The impact of memory on cooperation

Nikoleta E. Glynatsi

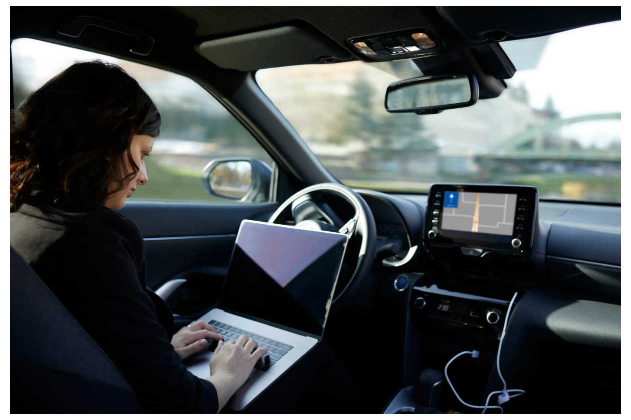
CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD

Axelrod

Software
Sustainability
Institute

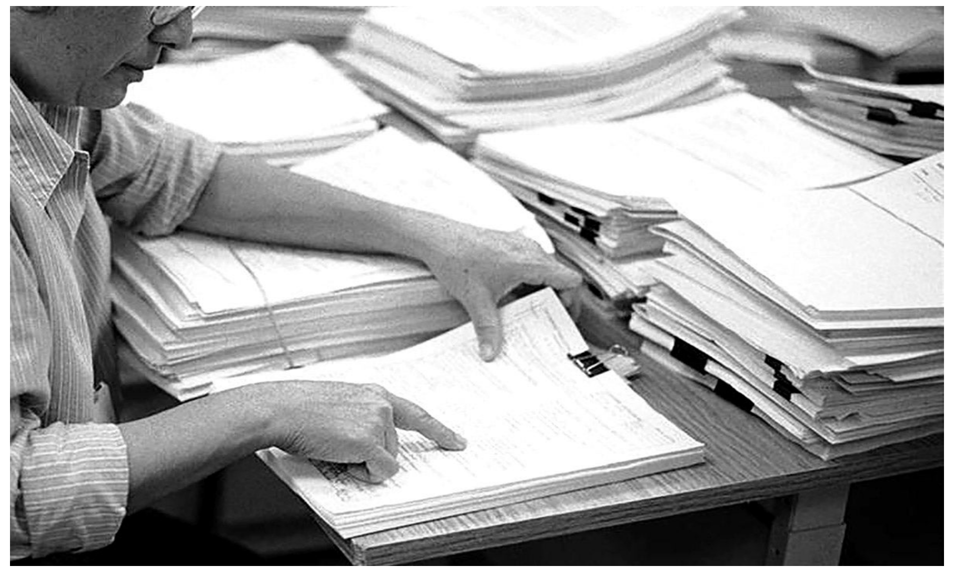
Social Behavior

Understand Cooperation

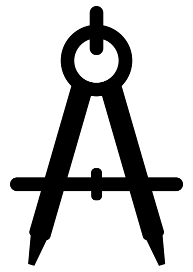



- Advance theoretical models
- Identify factors that can help sustain cooperation
- Train and understand autonomous learning agents

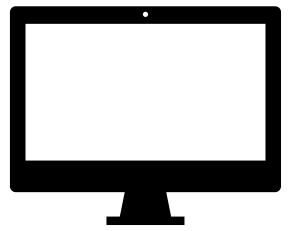
Analysing Scientific Collaboration



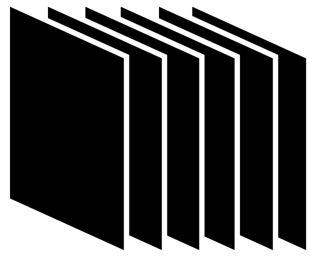
- Access authors' collaborativeness
- Characterize topics and understand their emergence



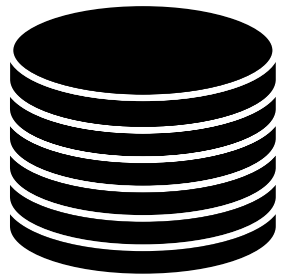
Mathematical Analysis



Agent Based Simulations



Parallel Computing



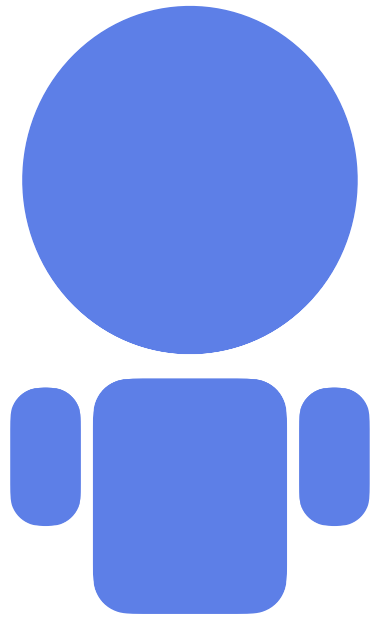
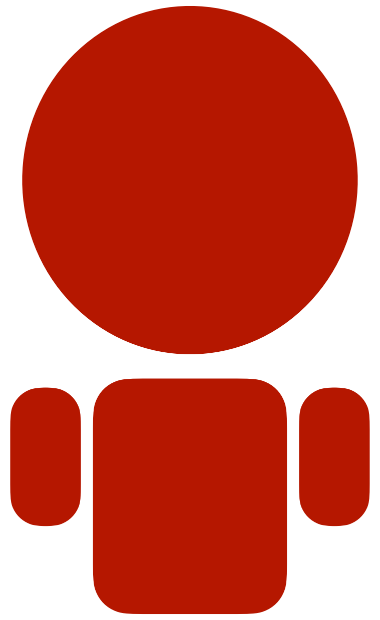
Data Scraping

Data Analysis

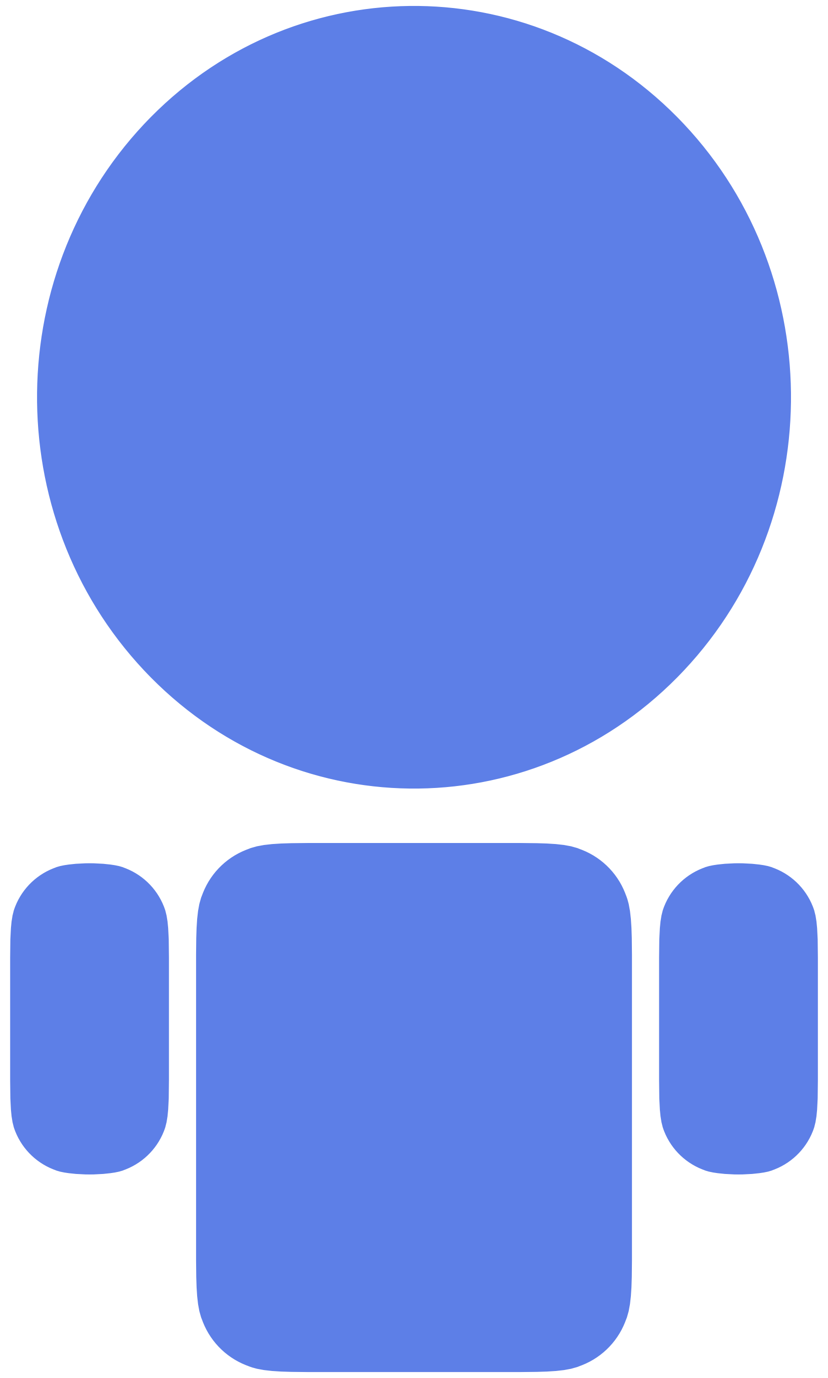
$$
\begin{array}{ccc}
 & C & D \\
\begin{array}{c} C \\ D \end{array} & \multicolumn{2}{c}{\begin{pmatrix} b-c & -c \\ b & \boxed{0} \end{pmatrix}}
\end{array}
$$

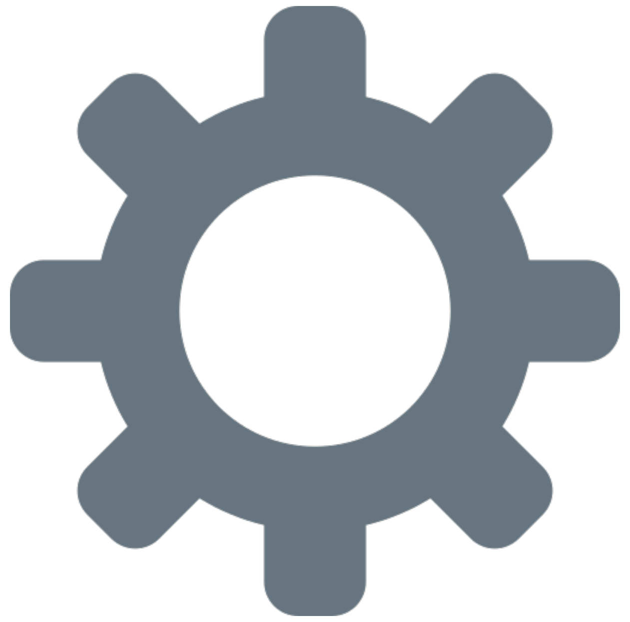
Nash Equilibrium

$$b > c > 0$$

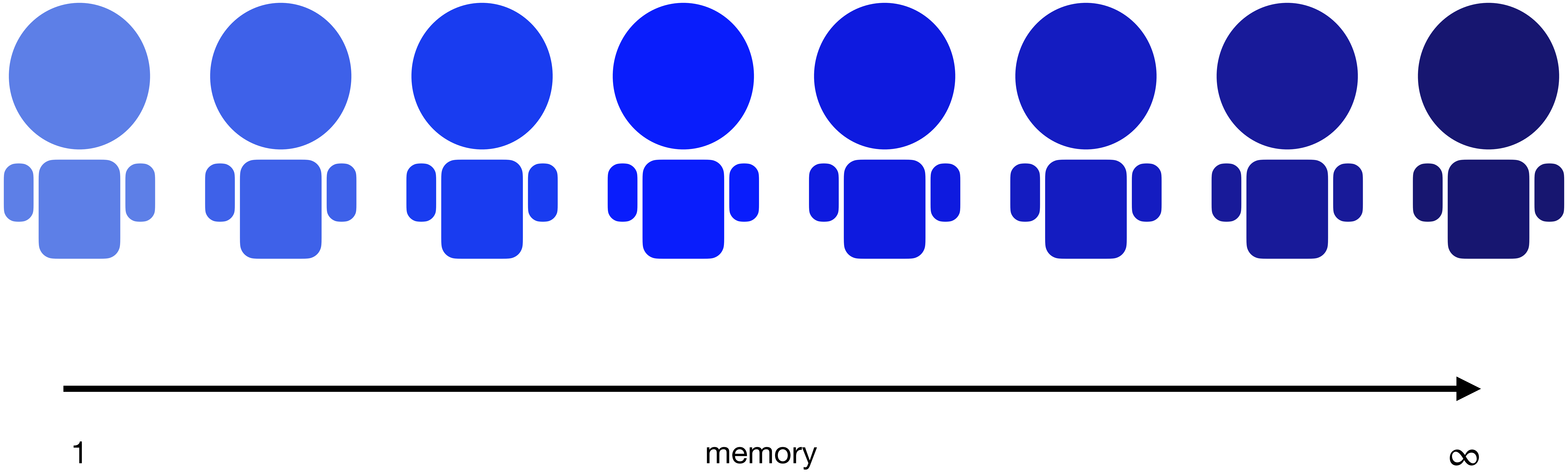
	1	2	3		n
	$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$	$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$	$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$	$\cdots$	$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$
	D	C	C	$\cdots$	C
	D	D	C	$\cdots$	C

Direct reciprocity



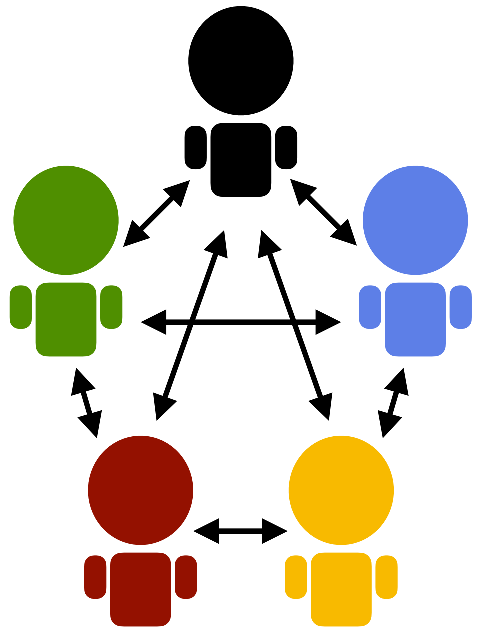


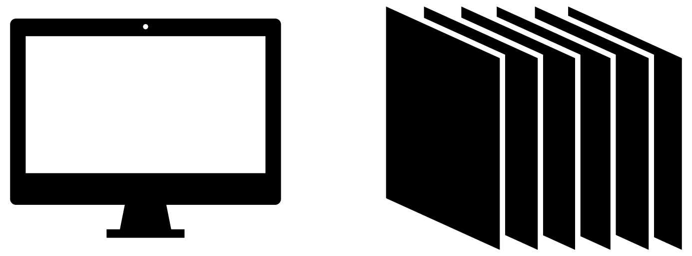
remember &
process information


1
memory
∞

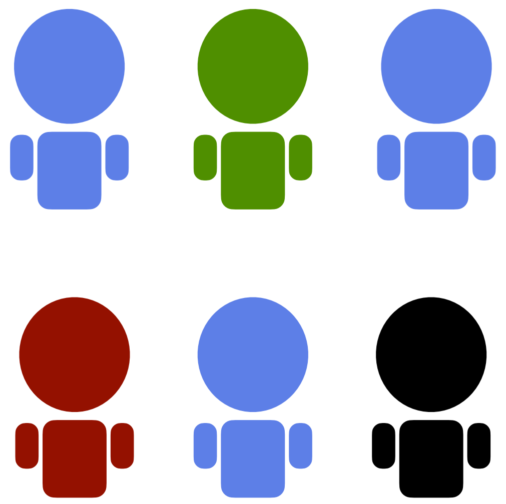
Current Research

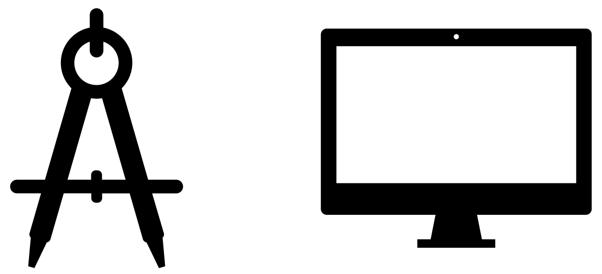
1. Strategies in computer tournaments



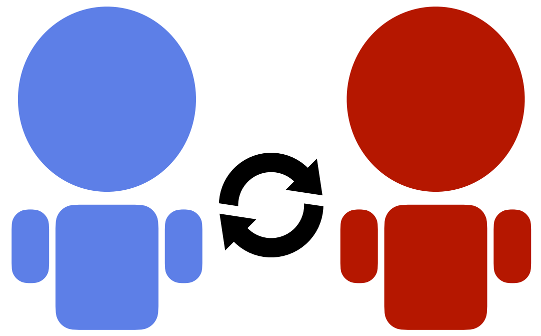


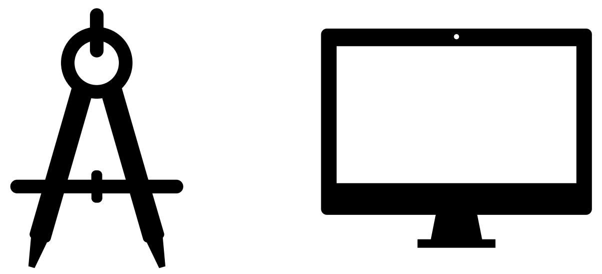
2. Learning in populations



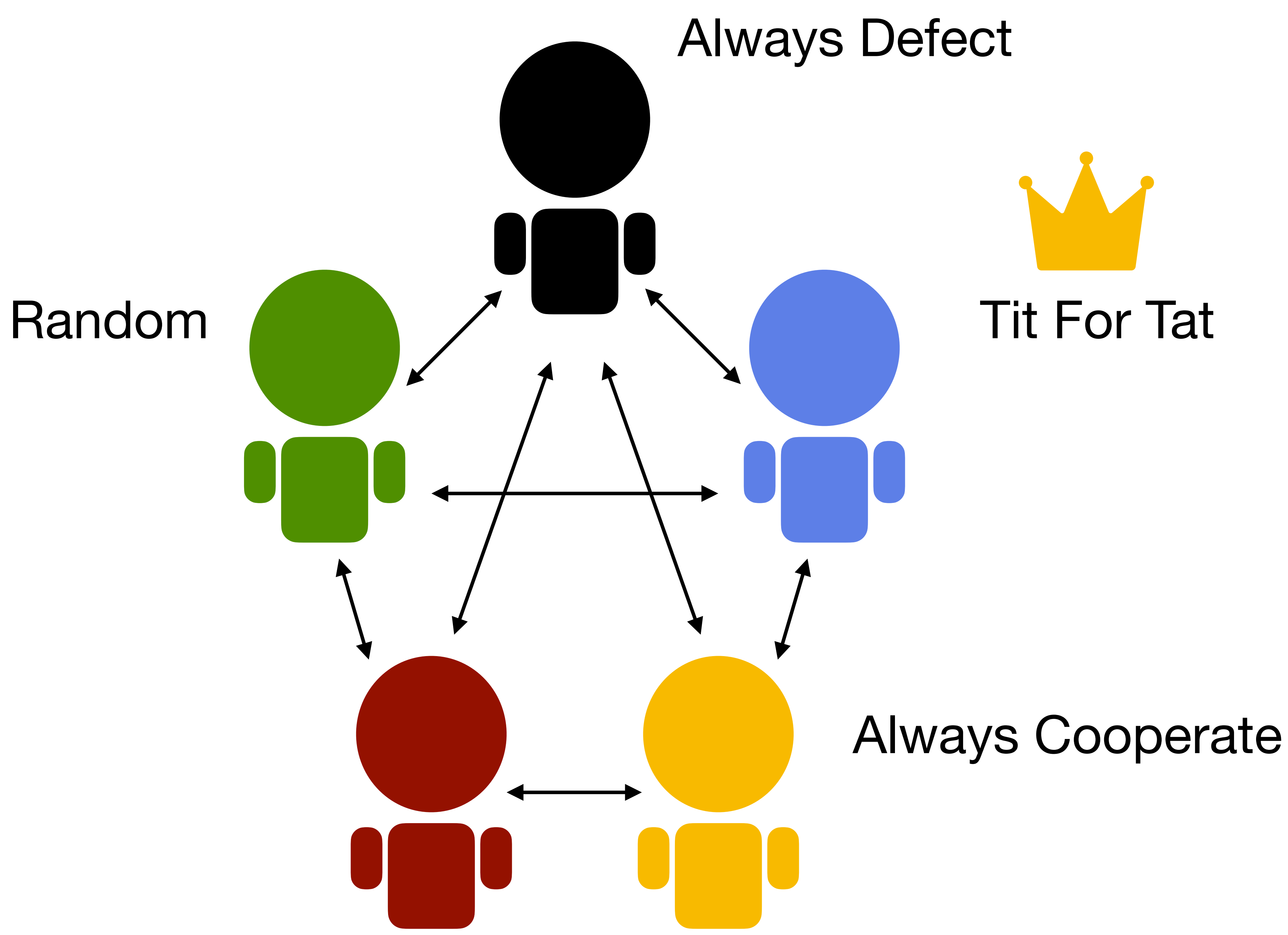


3. Strategies in repeated interactions





1. Strategies in computer tournaments



Most strategies are quite simple rules

↓

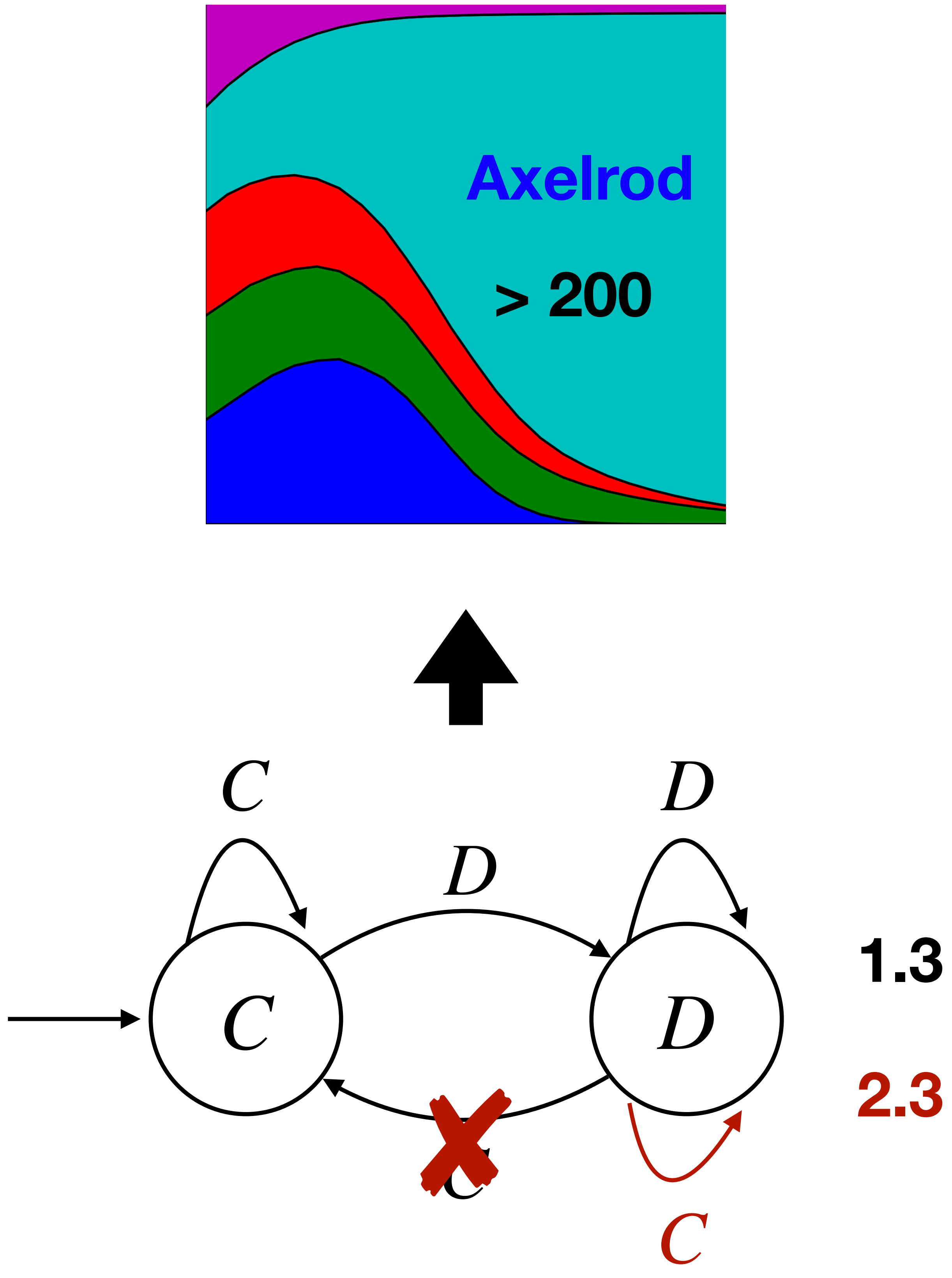
Interpretability

Introduce complex strategies

↓

Understand properties of them

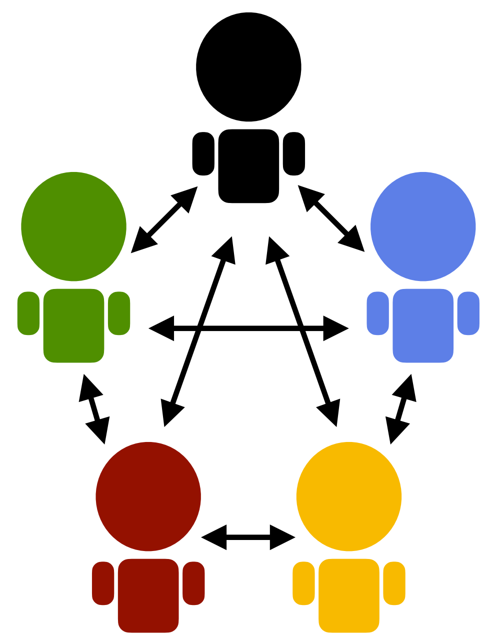
1. Strategies in computer tournaments



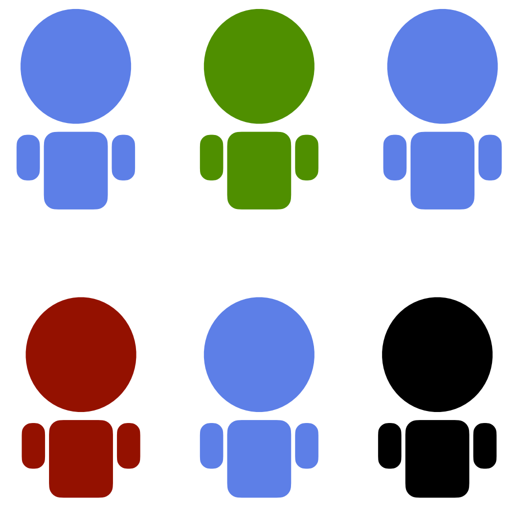
- From the training emerged strategies that were cooperative but also took advantage of simple strategies
- Strategies trained in environments with errors were more adaptable

[1] Reinforcement learning produces dominant strategies for the iterated prisoner’s dilemma. https://doi.org/10.1371/journal.pone.0188046
[2] Evolution reinforces cooperation with the emergence of self-recognition mechanisms. https://doi.org/10.1371/journal.pone.0204981
[3] Properties of Winning Iterated Prisoner's Dilemma Strategies. https://arxiv.org/abs/2001.05911

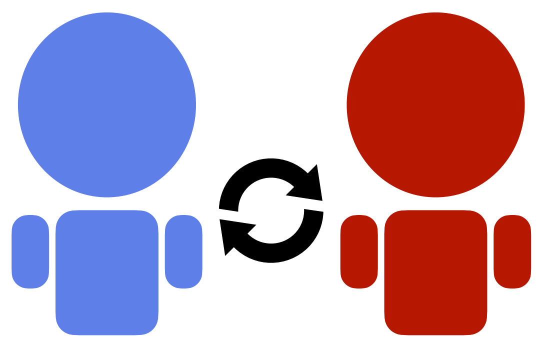
1. Strategies in computer tournaments



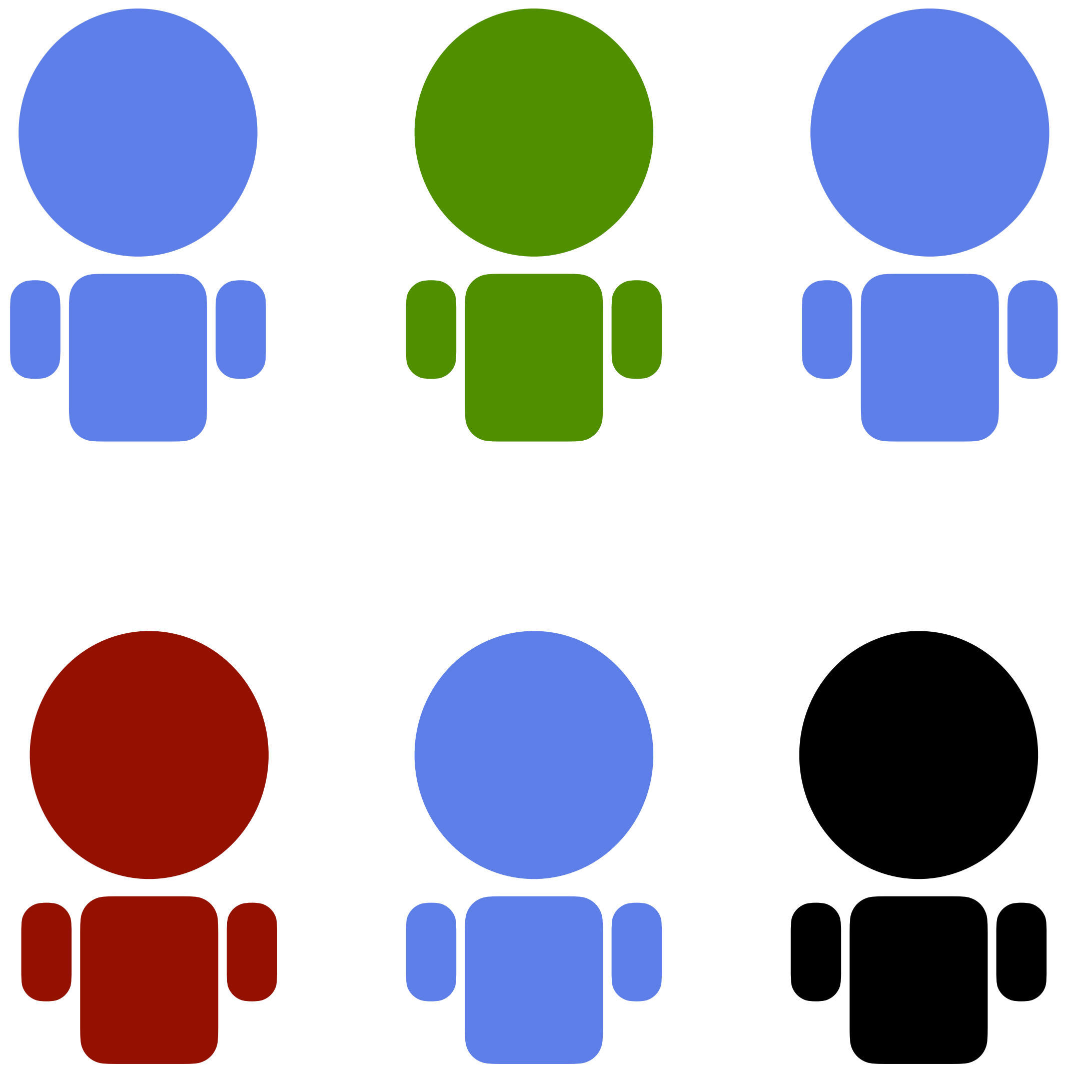
2. Learning in populations

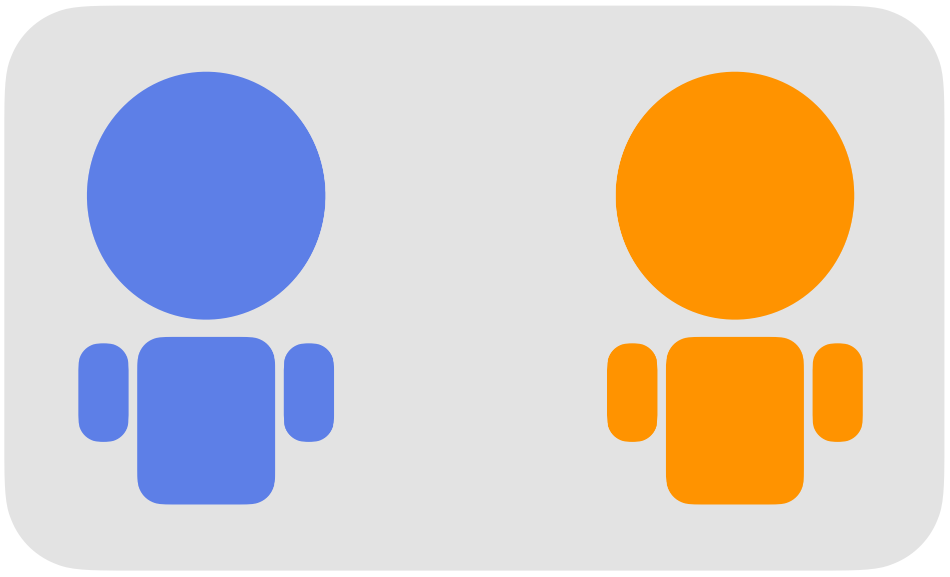


3. Strategies in repeated interactions

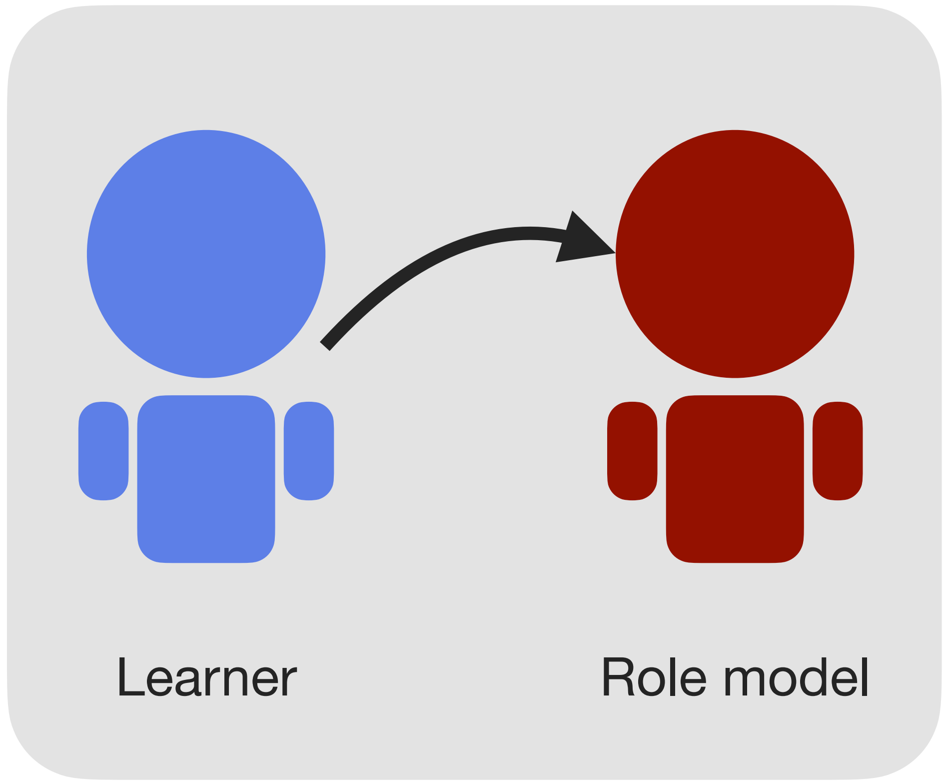


2. Learning in populations



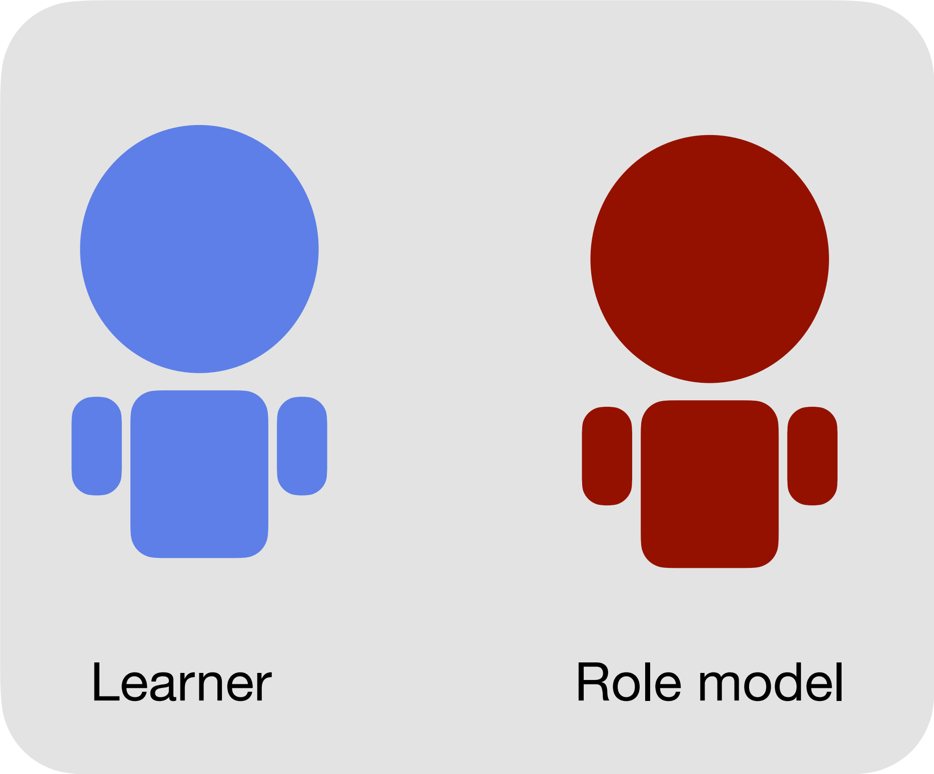


μ: **mutation**

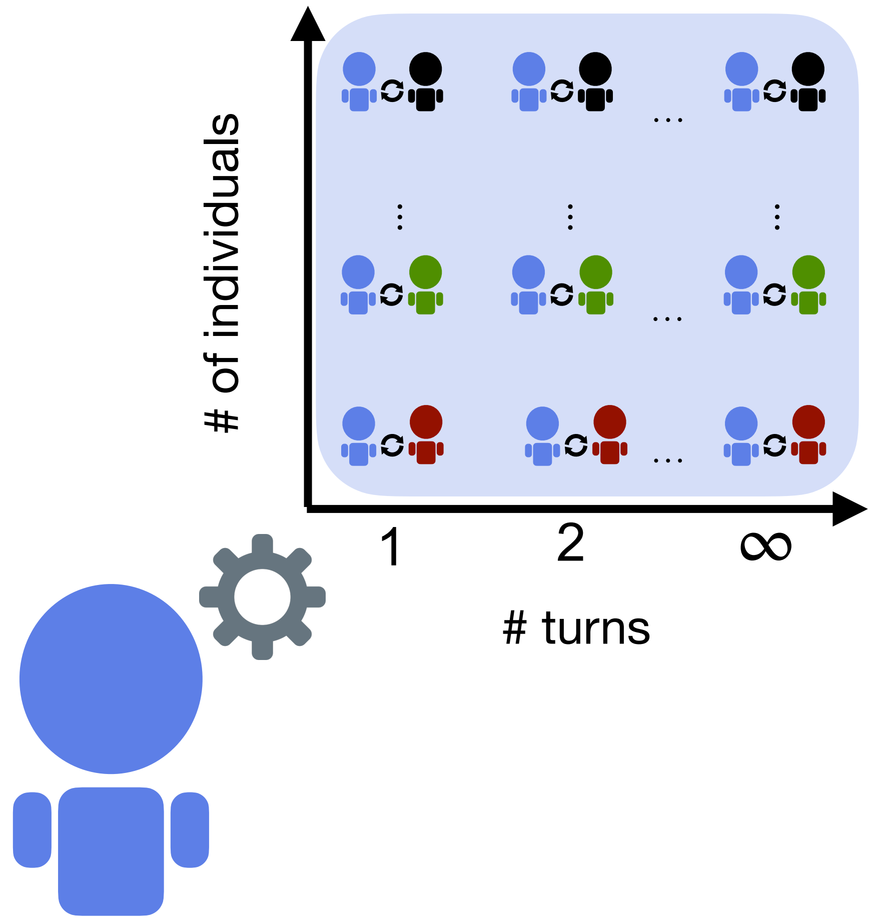


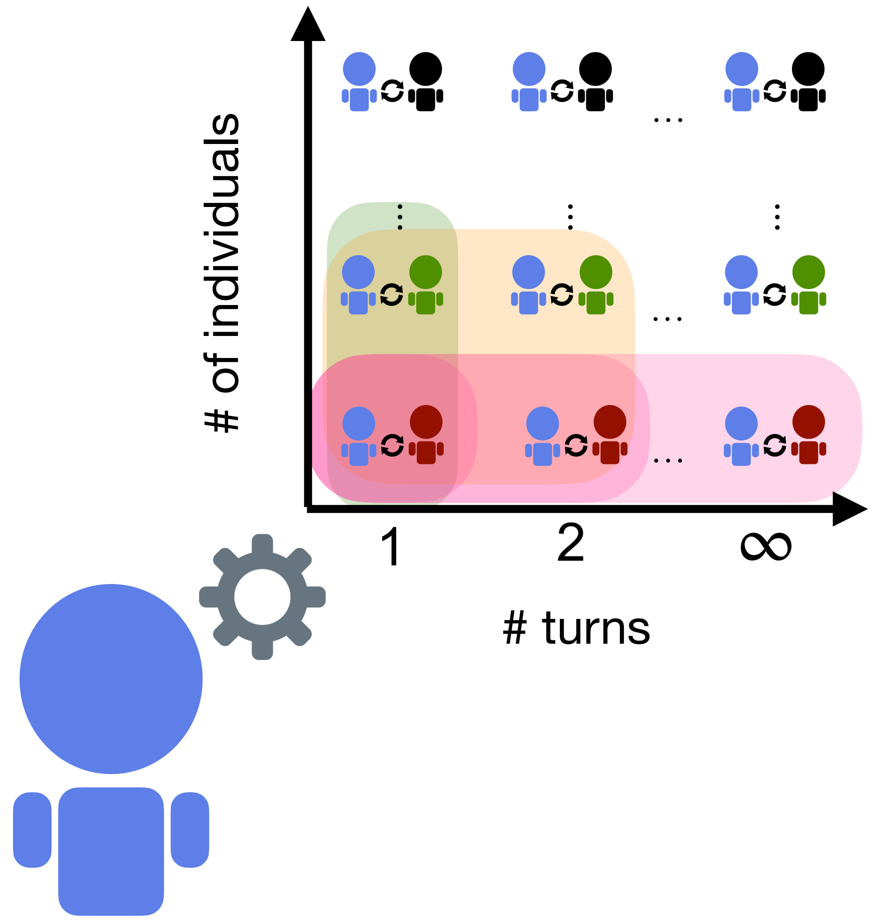
$1 - \mu$: **imitaton**

2. Learning in populations



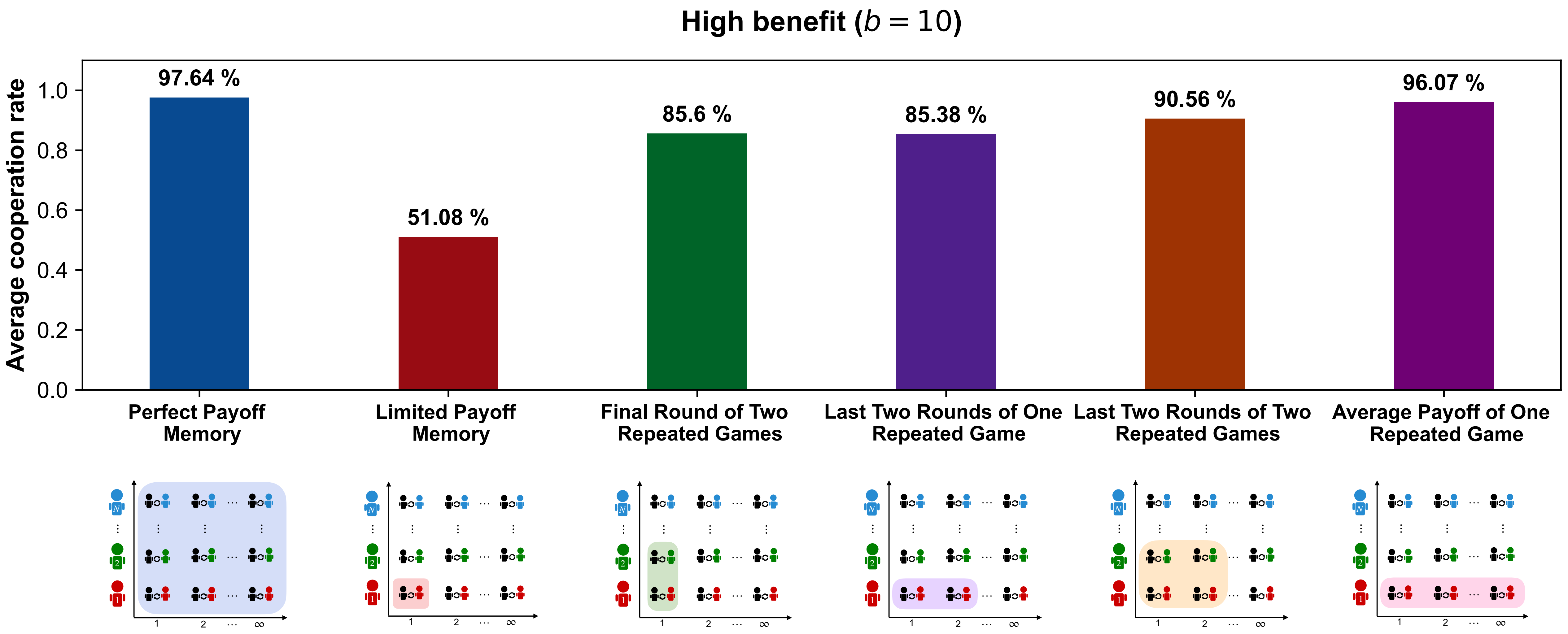
$1 - \mu$: **imitaton**





[4] Evolution of reciprocity with limited payoff memory. https://doi.org/10.1098/rspb.2023.2493

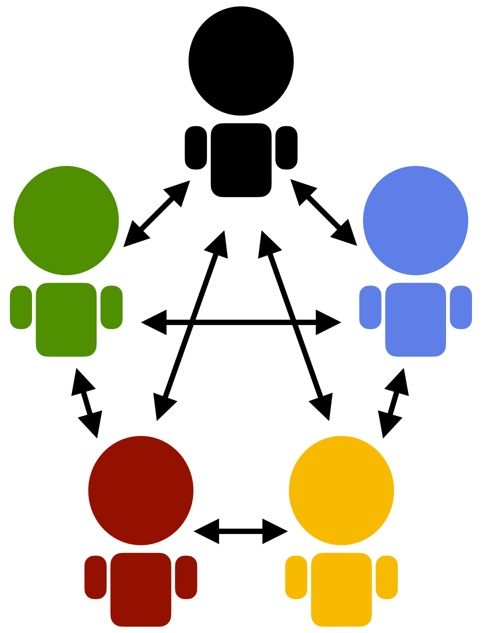
2. Learning in populations



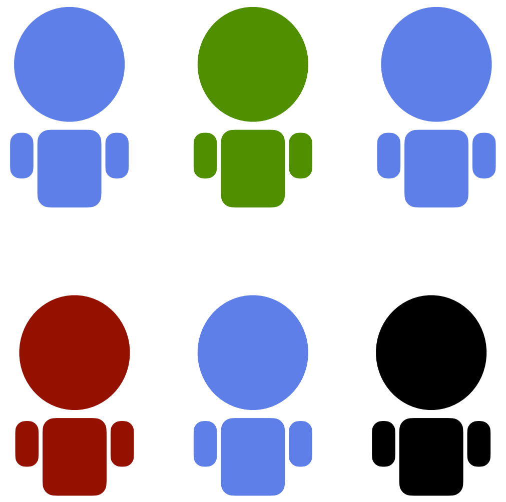
- Cooperation still evolves even with limited memory
- As individuals remember two or three recent interactions, the cooperation rates approach the classical limit

[4] Evolution of reciprocity with limited payoff memory. https://doi.org/10.1098/rspb.2023.2493

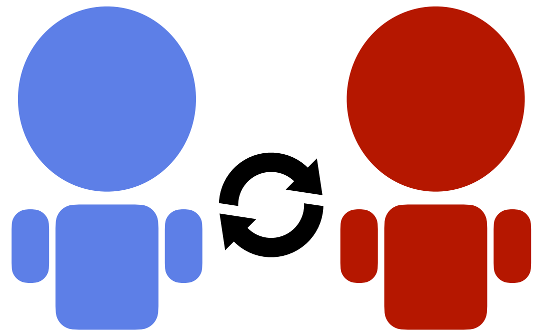
1. Strategies in computer tournaments



2. Learning in populations

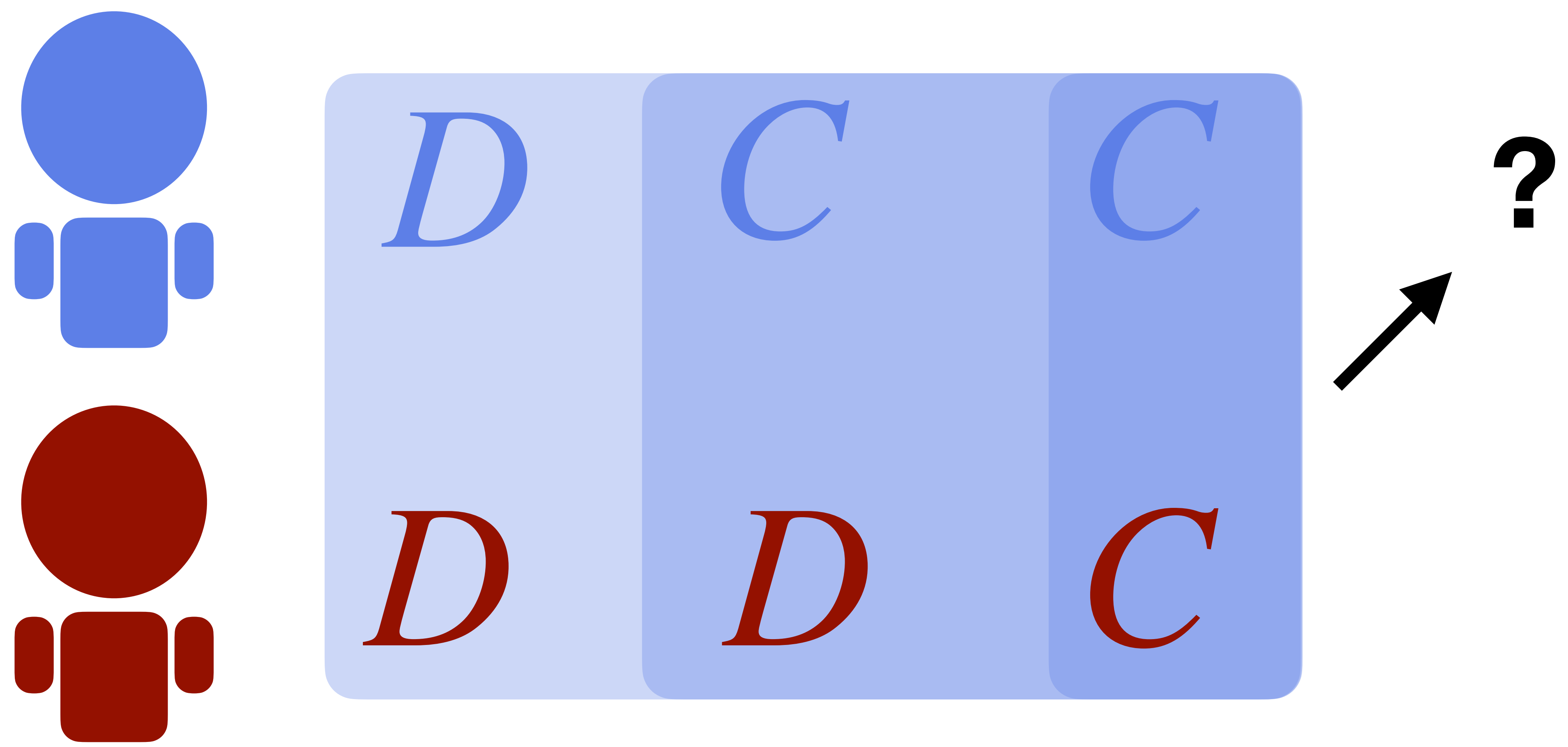


3. Strategies in repeated interactions



3. Strategies in repeated interactions

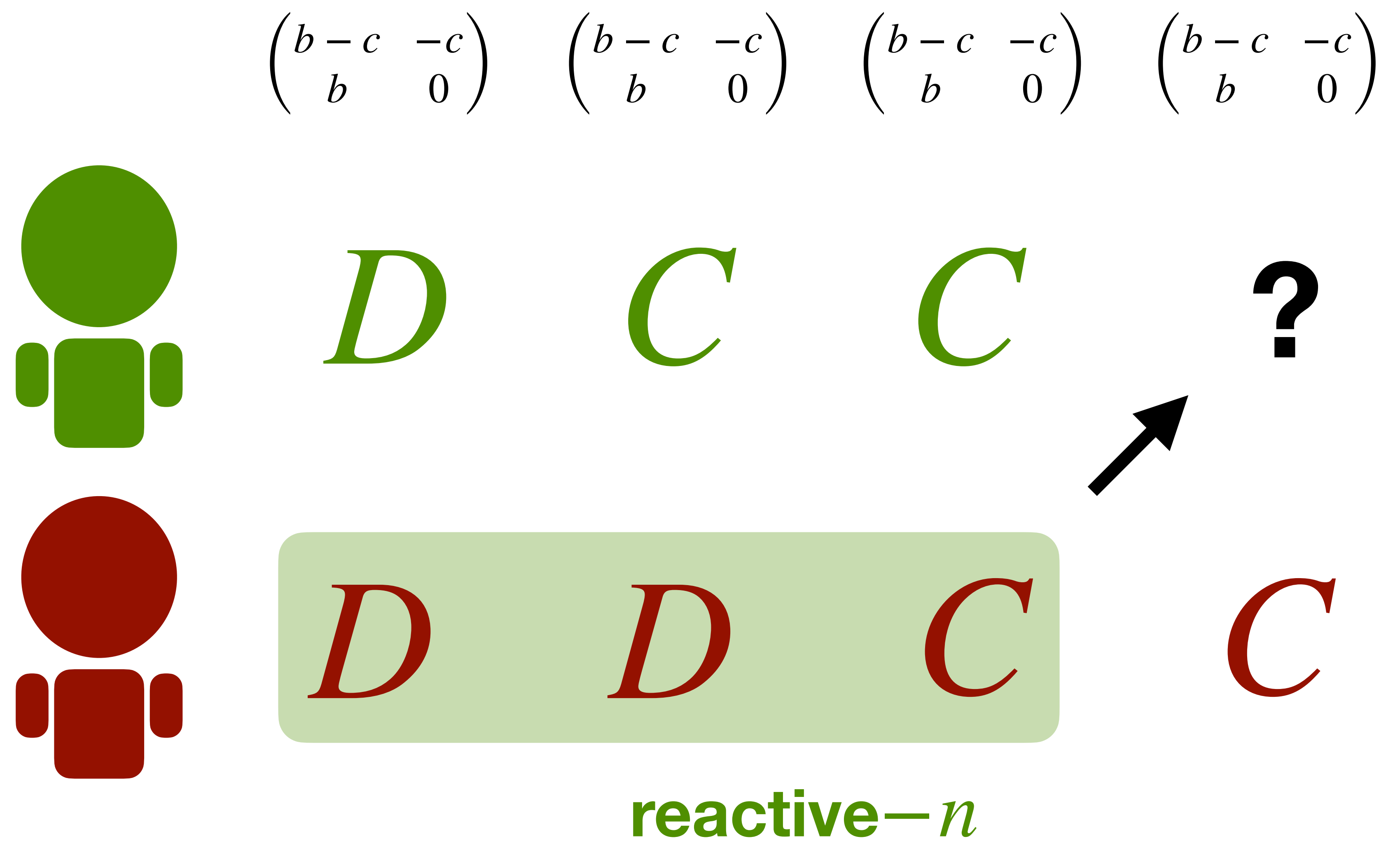
$$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix} \quad \begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix} \quad \begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix} \quad \begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$$



memory$-n$

Nash equilibria among memory-1 strategies

Can we say anything about Nash equilibria in repeated games with higher memory than $n = 1$?



Developed an algorithm that verifies if a given reactive-n strategy is Nash

[5] Conditional cooperation with longer memory. arXiv:2402.02437

3. Strategies in repeated interactions

$n = 2$

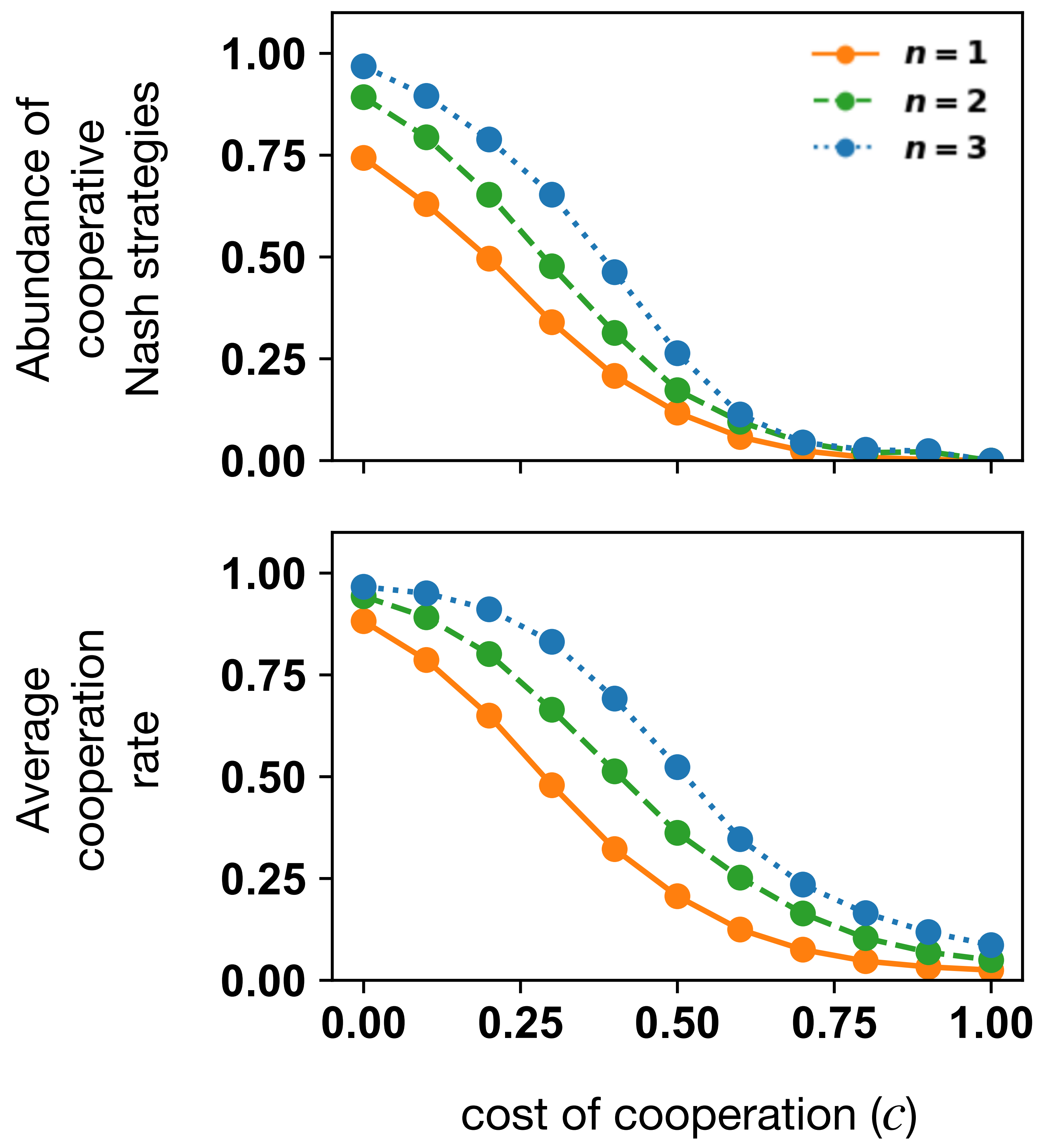
Theorem. A reactive-2 strategy can be defined as the vector $\mathbf{p} = (p_{CC}, p_{CD}, p_{DC}, p_{DD})$, and it is a cooperative Nash strategy if and only if, the strategy entries satisfy the conditions,

$$p_{CC} = 1, \qquad \frac{p_{CD} + p_{DC}}{2} < 1 - \frac{1}{2} \cdot \frac{c}{b} \qquad \textit{and} \qquad p_{DD} \leq 1 - \frac{c}{b}.$$

$n = 3$

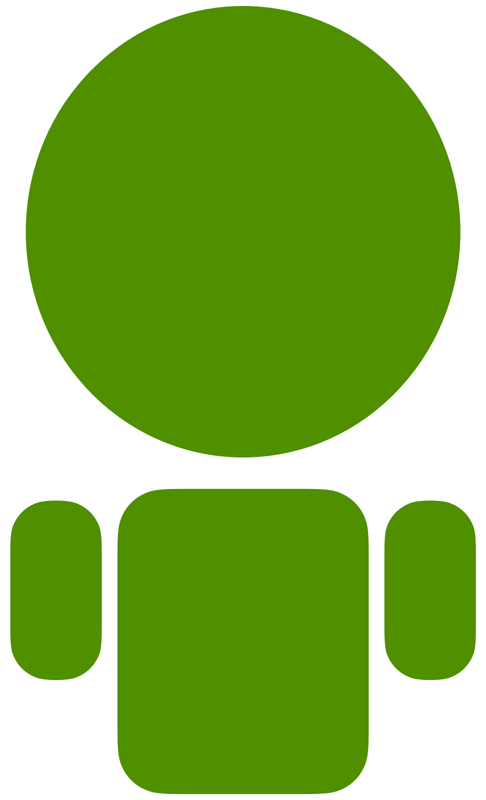
Theorem. A reactive-3 strategy is defined by the vector $\mathbf{p} = (p_{CCC}, p_{CCD}, p_{CDC}, p_{CDD}, p_{DCC}, p_{DCD}, p_{DDC}, p_{DDD})$, and it is a cooperative Nash strategy, if and only if the strategy entries satisfy the conditions,

$$p_{CCC} = 1$$
$$\frac{p_{CDC} + p_{DCD}}{2} \leq 1 - \frac{1}{2} \cdot \frac{c}{b}$$
$$\frac{p_{CCD} + p_{CDC} + p_{DCC}}{3} \leq 1 - \frac{1}{3} \cdot \frac{c}{b}$$
$$\frac{p_{CDD} + p_{DCD} + p_{DDC}}{3} \leq 1 - \frac{2}{3} \cdot \frac{c}{b}$$
$$\frac{p_{CCD} + p_{CDD} + p_{DCC} + p_{DDC}}{4} \leq 1 - \frac{1}{2} \cdot \frac{c}{b}$$
$$p_{DDD} \leq 1 - \frac{c}{b}$$



[5] Conditional cooperation with longer memory. arXiv:2402.02437

3. Strategies in repeated interactions



reactive$-n$

- Develop an algorithm to verify whether a given reactive-n strategy is Nash
- Characterize cooperative & defective Nash strategies for $n = 2$ and $n = 3$
- Show that longer memory increases the average cooperation rate

[5] Conditional cooperation with longer memory. arXiv:2402.02437

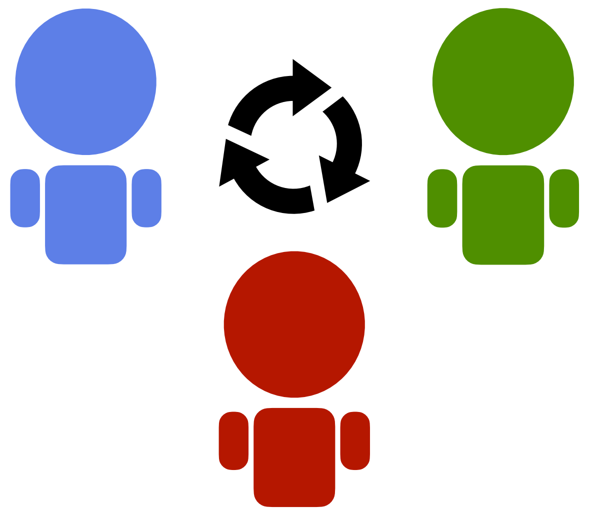
Current models on direct reciprocity make strong assumptions. Can we explore their impact?

What kinds of cognitive capacities are required for reciprocal altruism?

[1] Reinforcement learning produces dominant strategies for the iterated prisoner's dilemma. https://doi.org/10.1371/journal.pone.0188046
[2] Evolution reinforces cooperation with the emergence of self-recognition mechanisms. https://doi.org/10.1371/journal.pone.0204981
[3] Properties of Winning Iterated Prisoner's Dilemma Strategies. https://arxiv.org/abs/2001.05911
[4] Evolution of reciprocity with limited payoff memory. arXiv:2311.02365
[5] Conditional cooperation with longer memory. arXiv:2402.02437

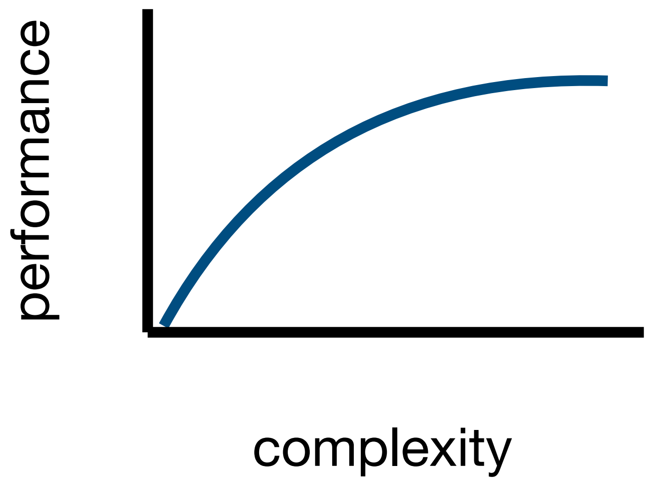
Future Research

1. Multi-player games / Multi agent learning

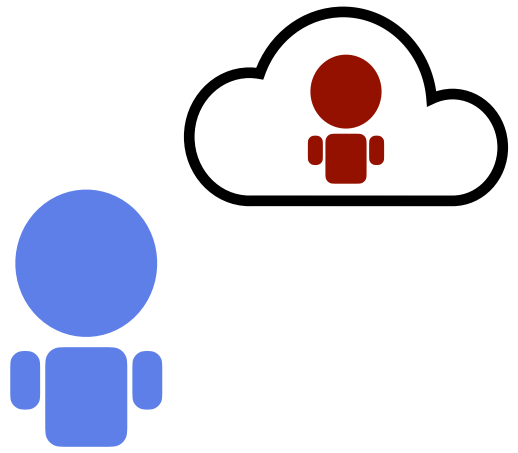


2. The benefits of increasing complexity

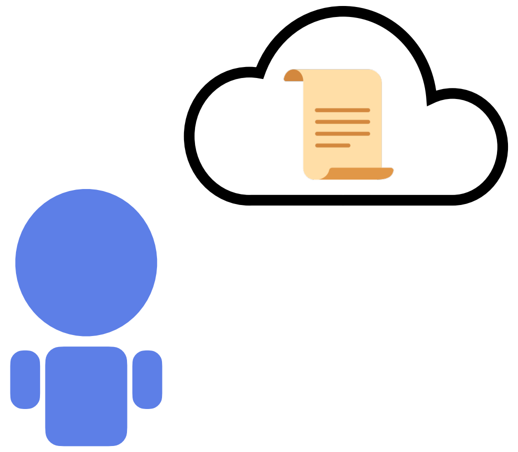
    - Memory
    - Finite state automata states



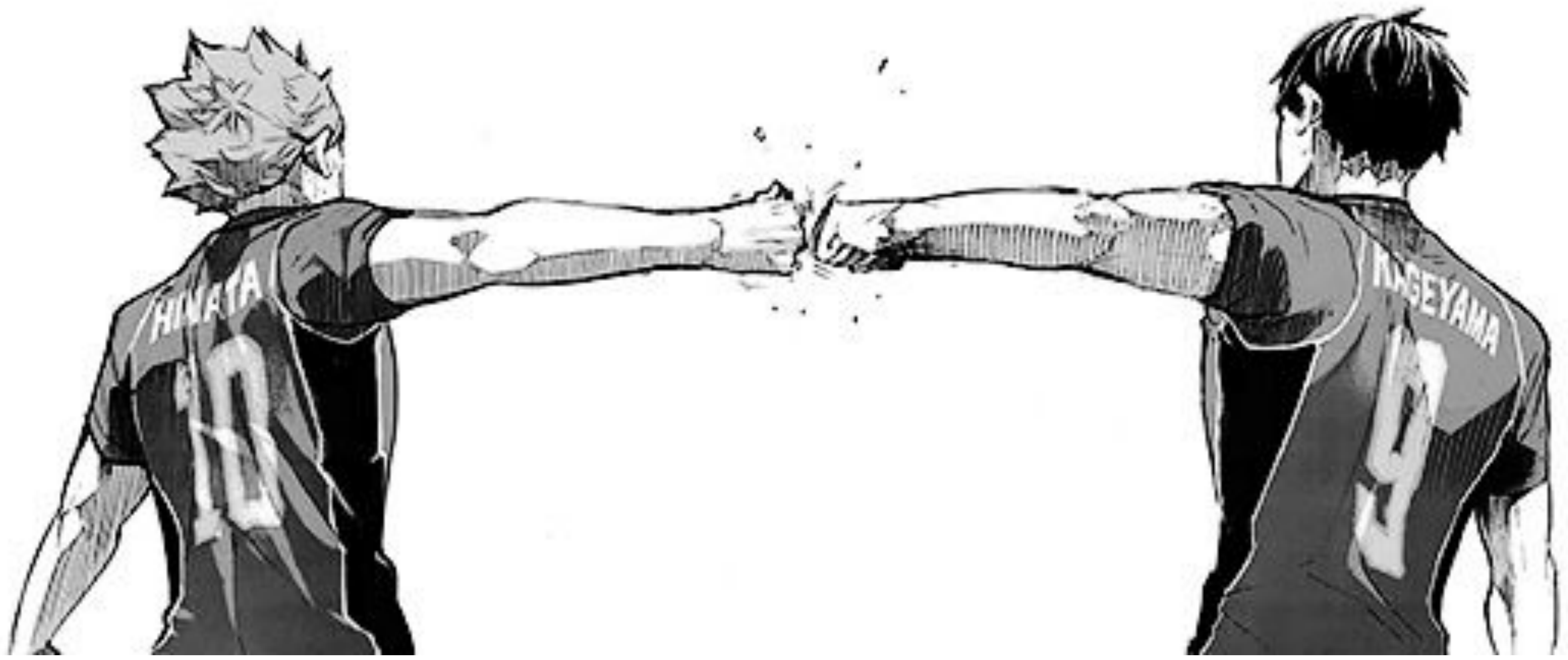
3. Strategy Inference



4. Explore how authors use citations



Future Research



Theoretical frameworks | Computational methodologies

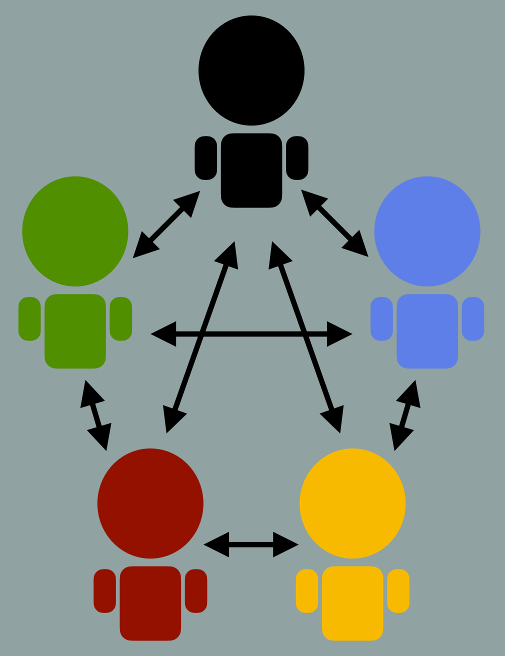
Future Research

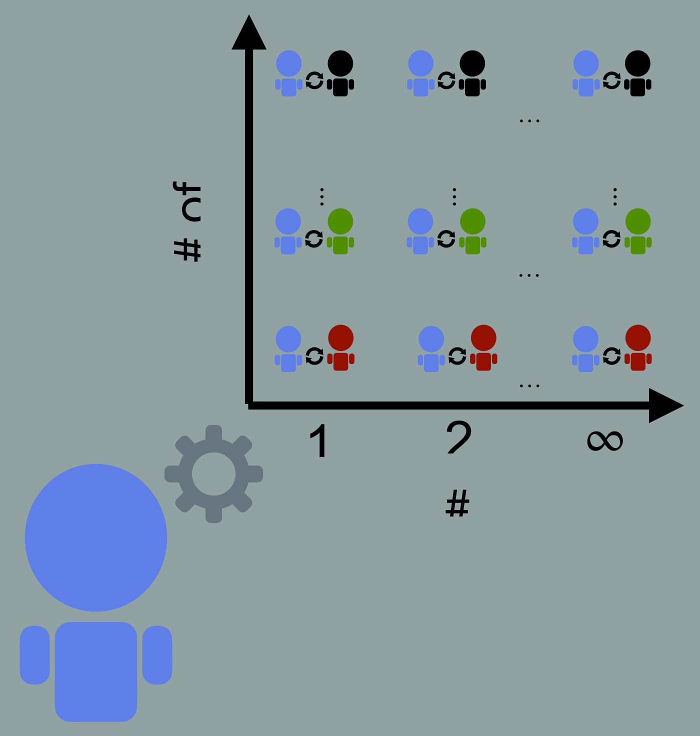
Why R-CCS?

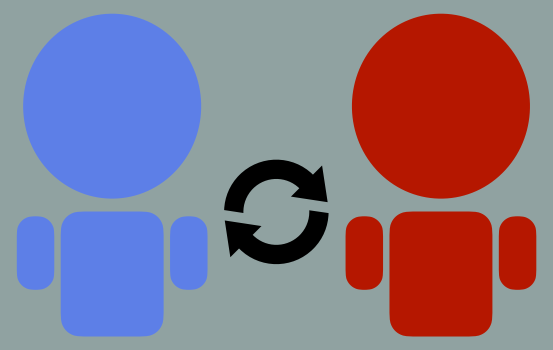
RIKEN R-CCS
Software Center

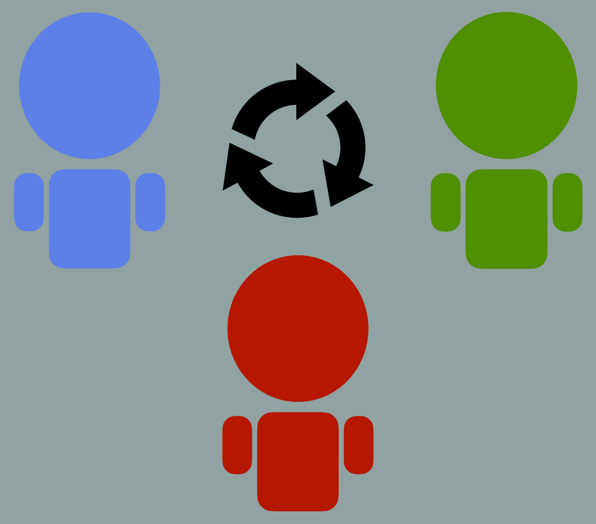
OACIS

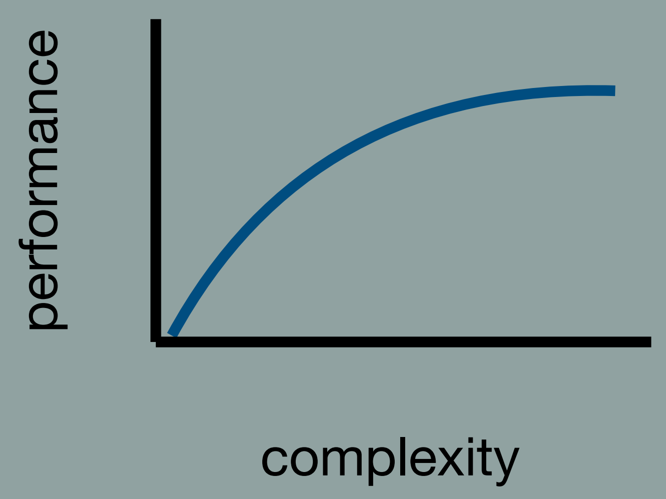
Yohsuke Murase, RIKEN Center for Computational Science
Hisashi Ohtsuki, The Graduate University for Advanced Studies
Michihiro Kandori, The University of Tokyo
Akihiko Matsui, University of Tokyo
Masahiko Ueda, Yamaguchi University
Isamu Okada, Soka University
Nobuhiro Mifune, Kochi University of Technology

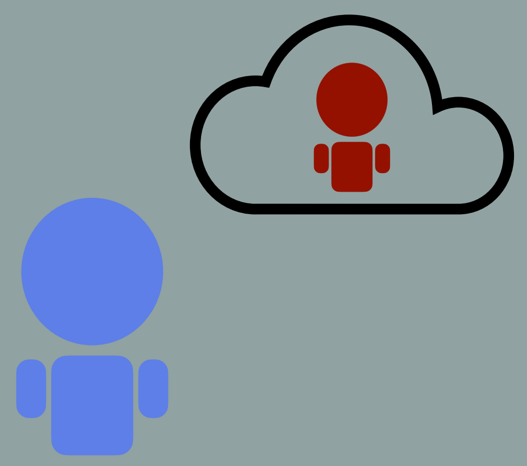












Thank you for your attention!

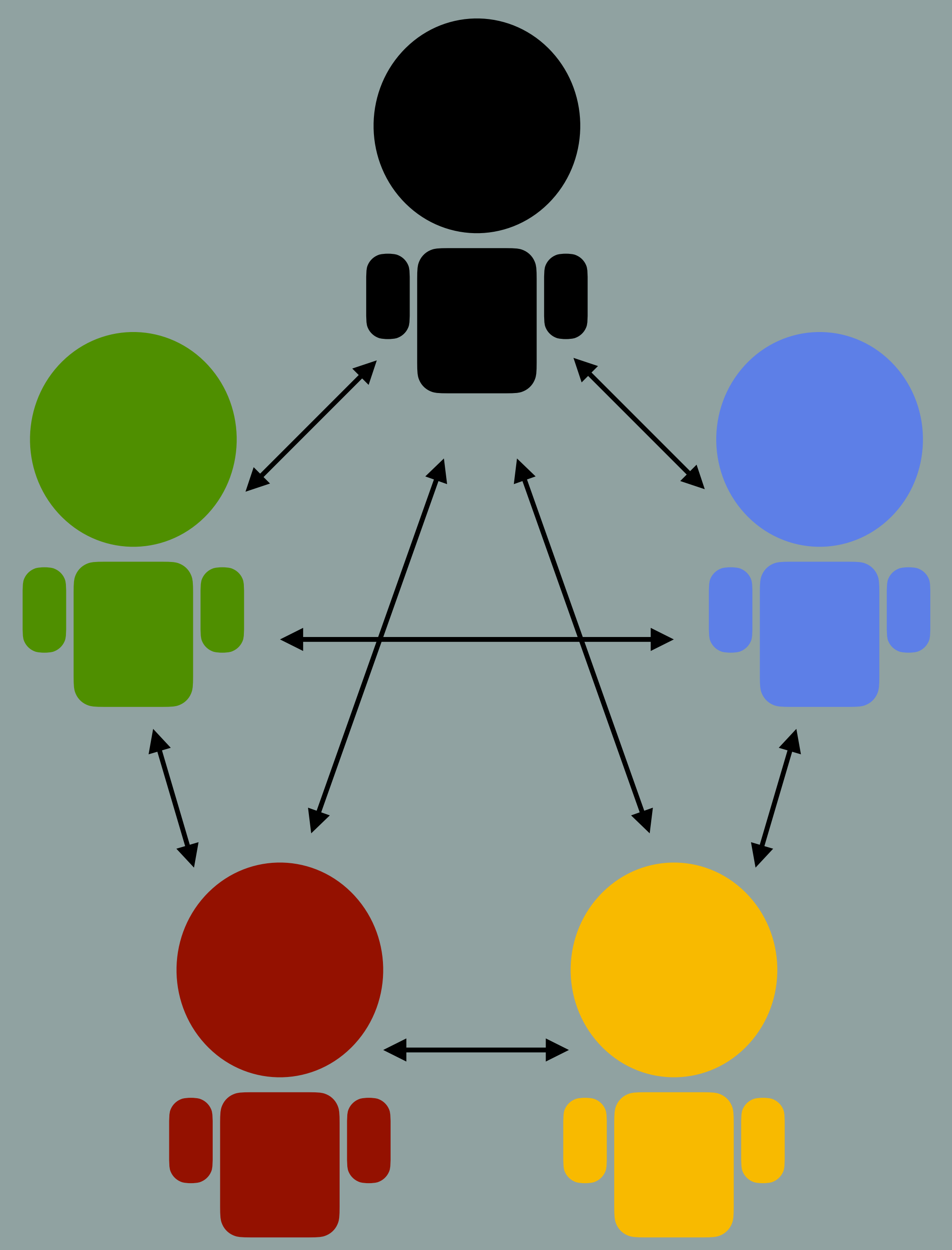
Collaborators

- Christian Hilbe
- Vincent Knight
- Marc Harper
- Martin Jones
- George Koutsovoulos
- Owen Campbell
- Alex McAvoy
- Ethan Akin
- Martin Nowak

Nikoleta-v3

@NikoletaGlyn

http://nikoleta-v3.github.io



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Nikoleta-v3

@NikoletaGlyn

http://nikoleta-v3.github.io

Definition. A reactive-n strategy can be defined as 2^n-dimensional vector

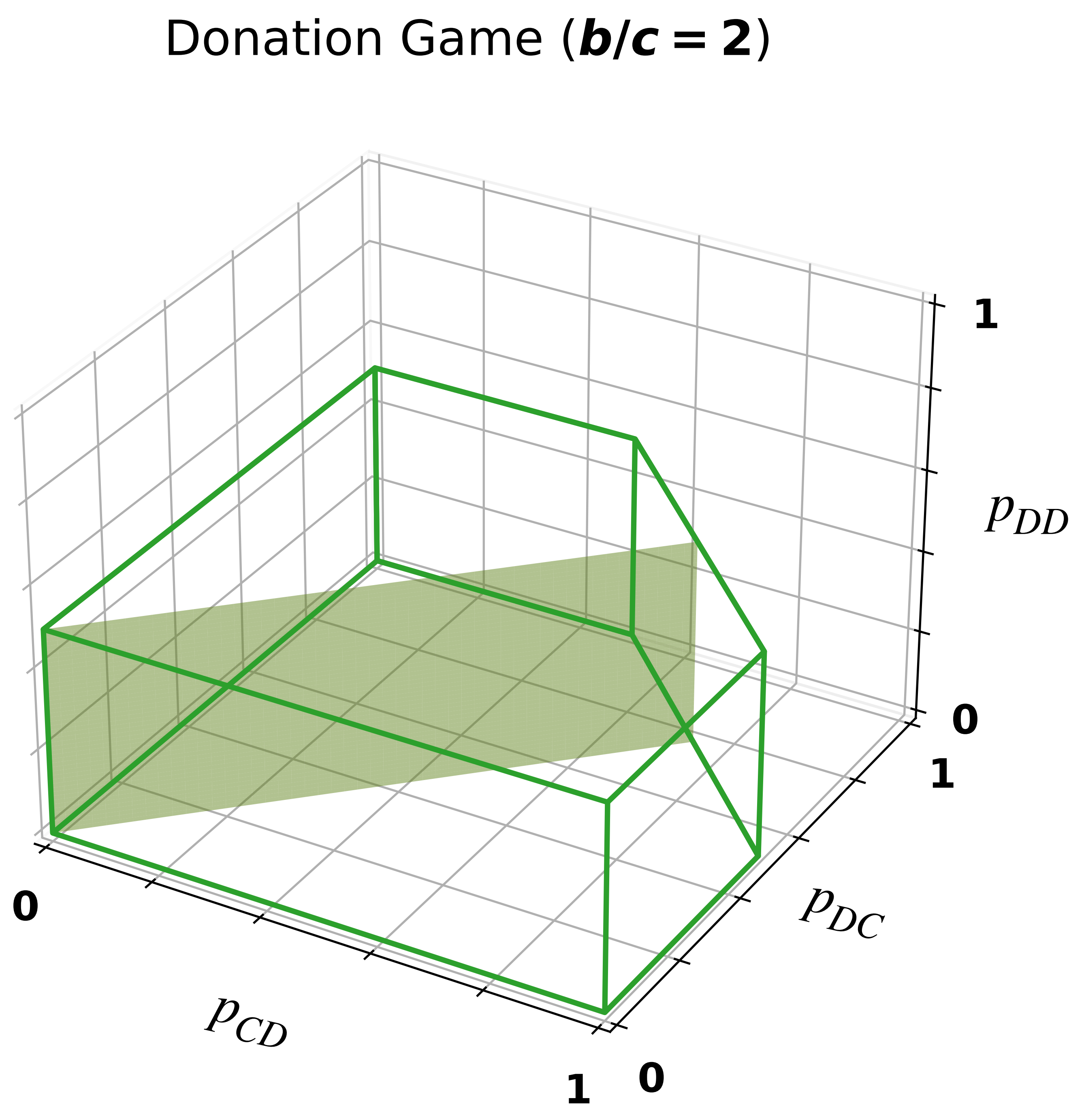
$$\mathbf{p} = (p_{\mathbf{h^{-i}}})_{\mathbf{h^{-i}} \in H^{-i}} \quad \text{with} \quad 0 \leq p_{\mathbf{h^{-i}}} \leq 1 \quad \text{for all} \quad \mathbf{h^{-i}} \in H^{-i}.$$

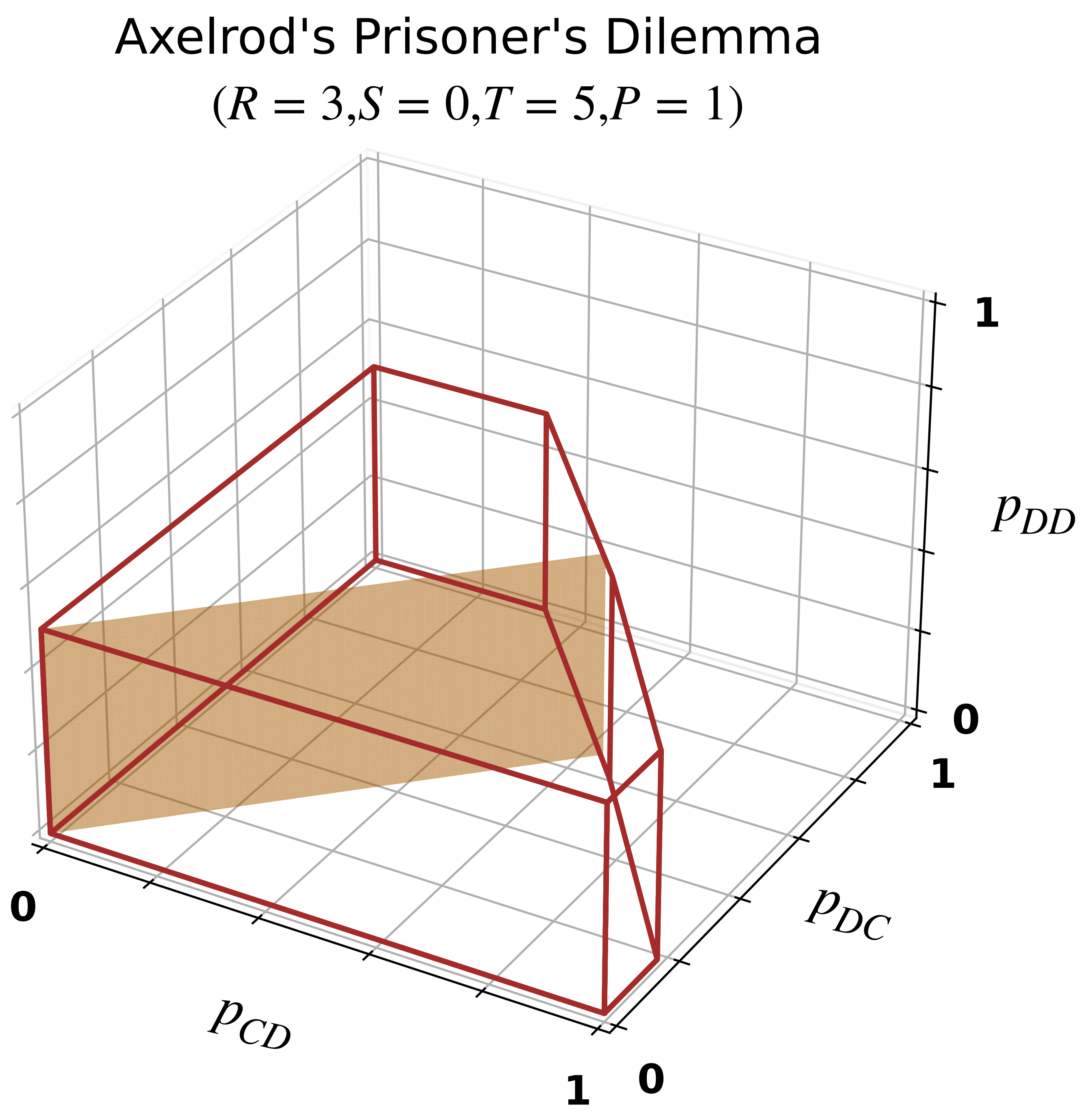
Examples. Tit For Tat:

Memory size	Strategy Vector
$n = 1$	$\mathbf{p} = (1, p_D)$
$n = 2$	$\mathbf{p} = (1, p_{CD}, p_{DC}, p_{DD})$
$n = 3$	$\mathbf{p} = (1, p_{CCD}, p_{CDC}, p_{CDD}, p_{DCC}, p_{DCD}, p_{DDC}, p_{DDD})$

[5] Conditional cooperation with longer memory. arXiv:2402.02437

$$p_{CC} = 1$$

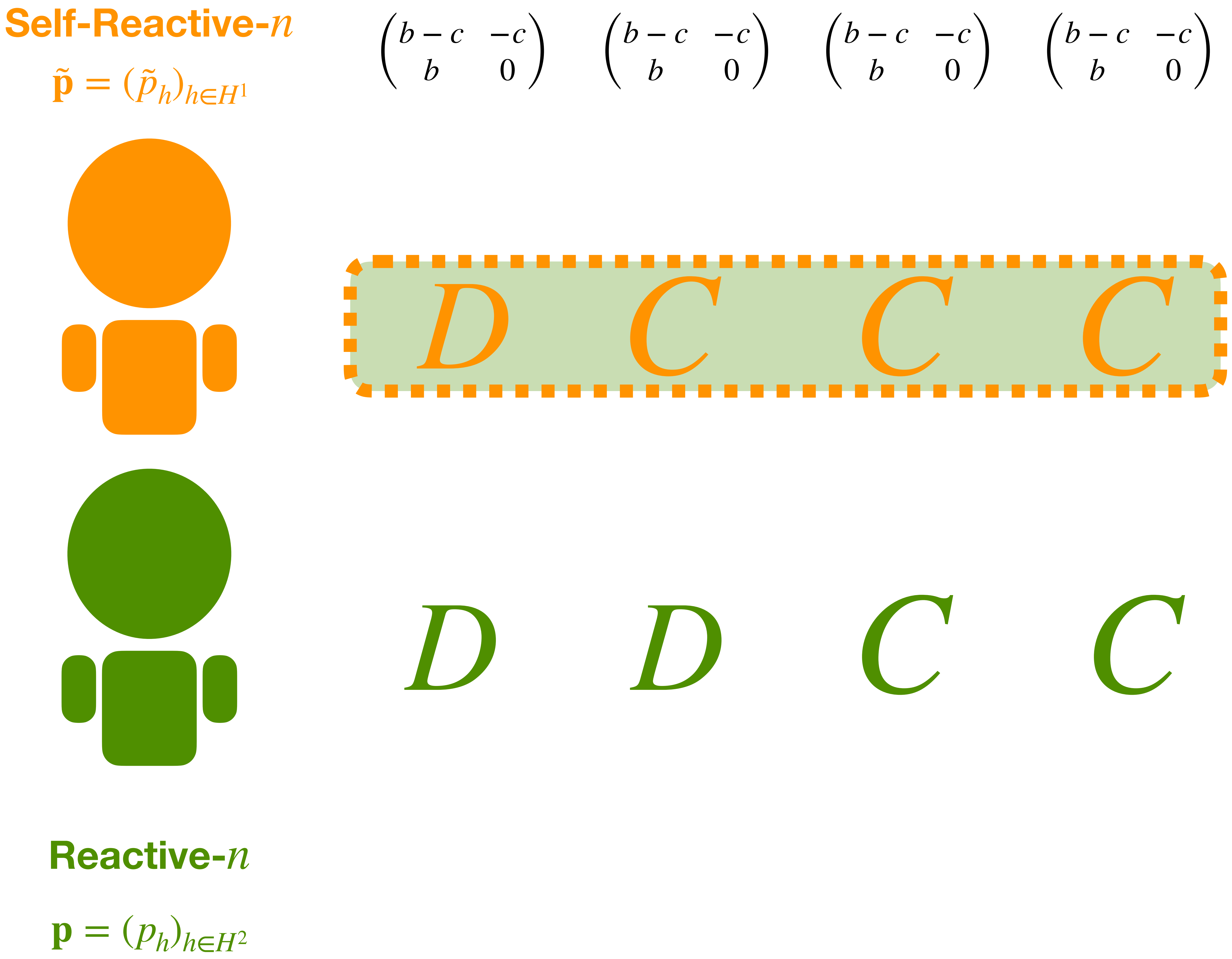




$$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$$

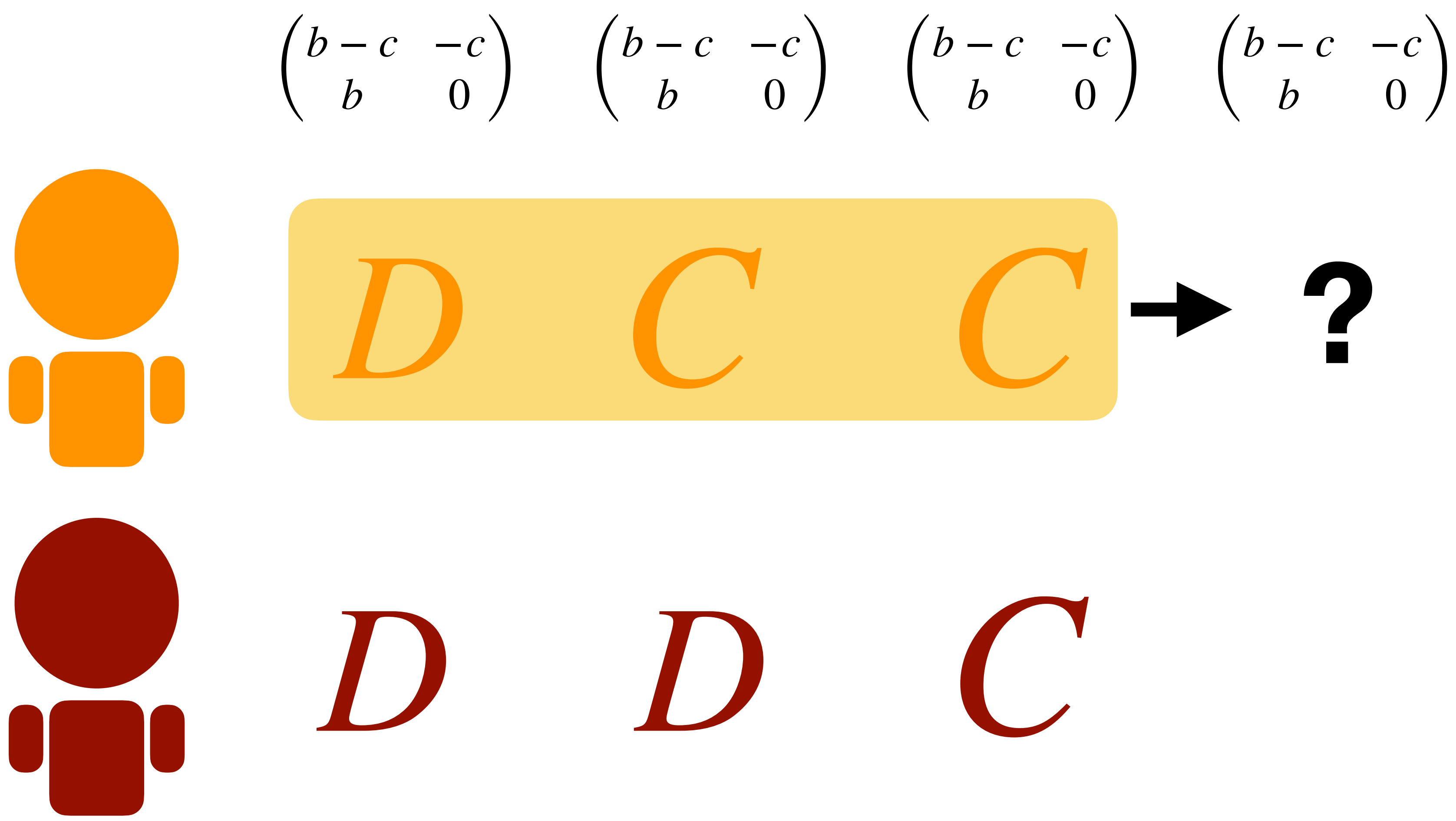
$$\begin{pmatrix} R & S \\ T & P \end{pmatrix}$$

[5] Conditional cooperation with longer memory. arXiv:2402.02437


Self-Reactive-n
$\tilde{\mathbf{p}} = (\tilde{p}_h)_{h \in H^1}$
$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$ $\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$ $\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$ $\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}$
D C C C
D D C C
Reactive-n
$\mathbf{p} = (p_h)_{h \in H^2}$

3. Strategies in repeated interactions

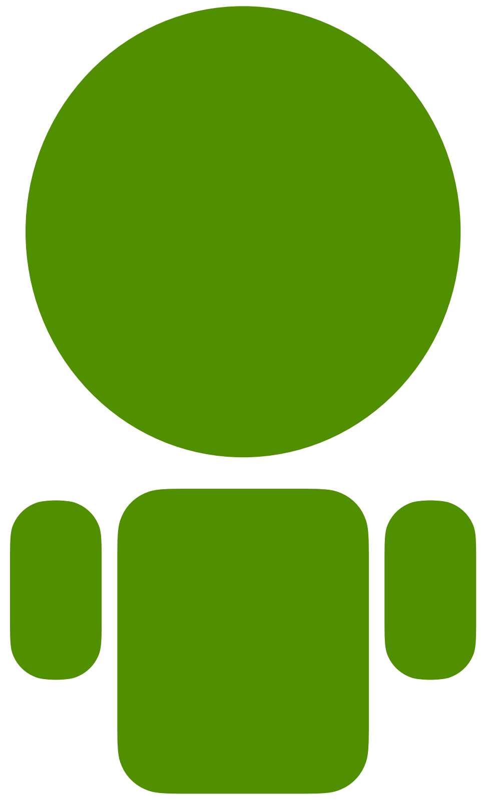
Theorem. A reactive strategy $\mathbf{p} \in \mathscr{R}_n$ is a Nash equilibrium if and only if $\pi^1(\mathbf{p}, \mathbf{p}) \geq \pi^1(\tilde{\mathbf{p}}, \mathbf{p})$ for all pure self-reactive strategies $\tilde{\mathbf{p}}$.



self-reactive$-n$

[5] Conditional cooperation with longer memory. arXiv:2402.02437

3. Strategies in repeated interactions



reactive$-n$

Nash Equilibrium

Cooperative Nash Equilibrium

Memory size	Strategy Vector	# pure self-reactive$-n$
$n = 1$	$\mathbf{p} = (1, p_D)$	4
$n = 2$	$\mathbf{p} = (1, p_{CD}, p_{DC}, p_{DD})$	16
$n = 3$	$\mathbf{p} = (1, p_{CCD}, p_{CDC}, p_{CDD}, p_{DCC}, p_{DCD}, p_{DDC}, p_{DDD})$	256

[5] Conditional cooperation with longer memory. arXiv:2402.02437