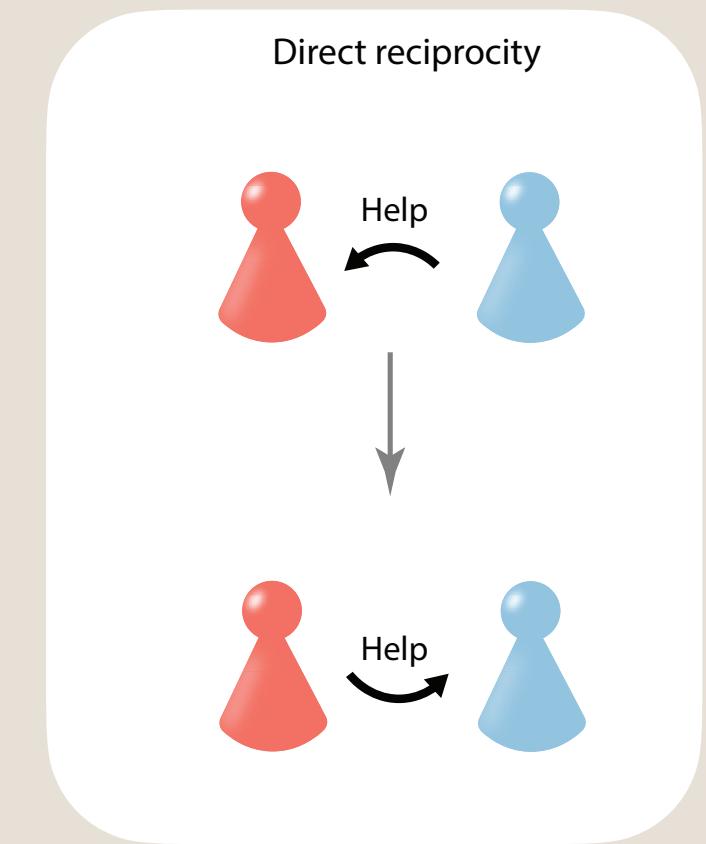
- Strategic interaction among two individuals ("Players")



2. Direct reciprocity: Repeated prisoner's dilemma

Direct reciprocity: I help you, you help me later

- Strategic interaction among two individuals ("Players")
- In each round, players can cooperate (C) or defect (D). Cooperation means to pay a cost $c > 0$ for the co-player to get a benefit $b > c$

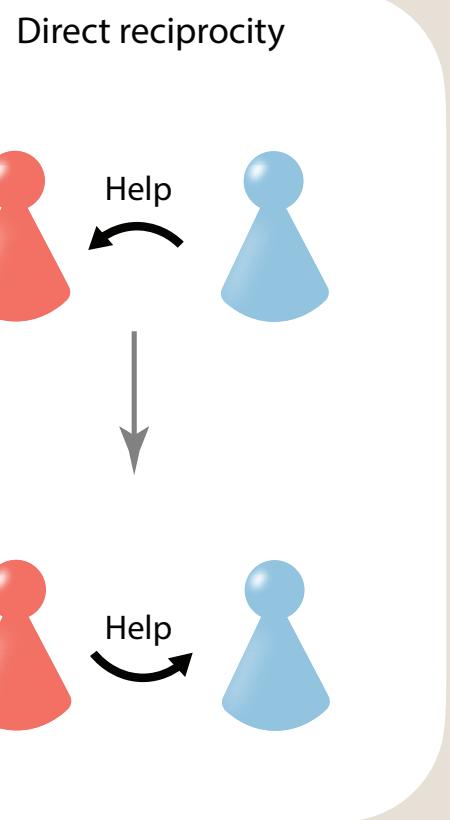


	C	D
C	$b - c$	$-c$
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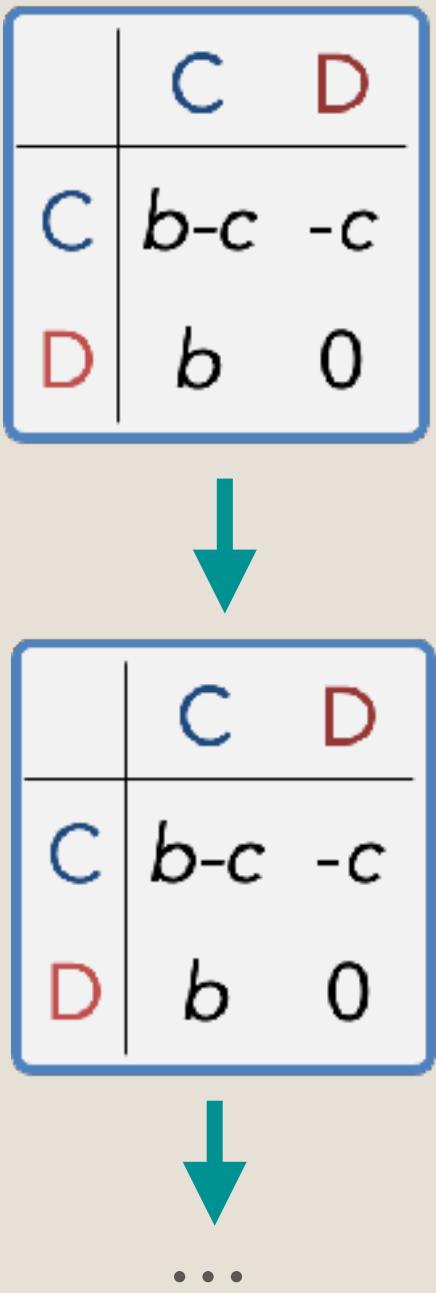
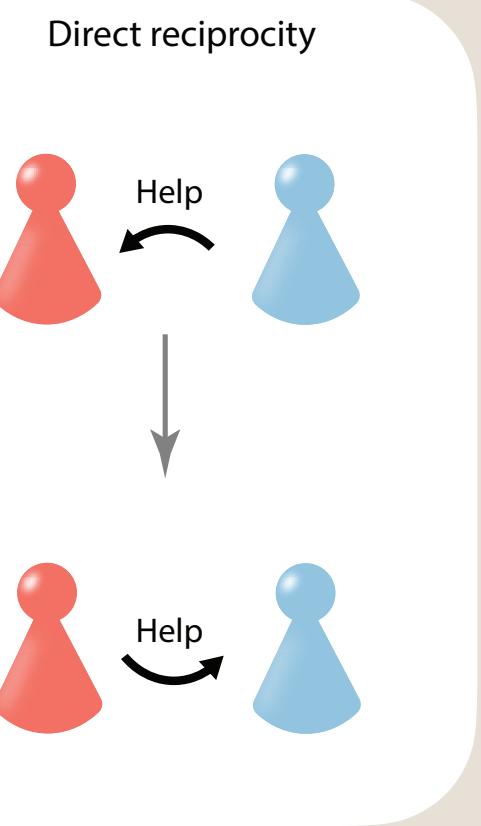


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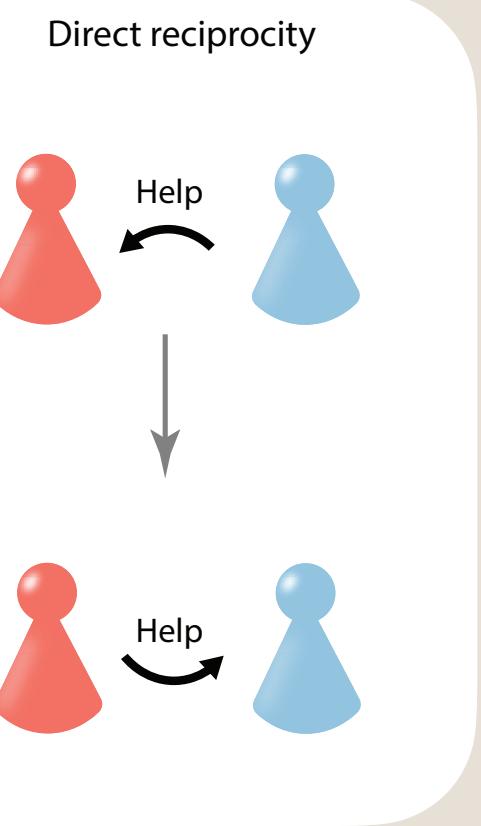
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A strategy is a map that take any previous history of the game and outputs an action, $\sigma : \mathcal{H} \rightarrow \{C, D\}$.



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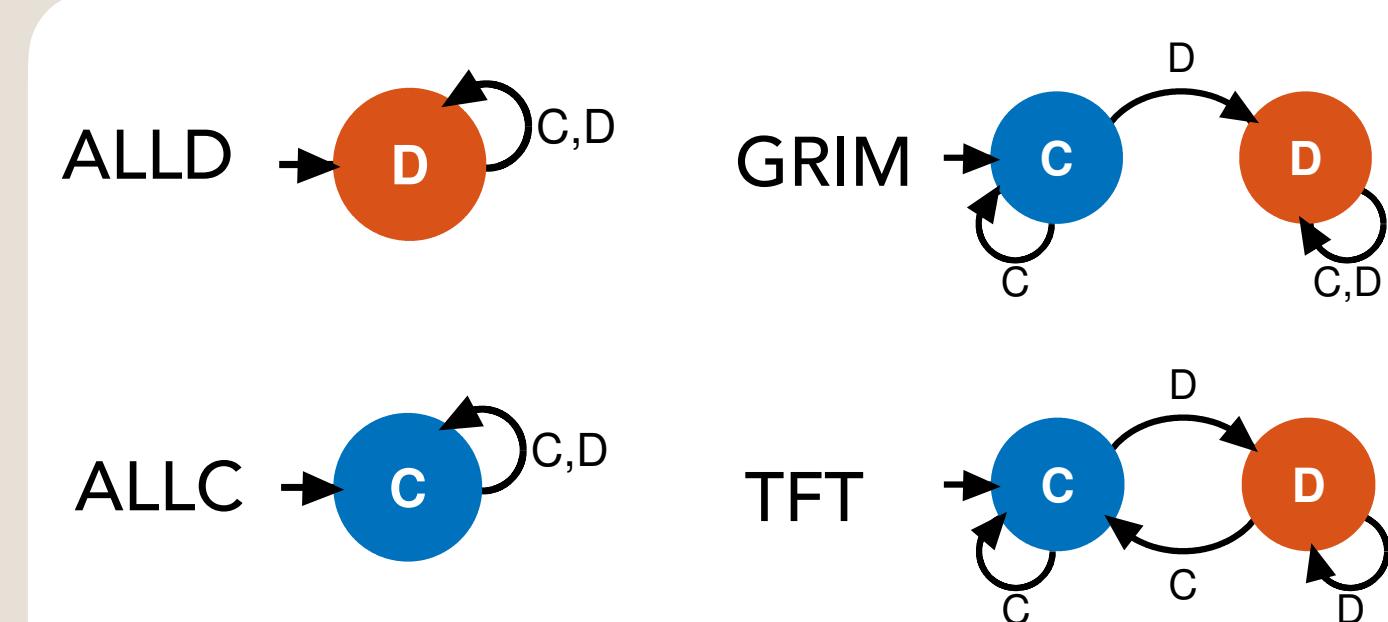
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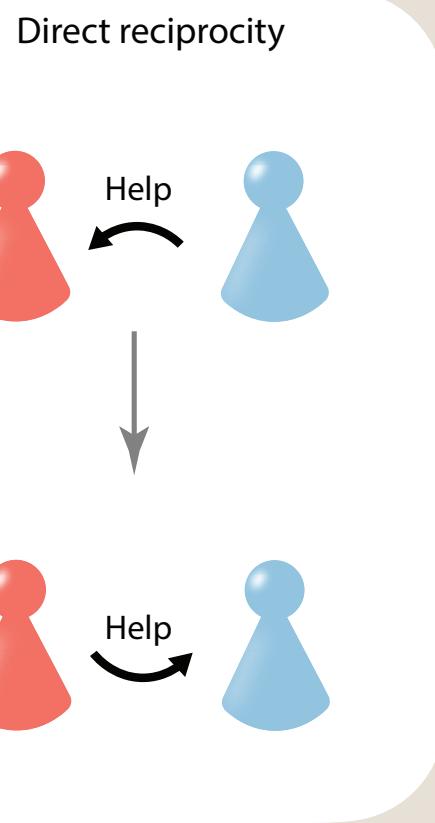
There are (uncountably) many other strategies

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A strategy is a map that takes any previous history of the game and outputs an action, $\sigma : \mathcal{H} \rightarrow \{C, D\}$.
- Players want to choose strategies that maximise their average payoffs.
If player i 's payoff in round t is $\pi_i(t)$, the player wishes to maximise

$$\pi_i = \lim_{T \rightarrow \infty} \frac{1}{T} \sum_{t=1}^T \pi_i(t)$$

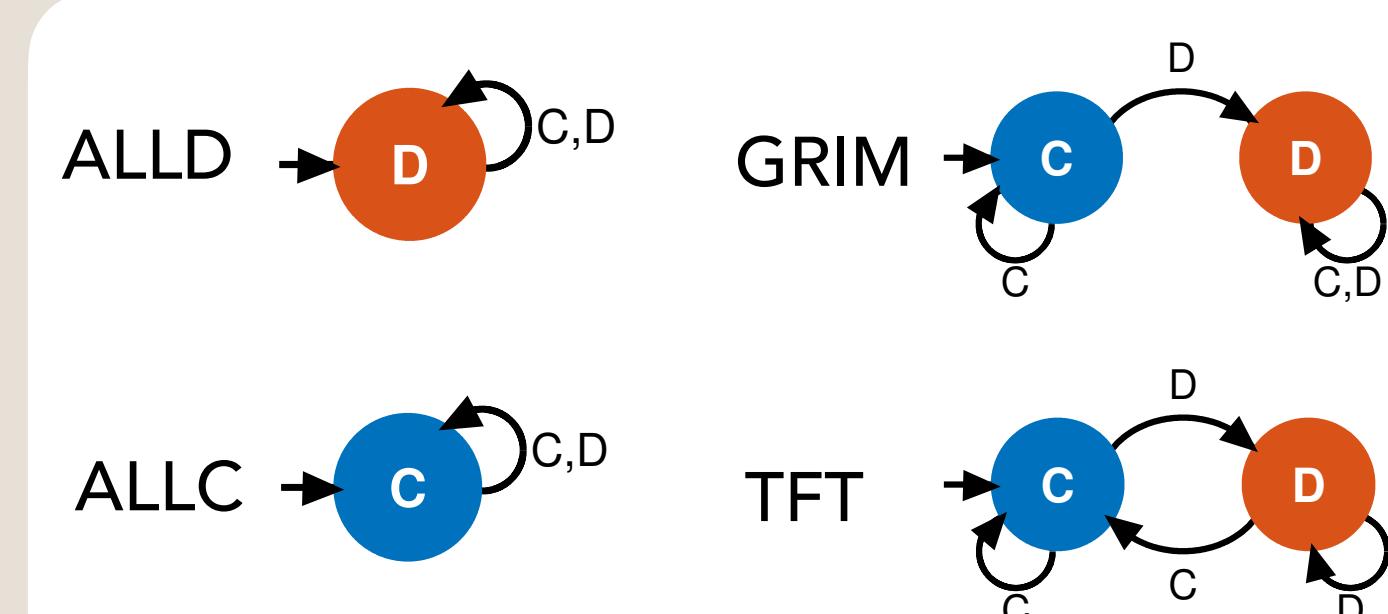


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2. Direct reciprocity: Axelrod & Hamilton (1981)

The Evolution of Cooperation

Robert Axelrod and William D. Hamilton

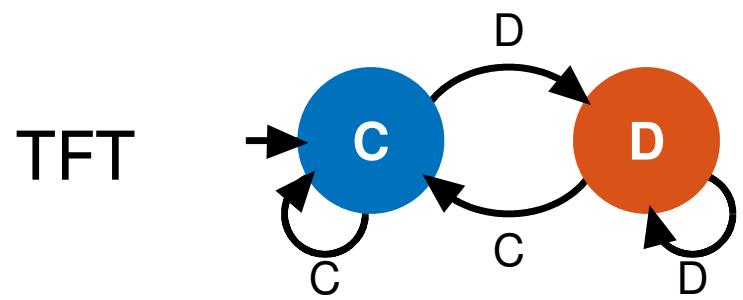
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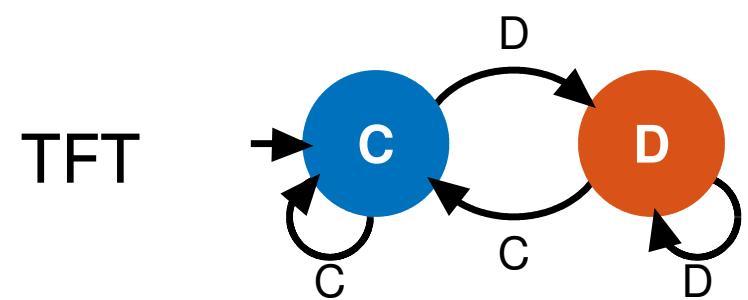


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TFT vs. TFT:

Round	1	2	3	...
TFT	C	C	C	
TFT	C	C	C	

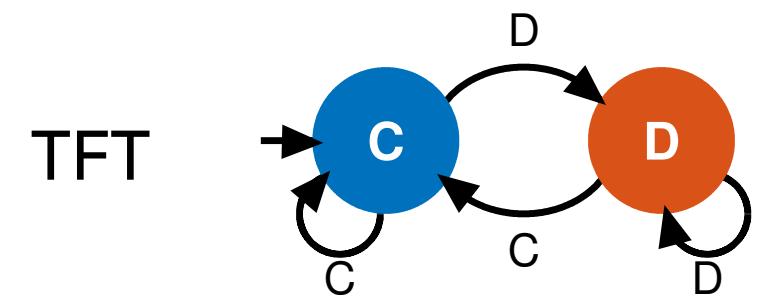
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TFT vs. TFT:

Round	1	2	3	...
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Expected Payoff TFT: $200(b-c)$

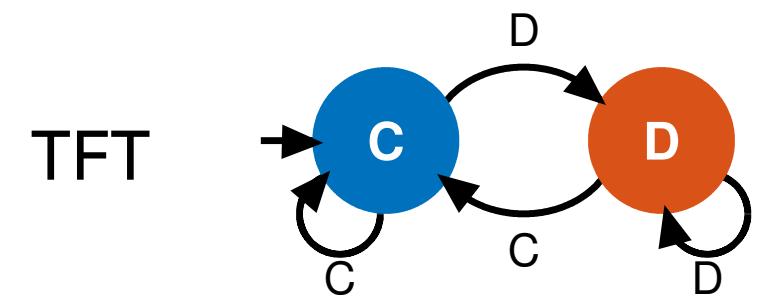
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TFT vs. Defector:

Round	1	2	3	...
TFT	C	D	D	
AllD	D	D	D	

Expected Payoff TFT: $200(b-c)$

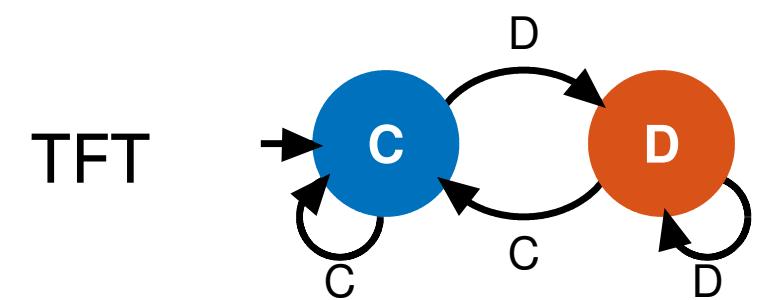
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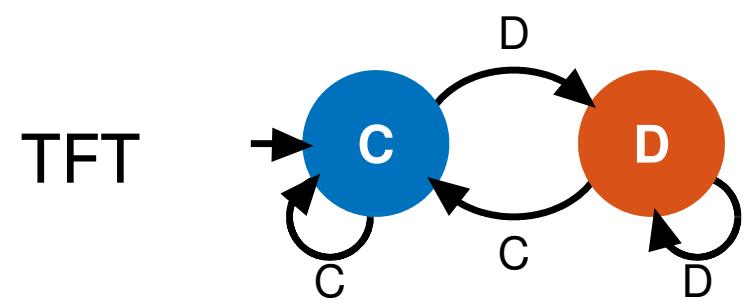
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Expected Payoff AllD: b

Tit-for-tat is better when $b > \frac{200}{199}c$

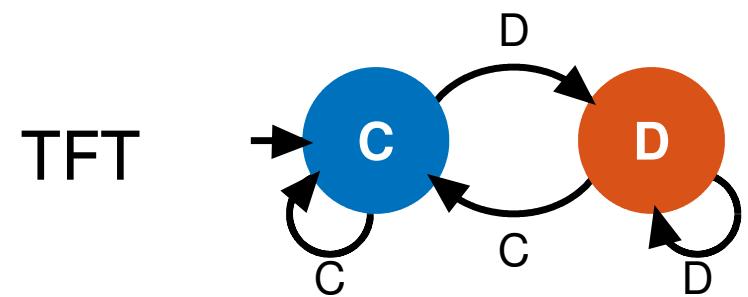
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RESEARCH ARTICLE
Is Tit-for-Tat the Answer? On the Conclusions
Drawn from Axelrod's Tournaments

Amnon Rapoport¹, Darryl A. Seale^{2*}, Andrew M. Colman³

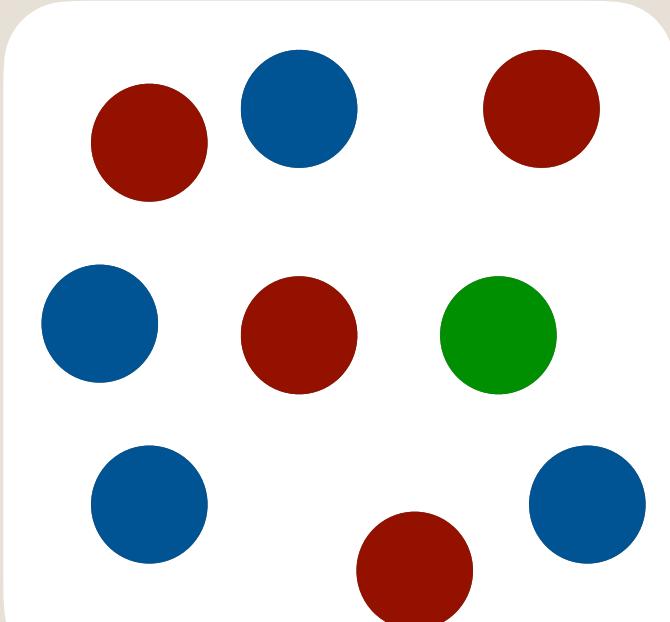
PLoS One, 2015

2. Direct reciprocity: Evolutionary approaches

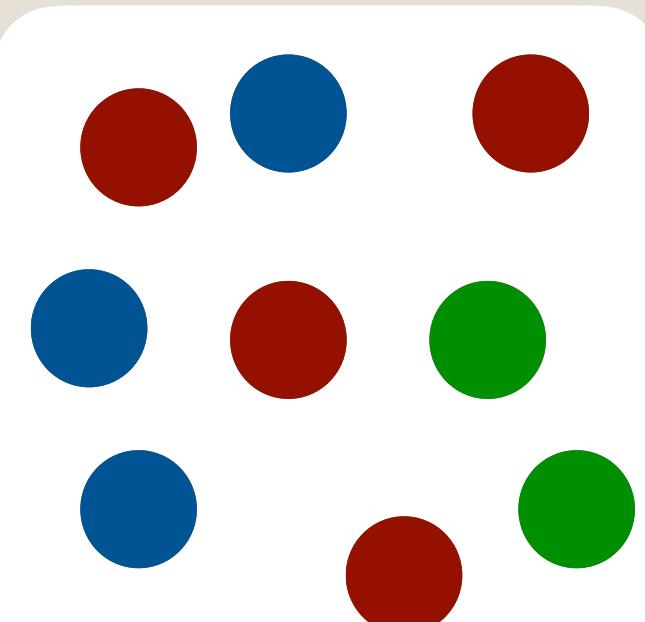
A (perhaps) more objective approach:

- Allow for **all** strategies of a given complexity class
- Let evolution determine the winner

Population
at time t



Population
at time $t+1$

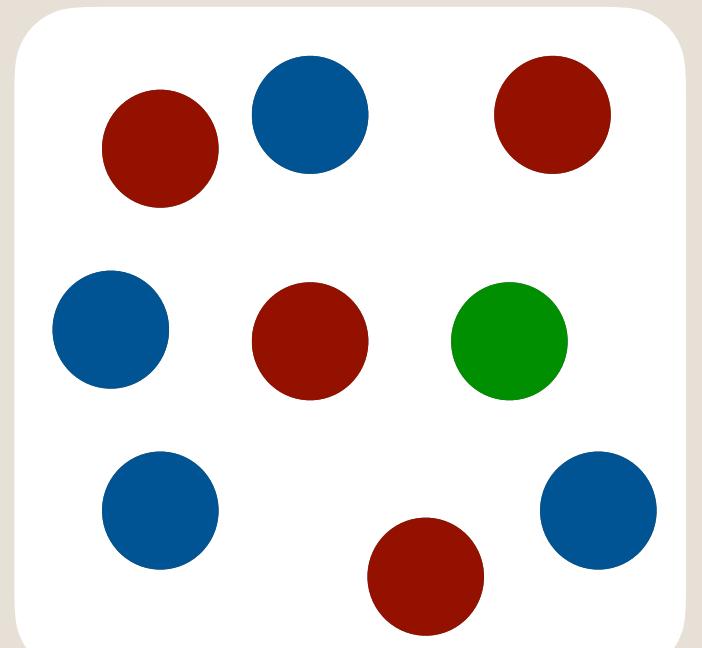


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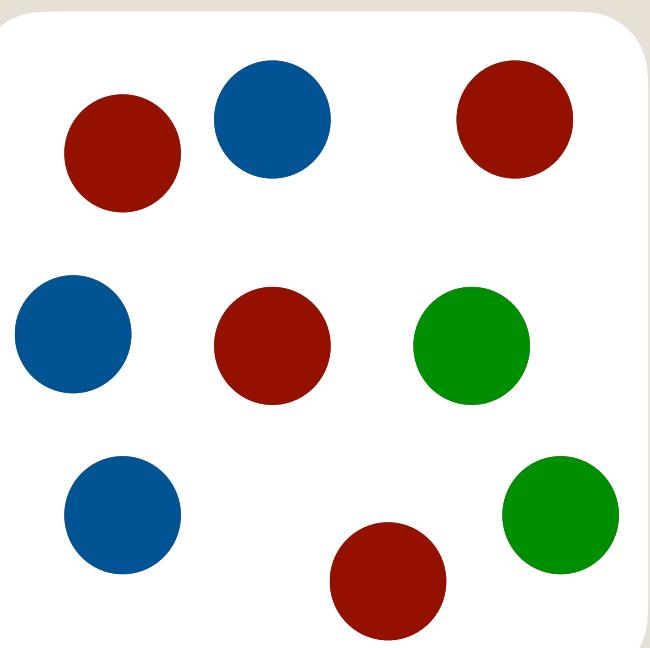
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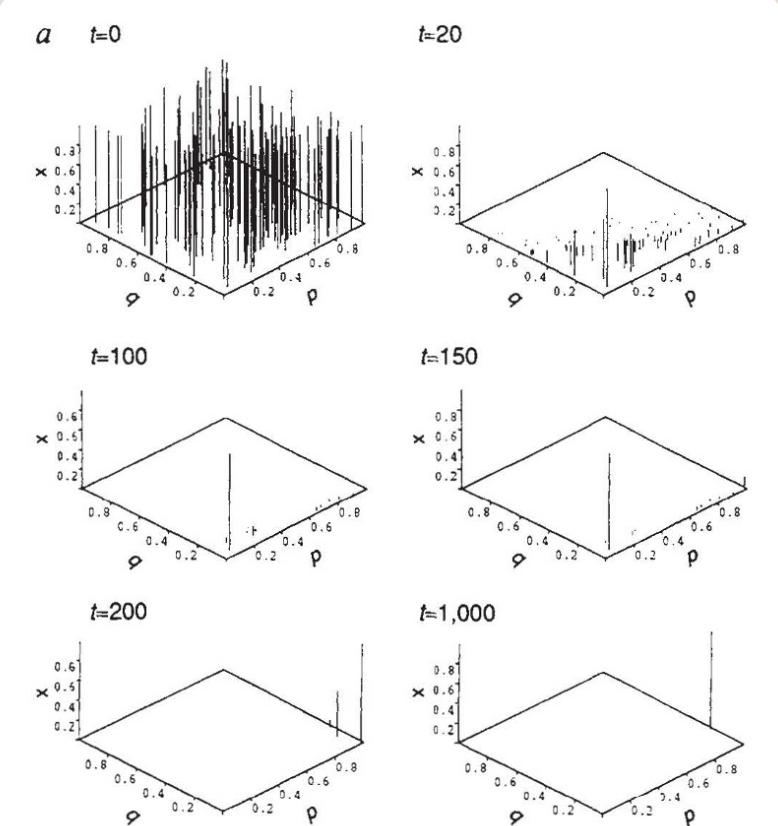


Nowak & Sigmund (1992)

- Evolutionary simulations for reactive strategies (p,q)
- This space includes ALLD = $(0,0)$ or TFT = $(1,0)$
- Simulations lead to Generous Tit-for-Tat: GTFT= $(1,1-c/b)$
- Compared to TFT, GTFT is more robust with respect to noise

Tit for tat in heterogeneous populations

Martin A. Nowak* & Karl Sigmund†

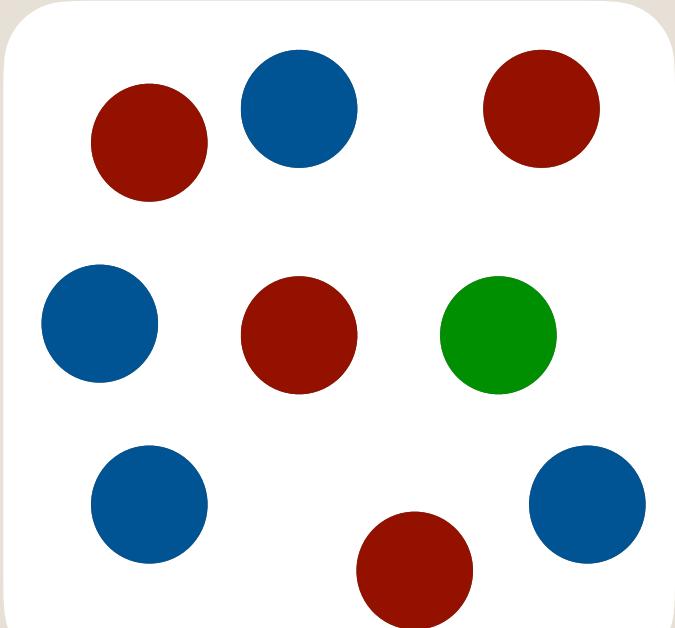


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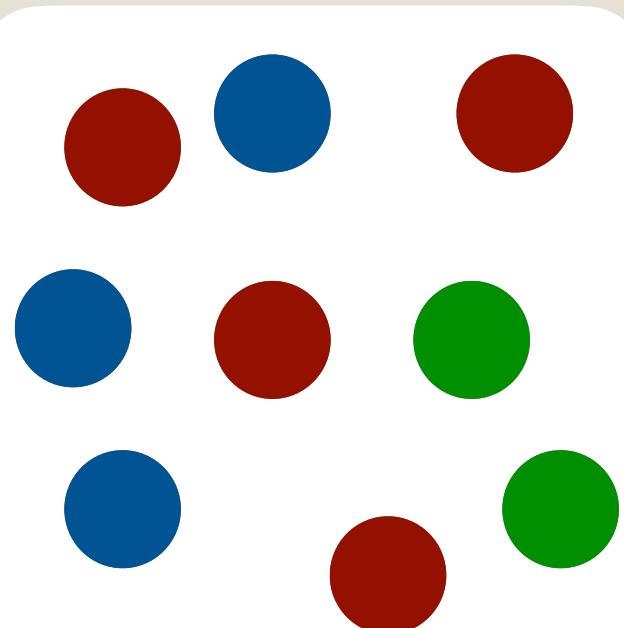
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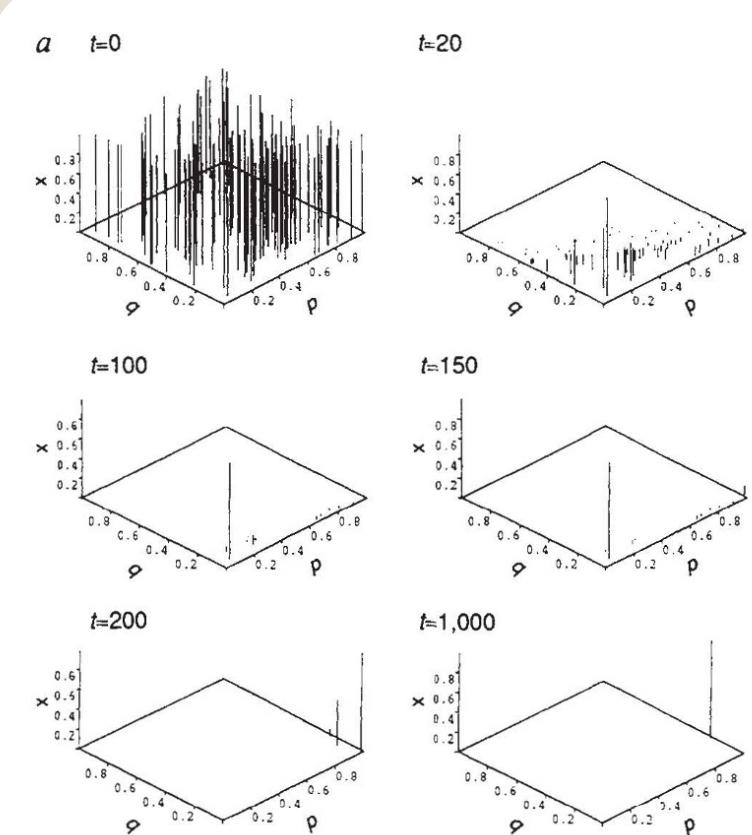


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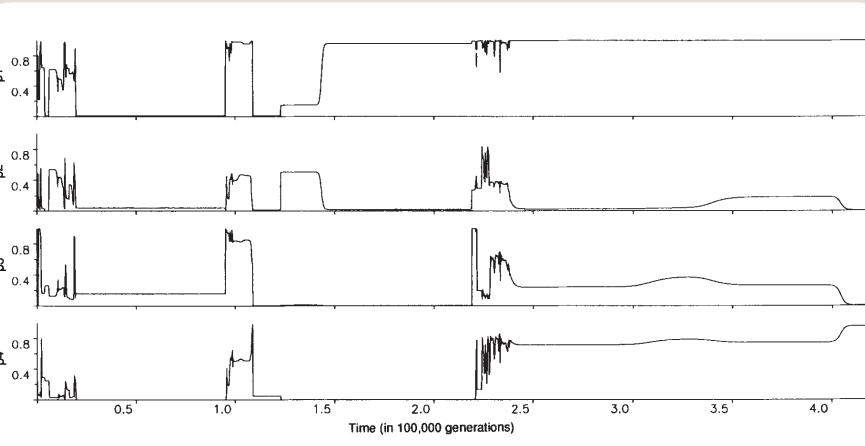


Nowak & Sigmund (1993)

- Similar to previous paper, but now simulations allowed for all memory-1 strategies, $(p_{CC}, p_{CD}, p_{DC}, p_{DD})$
- Now evolution leads to Win-Stay Lose-Shift = $(1, 0, 0, 1)$

A strategy of win-stay, lose-shift that outperforms tit-for-tat in the Prisoner's Dilemma game

Martin Nowak* & Karl Sigmund†



2. Direct reciprocity: Press & Dyson

- By the 2010s, the field largely believed that the repeated prisoner's dilemma almost naturally leads to cooperation.

2. Direct reciprocity: Press & Dyson

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Iterated Prisoner's Dilemma contains strategies that dominate any evolutionary opponent

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^aDepartment of Computer Science and School of Biological Sciences, University of Texas at Austin, Austin, TX 78712; and ^bSchool of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540

Contributed by William H. Press, April 19, 2012 (sent for review March 14, 2012)

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Then, irrespective of player 2's strategy, payoffs satisfy $\alpha\pi_1 + \beta\pi_2 + \gamma = 0$. Such a strategy \mathbf{p} is called a zero-determinant (ZD) strategy.



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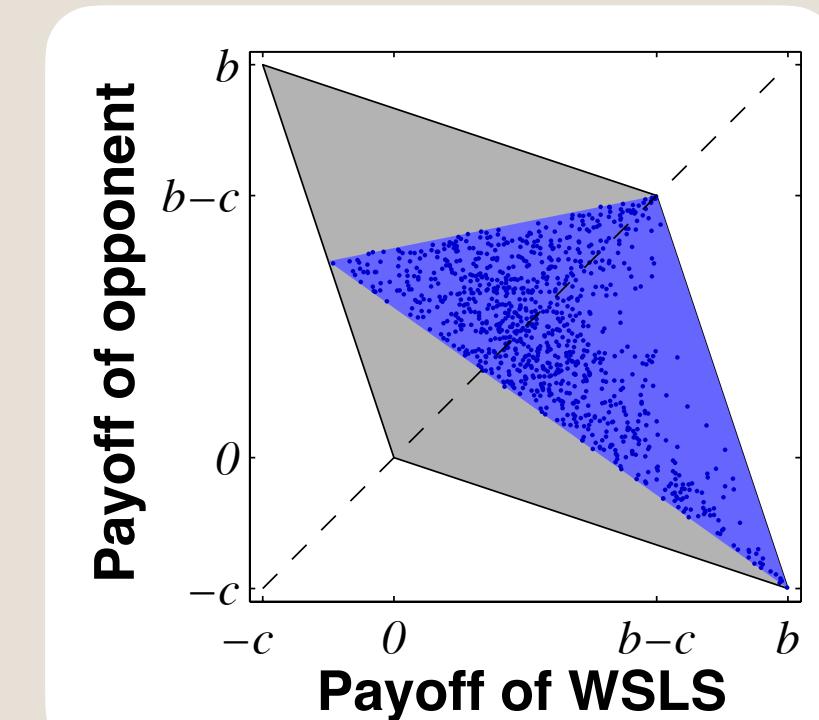
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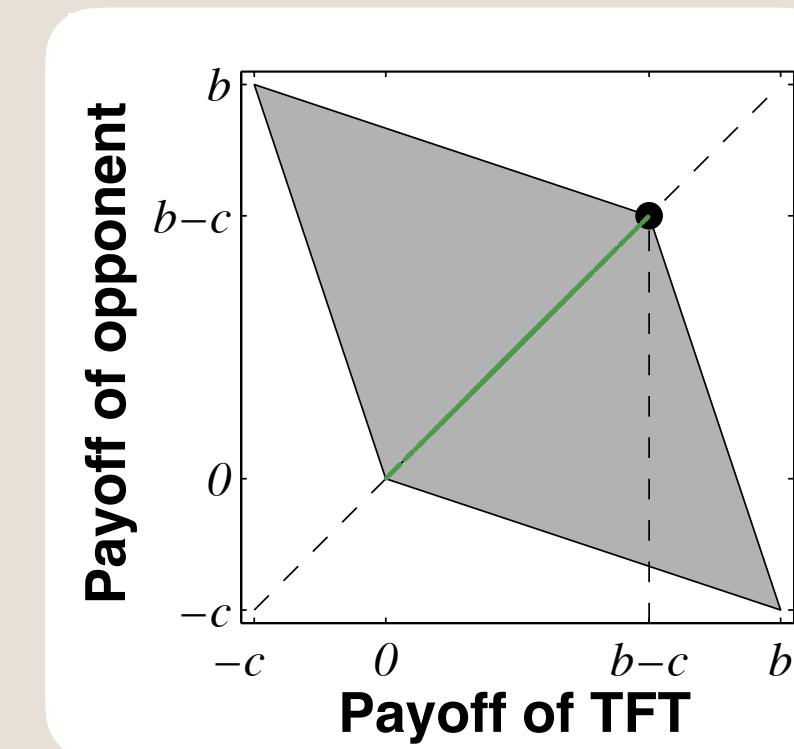
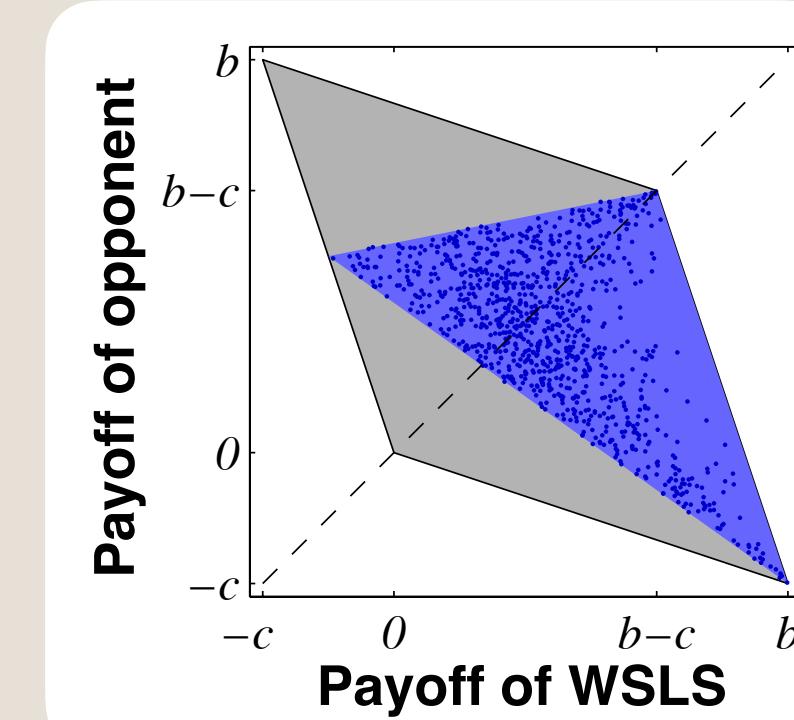
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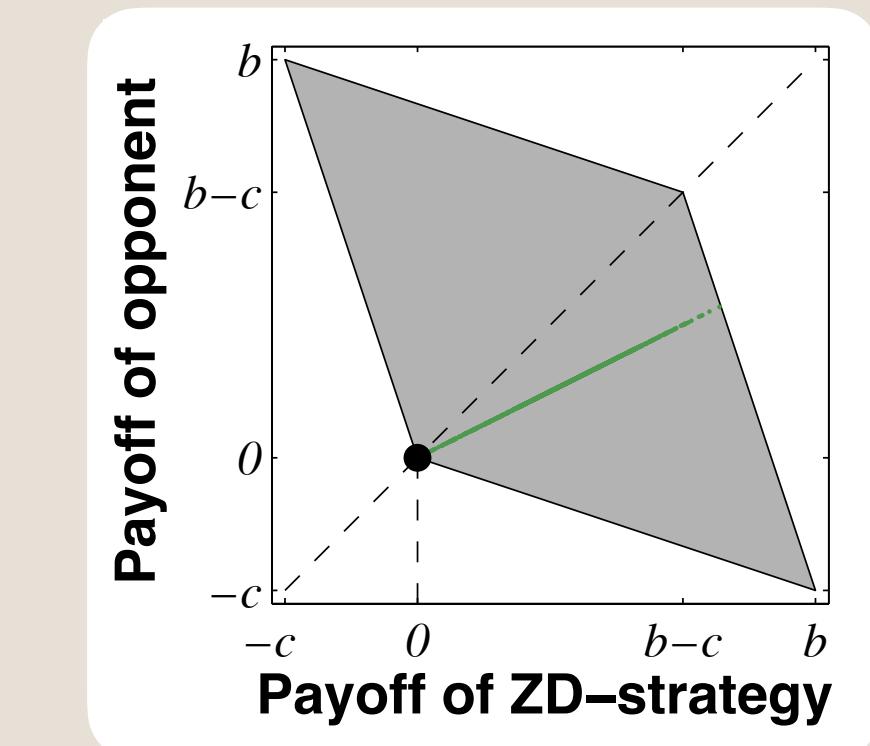
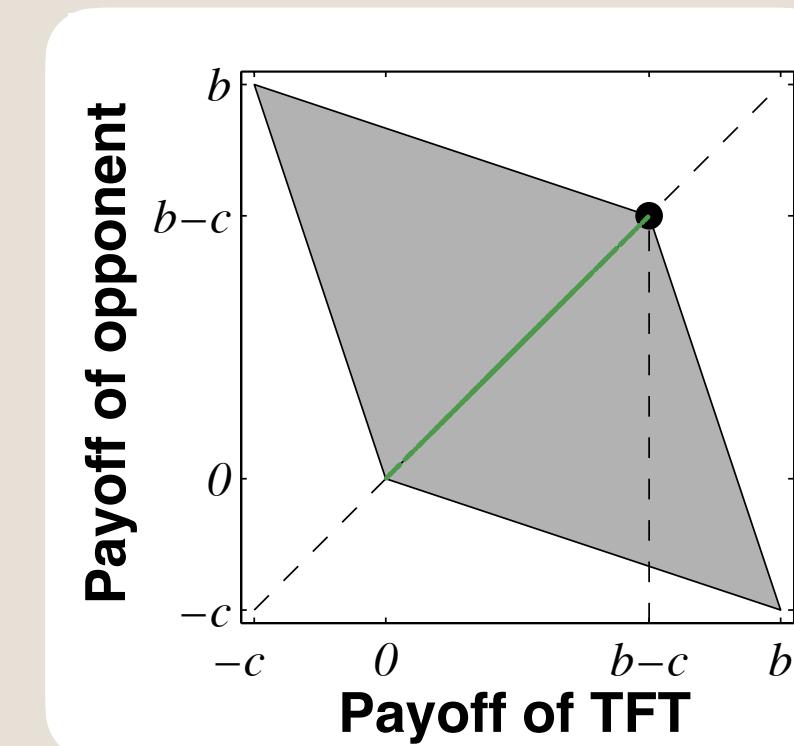
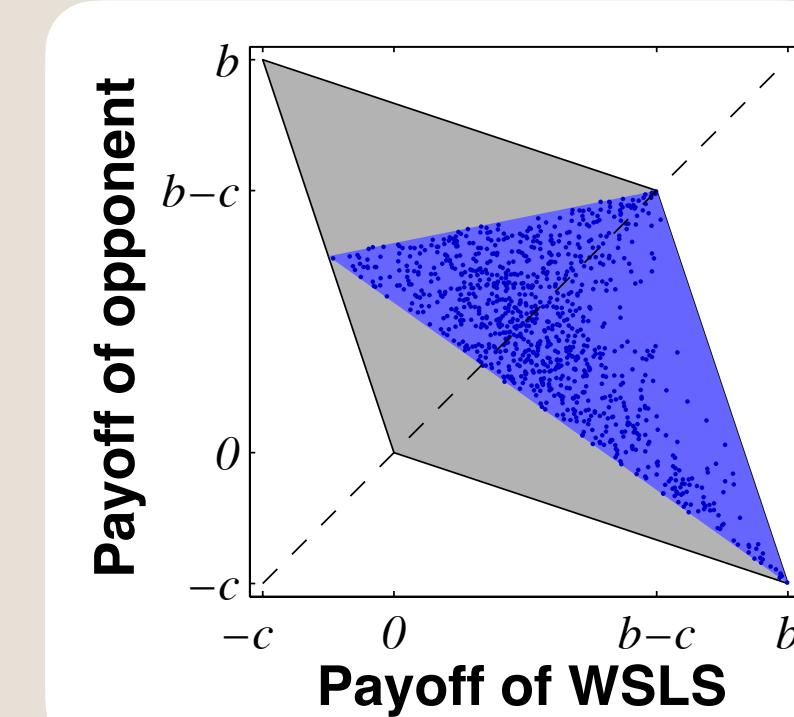
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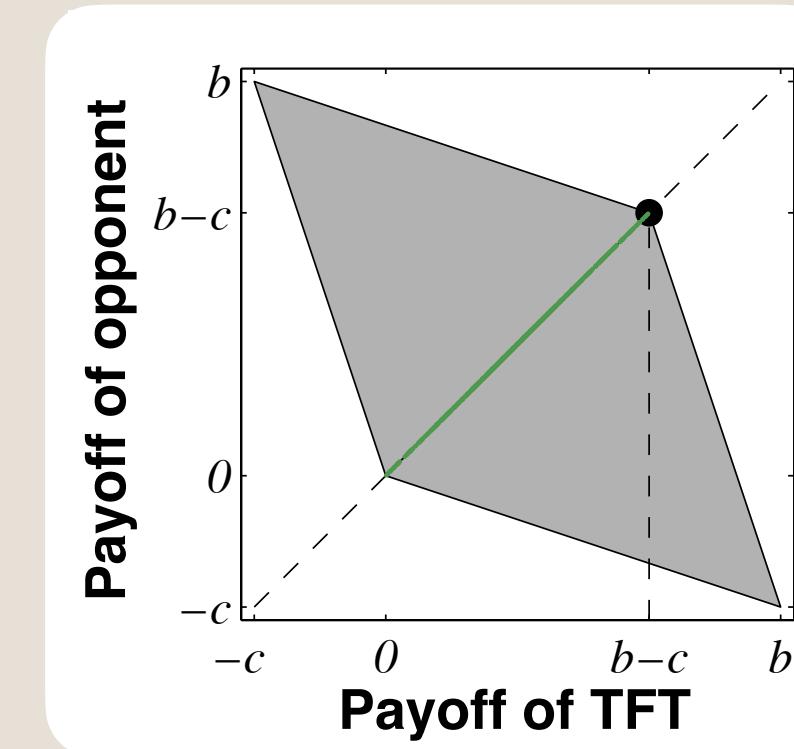
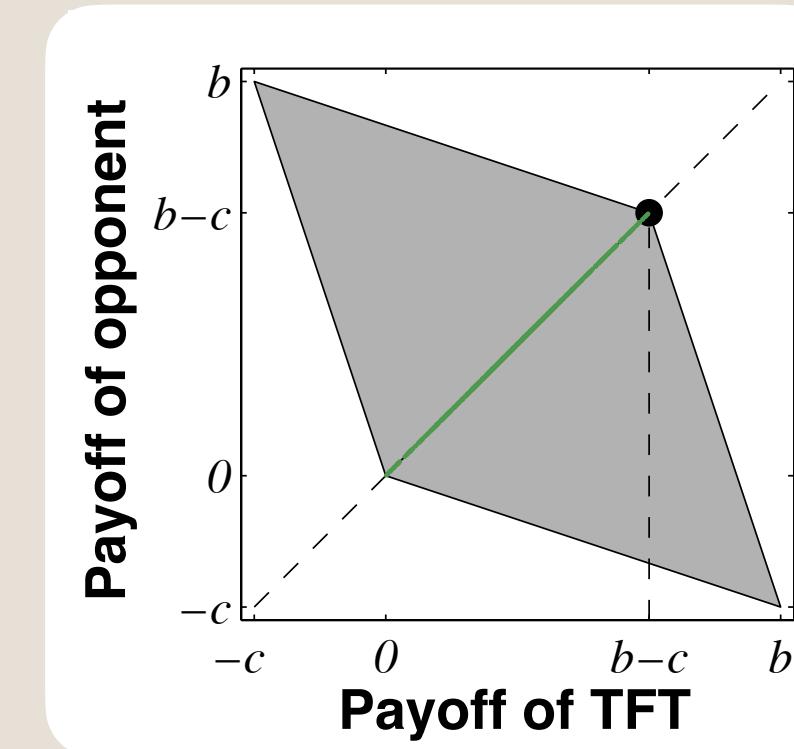
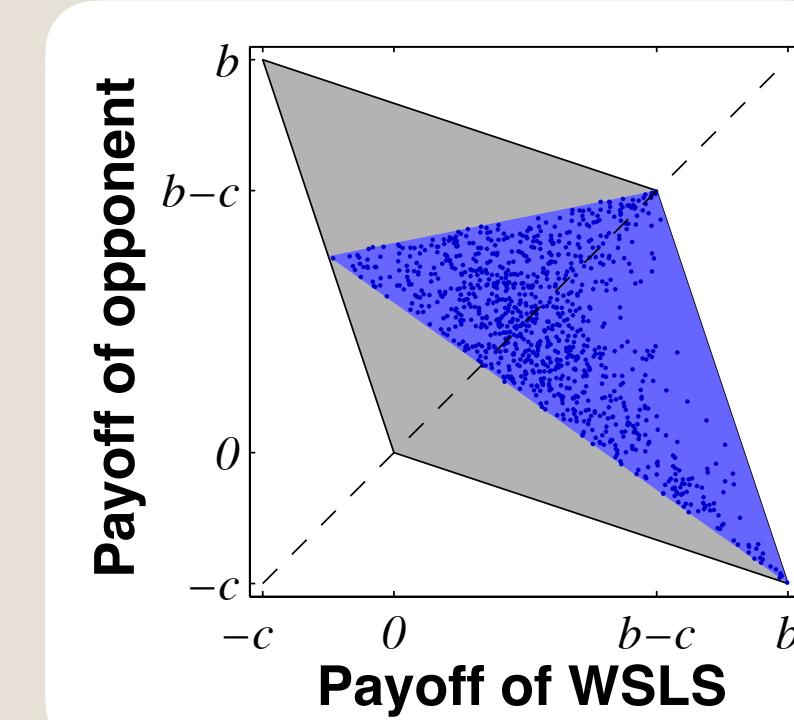
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Extortionate
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2. Direct reciprocity: Some research on extortion

Partners or rivals? Strategies for the iterated prisoner's dilemma[☆]

Christian Hilbe ^{a,*}, Arne Traulsen ^b, Karl Sigmund ^{c,d}

Theoretical work on extortion

- Is extortion possible if games are only finitely repeated?
Yes (Hilbe, Traulsen & Sigmund, 2015)
- Is extortion possible in games with more players?
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- Does extortion naturally evolve in dynamic populations?
It depends (Hilbe, Nowak & Sigmund, 2013)
- Can we use this mathematical framework to construct other powerful strategies of direct reciprocity? **Yes** (Murase & Ki Baek, 2020)

Cooperation and control in multiplayer social dilemmas

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Empirical work on extortion

- How do humans react to extortionate play?
(Hilbe, Röhl & Milinski, 2014)
- Do humans preferentially delegate tasks to extortionate leaders?
Yes (Milinski et al. 2016)
- What about fairness and extortion when people use more than one-round memory? (Li et al 2022)

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Christian Hilbe^{1,2}, Torsten Röhl¹ & Manfred Milinski³

Humans choose representatives who enforce cooperation in social dilemmas through extortion

Manfred Milinski¹, Christian Hilbe^{2,3}, Dirk Semmann¹, Ralf Sommerfeld¹ & Jochem Marotzke⁴

Evolution of cooperation through cumulative reciprocity



2. Direct reciprocity: Some research on extortion (continued)

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Nature Communications 2014

How do humans react to extortion?

- We invited 60 students to participate in an experiment.
- Each participant played for 60 rounds.

	Cooperate	Defect
Cooperate	0.30 Euro	0.00 Euro
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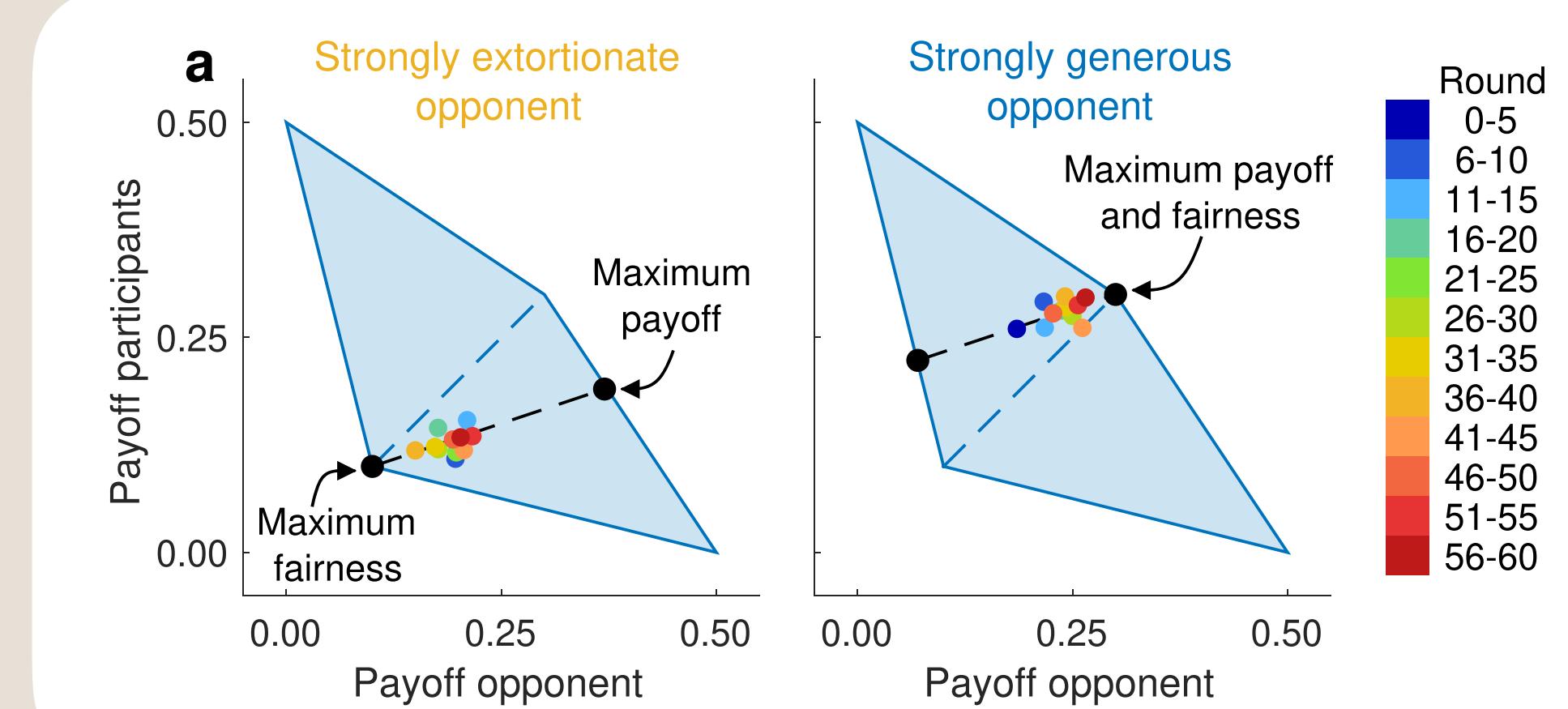
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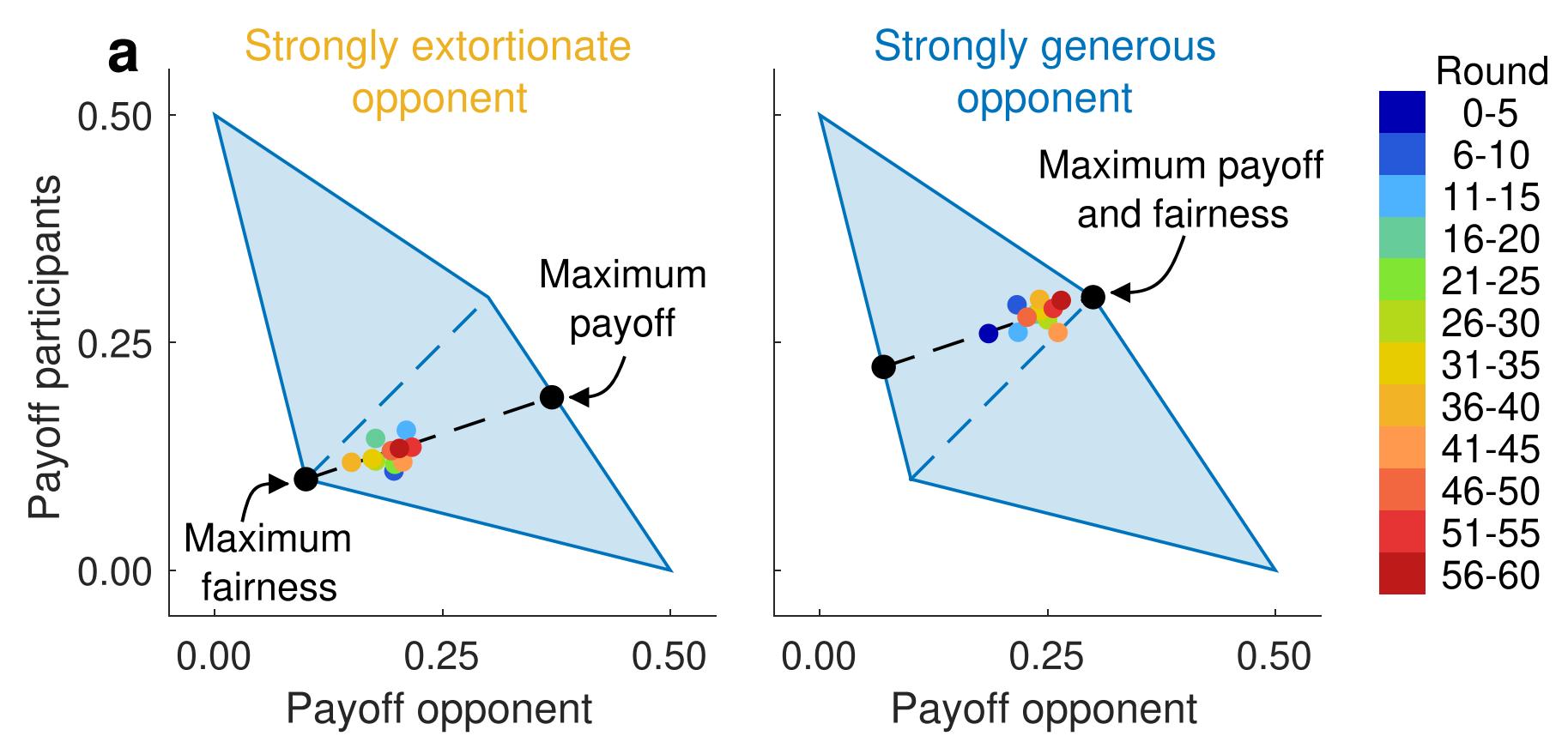
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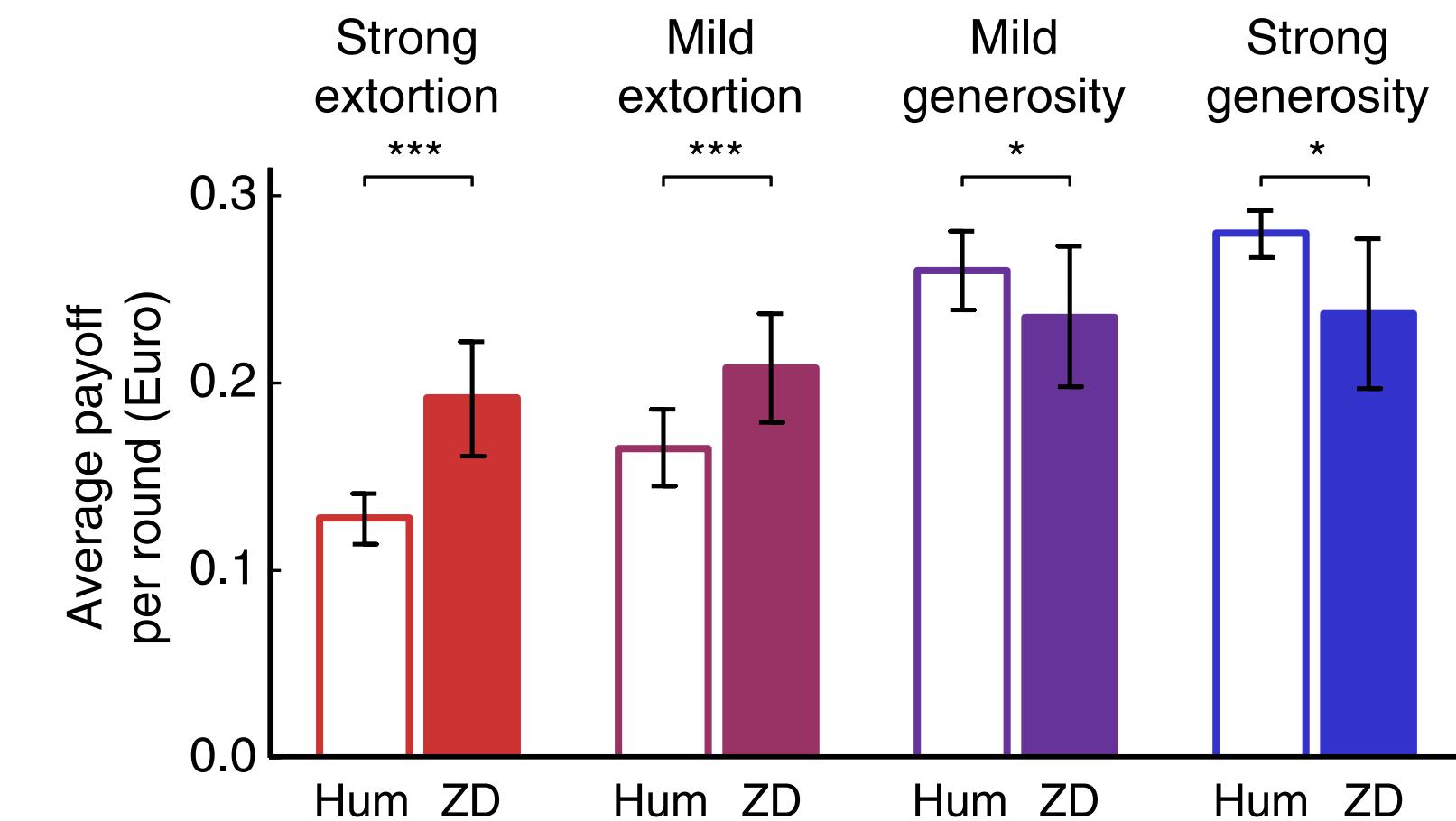
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2. Direct reciprocity: Cooperation in more complex environments

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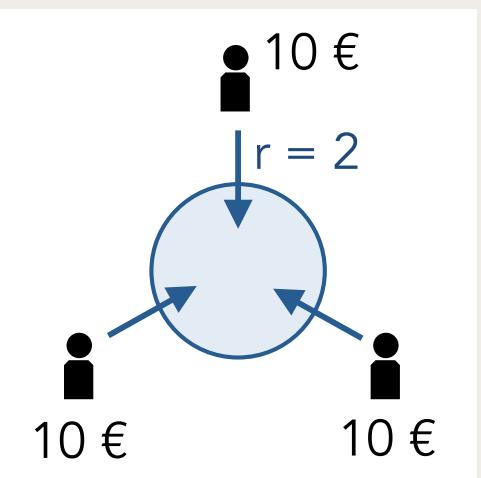
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Example: Public goods game

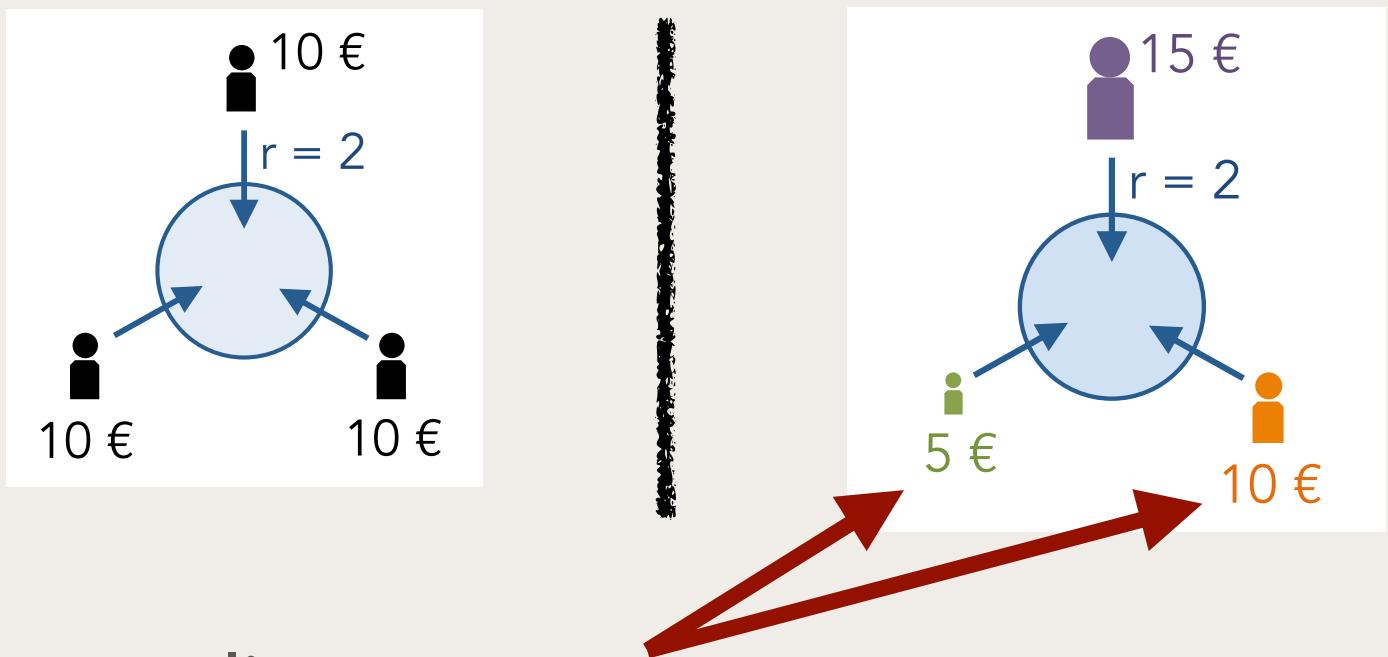


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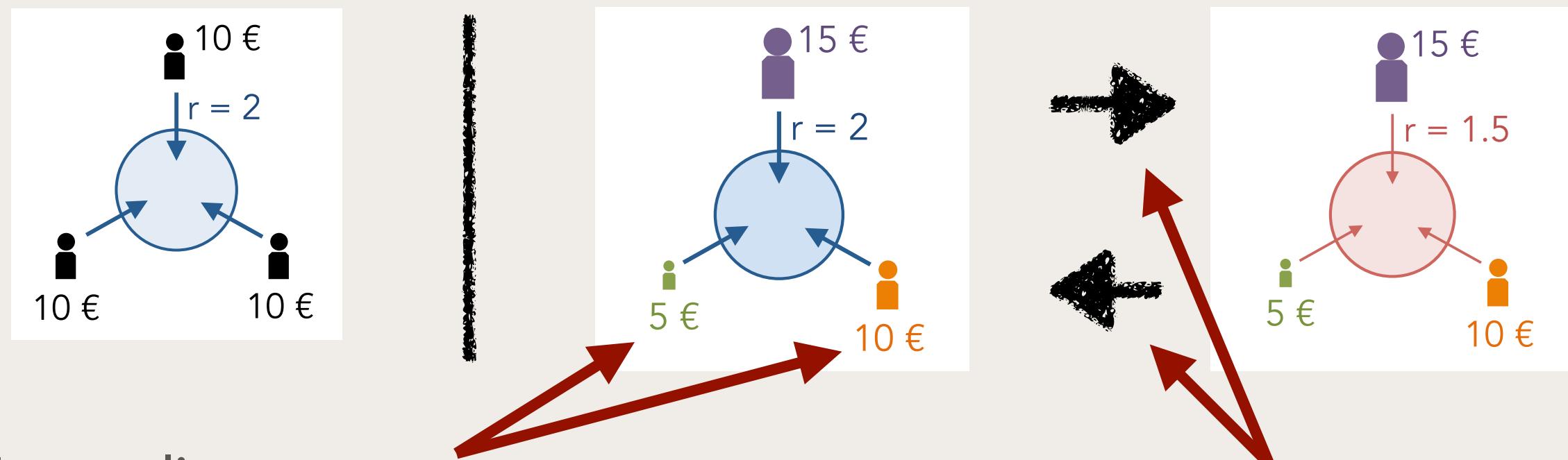
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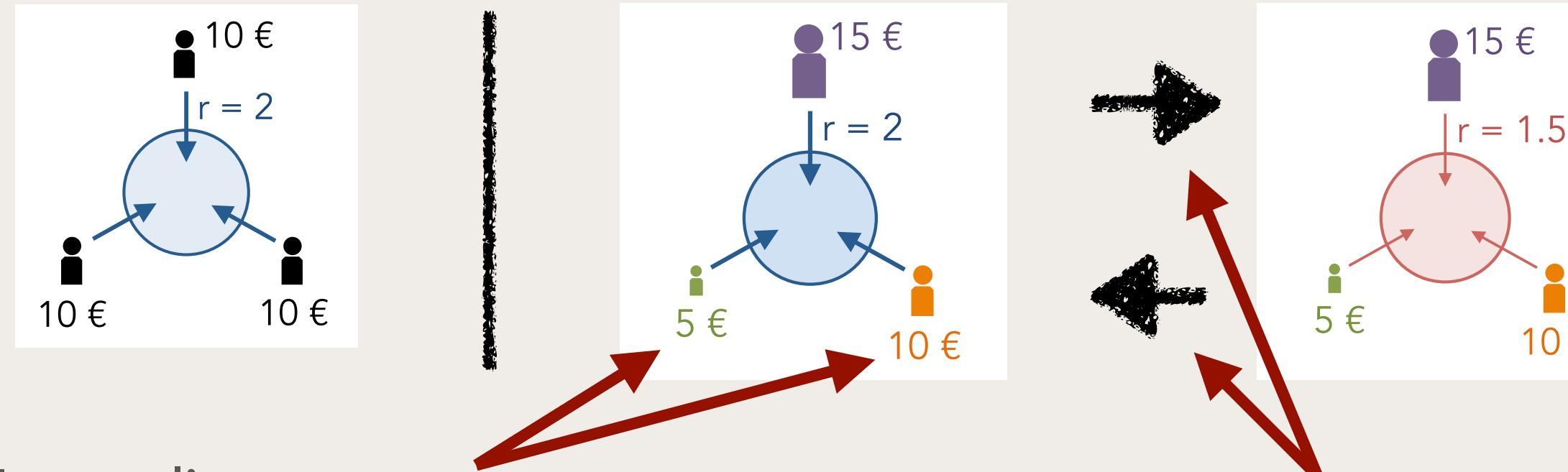
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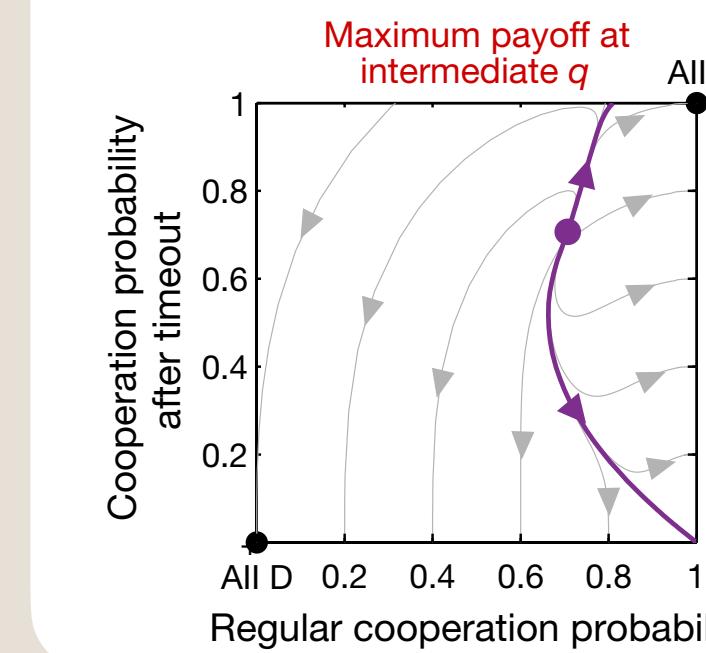
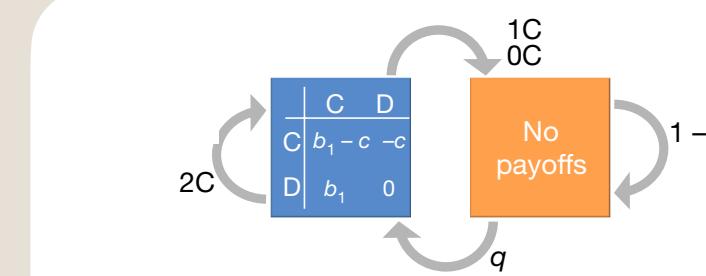
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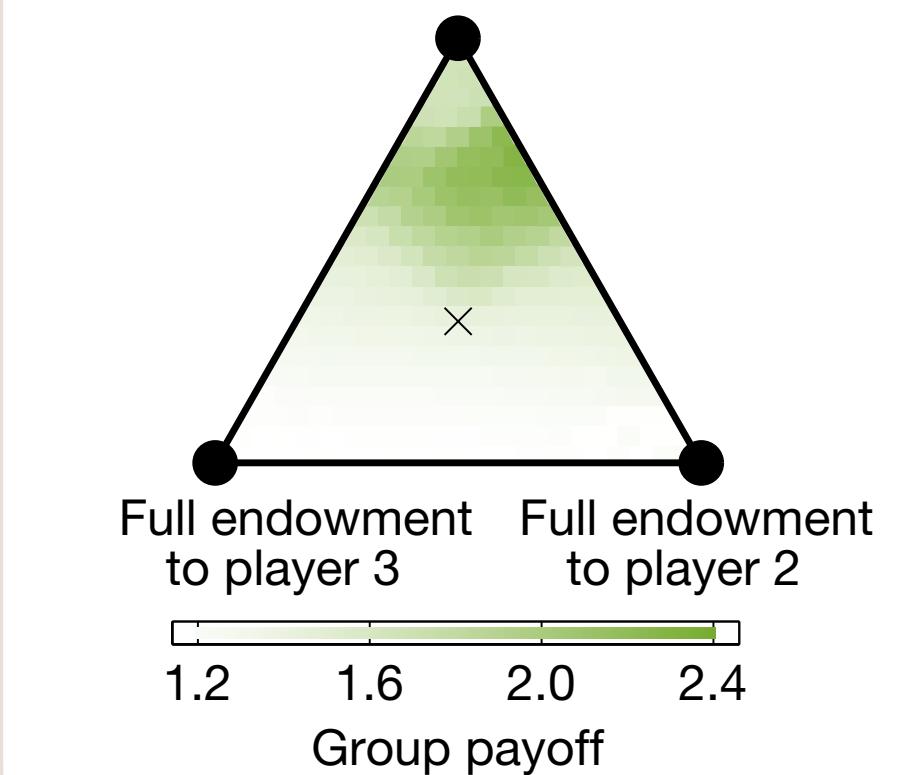
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Social dilemmas among unequals

Oliver P. Hauser^{1,6*}, Christian Hilbe^{2,6*}, Krishnendu Chatterjee² & Martin A. Nowak^{3,4,5*}

Full endowment to player 1

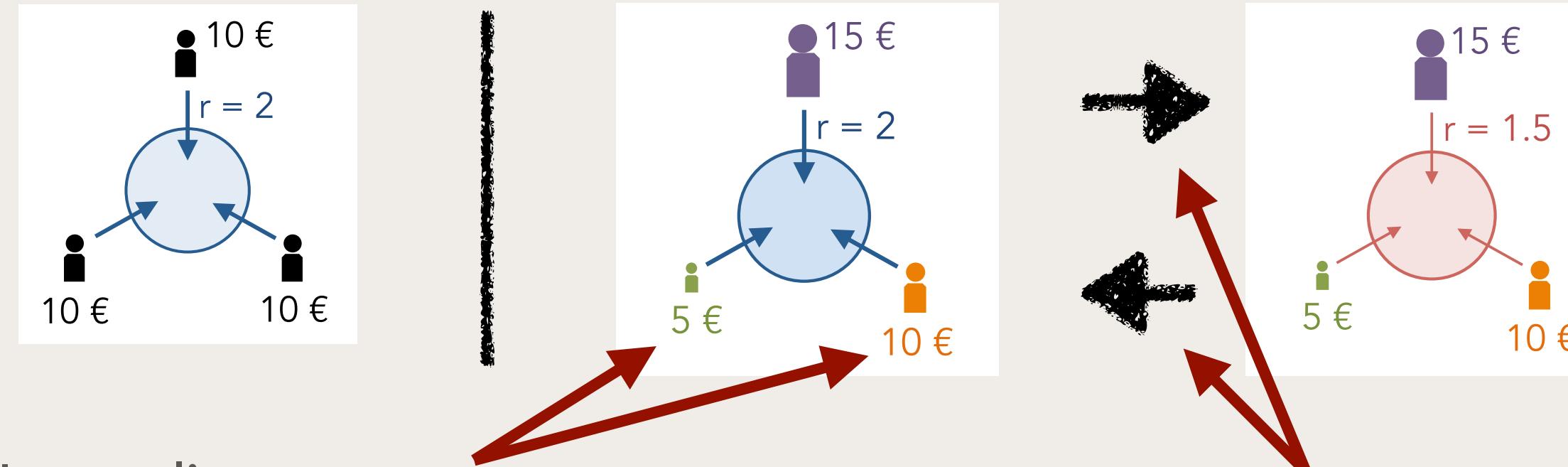


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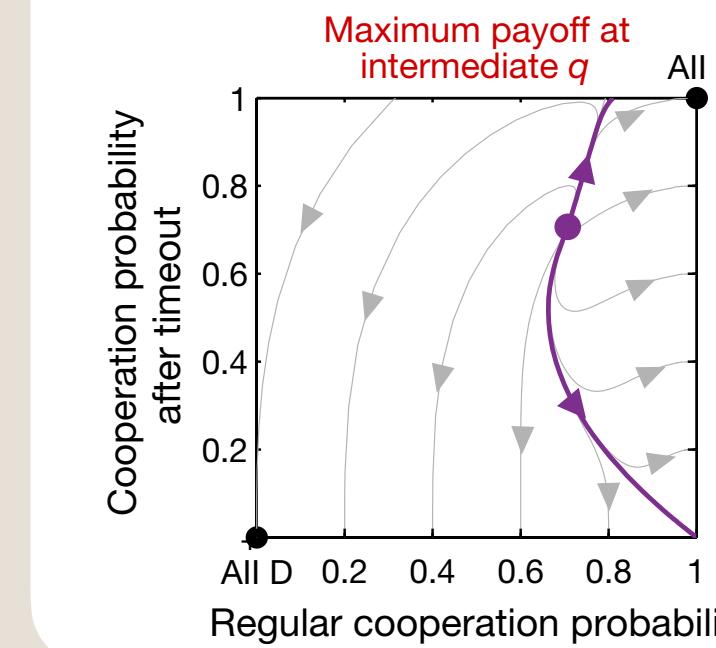
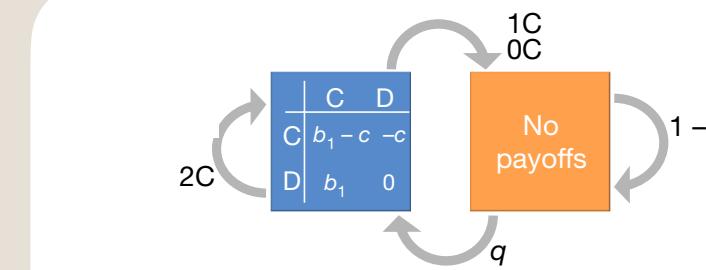


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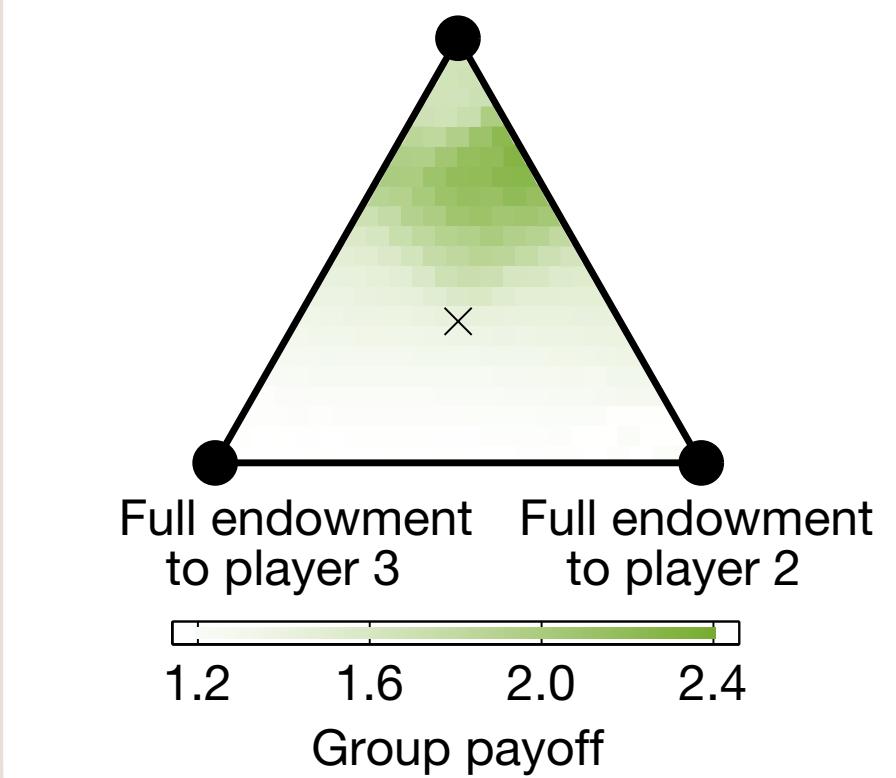
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Introspection dynamics: a simple model of counterfactual learning in asymmetric games

M C Couto^{1,*}, S Gaiamo² and C Hilbe¹

New Journal of Physics, 2022



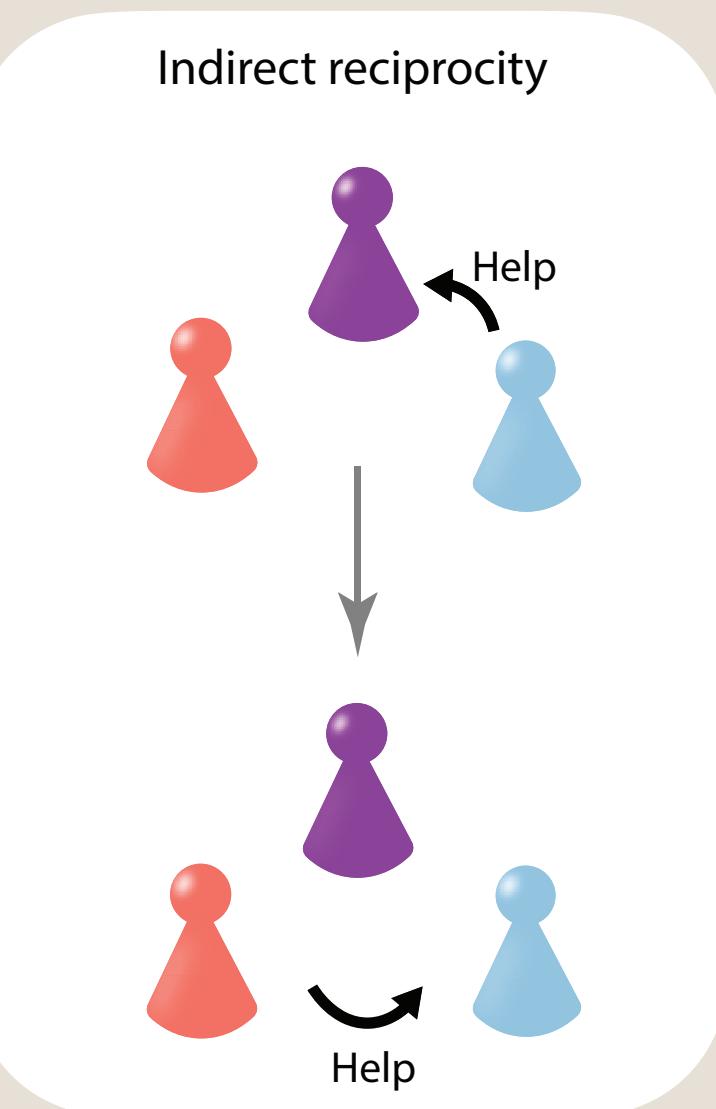
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- Part 1: Intro  Overview of our research agenda
- Part 2: A brief history of direct reciprocity  Repeated prisoner's dilemma / Extortion / Reciprocity in complex environments
- Part 3: A brief history of indirect reciprocity
Image scoring / Leading eight / Private information
- Part 4: How to merge direct and indirect reciprocity
A first modest approach by Schmid et al (2021)

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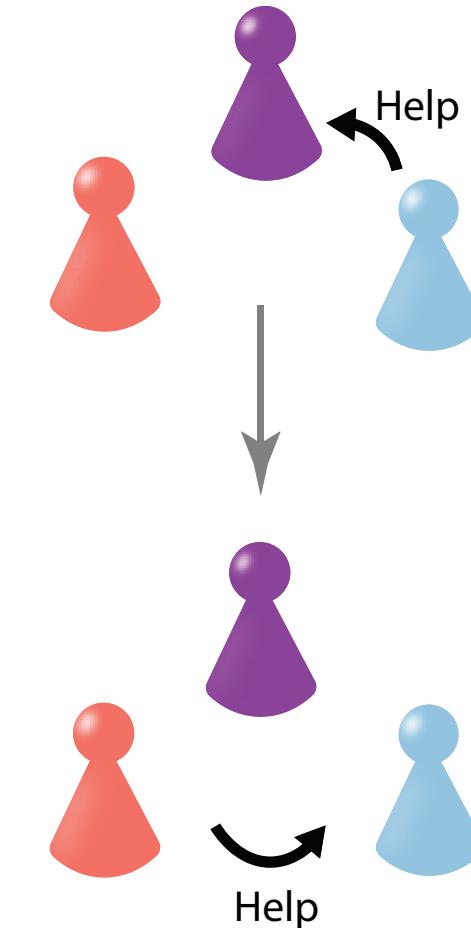
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Indirect reciprocity



My (selective) historical timeline:

Kandori
(1992)

Leimar and Hammerstein
(2001)

Nowak and Sigmund
(1998)

Ohtsuki and Iwasa
(2004)

Some of my
own work

Social Norms and Community Enforcement

MICHIHIRO KANDORI
Princeton University

Evolution of indirect reciprocity by image scoring

Martin A. Nowak^{*†} & Karl Sigmund[‡]

Evolution of cooperation through indirect reciprocity

Olof Leimar^{1*} and Peter Hammerstein²

How should we define goodness?—reputation dynamics in indirect reciprocity

Hisashi Ohtsuki*, Yoh Iwasa

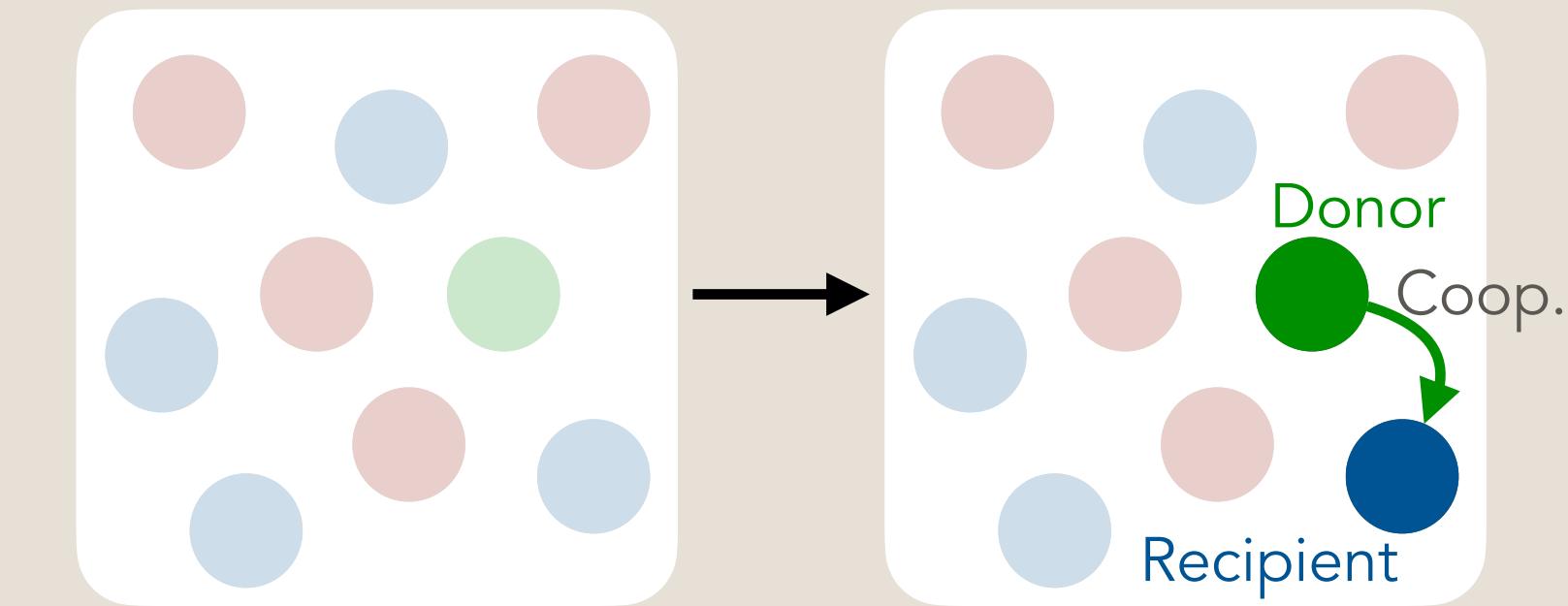
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Nowak & Sigmund (1998): Image Scoring

- Population of n individuals
- In each step, two individuals are randomly chosen, a donor and a recipient.
- Donor decides whether to pay a cost c to deliver a benefit b to recipient.
- Players' reputations are measured by integer scores
- Players cooperate if and only if their co-player's score is sufficiently good (above a threshold k).

Evolution of indirect reciprocity by image scoring

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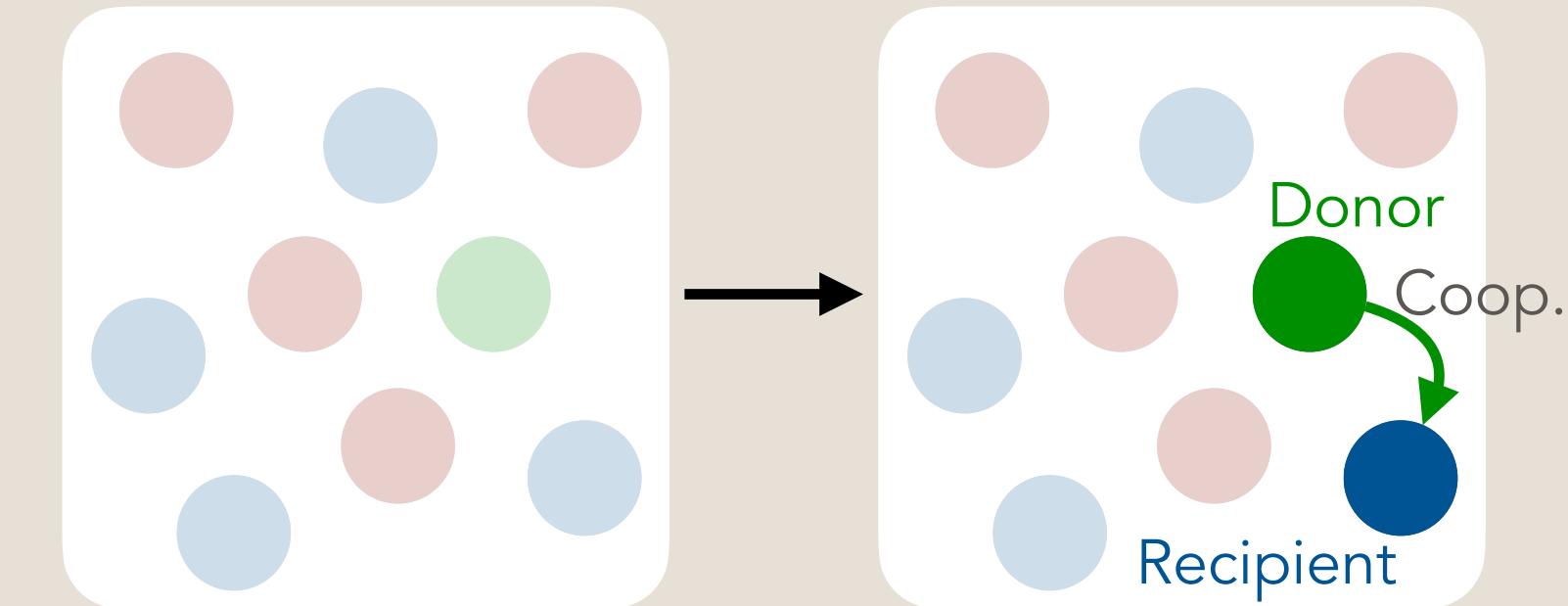
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- **Finding:** Cooperation evolves, and players evolve to have a threshold of $k = 0$.

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Martin A. Nowak^{*†} & Karl Sigmund[‡]



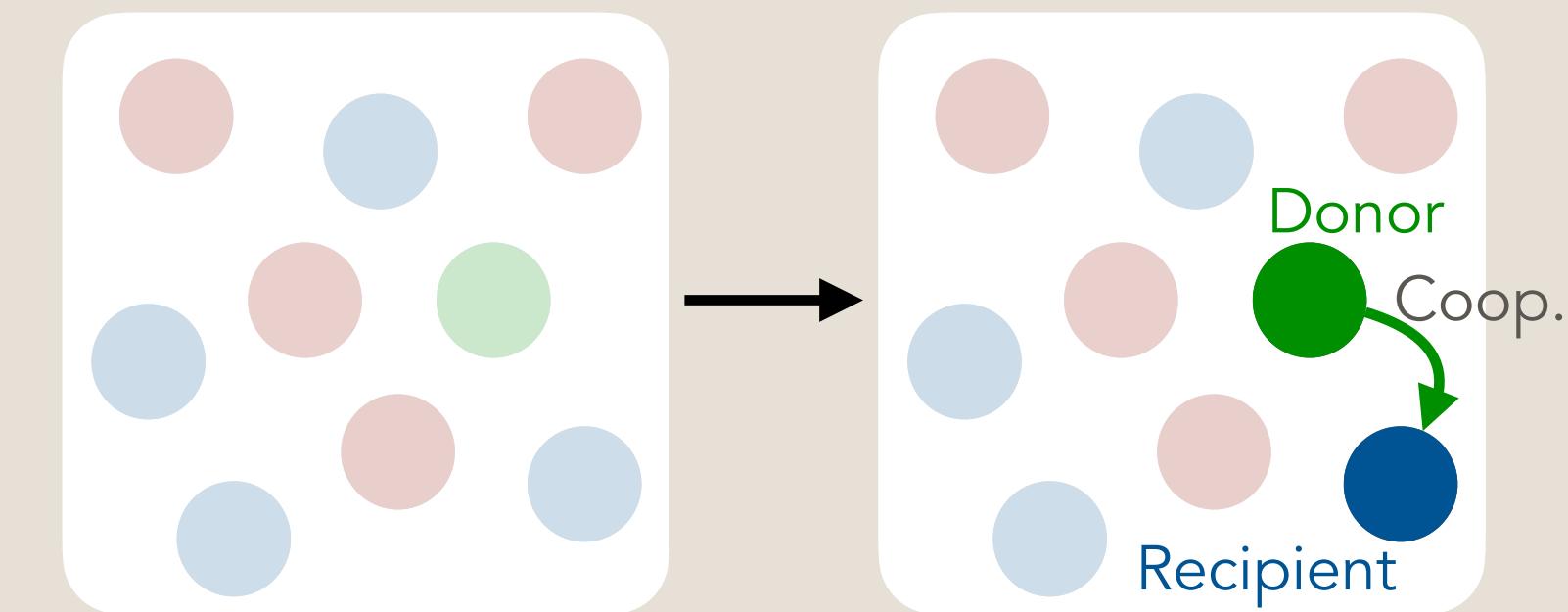
3. Indirect reciprocity: Early evolutionary simulations

Nowak & Sigmund (1998): Image Scoring

- Population of n individuals
- In each step, two individuals are randomly chosen, a donor and a recipient.
- Donor decides whether to pay a cost c to deliver a benefit b to recipient.
- Players' reputations are measured by integer scores
- Players cooperate if and only if their co-player's score is sufficiently good (above a threshold k).
- **Finding:** Cooperation evolves, and players evolve to have a threshold of $k = 0$.

Evolution of indirect reciprocity by image scoring

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Leimar and Hammerstein (2001)

- Nowak & Sigmund's Image Scoring is unstable
- Social norms need to distinguish between justified and unjustified defection.

Evolution of cooperation through indirect reciprocity

Olof Leimar^{1*} and Peter Hammerstein²

3. Indirect reciprocity: The leading eight

How should we define goodness?—reputation dynamics in indirect reciprocity

Hisashi Ohtsuki*, Yoh Iwasa

Ohtsuki & Iwasa (2004)

- Similar setup as Nowak & Sigmund, but there are only two possible reputations, $k \in \{0,1\}$
- However, players are now allowed to use more complex strategies (social norms)

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- The first component α is called *assessment rule*. It determines which behaviors are considered as good, $\alpha = (\alpha_{gCg}, \alpha_{gCb}, \alpha_{bCg}, \alpha_{bCb}, \alpha_{gDg}, \alpha_{gDb}, \alpha_{bDg}, \alpha_{bDb}) \in \{0,1\}^8$

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Some examples:

- ALLD: $\alpha = (0,0,0,0,0,0,0,0)$, $\beta = (0,0,0,0)$

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Some examples:

- ALLD: $\alpha = (0,0,0,0,0,0,0,0)$, $\beta = (0,0,0,0)$
- ALLC: $\alpha = (1,1,1,1,1,1,1,1)$, $\beta = (1,1,1,1)$

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Some examples:

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- ALLC: $\alpha = (1,1,1,1,1,1,1,1)$, $\beta = (1,1,1,1)$
- (Simple) Scoring: $\alpha = (1,1,1,1,0,0,0,0)$, $\beta = (1,0,1,0)$

3. Indirect reciprocity: The leading eight (continued)

How should we define goodness?—reputation dynamics in indirect reciprocity

Hisashi Ohtsuki*, Yoh Iwasa

Question: Is there a social norm such that:

- If the entire population adopts it, then everybody cooperates in the long run.
- The norm is self-enforcing (no one wants to deviate).

If there are several such norms, what is their shared characteristics?

3. Indirect reciprocity: The leading eight (continued)

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“Leading eight”

Assessment rule	* L1	Consistent Standing	Simple Standing	* L4	* L5	Stern Judging	Staying	Judging
	L2	L3	L6	L7	L8			
Good cooperates with Good	g	g	g	g	g	g	g	g
Good cooperates with Bad	g	b	g	g	b	b	g	b
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Action rule	L1	L2	L3	L4	L5	L6	L7	L8
Good meets Good	C	C	C	C	C	C	C	C
Good meets Bad	D	D	D	D	D	D	D	D
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3. Indirect reciprocity: The leading eight (continued)

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If there are several such norms, what is their shared characteristics?

- Always good to cooperate with good players
 - Always bad to defect against good players
 - Norms differ in how to evaluate interactions with bad players.

“Leading eight”

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3. Indirect reciprocity: Are the leading eight the answer?

The model of Ohtsuki & Iwasa assumes:

- All relevant information is public knowledge
- There are no perception errors
- Everybody uses the same assessment rule

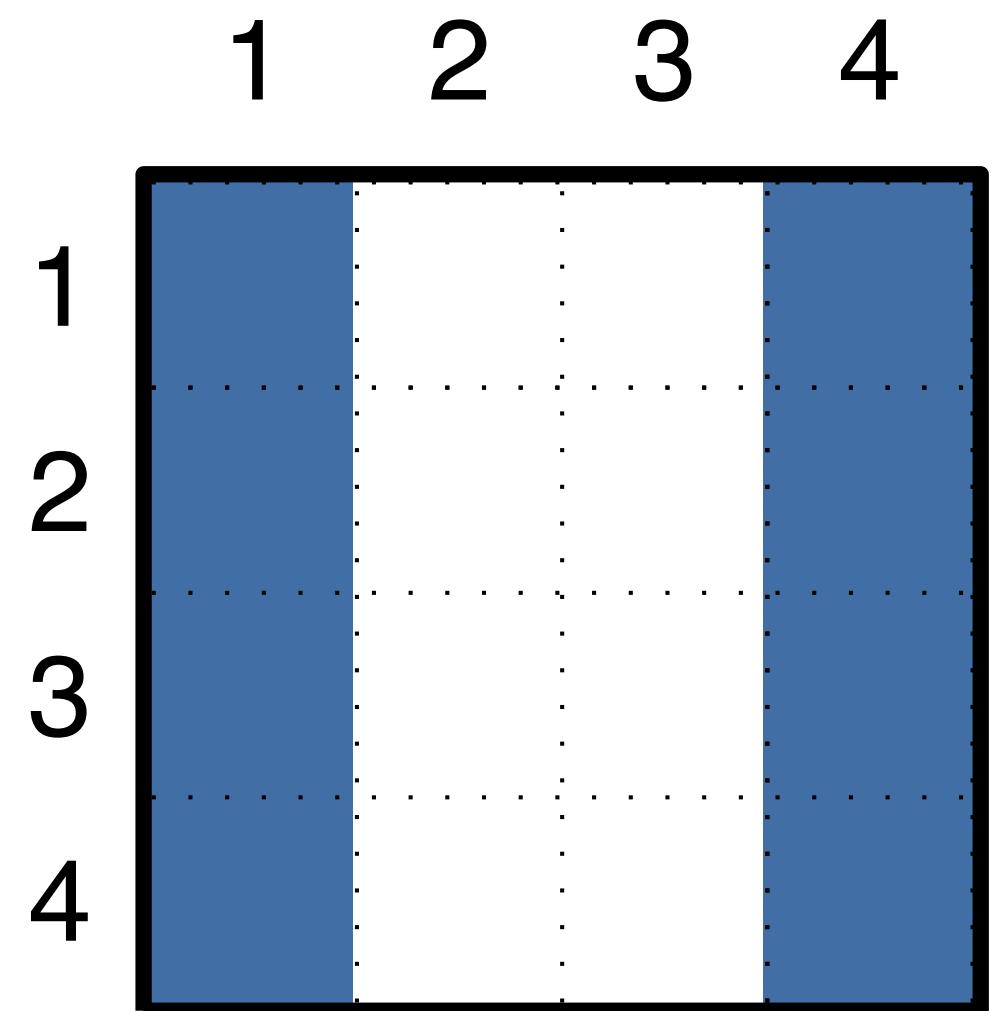
⇒ The players' assessments are perfectly correlated.

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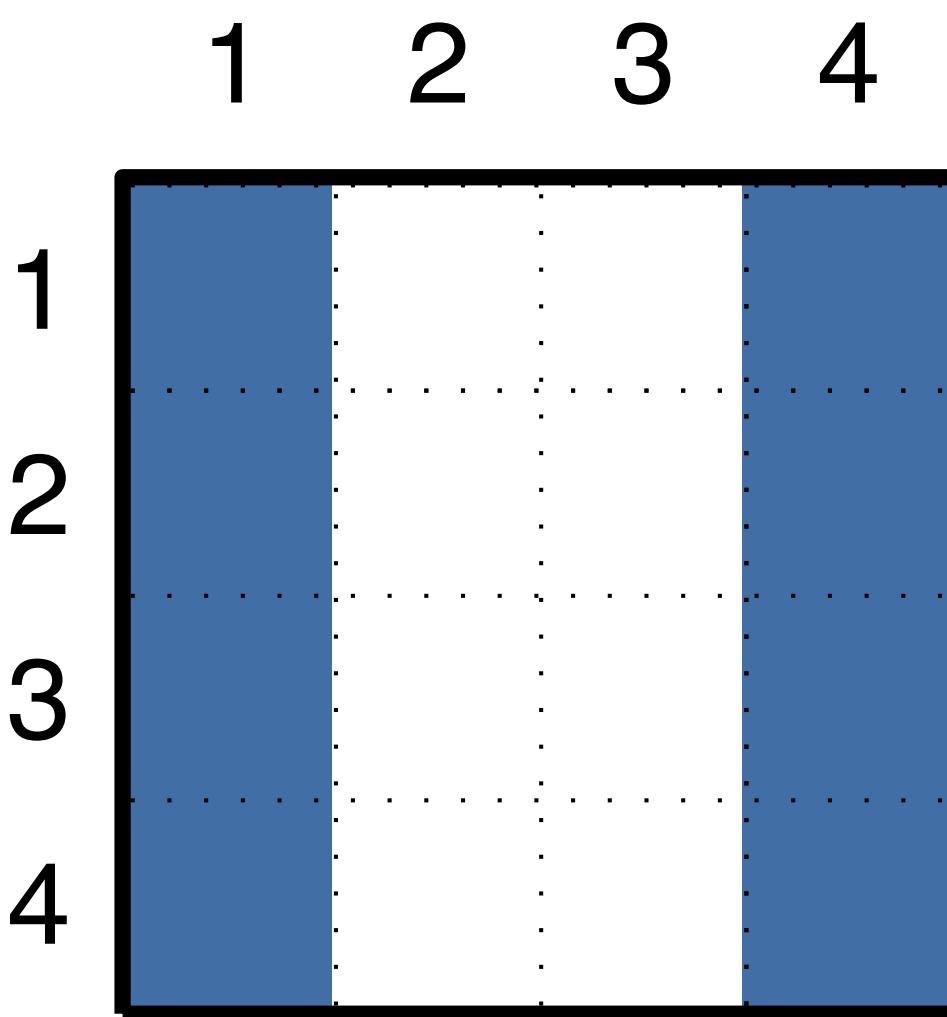
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- Different individuals may have access to different pieces of information
- People may misinterpret the actions of others

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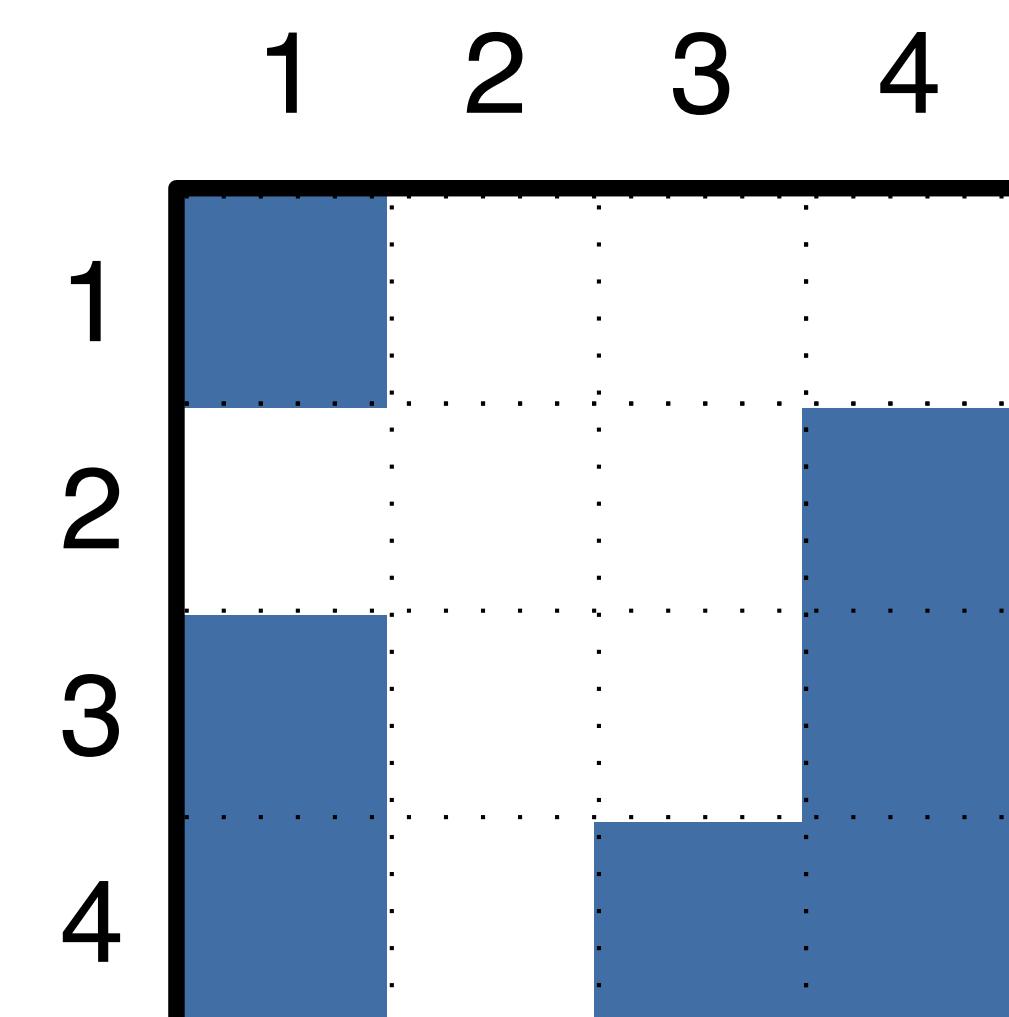
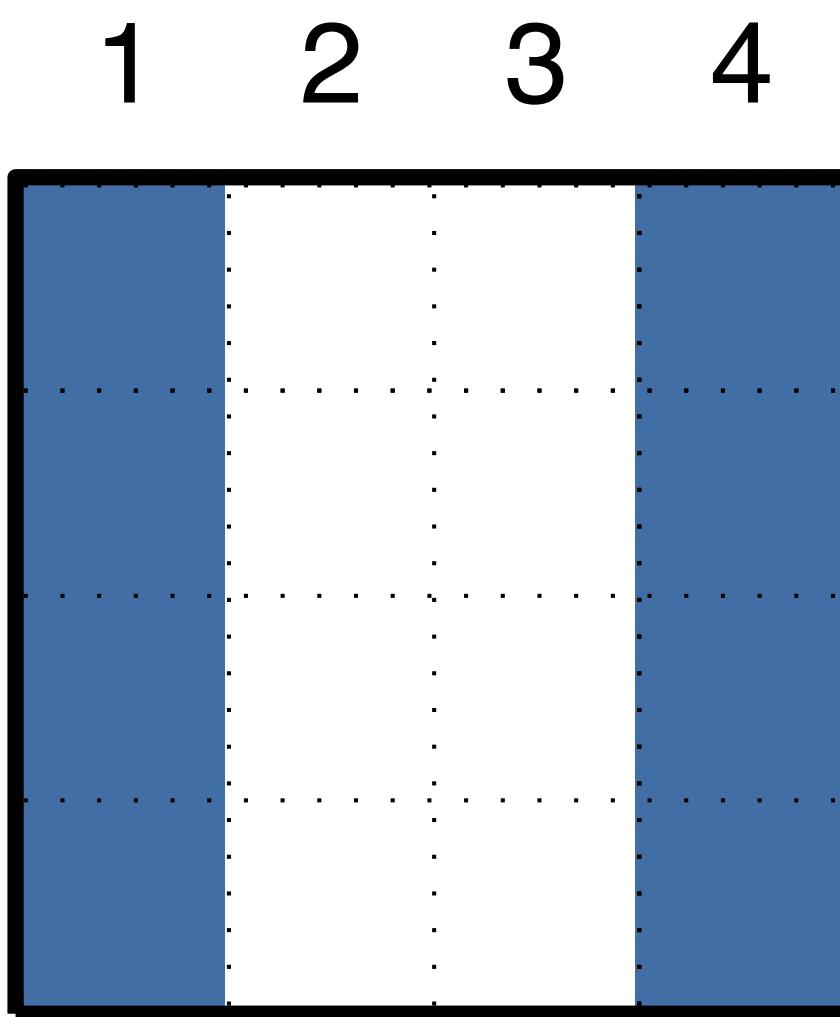
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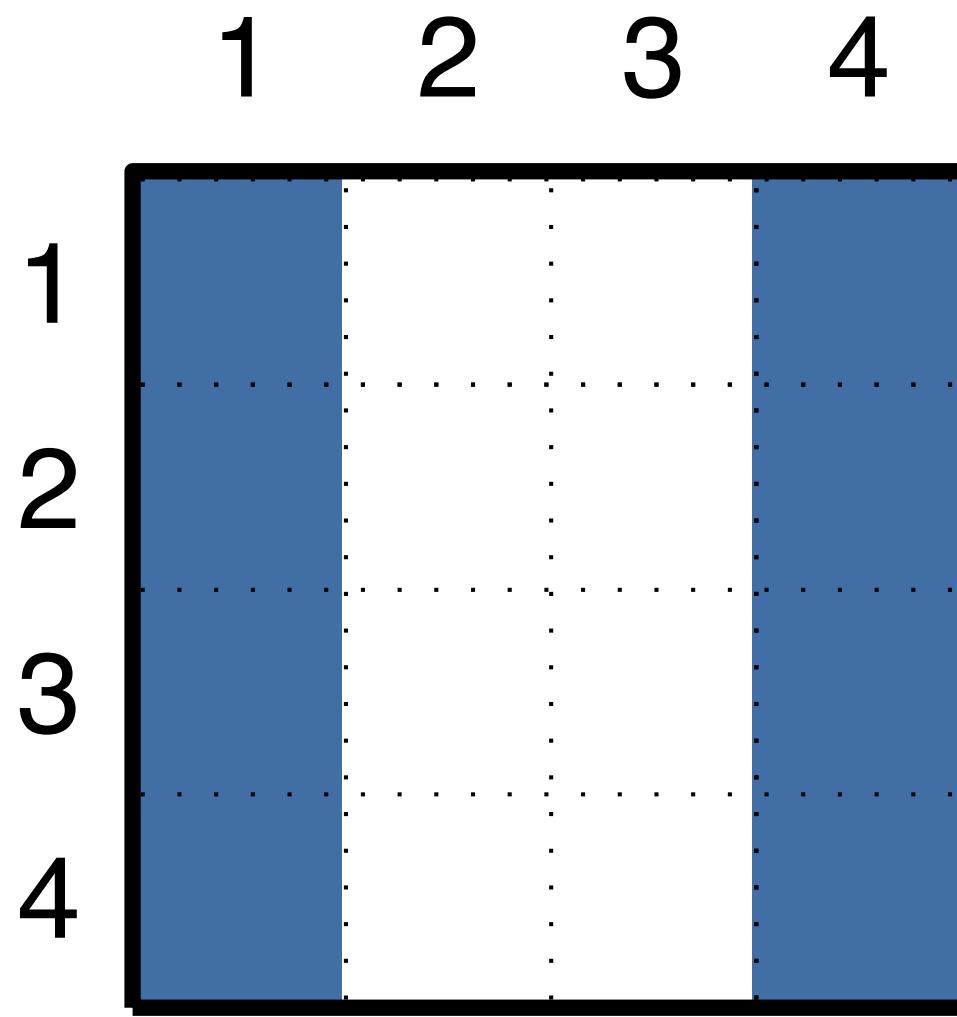
Indirect reciprocity with private, noisy, and incomplete information

Christian Hilbe^{a,1}, Laura Schmid^a, Josef Tkadlec^a, Krishnendu Chatterjee^a, and Martin A. Nowak^{b,c,d}

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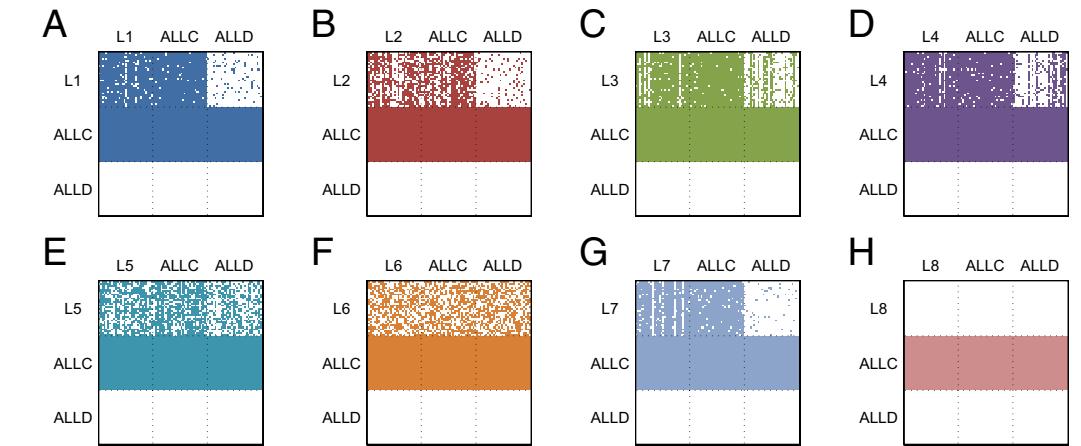
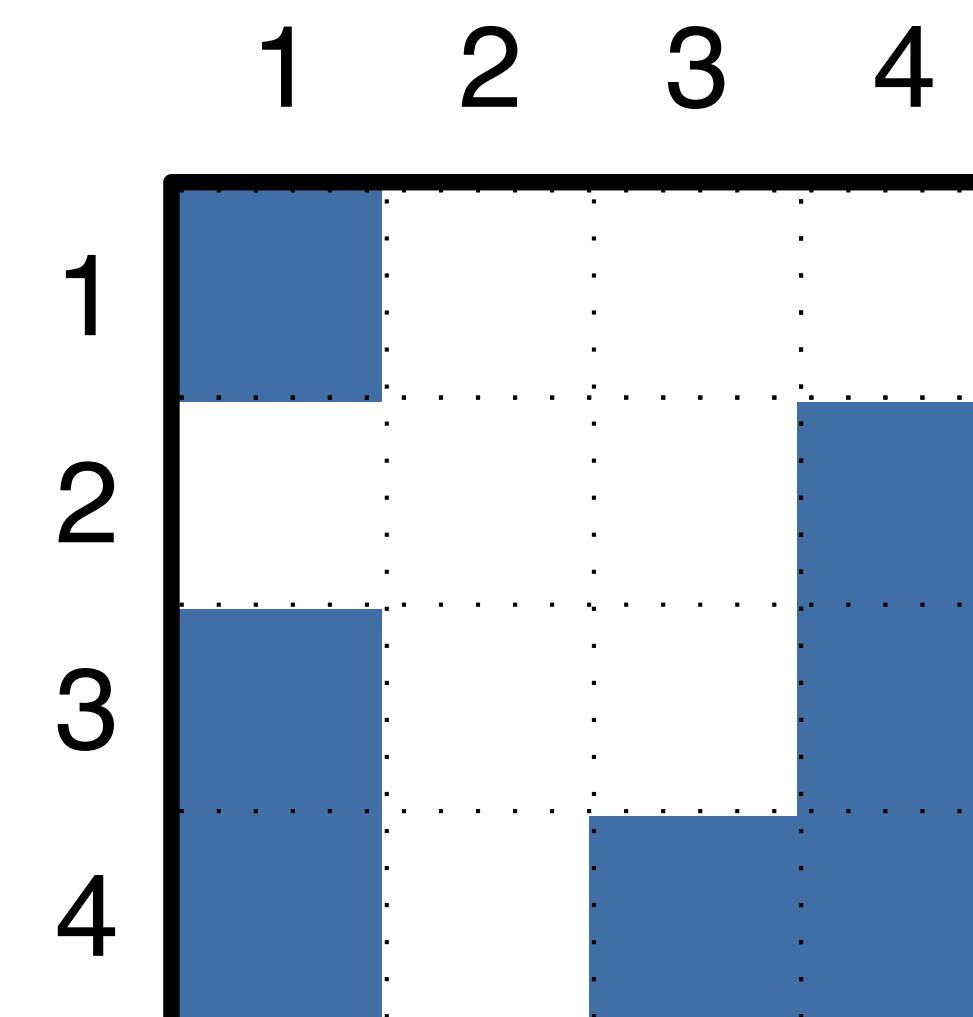
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Stable cooperation rarely evolves.

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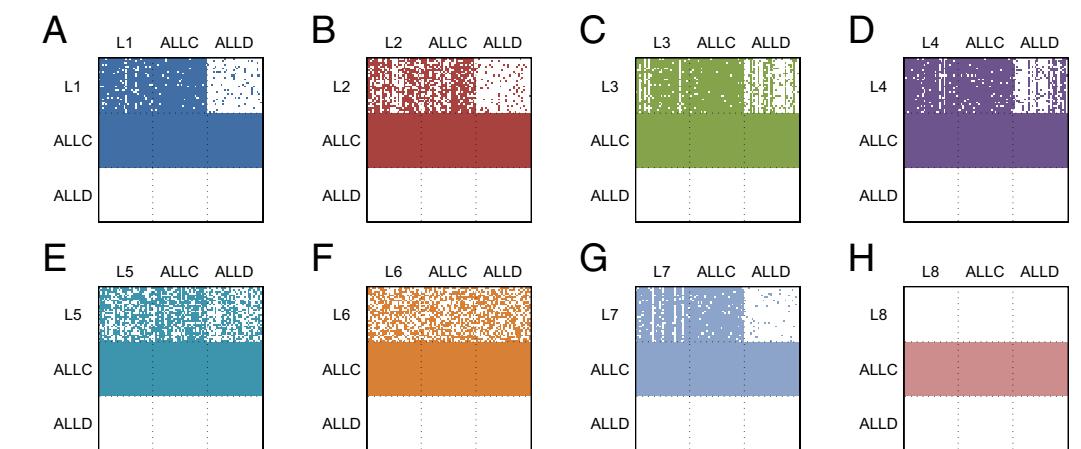
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Stable cooperation rarely evolves.

Possible solutions:

Evolution of empathetic moral evaluation

Arunas L Radzvilavicius^{1*}, Alexander J Stewart², Joshua B Plotkin^{1*}

eLife, 2019

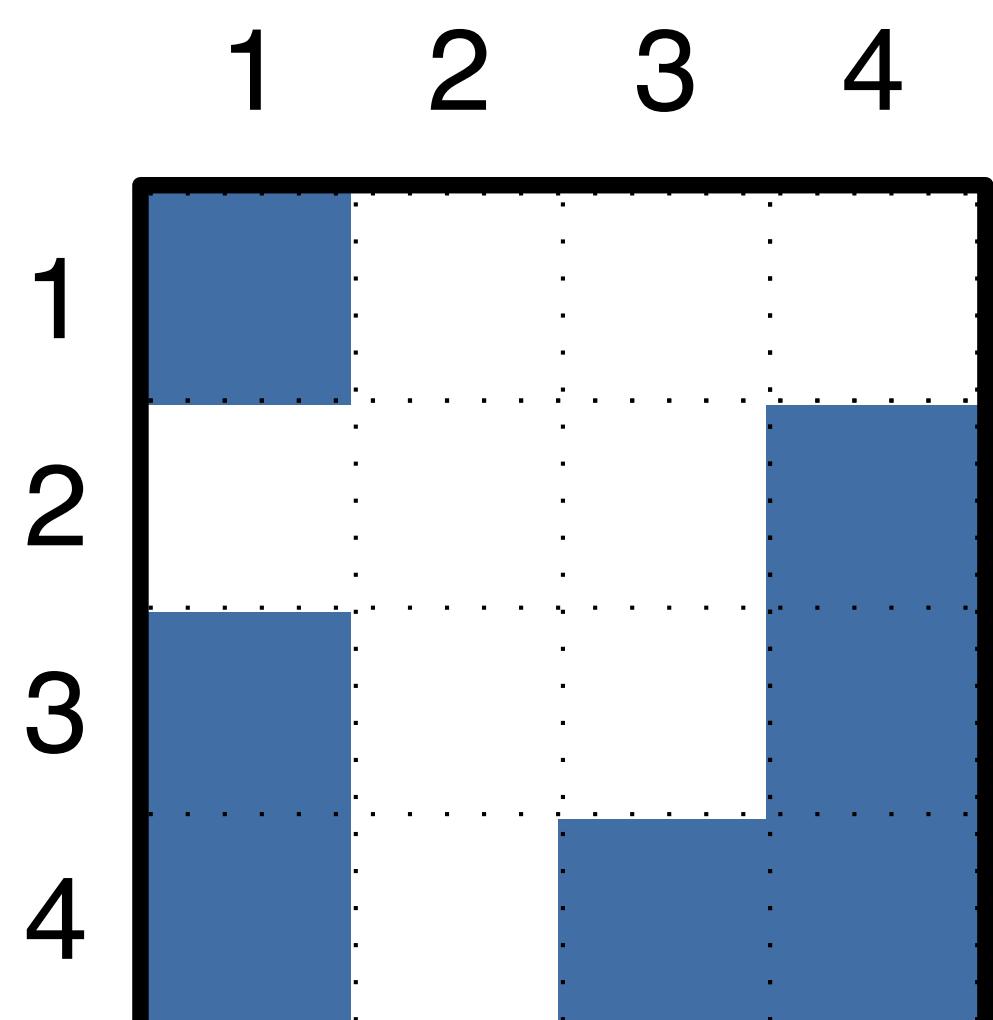
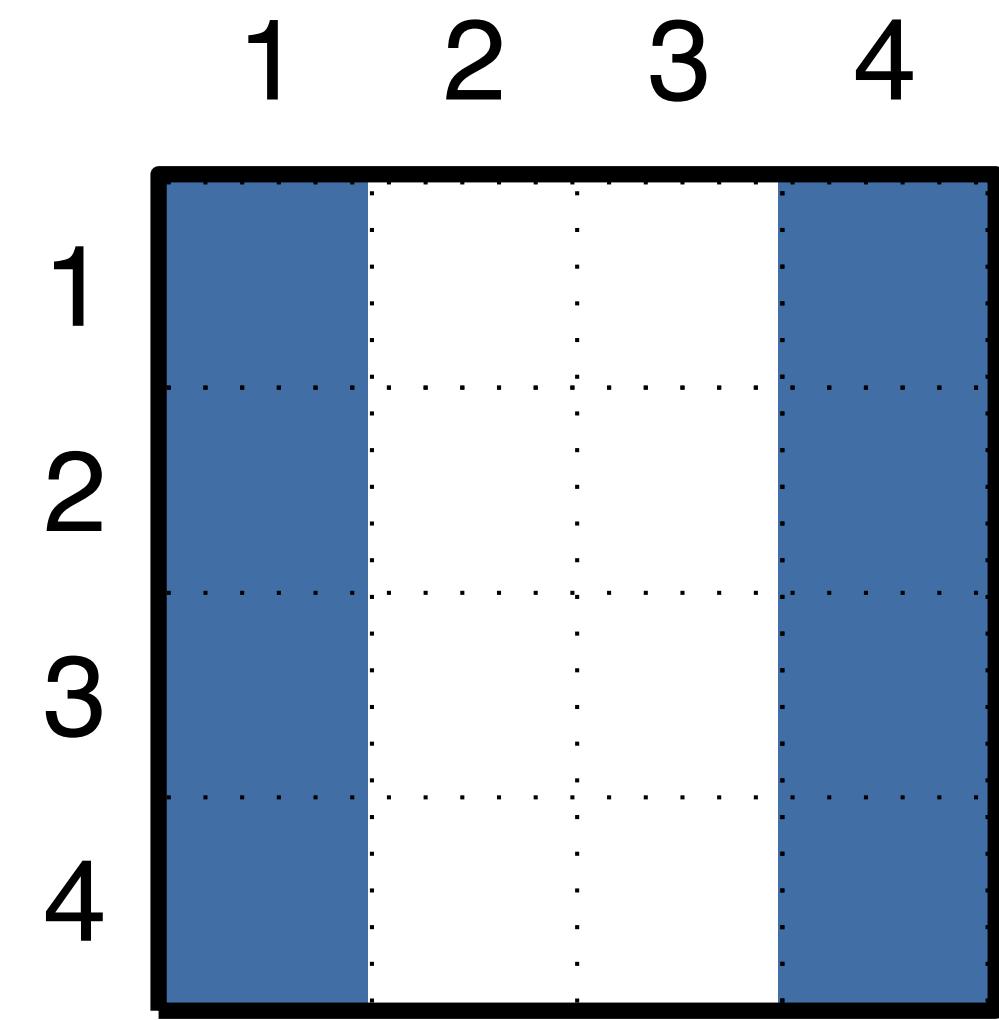
Adherence to public institutions that foster cooperation

Arunas L. Radzvilavicius^{1,2}, Taylor A. Kessinger^{1,2} & Joshua B. Plotkin¹

Nature Communications, 2021

Gossip?

Further research required...



Today's menu.

- Part 1: Intro 

Overview of our research agenda

- Part 2: A brief history of direct reciprocity 

Repeated prisoner's dilemma / Extortion / Reciprocity in complex environments

- Part 3: A brief history of indirect reciprocity 

Image scoring / Leading eight / Private information

- Part 4: How to merge direct and indirect reciprocity

A first modest approach by Schmid et al (2021)

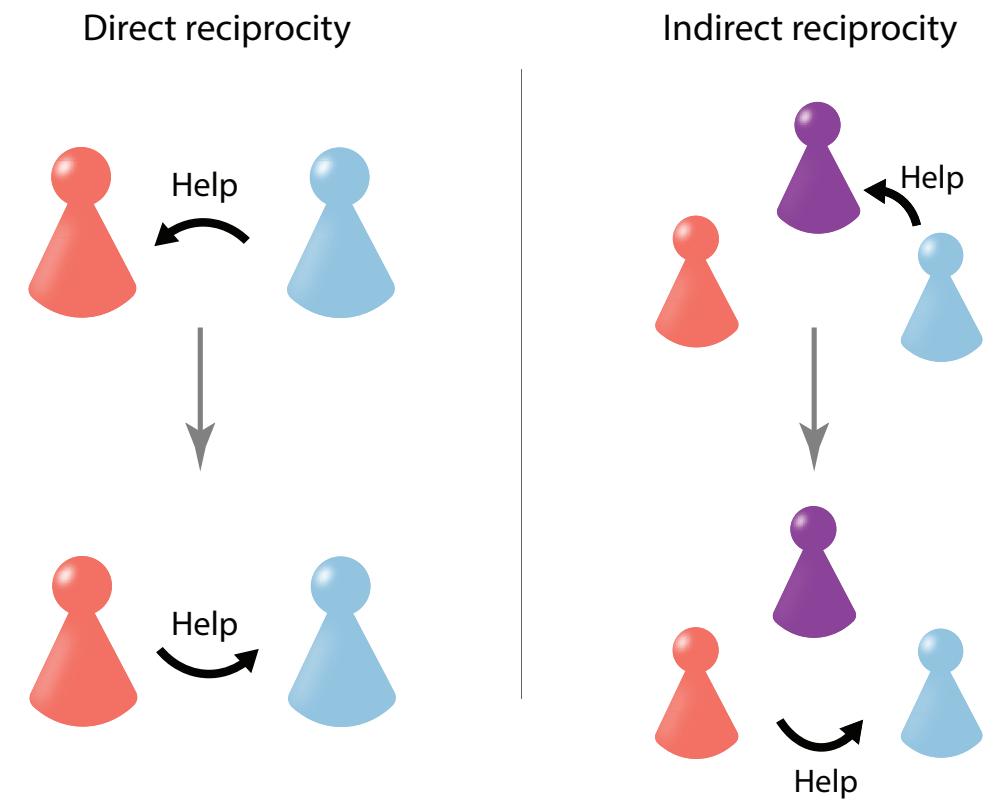
4. Merging direct and indirect reciprocity

Motivation for a unified framework

- **Conceptual motivation.** From the outset, direct and indirect reciprocity feel very similar. It is somewhat odd that the respective models are rather different regarding their complexity.

A unified framework of direct and indirect reciprocity

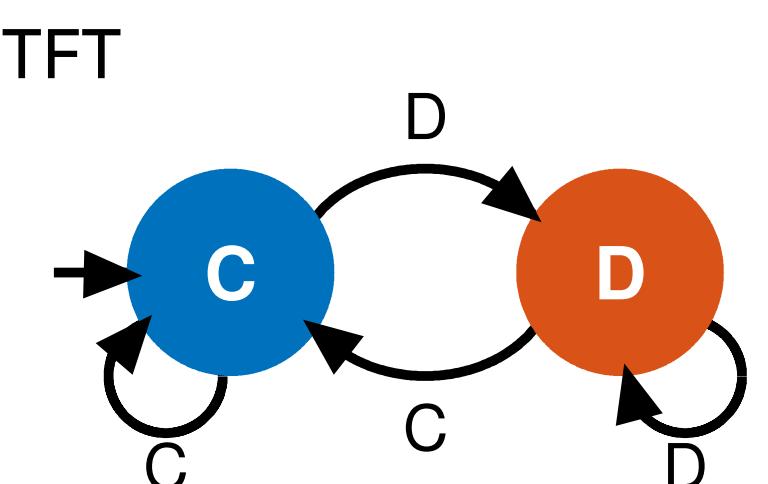
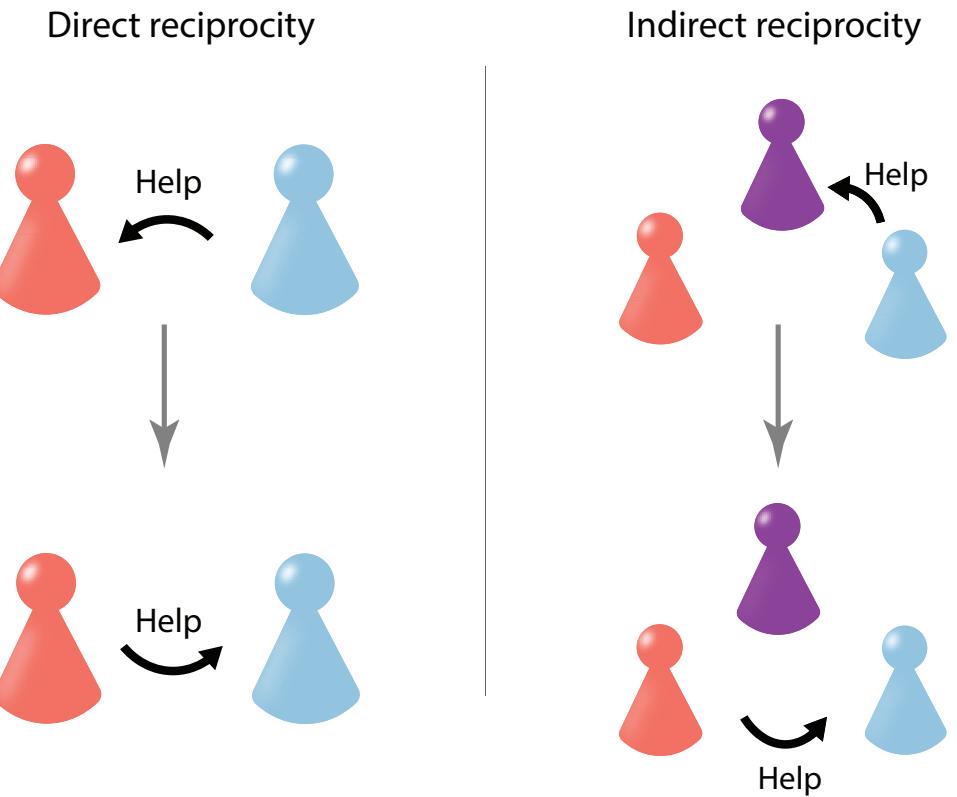
Laura Schmid¹✉, Krishnendu Chatterjee¹, Christian Hilbe^{2,4} and Martin A. Nowak^{3,4}



4. Merging direct and indirect reciprocity

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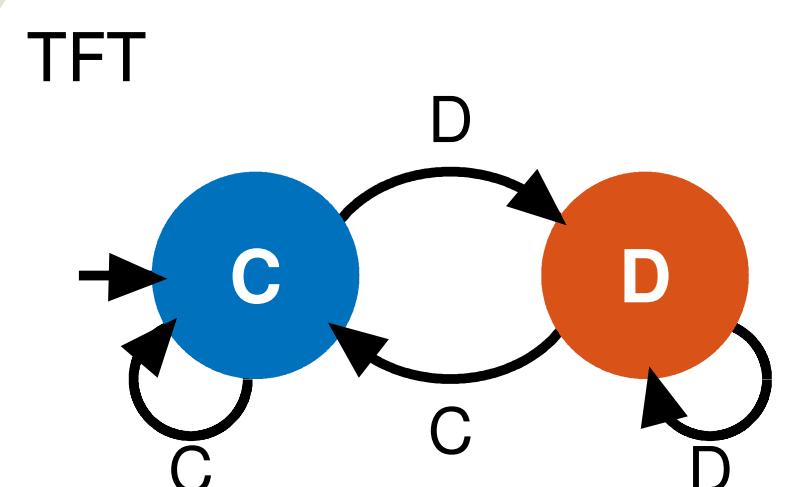
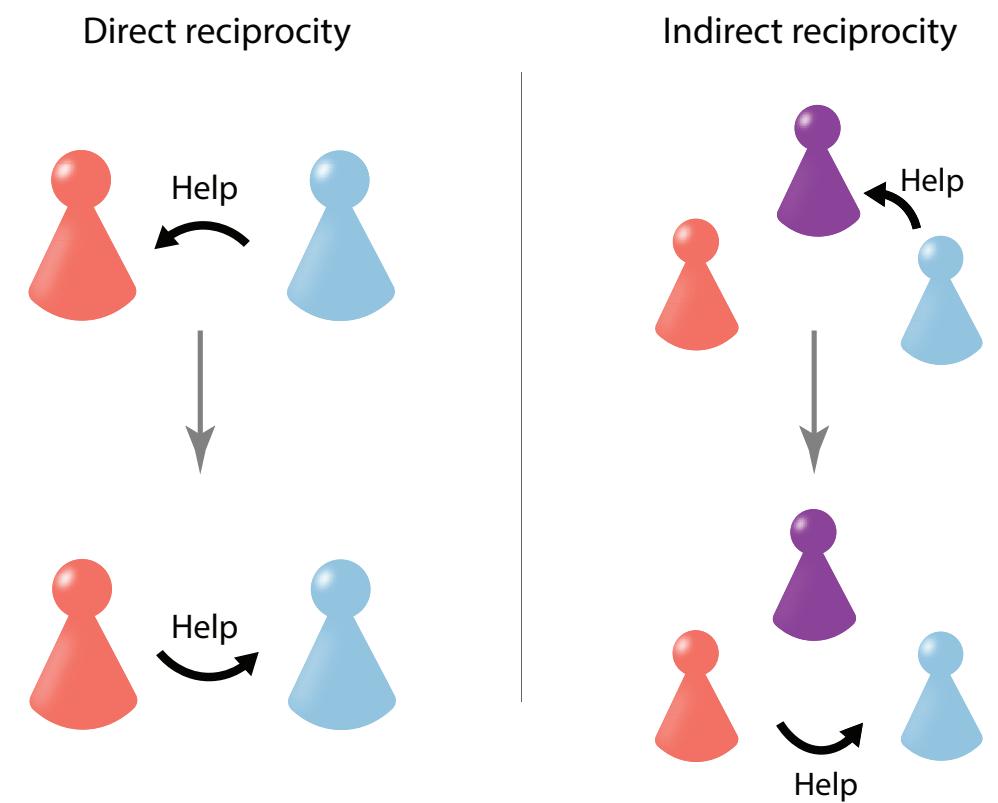
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Motivation for a unified framework

- **Conceptual motivation.** From the outset, direct and indirect reciprocity feel very similar. It is somewhat odd that the respective models are rather different regarding their complexity.
 - **Practical motivation.** In real life, we often have both direct and indirect information about each other. How do people combine these pieces of information?

A unified framework of direct and indirect reciprocity

Laura Schmid¹✉, Krishnendu Chatterjee¹, Christian Hilbe^{1,2,4} and Martin A. Nowak^{1,3,4}

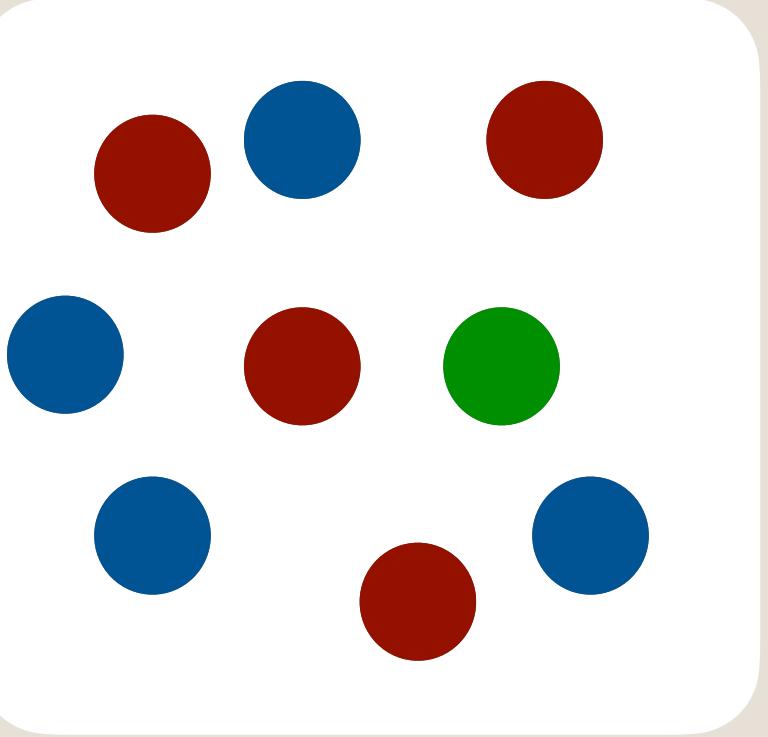


Assessment rule	*	Consistent Standing	Simple Standing	*	*	Stern Judging	Staying	Judging
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4. Merging direct and indirect reciprocity

Rules of
the game

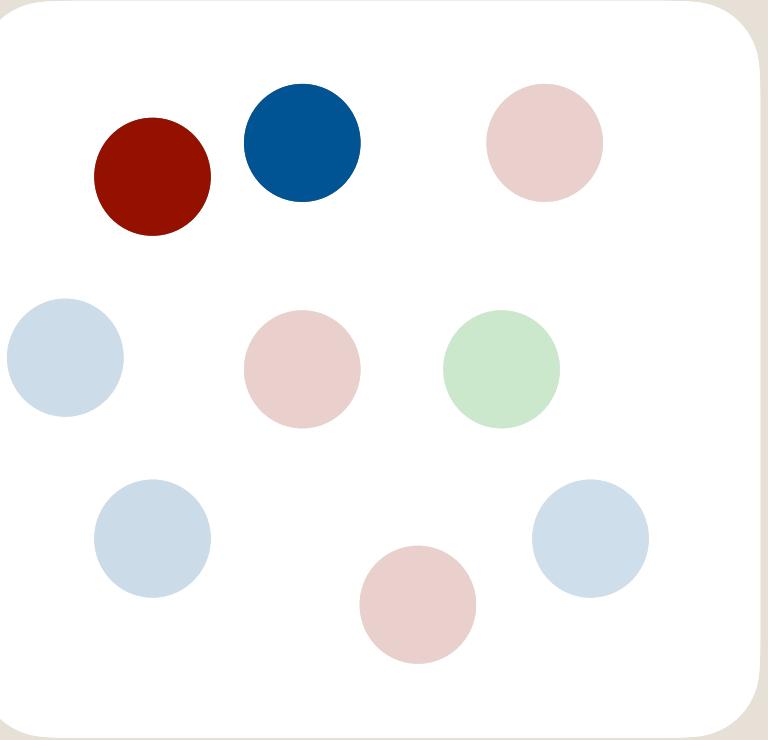
- Consider a well-mixed population with n individuals



4. Merging direct and indirect reciprocity

Rules of
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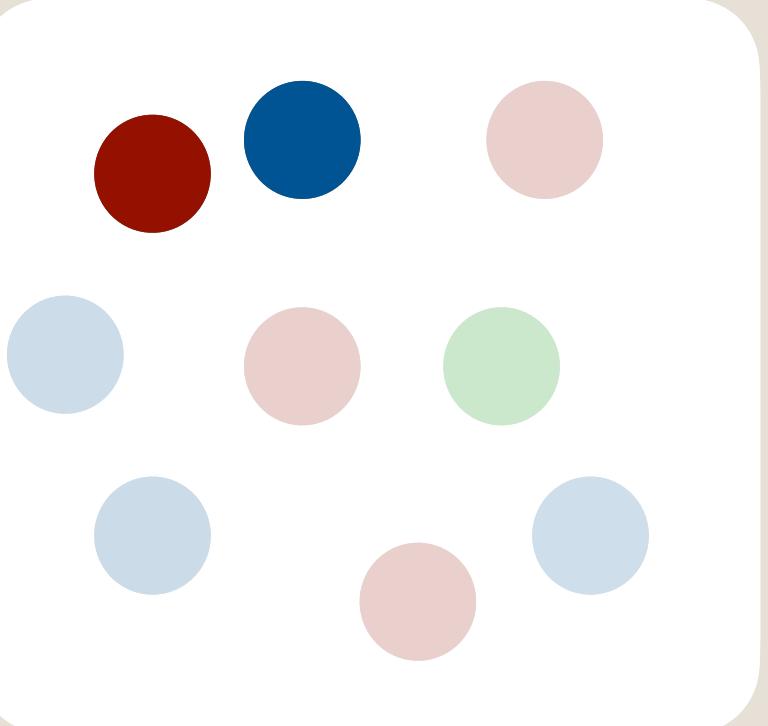
- Consider a well-mixed population with n individuals
- Two individuals are randomly chosen



4. Merging direct and indirect reciprocity

Rules of
the game

- Consider a well-mixed population with n individuals
- Two individuals are randomly chosen
- Each individual can then choose whether to cooperate

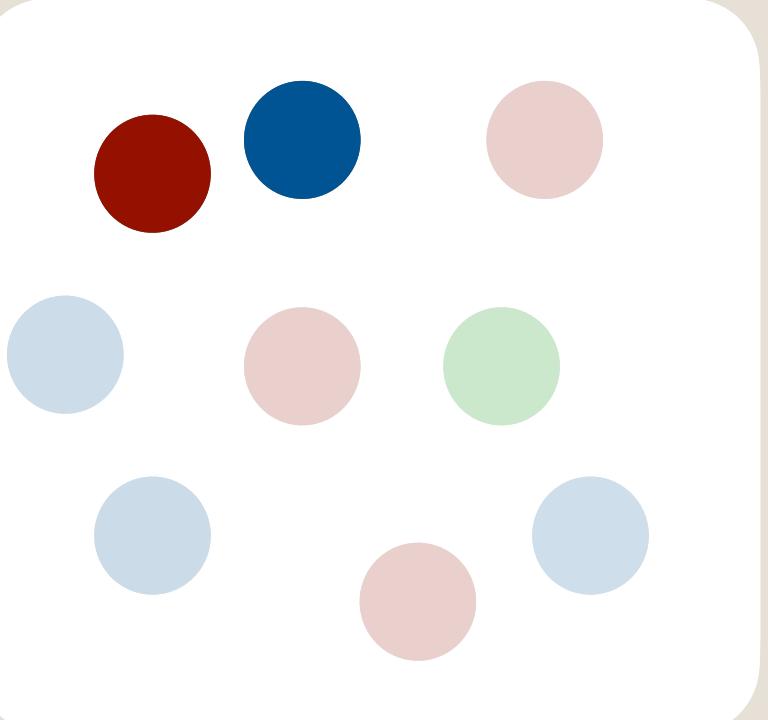


	C	D
C	$b-c$	$-c$
D	b	0

4. Merging direct and indirect reciprocity

Rules of
the game

- Consider a well-mixed population with n individuals
- Two individuals are randomly chosen
- Each individual can then choose whether to cooperate
- All other individuals observe the interaction; but they may misperceive the player's actions with probability ϵ

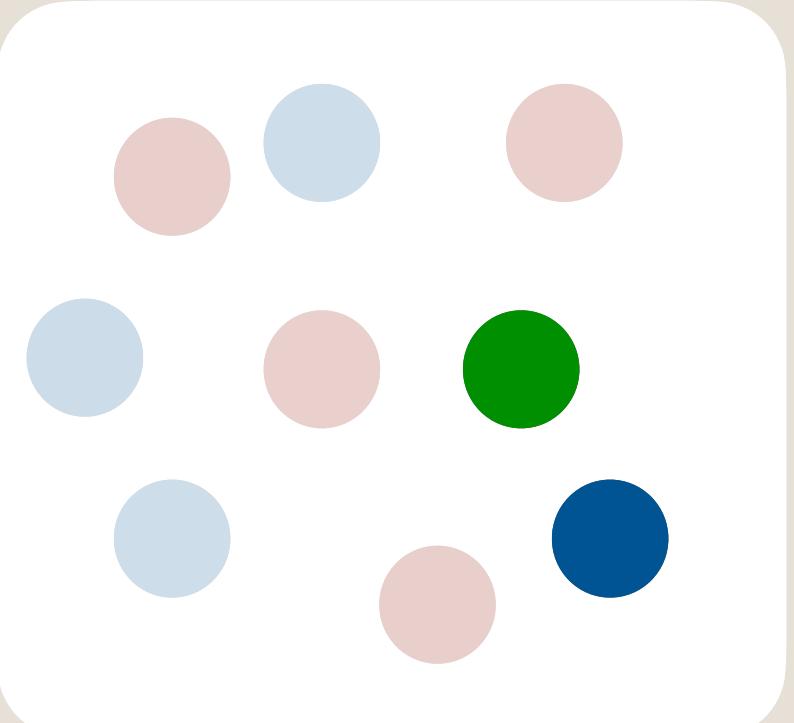


	C	D
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4. Merging direct and indirect reciprocity

Rules of the game

- Consider a well-mixed population with n individuals
- Two individuals are randomly chosen ←
- Each individual can then choose whether to cooperate
- All other individuals observe the interaction; but they may misperceive the player's actions with probability ϵ
- After each interaction, there is another interaction with probability d

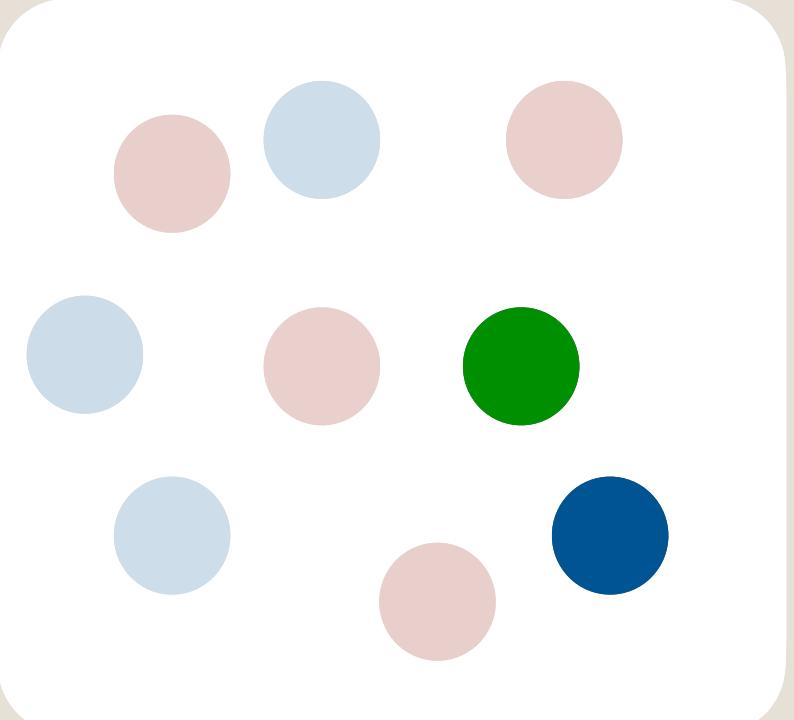


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Strategies

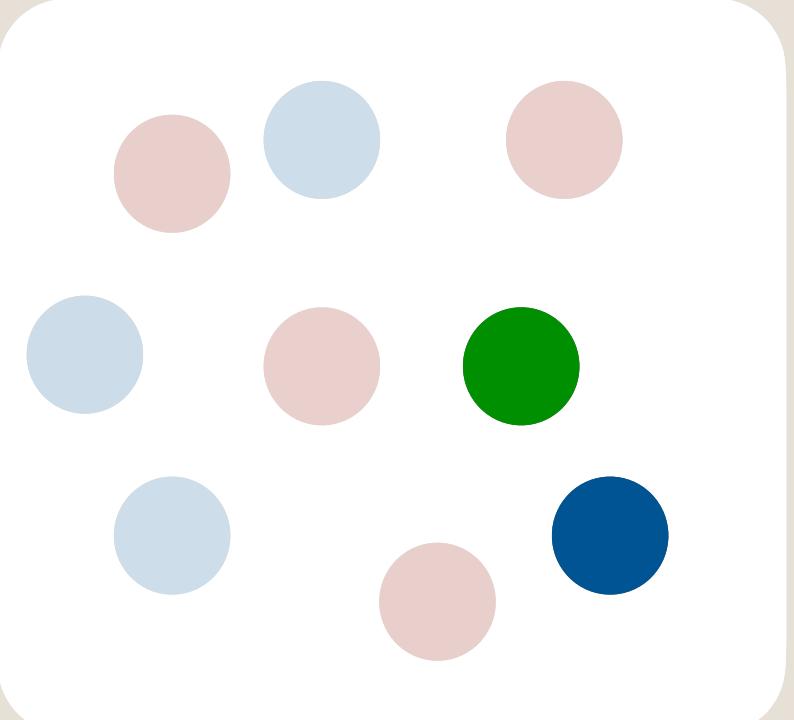
We consider strategies of the form (y, p, q, λ)

	C	D
C	$b-c$	$-c$
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4. Merging direct and indirect reciprocity

Rules of the game

- Consider a well-mixed population with n individuals
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- All other individuals observe the interaction; but they may misperceive the player's actions with probability ε
- After each interaction, there is another interaction with probability d ↗



Strategies

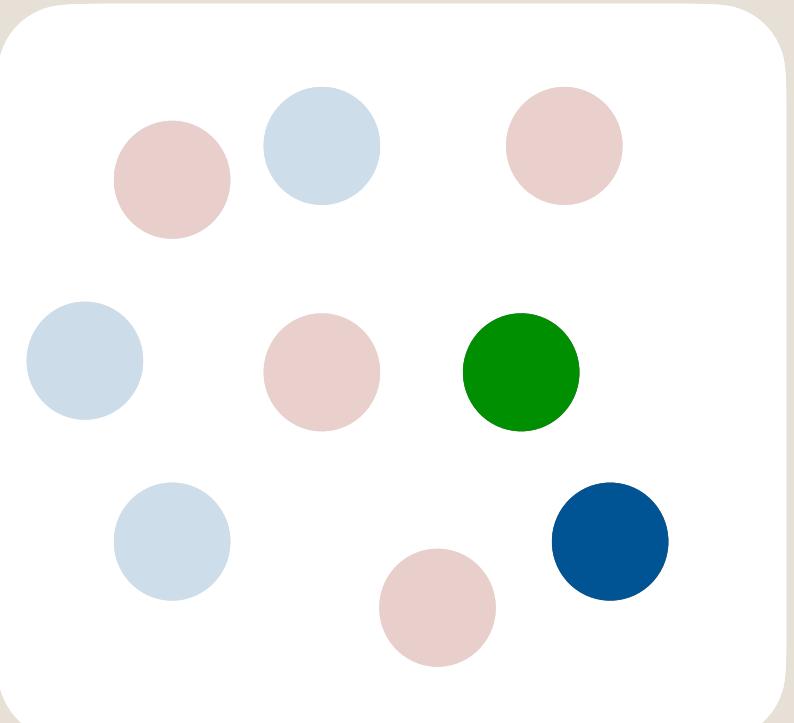
We consider strategies of the form (y, p, q, λ)
 y ...Probability to initially assign a good reputation

	C	D
C	$b-c$	$-c$
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4. Merging direct and indirect reciprocity

Rules of the game

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- Two individuals are randomly chosen ←
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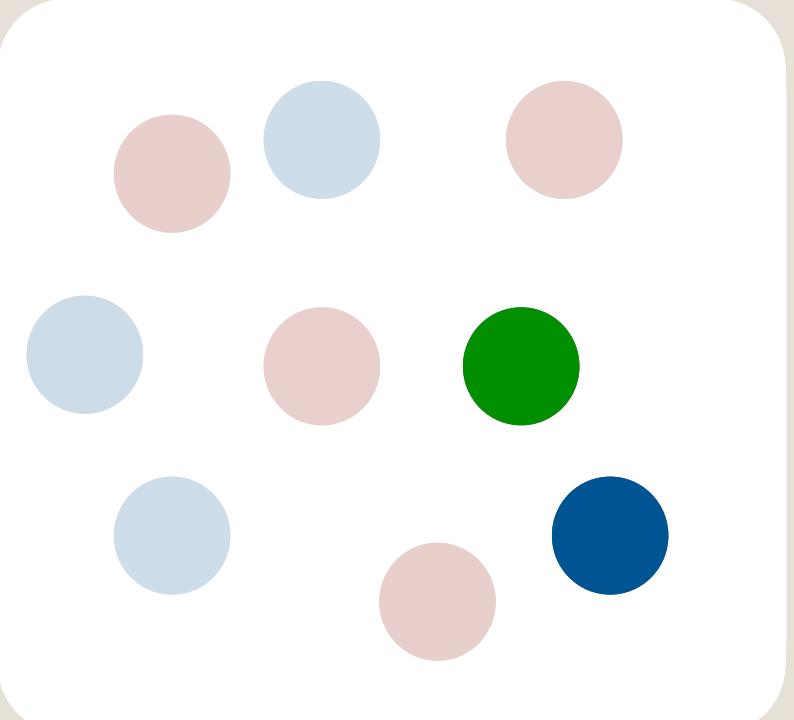
p ...Probability to assign a good reputation after co-player cooperated

	C	D
C	$b-c$	$-c$
D	b	0

4. Merging direct and indirect reciprocity

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Strategies

We consider strategies of the form (y, p, q, λ)

y ...Probability to initially assign a good reputation

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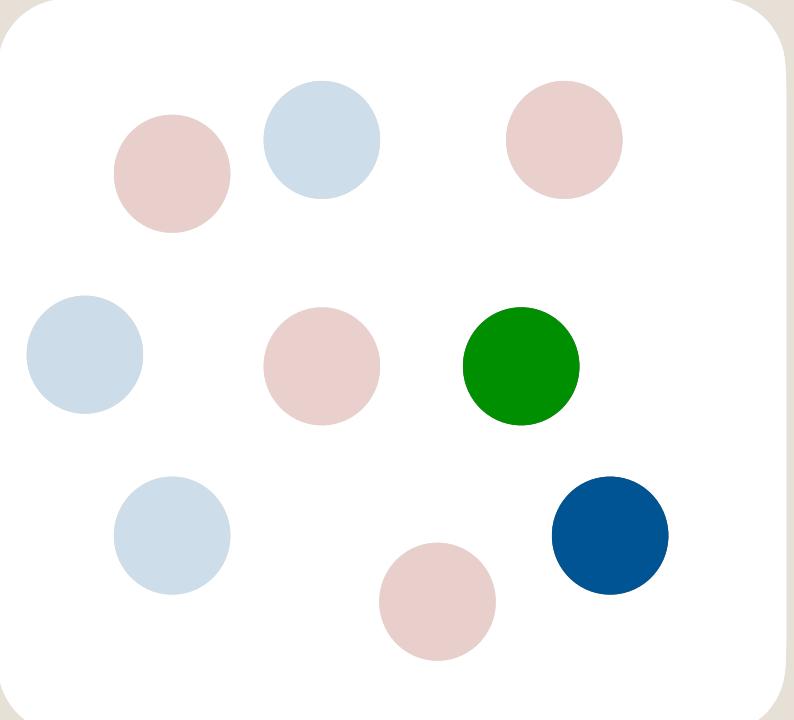
q ...Probability to assign a good reputation after co-player defected

	C	D
C	$b-c$	$-c$
D	b	0

4. Merging direct and indirect reciprocity

Rules of the game

- Consider a well-mixed population with n individuals
- Two individuals are randomly chosen ←
- Each individual can then choose whether to cooperate
- All other individuals observe the interaction; but they may misperceive the player's actions with probability ϵ
- After each interaction, there is another interaction with probability d



Strategies

We consider strategies of the form (y, p, q, λ)

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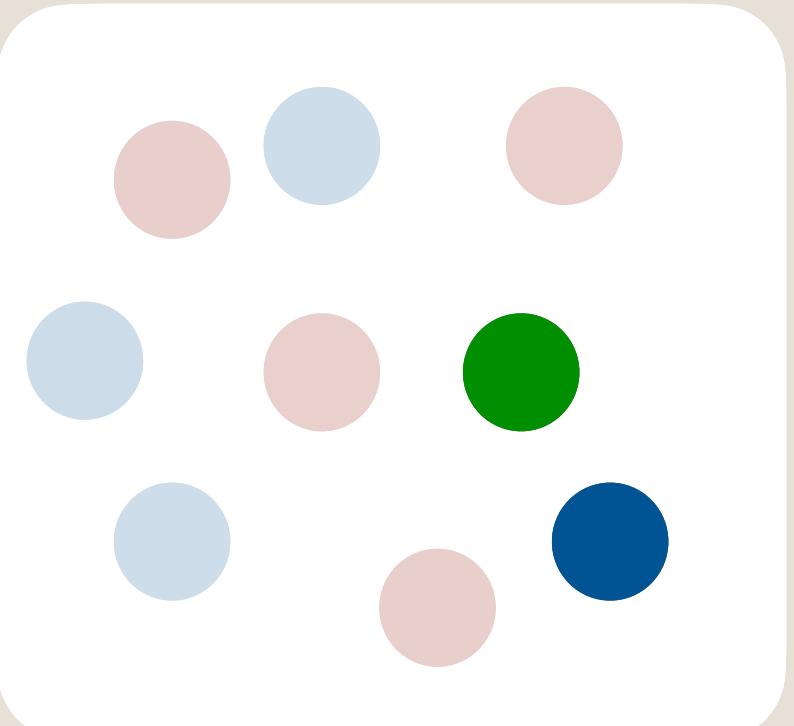
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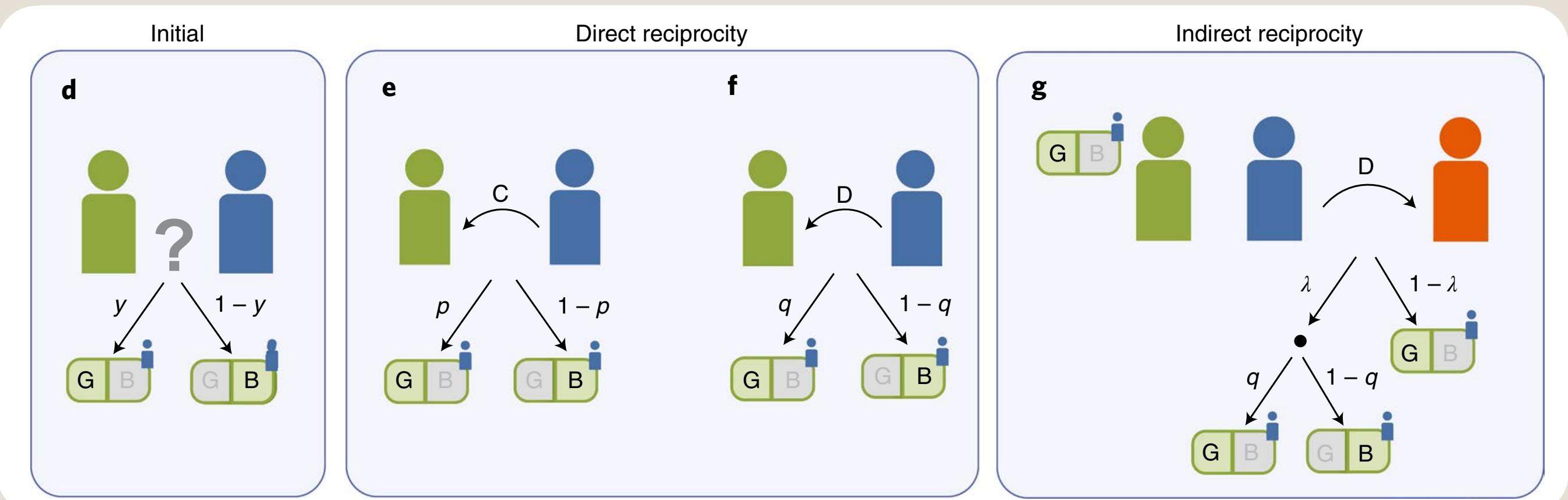
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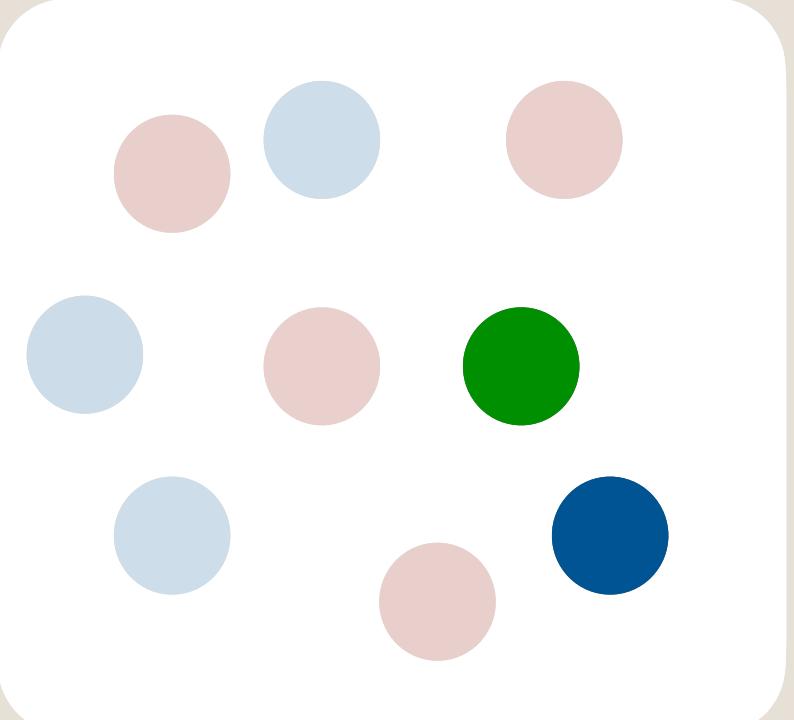
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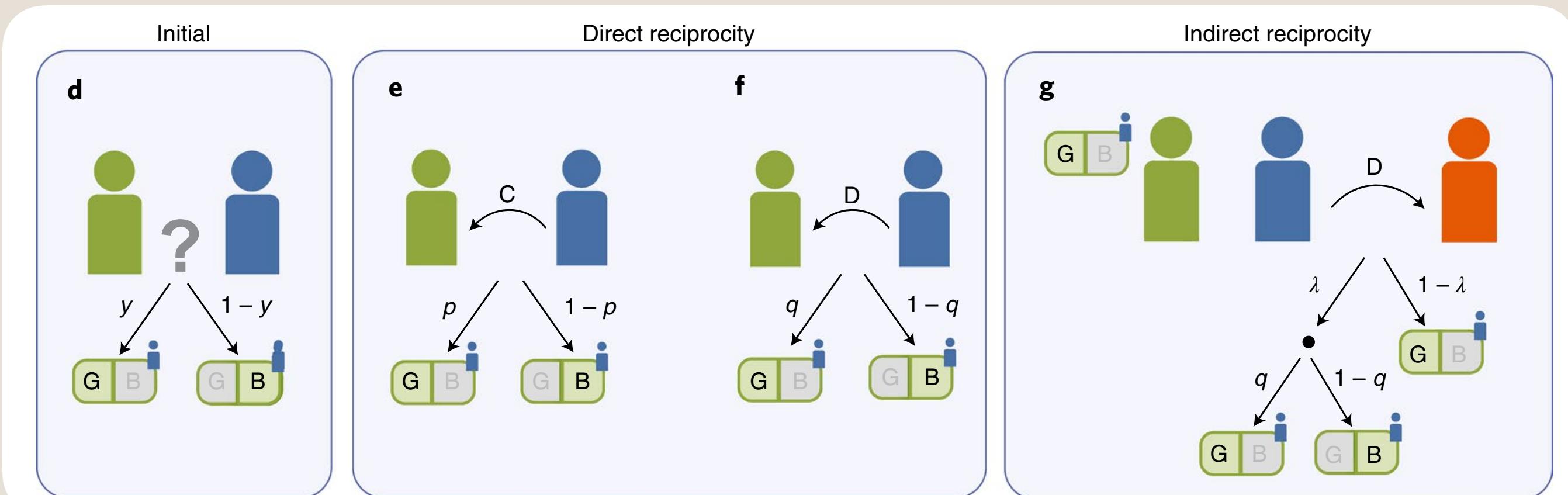
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$$\text{ALLD} = (0, 0, 0, \lambda)$$

$$\text{ALLC} = (1, 1, 1, \lambda)$$

$$\text{TFT} = (1, 1, 0, 0)$$

$$\text{SCO} = (1, 1, 0, 1)$$

4. Merging direct and indirect reciprocity

A unified framework of direct and indirect reciprocity

Laura Schmid¹✉, Krishnendu Chatterjee¹, Christian Hilbe^{1,2,4} and Martin A. Nowak^{1,3,4}

Insights
from this
model

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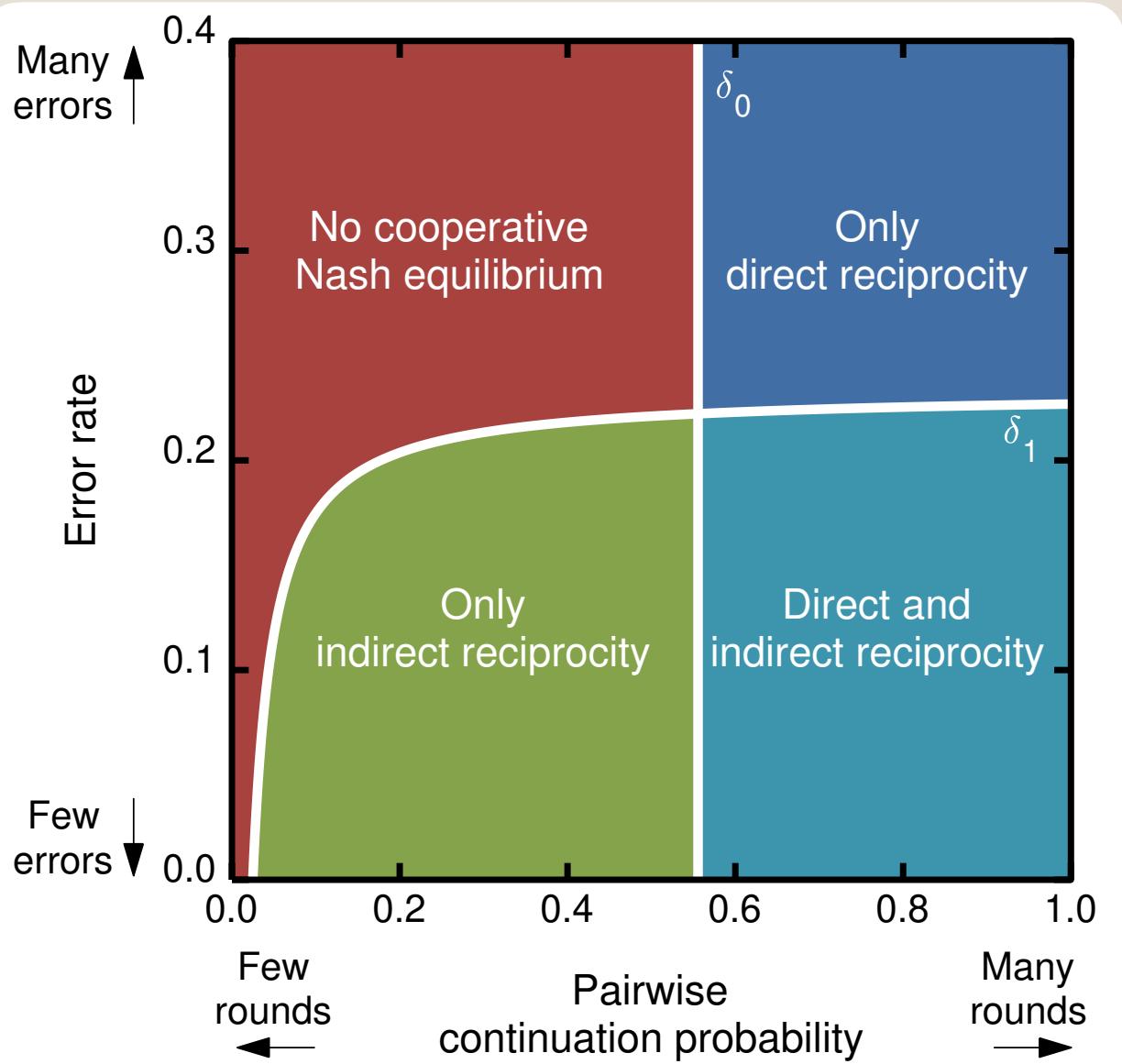
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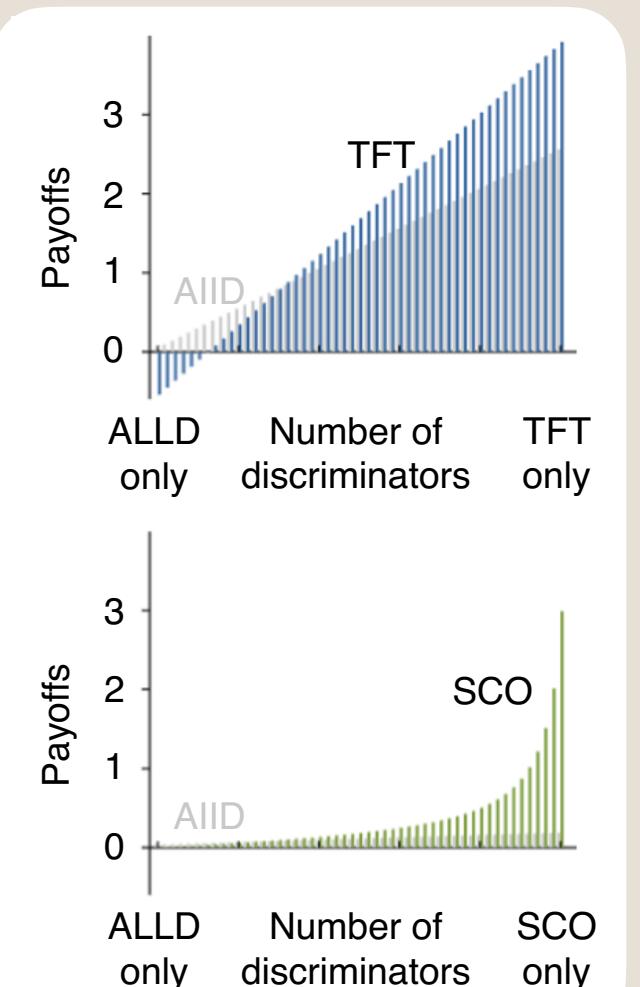
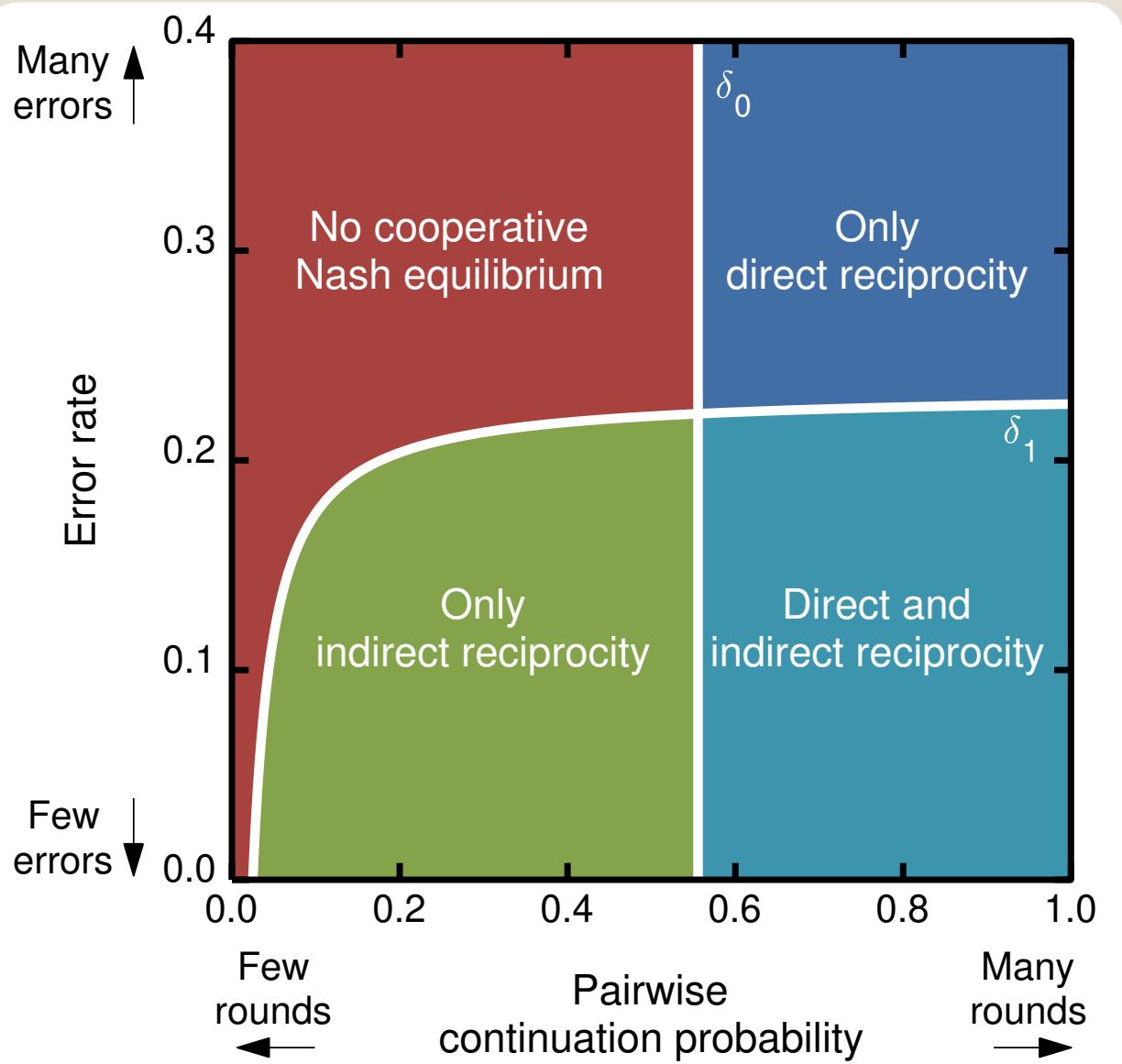
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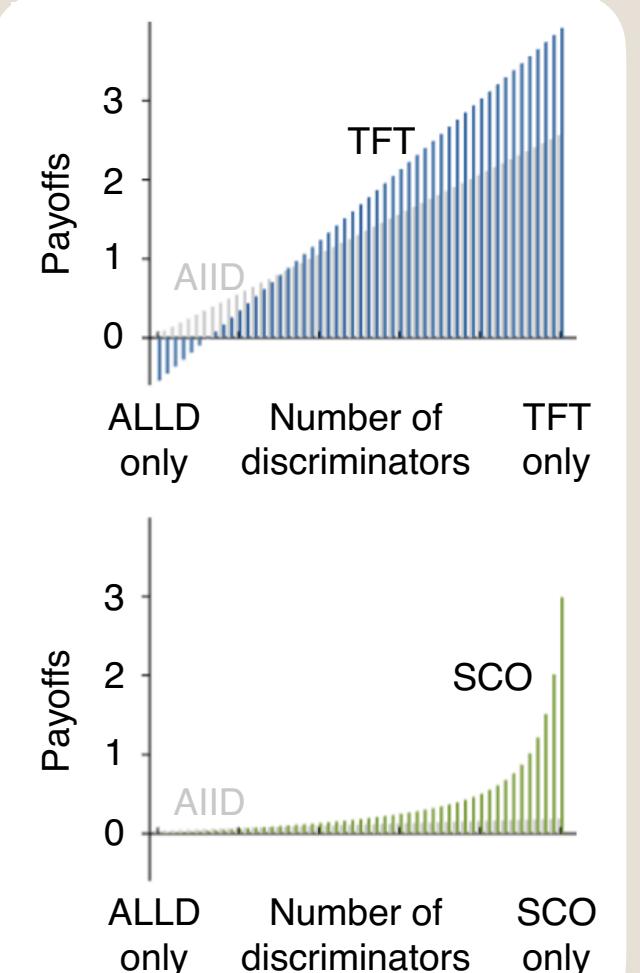
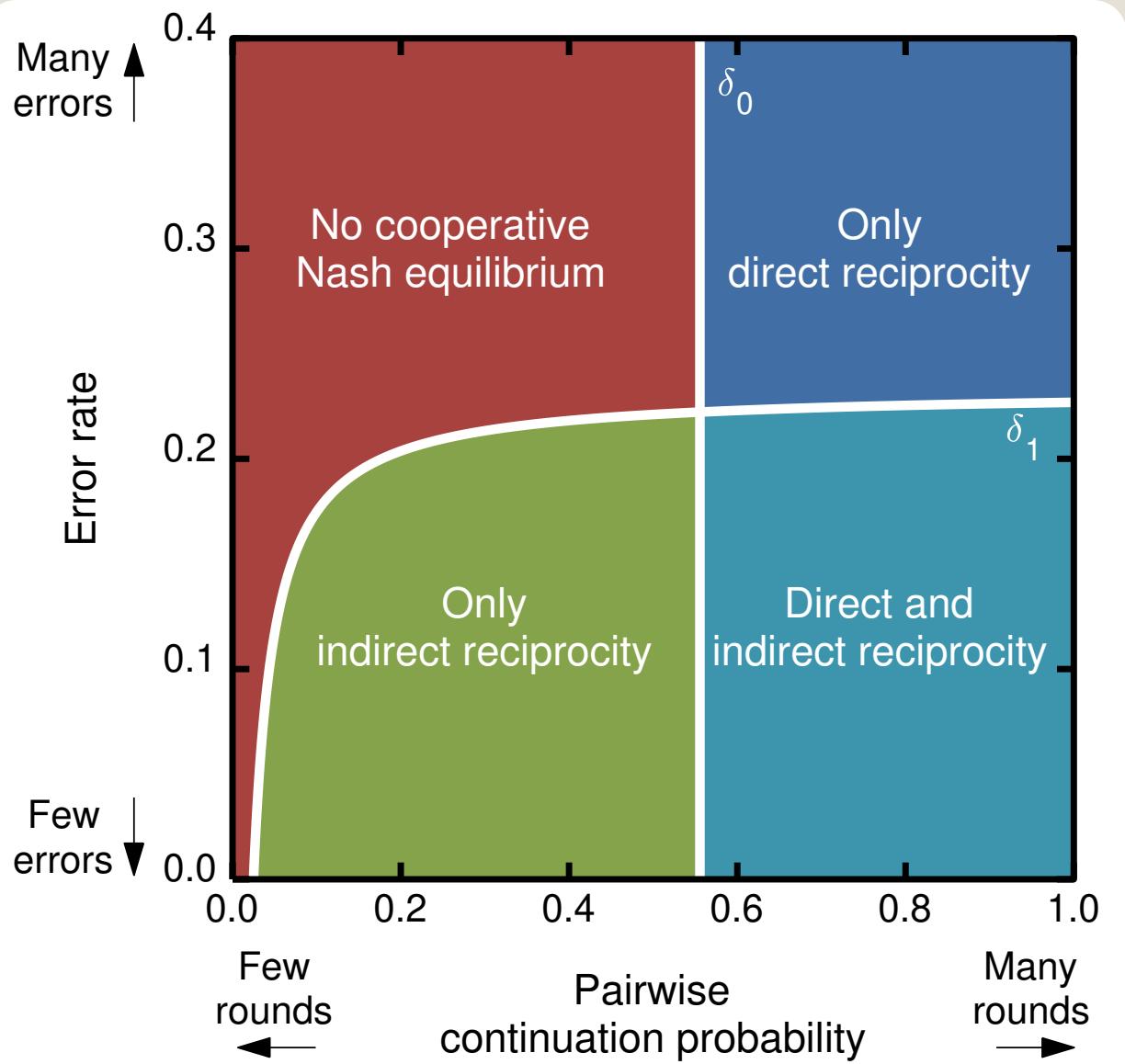
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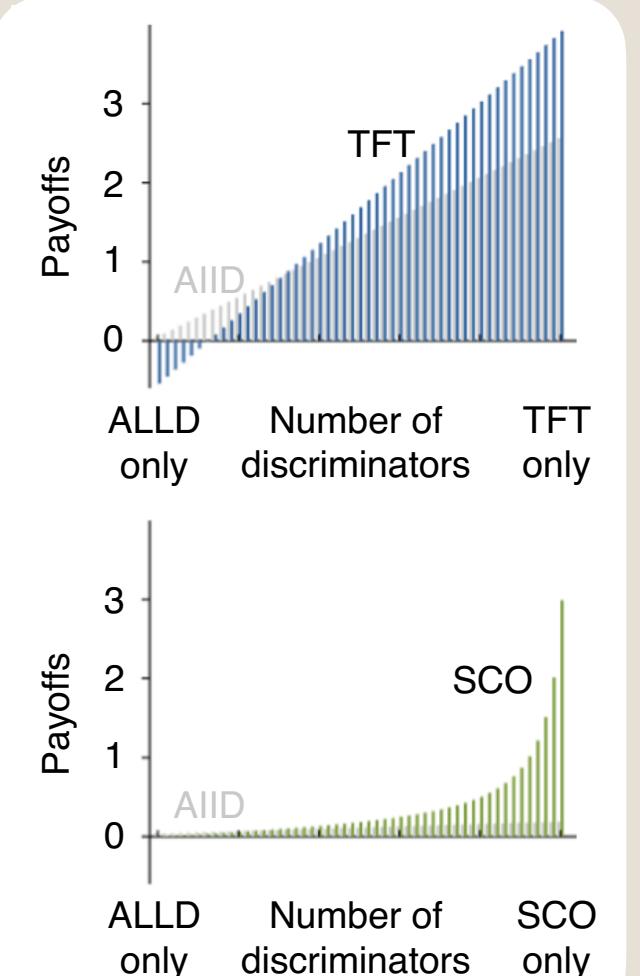
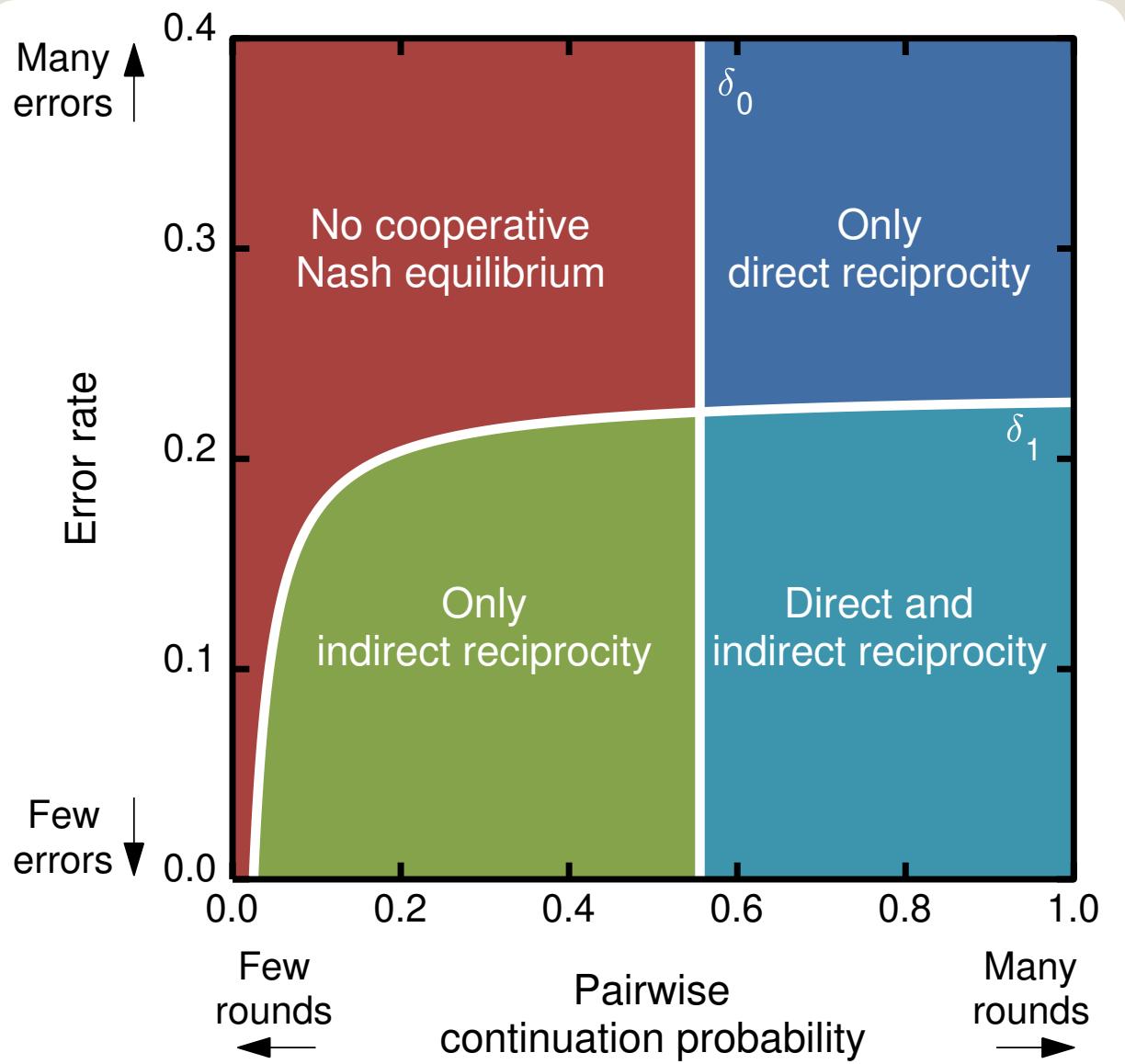
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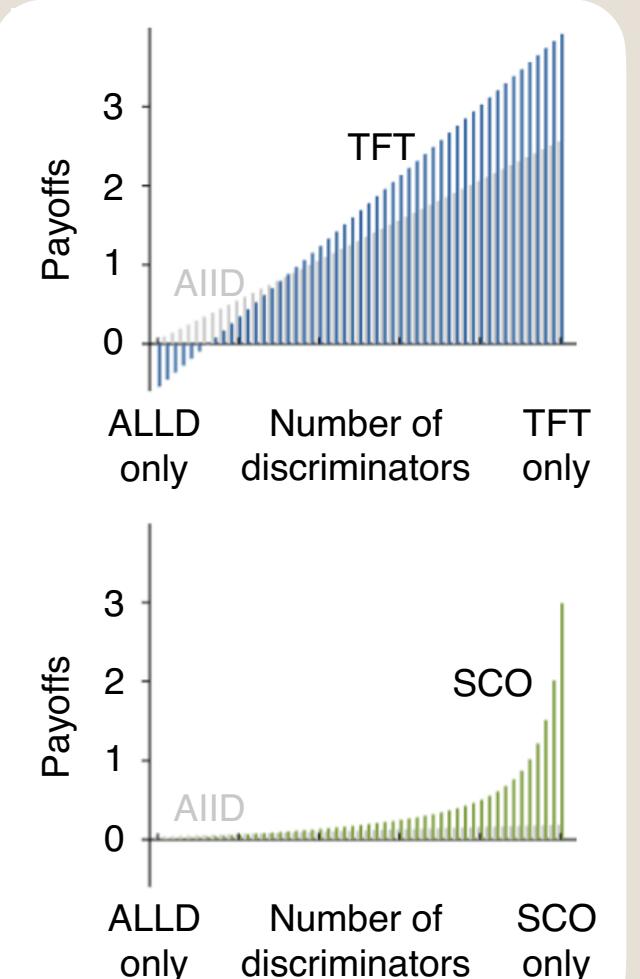
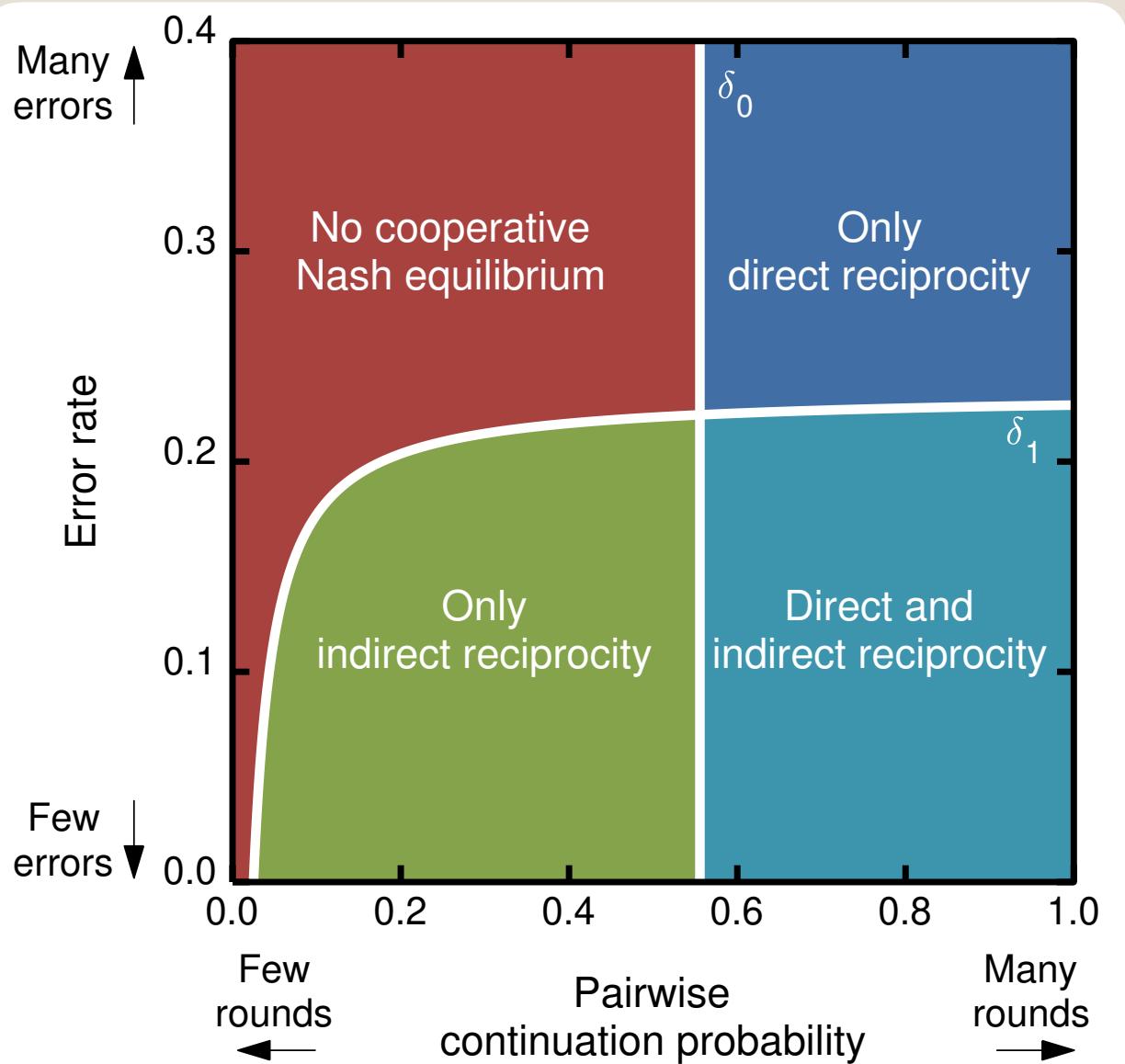
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- How to include alternative versions of reciprocity, like generalised reciprocity?



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A brief history of modeling direct and indirect reciprocity

Summary

1. With this talk, I wanted to make you familiar with the way how modellers think about direct and indirect reciprocity.
2. Good models can help people to be *less surprised* about the world.



Max-Planck-Institut für
Evolutionary Biology, Plön

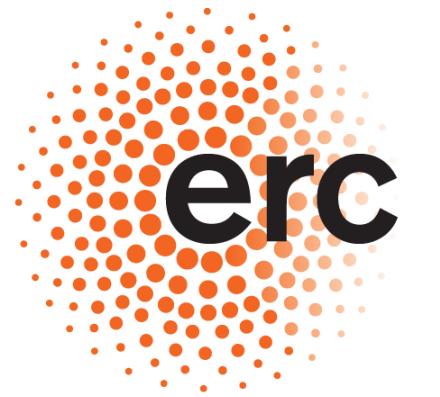


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Funding gratefully acknowledged

Some of my (very cooperative) co-authors



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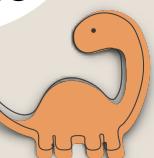
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Where to find more information:
<http://web.evolbio.mpg.de/social-behaviour/>

Thank you for your attention!