HPCを用いた進化ゲーム理論研究

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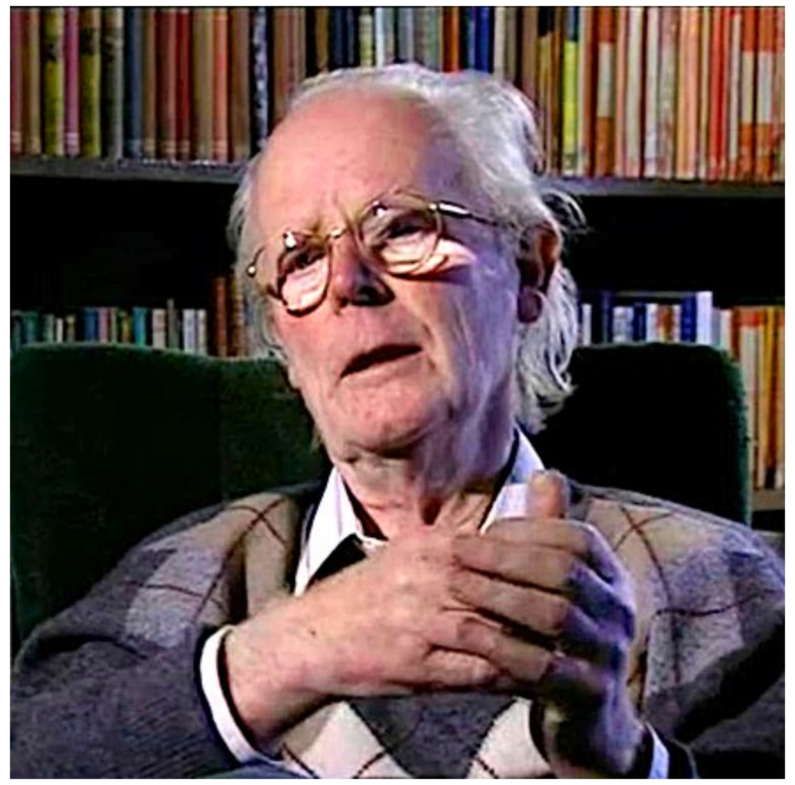
内容

- ゲーム理論、進化ゲーム理論の概要
- 繰り返し囚人のジレンマにおける負けないことが保証された直接互恵戦略
- 今後の展望

ゲーム理論: 意思決定の科学

- ゲーム理論
  - 複数の意思決定主体の行動を記述する数学的枠組み
  - John von Neumann, Oskar Morgenstern 「ゲームの理論と経済行動」(1944) が始まり
  - 経済学、社会学、政治学
  - 進化生物学
    - John Maynard Smith 進化ゲーム理論
  - 計算機科学
    - 分散処理、マルチエージェント学習

http://www.lanl.gov/history/atomicbomb/images/NeumannL.GIF



https://commons.wikimedia.org/wiki/File:John_Maynard_Smith.jpg

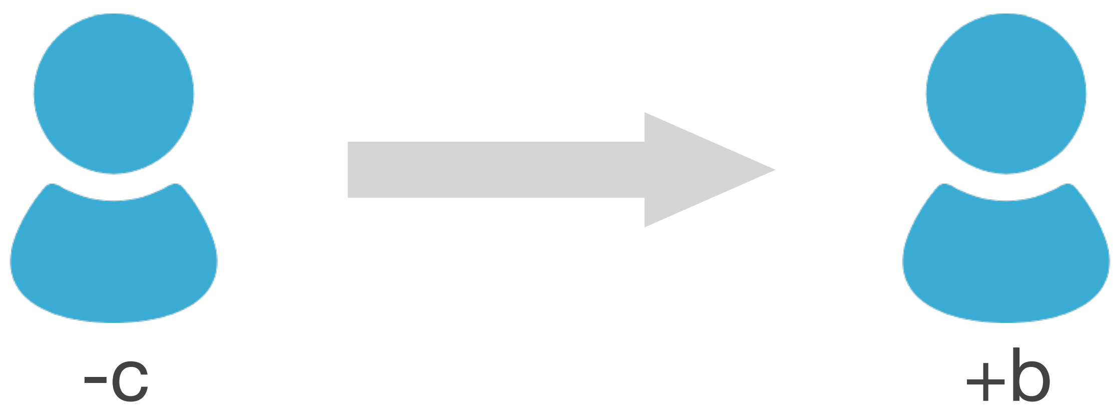
囚人のジレンマ

	cooperation	defection
cooperation	(3,3)	(0,5)
defection	(5,0)	(1,1)

- 戦略: 協力、裏切りをプレイヤーが選択する
- 互いに裏切りあう状況が唯一のNash均衡
    - 自分が行動を変えるインセンティブがない安定した状態（物理系でいうと局所安定状態みたいなもの）
- 個人の利得の最適化 ≠ 社会全体の利得の最適化
    - 社会的ジレンマ、コモンズの悲劇、合成の誤謬
    - 地球温暖化、自然破壊、乱獲、過放牧、公共の施設の利用、買い占め、パンデミック下での行動変容

協力行動の進化

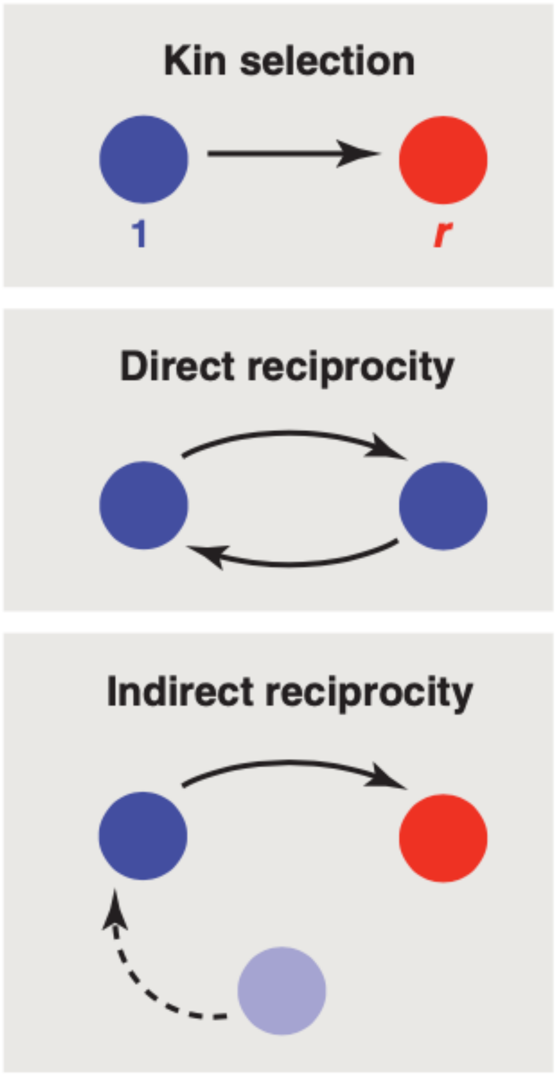
- 協力行動：コストを払って、相手に利益を与える (b > c)
- なぜ協力行動が進化した？



$$
\begin{array}{r} \\ \text{cooperate(C)} \\ \text{defect(D)} \end{array}
\begin{array}{c} \begin{array}{cc} \text{C} & \text{D} \end{array} \\ \begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix} \end{array}
$$

Five Rules for the Evolution of Cooperation

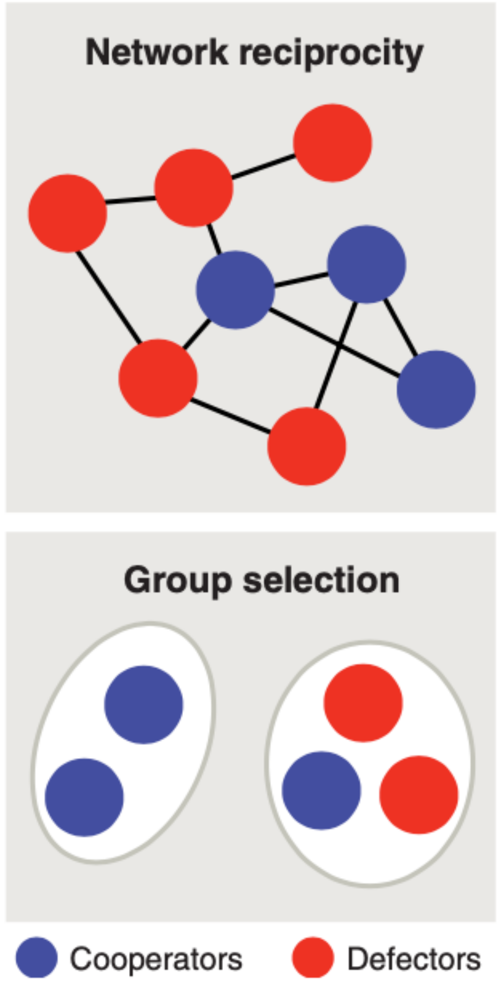
Martin A. Nowak



近親選択

直接互恵

間接互恵



ネットワーク（空間）互恵

グループ選択

内容

- ゲーム理論、進化ゲーム理論の概要
- 繰り返し囚人のジレンマにおける負けないことが保証された直接互恵戦略
- 今後の展望

iterated Prisoner's Dilemma

Social Dilemma : social optimum ≠ individual benefit

player B

player A

	cooperation	defection
cooperation	(3,3)	(0,5)
defection	(5,0)	(1,1)

repeated the interaction => cooperation may be a rational choice.

long-term payoff in the repeated game

$$f_i \equiv \lim_{e\to 0} \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T-1} F_i^{(t)}$$

well known strategies

Tit-for-Tat

History	Next move
C,C	C
C,D	D
D,C	C
D,D	D

your payoff is no less than the other's

TFT	c	c	c	d	d	c
	c	c	d	d	c	c

fragile against an error

TFT	c	c	c	d	c	d
TFT	c	c	d	c	d	c

It cannot exploit naive cooperator.

TFT	c	c	c	c	c	c
AllC	c	c	c	c	c	c

Win-Stay-Lose-Shift

History	Next move
C,C	C
C,D	D
D,C	D
D,D	C

tolerant against an error

WSLS	c	c	c	d	c	c
WSLS	c	c	d	d	c	c

It can exploit naive cooperator.

WSLS	c	c	d	d	d	d
AllC	c	c	c	c	c	c

weak against defectors

WSLS	c	d	c	d	c	d
AllD	d	d	d	d	d	d

Zero-Determinant Strategy

Press&Dyson PNAS (2012)

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

William H. Press[a,1] and Freeman J. Dyson[b]

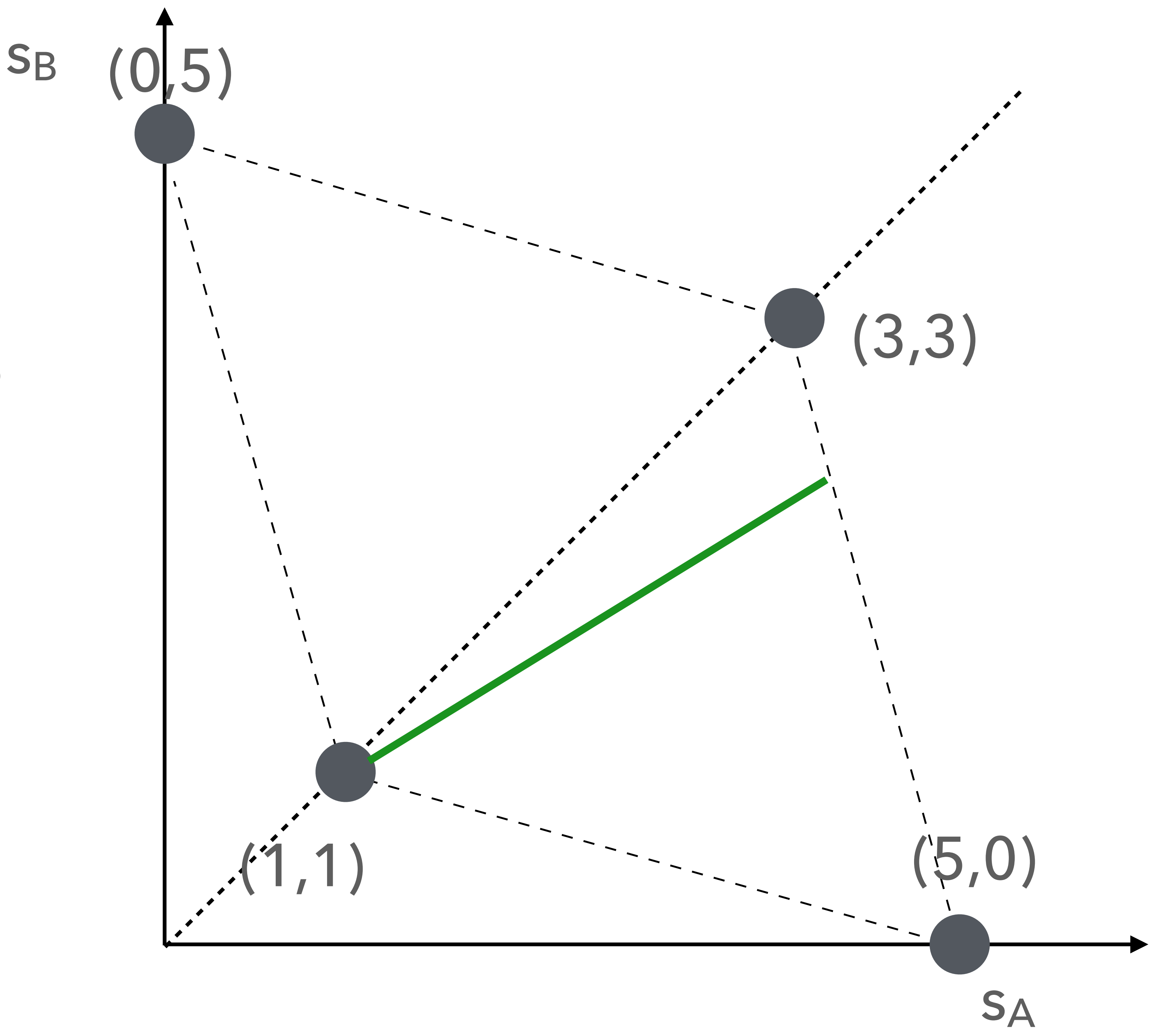
[a]Department of Computer Science and School of Biological Sciences, University of Texas at Austin, Austin, TX 78712; and [b]School of Natural Sciences, Inst for Advanced Study, Princeton, NJ 08540

History	probability of C
C,C	p
C,D	q
D,C	r
D,D	s

extortionate ZD strategy

It is guaranteed that your payoff is no less than the co-players'.

Cooperation is not maintained.



longer memory strategies

Tit-for-2Tat

tolerant against an error

TF2T c c d c c

TF2T c c c c c

weak against alternating defector

TF2T c c c c c

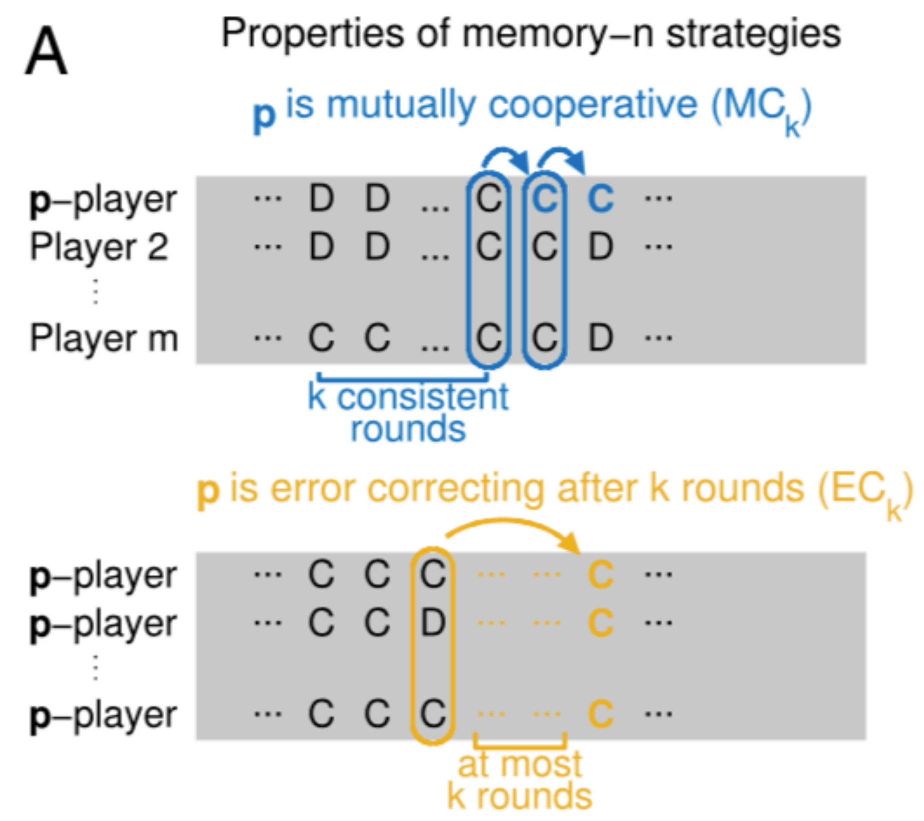
defector c d c d c

All-or-Nothing

generalization of WSLS

tolerant against an error

Fragile against AllD.



Memory-*n* strategies of direct reciprocity

Christian Hilbe[a,1,2], Luis A. Martinez-Vaquero[b,1], Krishnendu Chatterjee[a], and Martin A. Nowak[c,d,e]

Hilbe et al. PNAS(2017)

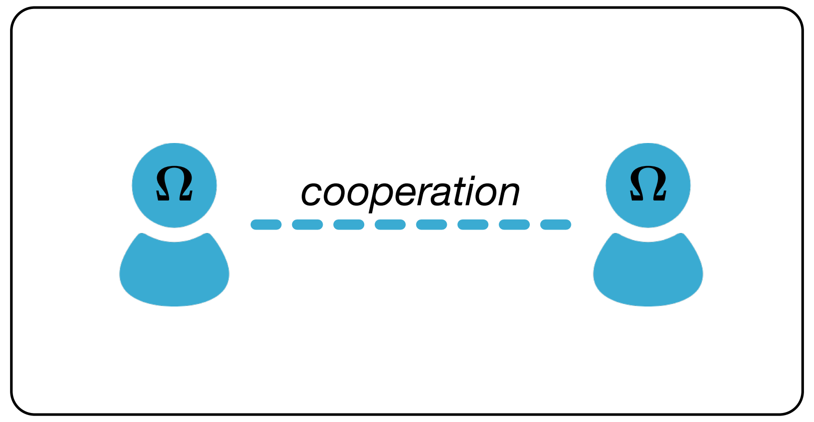
partners or rivals

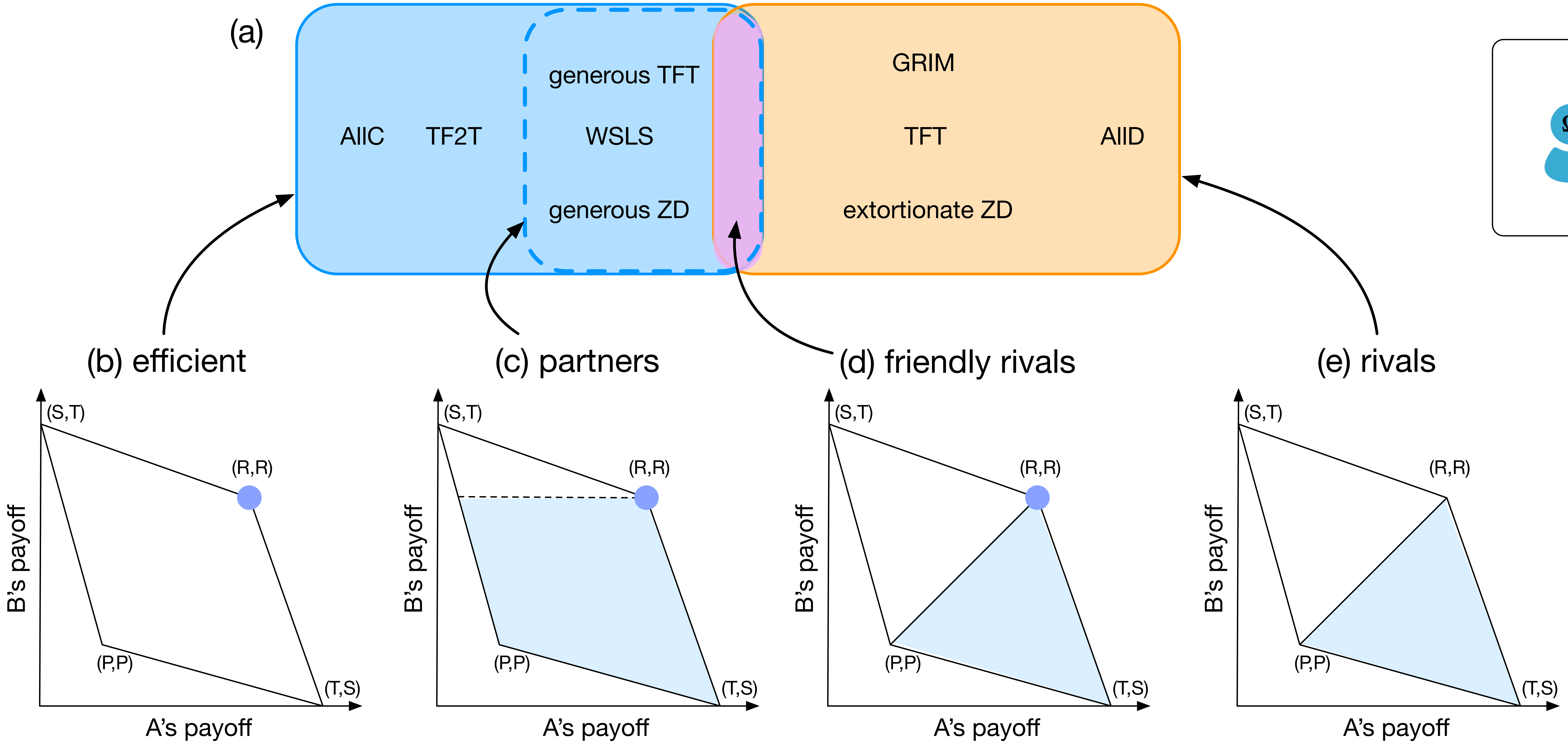
Hilbe et al., Nat.Hum.Behav. (2018)

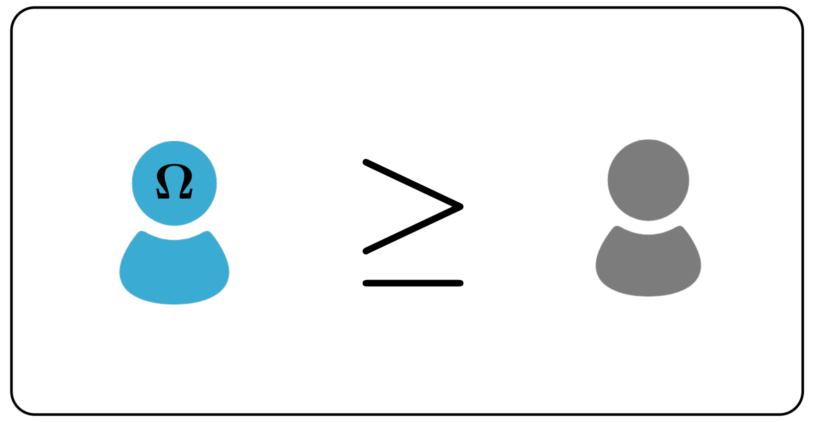
nature human behaviour
REVIEW ARTICLE
https://doi.org/10.1038/s41562-018-0320-9
Corrected: Publisher Correction

Partners and rivals in direct reciprocity

Christian Hilbe[1,2]*, Krishnendu Chatterjee[2] and Martin A. Nowak[1,3]







It would be great if a single strategy works as **a partner as well as a rival.**

friendly rivals

cooperative Nash equilibrium with a guarantee of never being defeated

TFT-ATFT: a friendly rival strategy

Yi et al., J. Theor. Biol. (2017)

- # of Memory-1 strategies: 16
  - => no strategy satisfies the criteria
- # of Memory-2 strategies: 2^16 = 65536
  - Eight FRs were found.

Contents lists available at ScienceDirect
Journal of Theoretical Biology
journal homepage: www.elsevier.com/locate/yjtbi

Combination with anti-tit-for-tat remedies problems of tit-for-tat

Su Do Yi[a], Seung Ki Baek[b,*], Jung-Kyoo Choi[c,*]

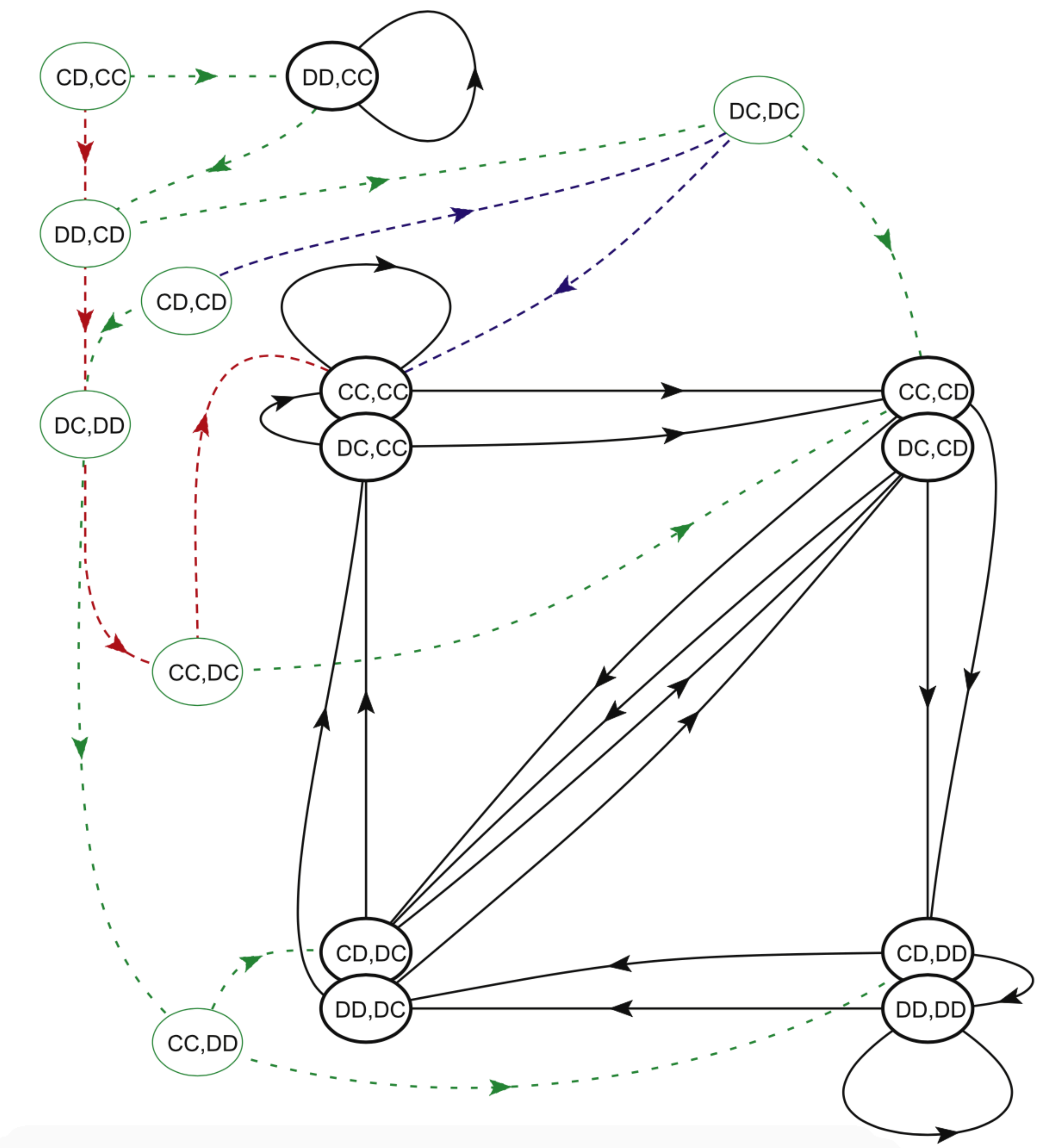


Table 1
List of moves in TFT-ATFT. This table shows the proposed moves at time t when the state is given as $(A_{t-2}A_{t-1}, B_{t-2}B_{t-1})$, where A_{t-2} and A_{t-1} (B_{t-2} and B_{t-1}) are the focal player's (the other player's) moves at the last two steps, respectively. The underlined moves are the same as prescribed by TFT. The states with the dagger symbol are related to the two players' simultaneous mistakes (see text).

State	Move	State	Move
(CC,CC)	$\underline{C}$	(DC,CC)	$\underline{C}$
(CC,CD)	$\underline{D}$	(DC,CD)	$\underline{D}$
(CC,DC)	C	(DC, DC)†	C
(CC,DD)	D	(DC,DD)	C
(CD,CC)	D	(DD,CC)	D
(CD, CD)†	C	(DD,CD)	C
(CD,DC)	$\underline{C}$	(DD,DC)	$\underline{C}$
(CD,DD)	$\underline{D}$	(DD,DD)	$\underline{D}$

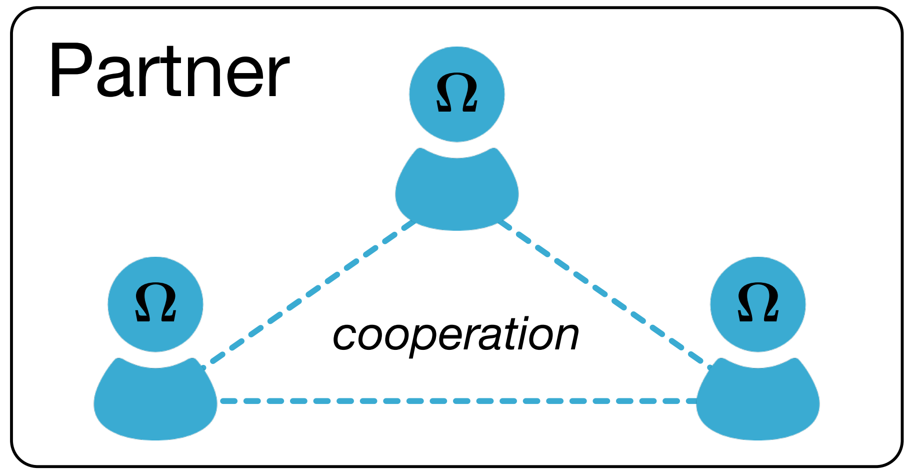
Games with more than two players?

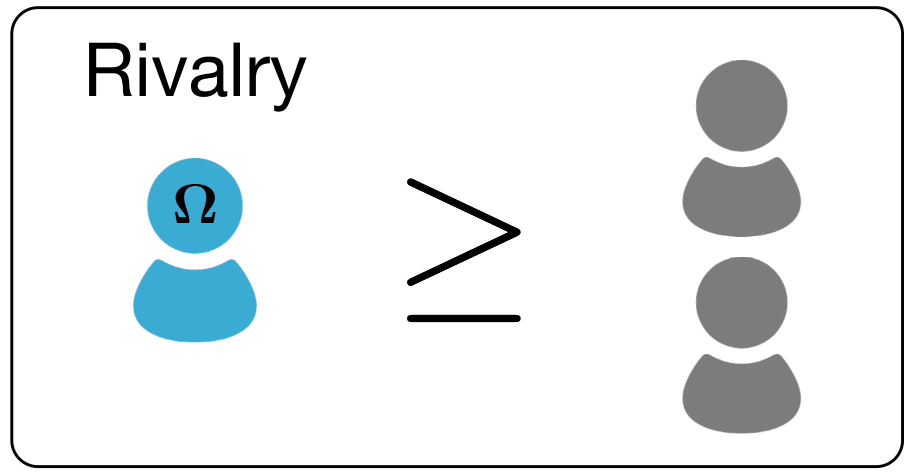
Y. Murase et al., J. Theor. Biol. (2018)

3-person public goods game

payoff matrix

$$M \equiv \left(\begin{array}{c|ccc} & 0 & 1 & 2 \\ c & \rho & \frac{2}{3}\rho & \frac{1}{3}\rho \\ d & 1+\frac{2}{3}\rho & 1+\frac{1}{3}\rho & 1 \end{array} \right)$$





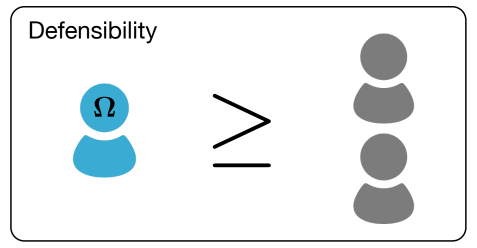
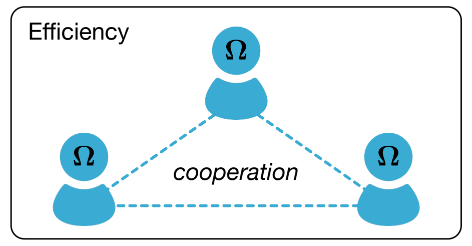
TFT-ATFT does not work.

$$2^{2^{nm}}$$

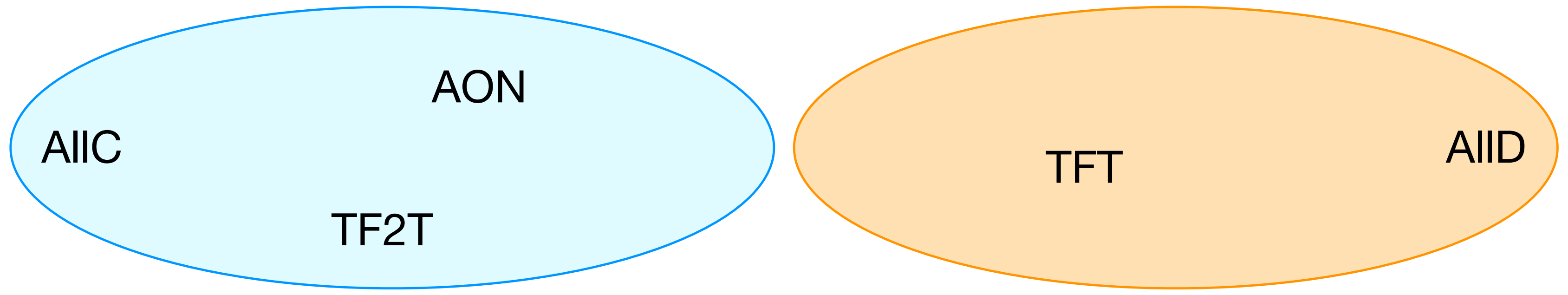
1,099,511,627,776 strategies

京 (スーパーコンピュータ). (2023, September 27). In *Wikipedia*. https://ja.wikipedia.org/wiki/%E4%BA%AC_(%E3%82%B9%E3%83%BC%E3%83%91%E3%83%BC%E3%82%B3%E3%83%B3%E3%83%94%E3%83%A5%E3%83%BC%E3%82%BF)

Enumeration of strategies

# of m=2 strategies		1,099,511,627,776
Defensibility against AllD		805,306,368
Defensibility		3,483,008
Efficiency		**0**

Impossibility : no friendly rival in memory-2 strategies.



What about memory-***3*** strategies?

2^{288}

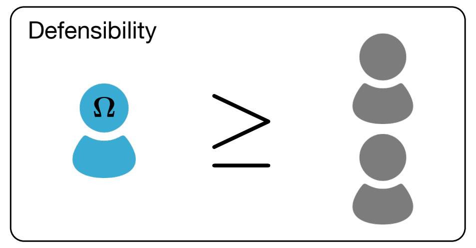
497323236409786642155382248146820840100456150797
347717440463976893159497012533375533056

comparable to the number of protons in the universe

partially successful strategy

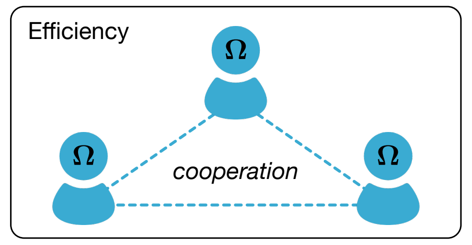
# of m=2 strategies	1,099,511,627,776
Defensibility against AllD	805,306,368

Defensibility



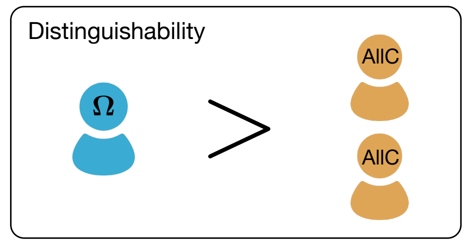
3,483,008

"Partial" Efficiency ($p_{cooperation} > 0$)



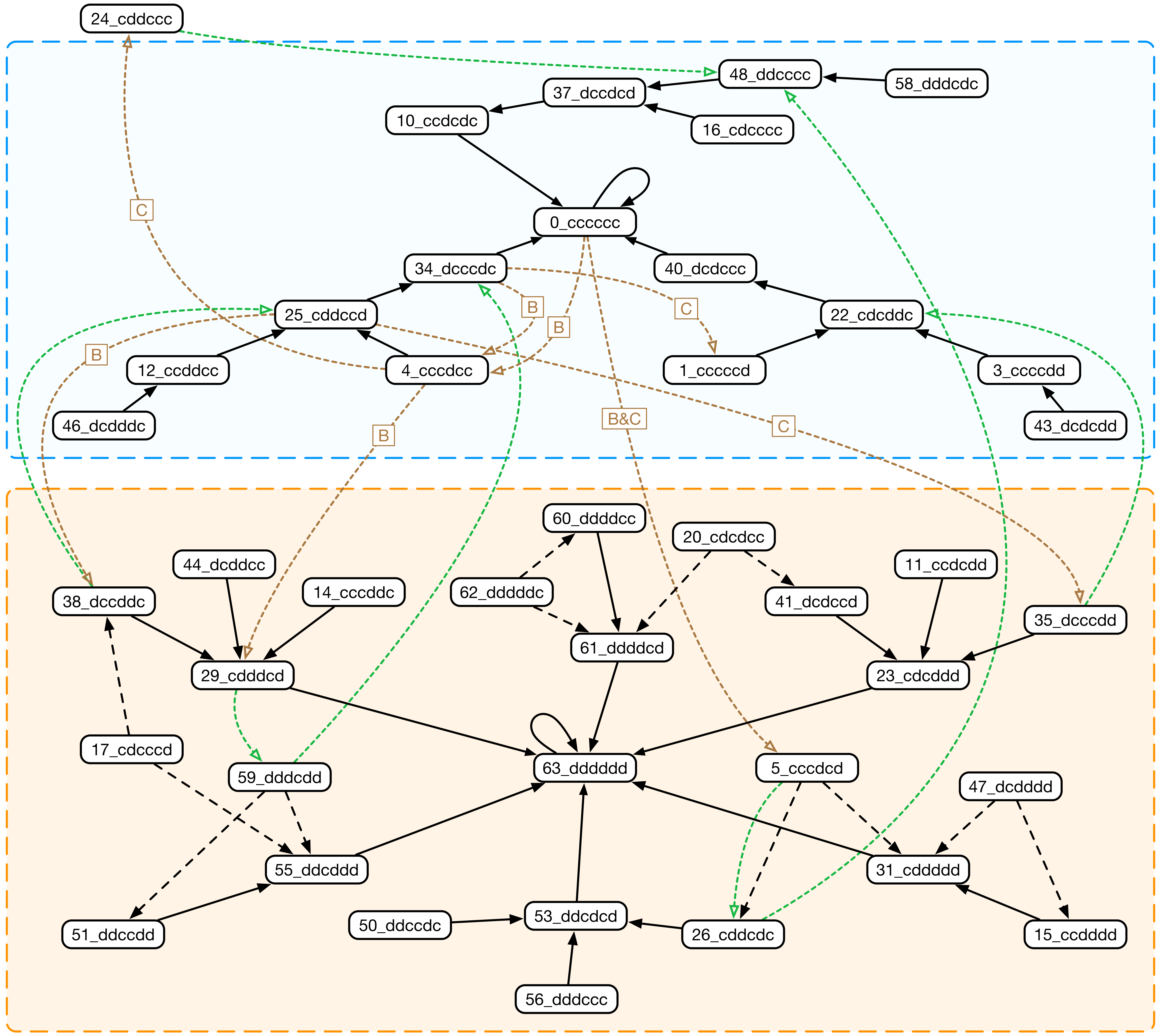
544

Distinguishability



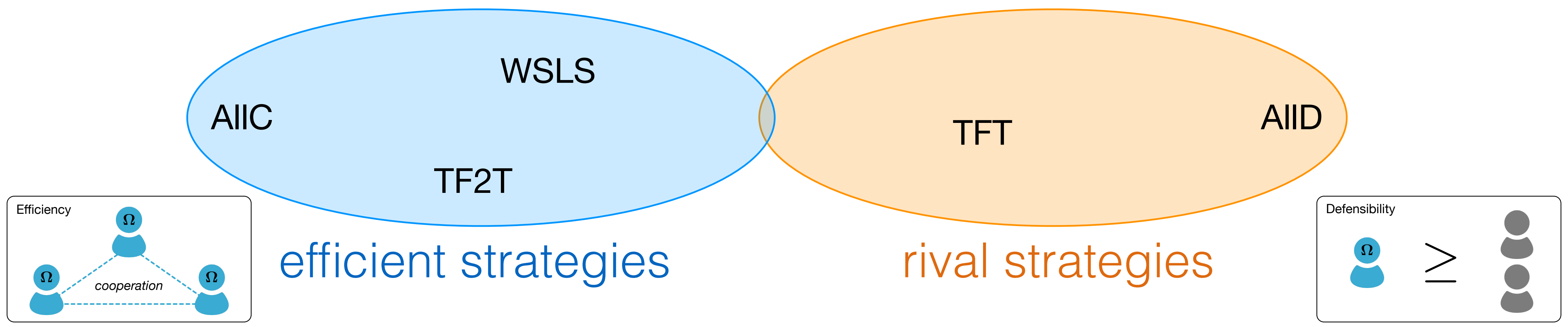
256

***"Partially"* friendly rival strategies**



24_cddccc
48_ddcccc
58_dddcdc
37_dcccdcd
16_cdcccc
10_ccdcdc
0_cccccc
34_dcccdc
40_dcdccc
25_cddccd
22_cdcddc
12_ccddcc
4_cccdcc
1_ccccdd
3_ccccdd
46_dcdddc
43_dcdcdd
C
B
B
B
C
B&C
C
B
60_ddddcc
20_cdcdcc
44_dcddcc
14_cccddc
62_dddddc
11_ccdcdd
38_dccddc
41_dcdccd
35_dcccdd
61_ddddcd
29_cddddd
23_cdcddd
17_cdcccd
63_dddddd
59_dddcdd
5_cccdcd
47_dcdddd
55_ddcddd
31_cddddd
51_ddccdd
50_ddccdc
53_ddcdcd
26_cddcdc
15_ccdddd
56_dddccc

$$\geq \frac{256}{2^{288}}$$



Friendly rival strategies are found.

Mutual cooperation is reached with probability 1 while keeping the defensibility and the distinguishability.

An example of friendly rival strategies.

Table 4
One of successful memory-3 strategies. We have picked up the strategy having the largest number of *c*. The left column shows the state of Bob and Charlie, whereas Alice's state is shown on the right.

$B_{t-3}B_{t-2}B_{t-1}C_{t-3}C_{t-2}C_{t-1}$	$A_{t-3}A_{t-2}A_{t-1}$							
	ccc	*ccd*	*cdc*	*cdd*	*dcc*	*dcd*	*ddc*	*ddd*
cccccc	*c*	*c*	*d*	*c*	*c*	*c*	*d*	*c*
cccccd/*ccdccc*	*d*	*c*	*c*	*c*	*d*	*c*	*c*	*c*
ccccdc/*cdcccc*	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
ccccdd/*cddccc*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
cccdcc/*dccccc*	*c*	*c*	*d*	*c*	*c*	*c*	*d*	*c*
cccdcd/*dcdccc*	*d*	*c*	*c*	*c*	*d*	*c*	*c*	*c*
cccddc/*ddcccc*	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
cccddd/*dddccc*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
ccdccd	*d*	*c*	*c*	*c*	*d*	*c*	*c*	*d*
ccdcdc/*cdcccd*	*c*	*c*	*c*	*c*	*d*	*c*	*d*	*c*
ccdcdd/*cddccd*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
ccddcc/*dccccd*	*d*	*c*	*c*	*c*	*d*	*c*	*c*	*c*
ccddcd/*dcdccd*	*d*	*c*	*c*	*d*	*d*	*c*	*c*	*d*
ccdddc/*ddcccd*	*d*	*c*	*d*	*c*	*d*	*c*	*d*	*c*
ccdddd/*dddccd*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
cdccdc	*c*	*d*	*c*	*d*	*c*	*c*	*c*	*d*
cdccdd/*cddcdc*	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*
cdcdcc/*dcccdc*	*c*	*d*	*c*	*c*	*c*	*d*	*c*	*d*
cdcdcd/*dcdcdc*	*d*	*c*	*d*	*c*	*d*	*c*	*d*	*c*
cdcddc/*ddccdc*	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
cdcddd/*dddcdc*	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*
cddcdd	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*
cdddcc/*dcccdd*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
cdddcd/*dcdcdd*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
cddddc/*ddccdd*	*d*	*d*	*c*	*c*	*d*	*d*	*c*	*d*
cddddd/*dddcdd*	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*
dccdcc	*c*	*c*	*d*	*c*	*c*	*c*	*d*	*c*
dccdcd/*dcddcc*	*d*	*c*	*c*	*c*	*d*	*c*	*c*	*c*
dccddc/*ddcdcc*	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
dccddd/*dddDcc*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
dcddcd	*d*	*c*	*c*	*d*	*d*	*c*	*c*	*d*
dcdddc/*ddcdcd*	*d*	*c*	*d*	*c*	*d*	*c*	*d*	*c*
dcdddd/*ddddcd*	*d*	*d*	*d*	*d*	*d*	*d*	*d*	*d*
ddcddc	*c*	*d*	*c*	*d*	*c*	*d*	*c*	*d*
ddcddd/*dddddc*	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*
dddddd	*d*	*d*	*c*	*d*	*d*	*d*	*c*	*d*

interpretation of m=3 successful strategies

Y. Murase et al., Sci.Rep. (2020)

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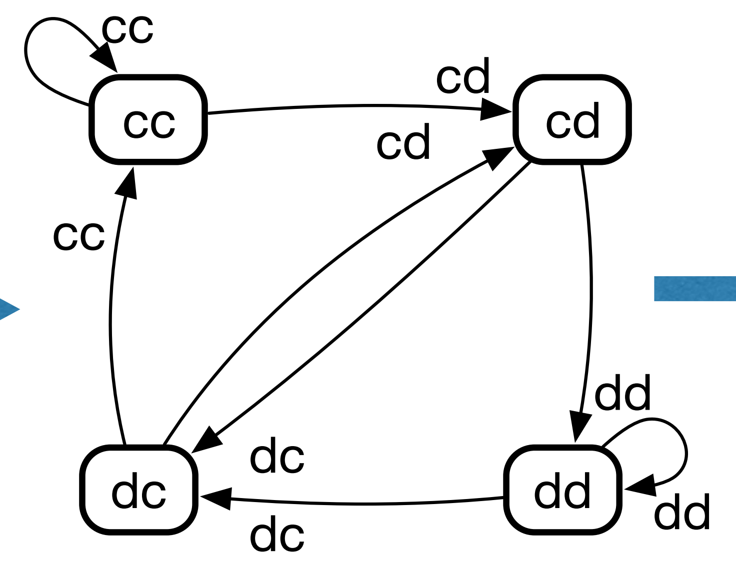
One of successful memory-3 strategies. We have picked up the strategy having the largest number of c. The left column shows the state of Bob and Charlie, whereas Alice's state is shown on the right.

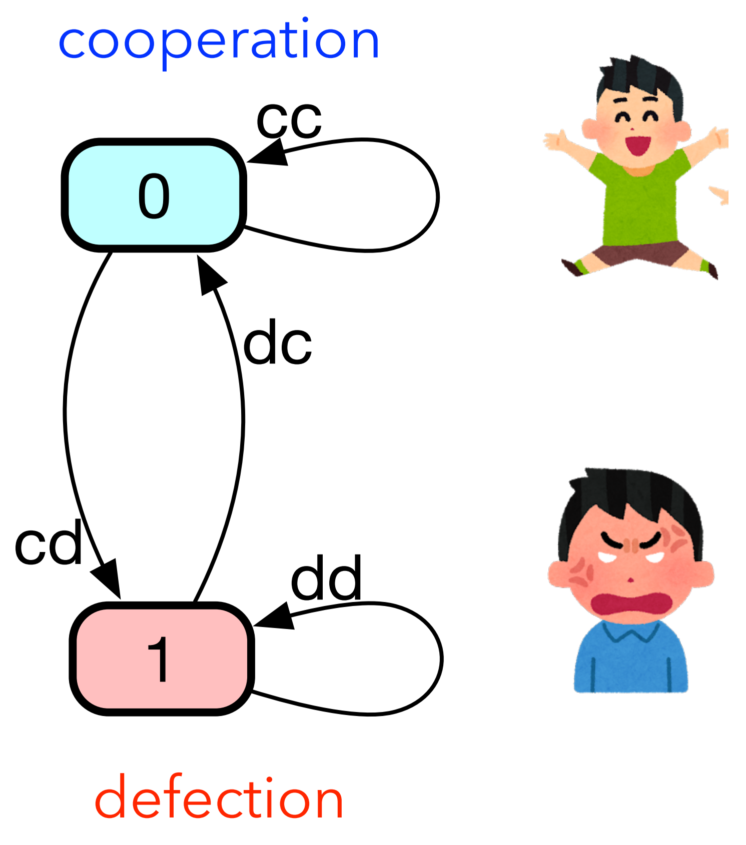
$B_{t-3}B_{t-2}B_{t-1}C_{t-3}C_{t-2}C_{t-1}$	$A_{t-3}A_{t-2}A_{t-1}$							
	ccc	ccd	cdc	cdd	dcc	dcd	ddc	ddd
cccccc	c	c	d	c	c	c	d	c
cccccd/ccdccc	d	c	c	c	d	c	c	c
ccccdc/cdcccc	c	d	c	d	c	d	c	d
ccccdd/cddccc	d	d	d	d	d	d	d	d
cccdcc/dccccc	c	c	d	c	c	c	d	c
cccdcd/dcdccc	d	c	c	c	d	c	c	c
cccddc/ddcccc	c	d	c	d	c	d	c	d
cccddd/dddccc	d	d	d	d	d	d	d	d
ccdccd	d	c	c	c	d	c	c	d
ccdcdc/cdcccd	c	c	c	c	d	c	d	c
ccdcdd/cddccd	d	d	d	d	d	d	d	d
ccddcc/dccccd	d	c	c	c	d	c	c	c
ccddcd/dcdccd	d	c	c	d	d	c	c	d
ccdddc/ddcccd	d	c	d	c	d	c	d	c
ccdddd/dddccd	d	d	d	d	d	d	d	d
cdccdc	c	d	c	d	c	c	c	d
cdccdd/cddcdc	d	d	c	d	d	d	c	d
cdcdcc/dcccdc	c	d	c	c	c	d	c	d
cdcdcd/dcdcdc	d	c	d	c	d	c	d	c
cdcddc/ddccdc	c	d	c	d	c	d	c	d
cdcddd/dddcdc	d	d	c	d	d	d	c	d
cddcdd	d	d	c	d	d	d	c	d
cdddcc/dcccdd	d	d	d	d	d	d	d	d
cdddcd/dcdcdd	d	d	d	d	d	d	d	d
cddddc/ddccdd	d	d	c	c	d	d	c	d
cddddd/dddcdd	d	d	c	d	d	d	c	d
dccdcc	c	c	d	c	c	c	d	c
dccdcd/dcddcc	d	c	c	c	d	c	c	c
dccddc/ddcdcc	c	d	c	d	c	d	c	d
dccddd/ddddcc	d	d	d	d	d	d	d	d
dcddcd	d	c	c	d	d	c	c	d
dcdddc/ddcdcd	d	c	d	c	d	c	d	c
dcdddd/ddddcd	d	d	d	d	d	d	d	d
ddcddc	c	d	c	d	c	d	c	d
ddcddd/dddddc	d	d	c	d	d	d	c	d
dddddd	d	d	c	d	d	d	c	d

an intuitive interpretation is lacking

action table

History	Next move
C,C	C
C,D	D
D,C	C
D,D	D





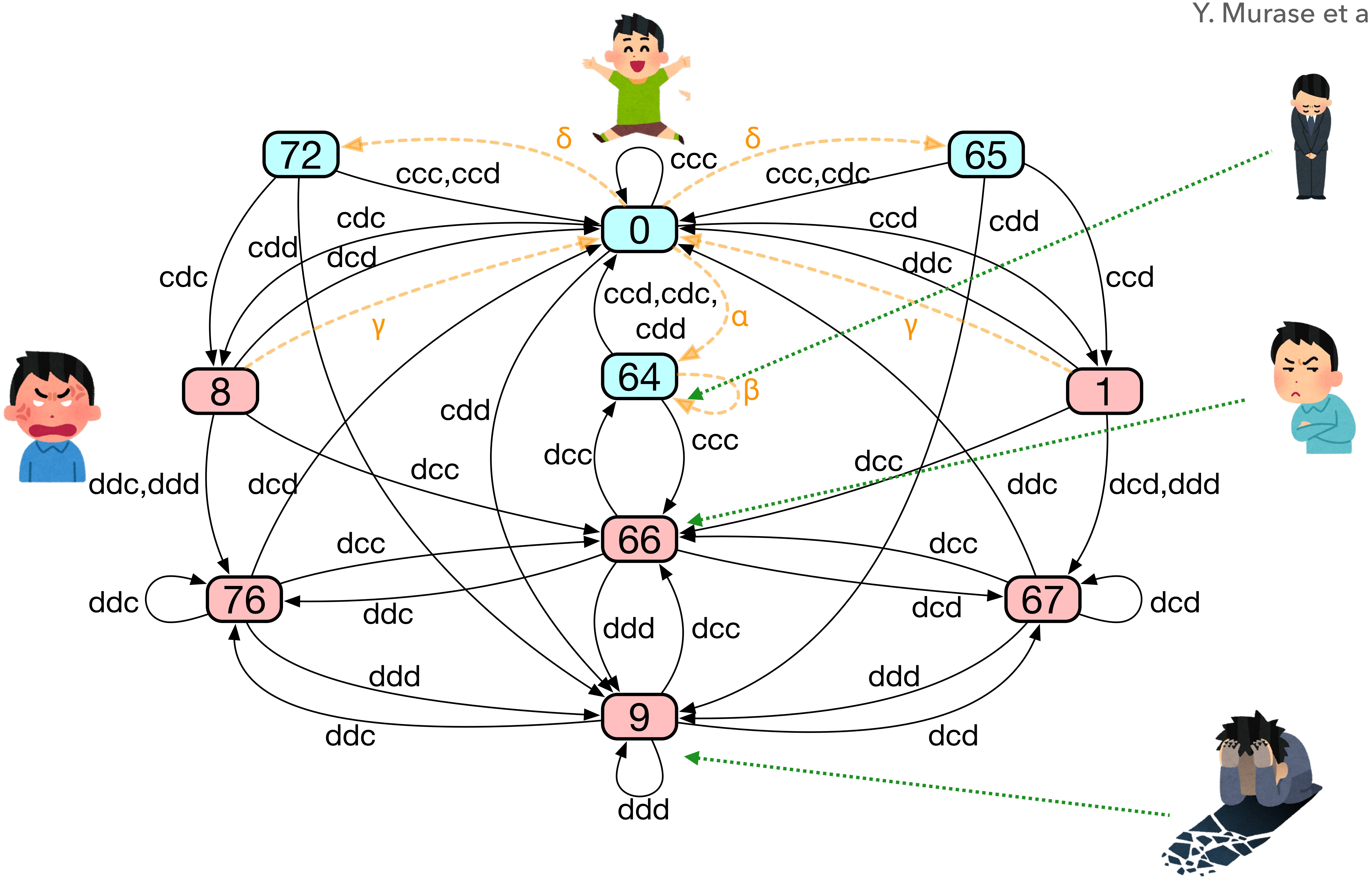
Core idea: Deterministic Finite Automaton minimization

convert a strategy defined by an action table into the equivalent automaton having minimum number of states

Y. Murase et al., Sci.Rep. (2020)

Table 4
One of successful memory-3 strategies. We have picked up the strategy having the largest number of *c*. The left column shows the state of Bob and Charlie, whereas Alice's state is shown on the right.

$B_{t-3}B_{t-2}B_{t-1}C_{t-3}C_{t-2}C_{t-1}$	$A_{t-3}A_{t-2}A_{t-1}$							
	ccc	ccd	cdc	cdd	dcc	dcd	ddc	ddd
cccccc	c	c	d	c	c	c	d	c
cccccd/ccdccc	d	c	c	c	d	c	c	c
ccccdc/cdcccc	c	d	c	d	c	d	c	d
ccccdd/cddccc	d	d	d	d	d	d	d	d
cccdcc/dccccc	c	c	d	c	c	c	d	c
cccdcd/dcdccc	d	c	c	c	d	c	c	c
cccddc/ddcccc	c	d	c	d	c	d	c	d
cccddd/dddccc	d	d	d	d	d	d	d	d
ccdccd	d	c	c	c	d	c	c	d
ccdcdc/cdcccd	c	c	c	c	d	c	d	c
ccdcdd/cddccd	d	d	d	d	d	d	d	d
ccddcc/dccccd	d	c	c	c	d	c	c	c
ccddcd/dcdccd	d	c	c	d	d	c	c	d
ccdddc/ddcccd	d	c	d	c	d	c	d	c
ccdddd/dddccd	d	d	d	d	d	d	d	d
cdccdc	c	d	c	d	c	c	c	d
cdccdd/cddcdc	d	d	c	d	d	d	c	d
cdcdcc/dcccdc	c	d	c	c	c	d	c	d
cdcdcd/dcdcdc	d	c	d	c	d	c	d	c
cdcddc/ddccdc	c	d	c	d	c	d	c	d
cdcddd/dddcdc	d	d	c	d	d	d	c	d
cddcdd	d	d	c	d	d	d	c	d
cdddcc/dcccdd	d	d	d	d	d	d	d	d
cdddcd/dcdcdd	d	d	d	d	d	d	d	d
cddddc/ddccdd	d	d	c	c	d	d	c	d
cddddd/dddcdd	d	d	c	d	d	d	c	d
dccdcc	c	c	d	c	c	c	d	c
dccdcd/dcddcc	d	c	c	c	d	c	c	c
dccddc/ddcdcc	c	d	c	d	c	d	c	d
dccddd/ddddcc	d	d	d	d	d	d	d	d
dcddcd	d	c	c	d	d	c	c	d
dcdddc/ddcdcd	d	c	d	c	d	c	d	c
dcdddd/ddddcd	d	d	d	d	d	d	d	d
ddcddc	c	d	c	d	c	d	c	d
ddcddd/dddddc	d	d	c	d	d	d	c	d
dddddd	d	d	c	d	d	d	c	d



memory length vs the number of players

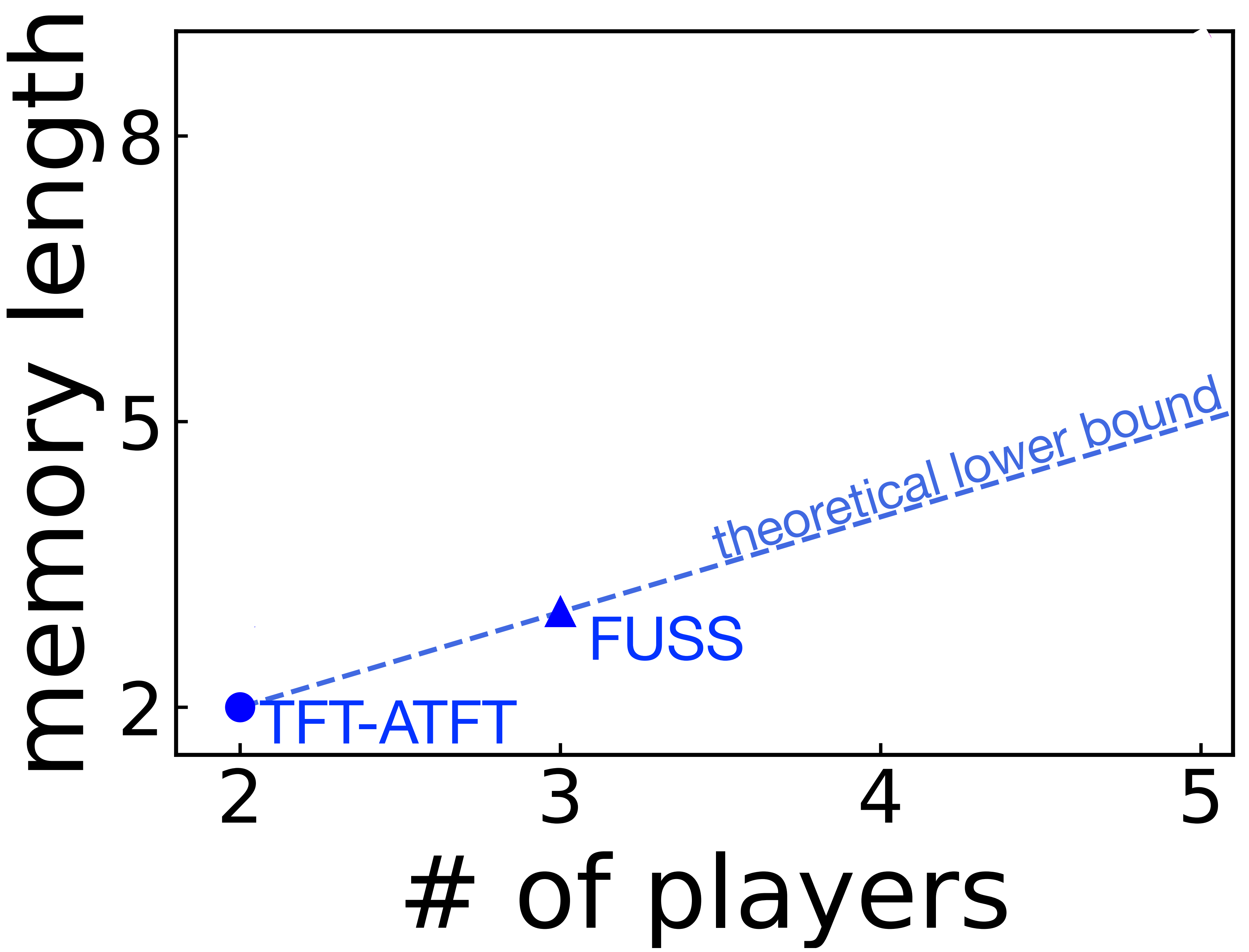
Y. Murase et al., J. Theor. Biol. (2018)

n=2 : TFT-ATFT (m=2)
n=3 : memory-3 friendly rival strategies
...

for general n (>=3), we show

$$m \geq n$$

There is a critical memory length above which friendly rivals may exist.

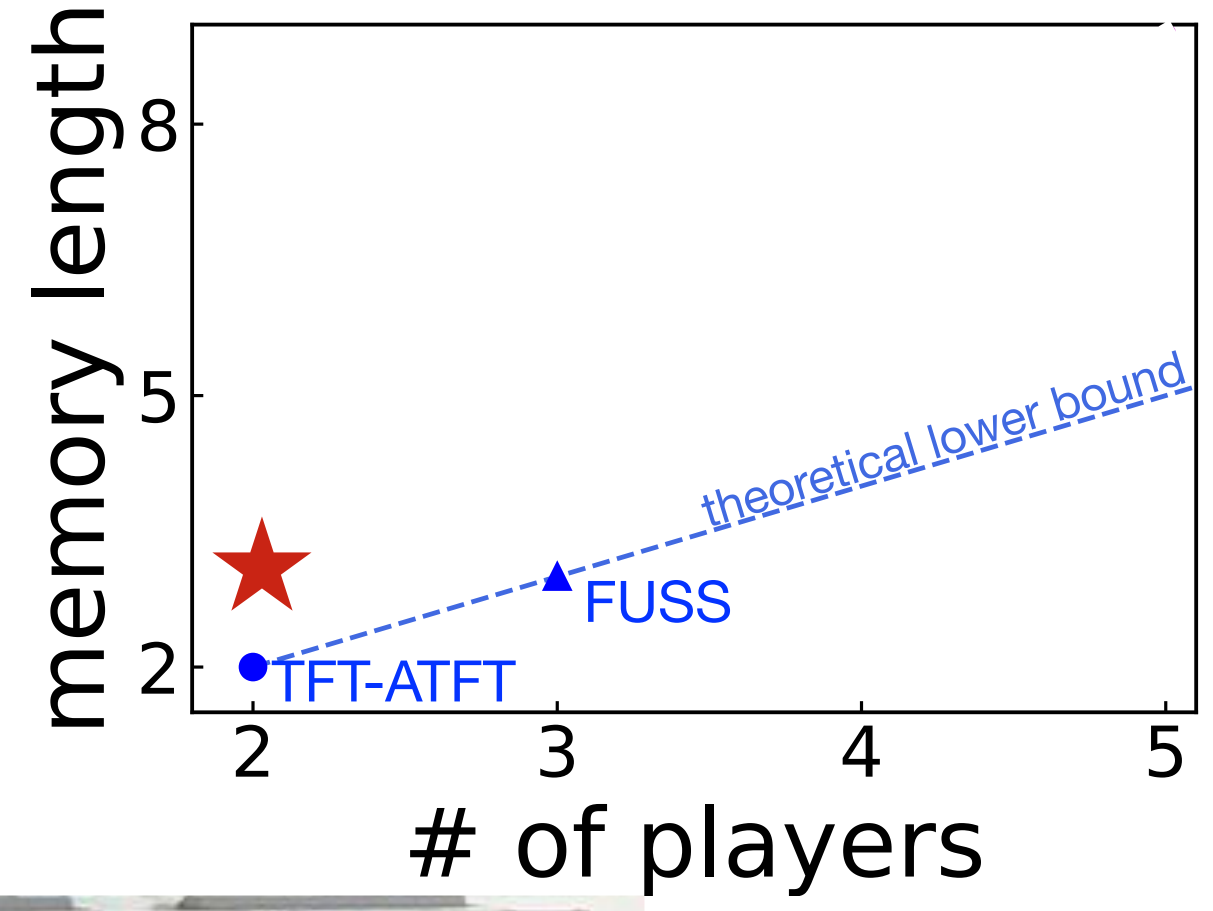


Y. Murase et al., Sci. Rep. (2020)

two-player memory-three strategies

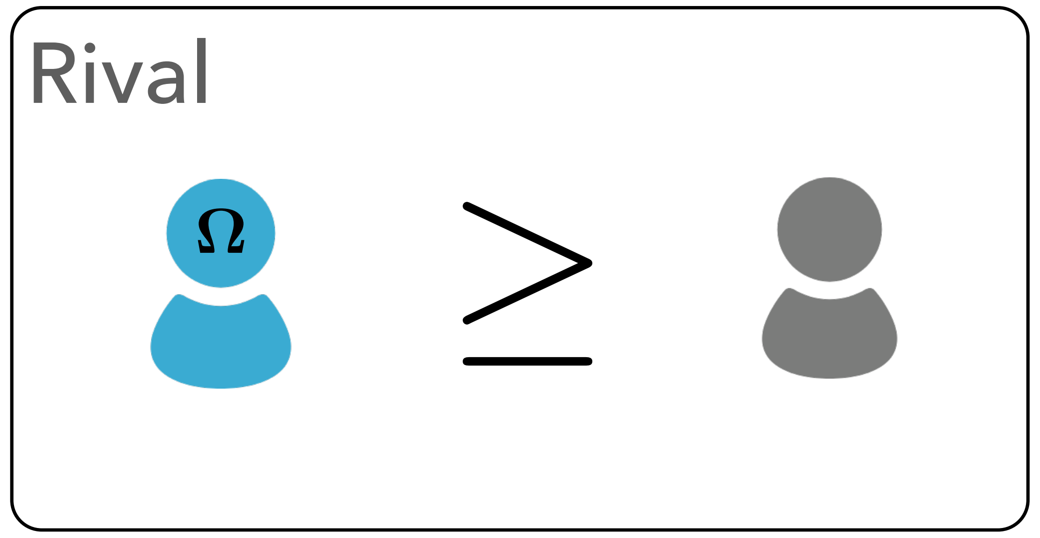
of memory-m strategies: $2^{2^{2m}}$

m=1 : 0 / 256
m=2 : 4 / 65,536
m=3 : ? / 18,446,744,073,709,551,616



Y. Murase et al., J. Theor. Bio. (2018)

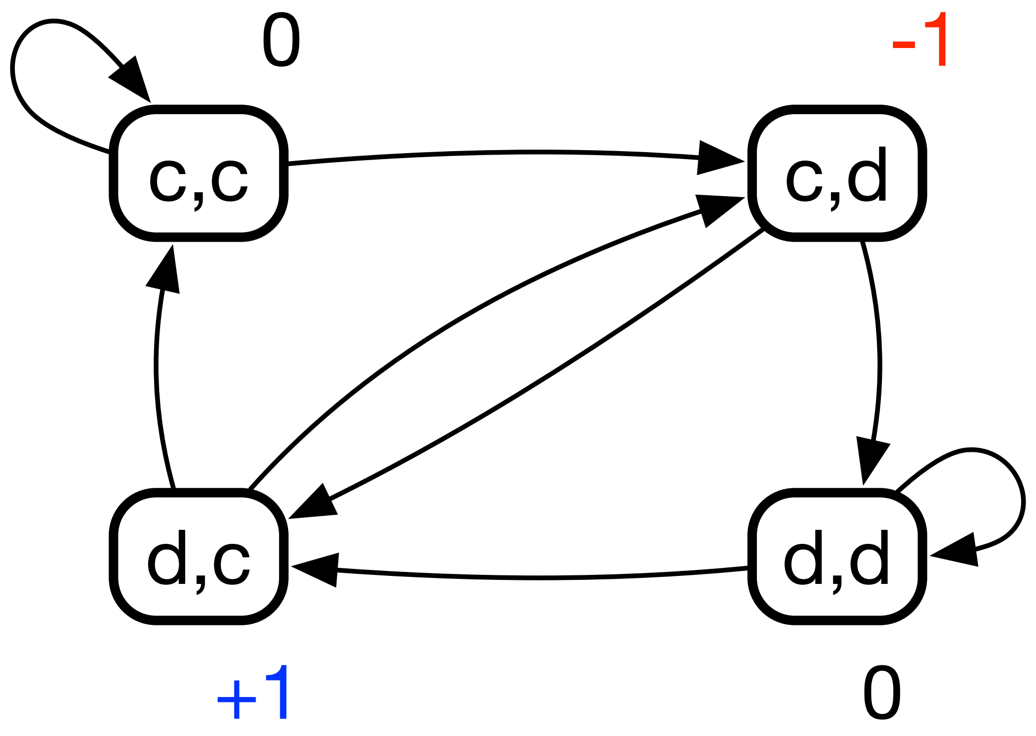
checking rivalry



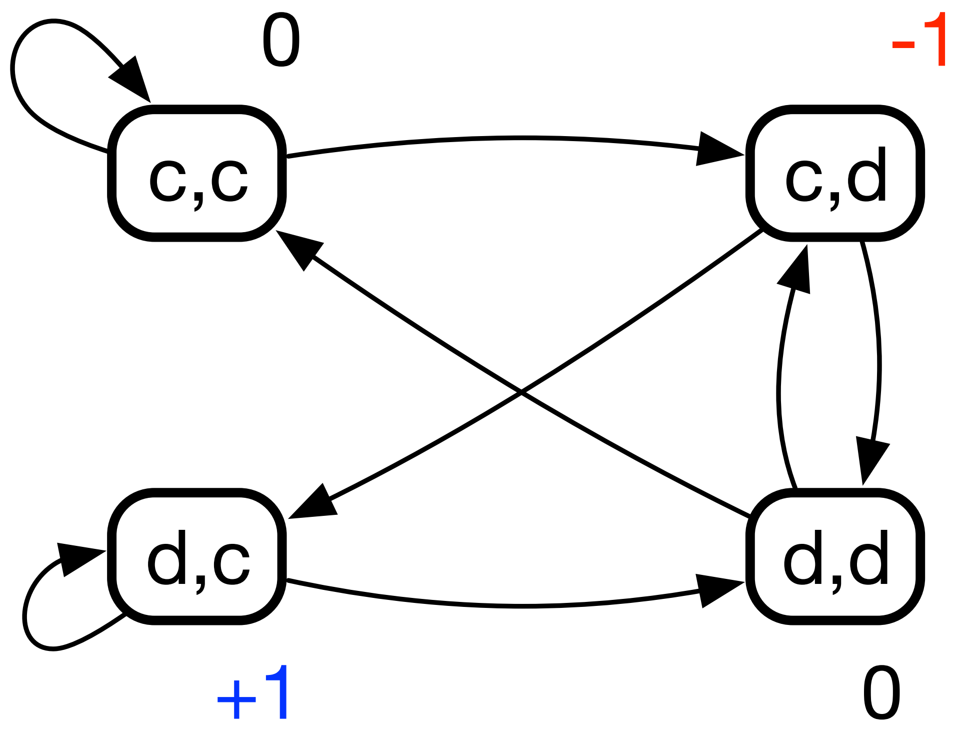
It is guaranteed that the long-term payoff is no less than any of co-players' payoff.

existence of a negative cycle in the state transition graph

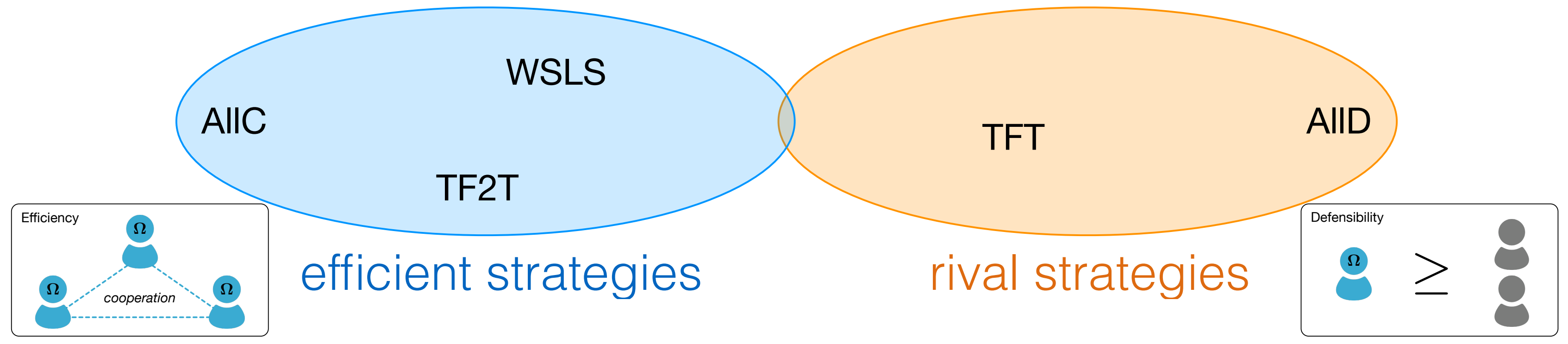
e.g. TFT strategy in 2-person game

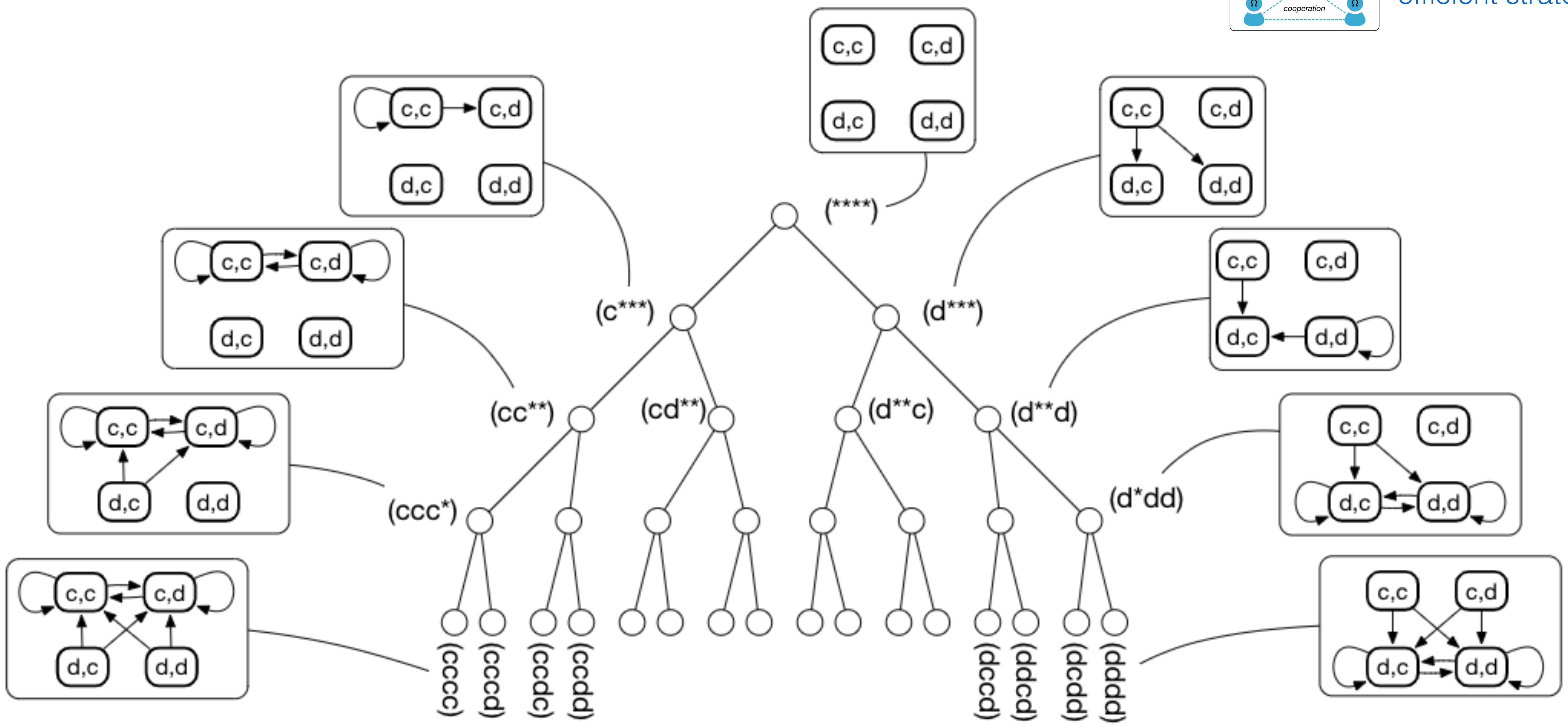


e.g. WSLS strategy in 2-person game



Floyd-Warshall algorithm





戦略を完全二分木で表現する。葉が戦略。ノードが戦略の共通部分に対応

できるだけ早く枝刈りができるように、rivalryとefficiencyを同時にチェックする

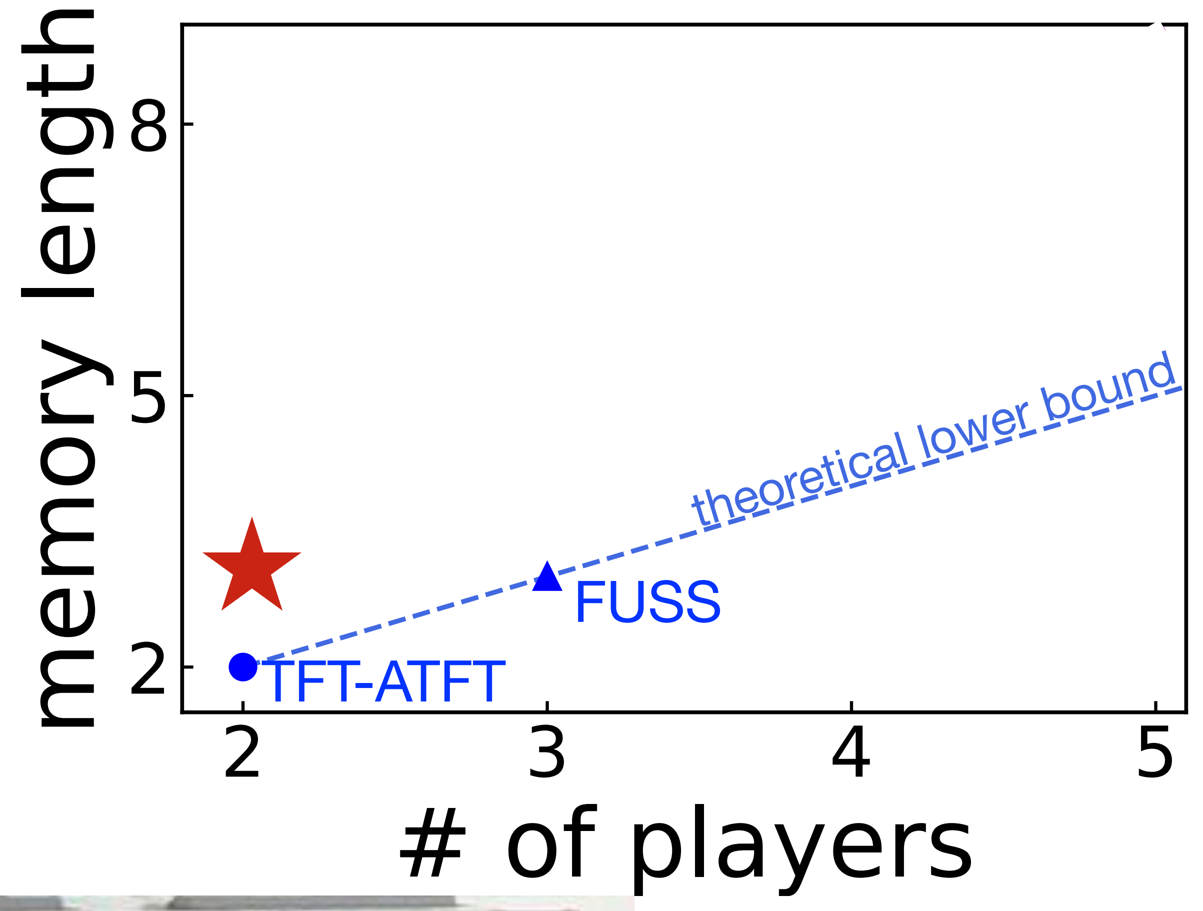
二分木を作るときの順番（どのビットから固定するか）も重要

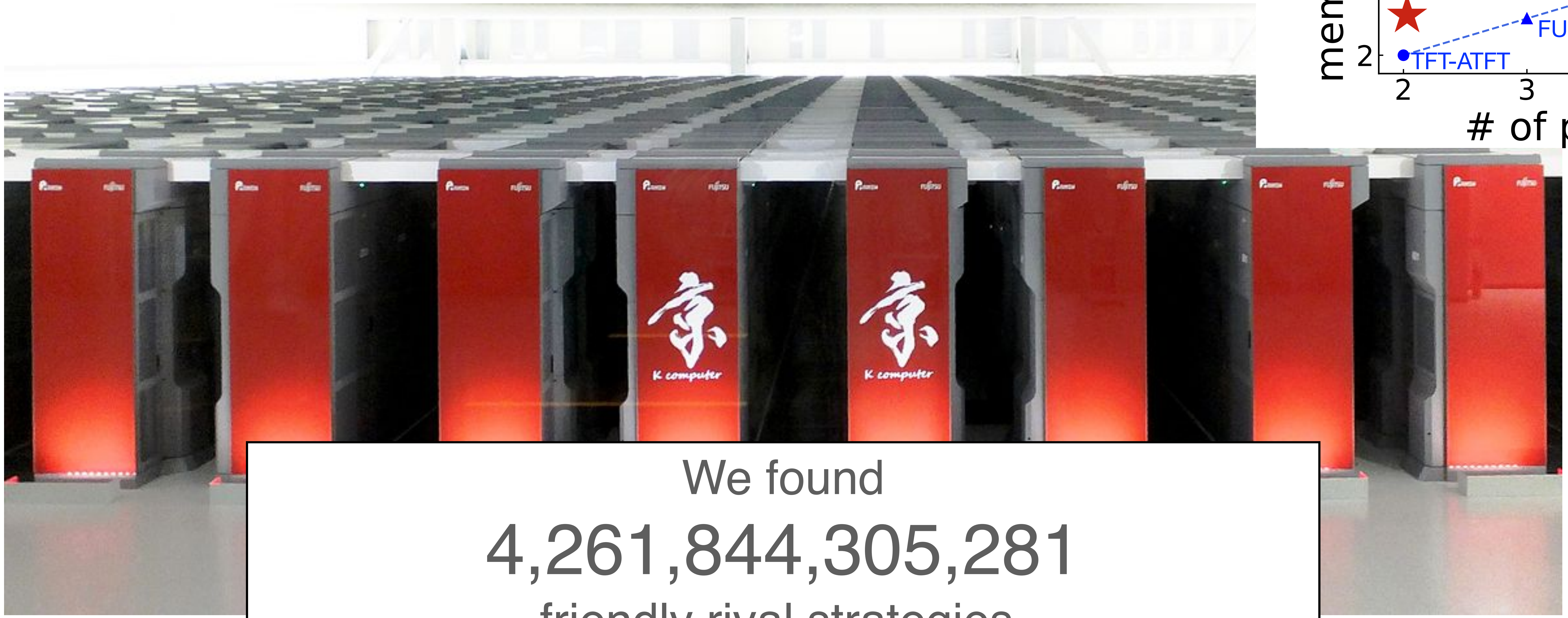
Y. Murase et al., Sci. Rep. (2020)

two-player memory-three strategies

of memory-m strategies: $2^{2^{2m}}$

m=1 : 0 / 256
m=2 : 4 / 65,536
m=3 : ? / 18,446,744,073,709,551,616

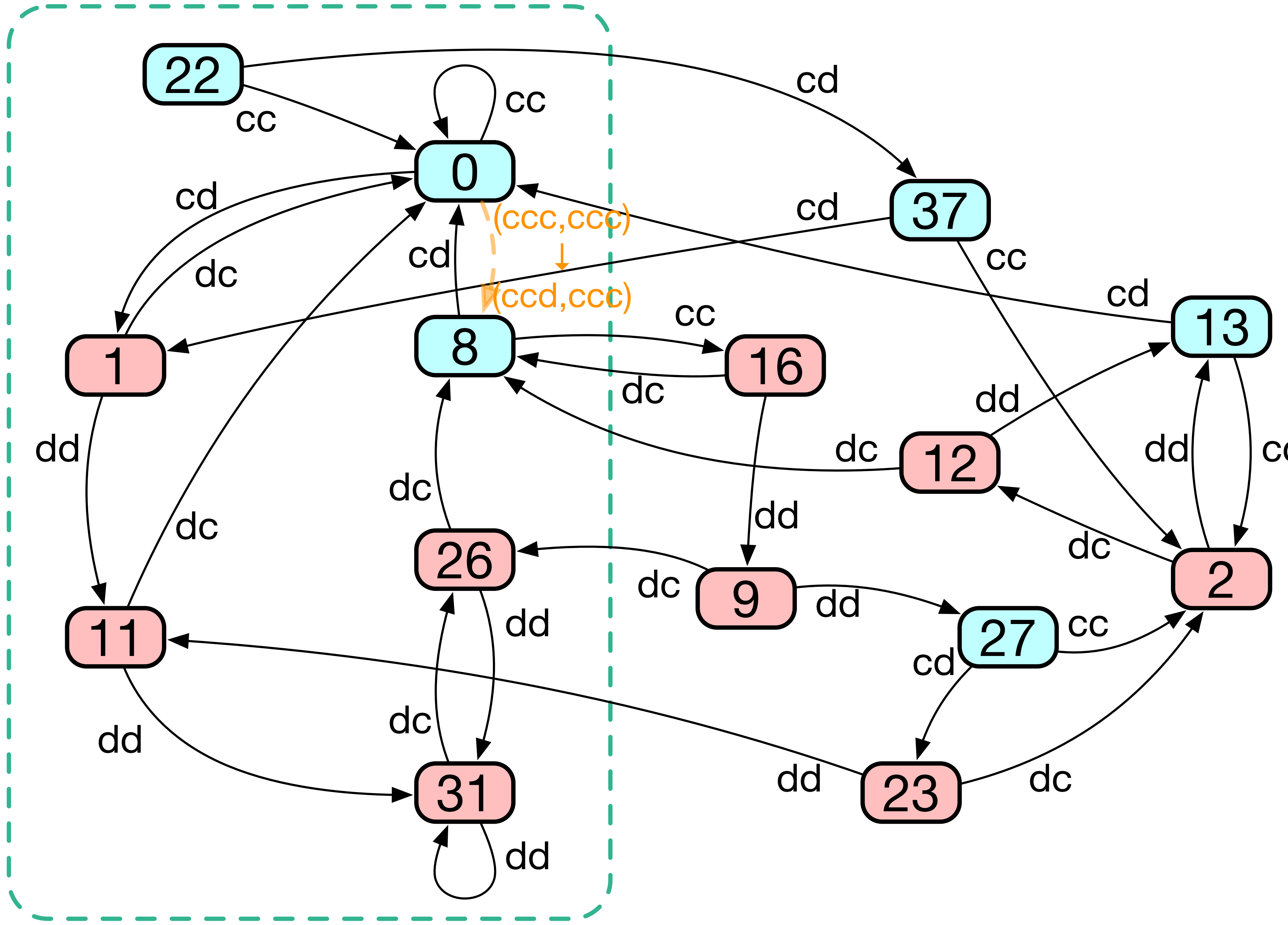


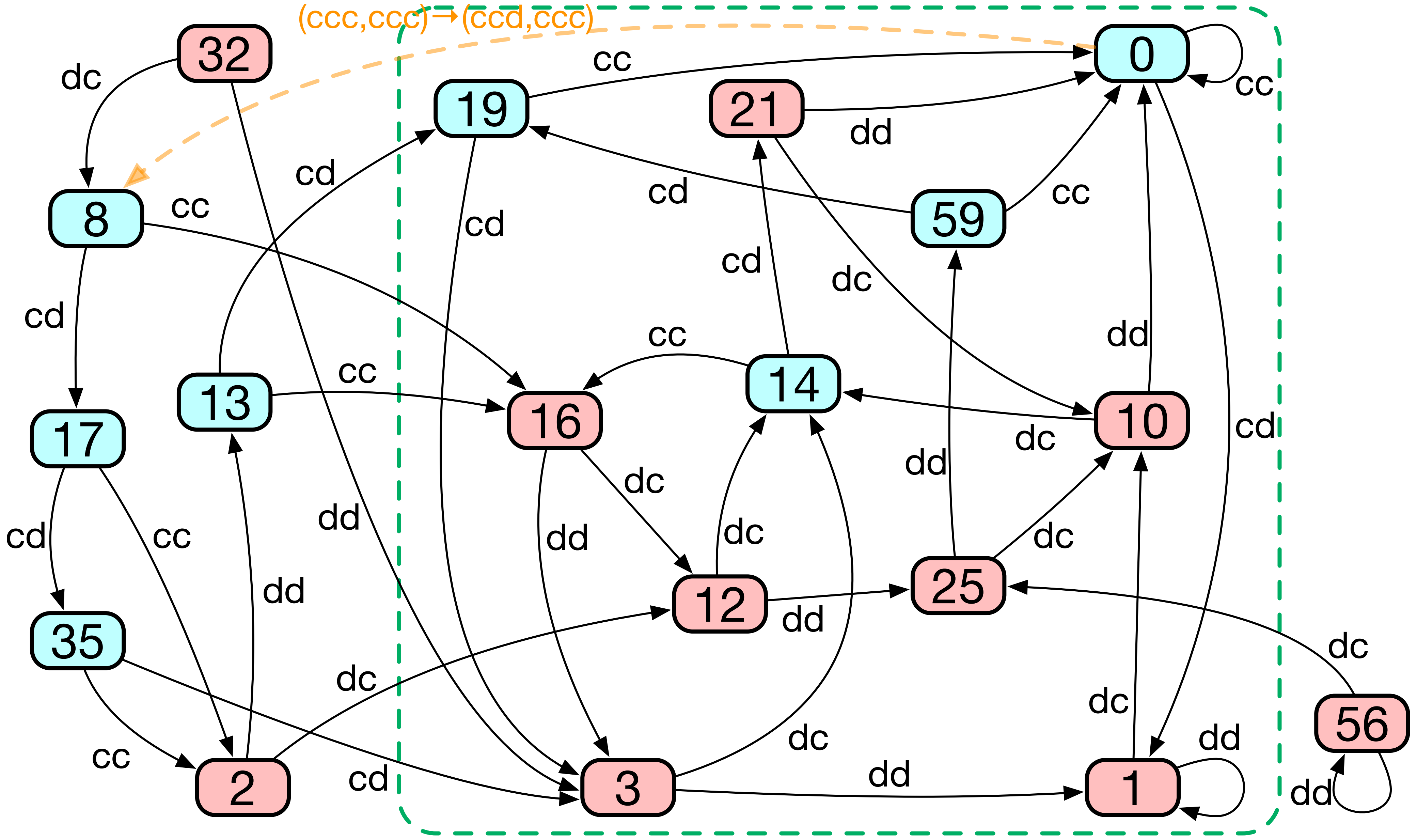


We found

4,261,844,305,281

friendly rival strategies.





most of the strategies are not easy to interpret...

Y. Murase et al., Sci. Rep. (2020)

CAPRI: a simple friendly rival

memory-3 strategy described by the five rules

$A_{t-3}A_{t-2}A_{t-1}$	$B_{t-3}B_{t-2}B_{t-1}$ ccc	ccd	cdc	cdd	dcc	dcd	ddc	ddd
ccc	[1]c	[3]d	d	d	[2,4]c	d	d	d
ccd	[2]c	d	[3]c	d	d	d	d	d
cdc	d	[2]c	d	d	[3]c	d	d	d
cdd	d	d	d	d	d	d	d	d
dcc	[3,4]c	d	[2]c	d	[4]c	d	[4]c	d
dcd	d	d	d	d	d	d	d	d
ddc	d	d	d	d	[4]c	d	[4]c	[4]c
ddd	d	d	d	d	d	d	[4]c	d

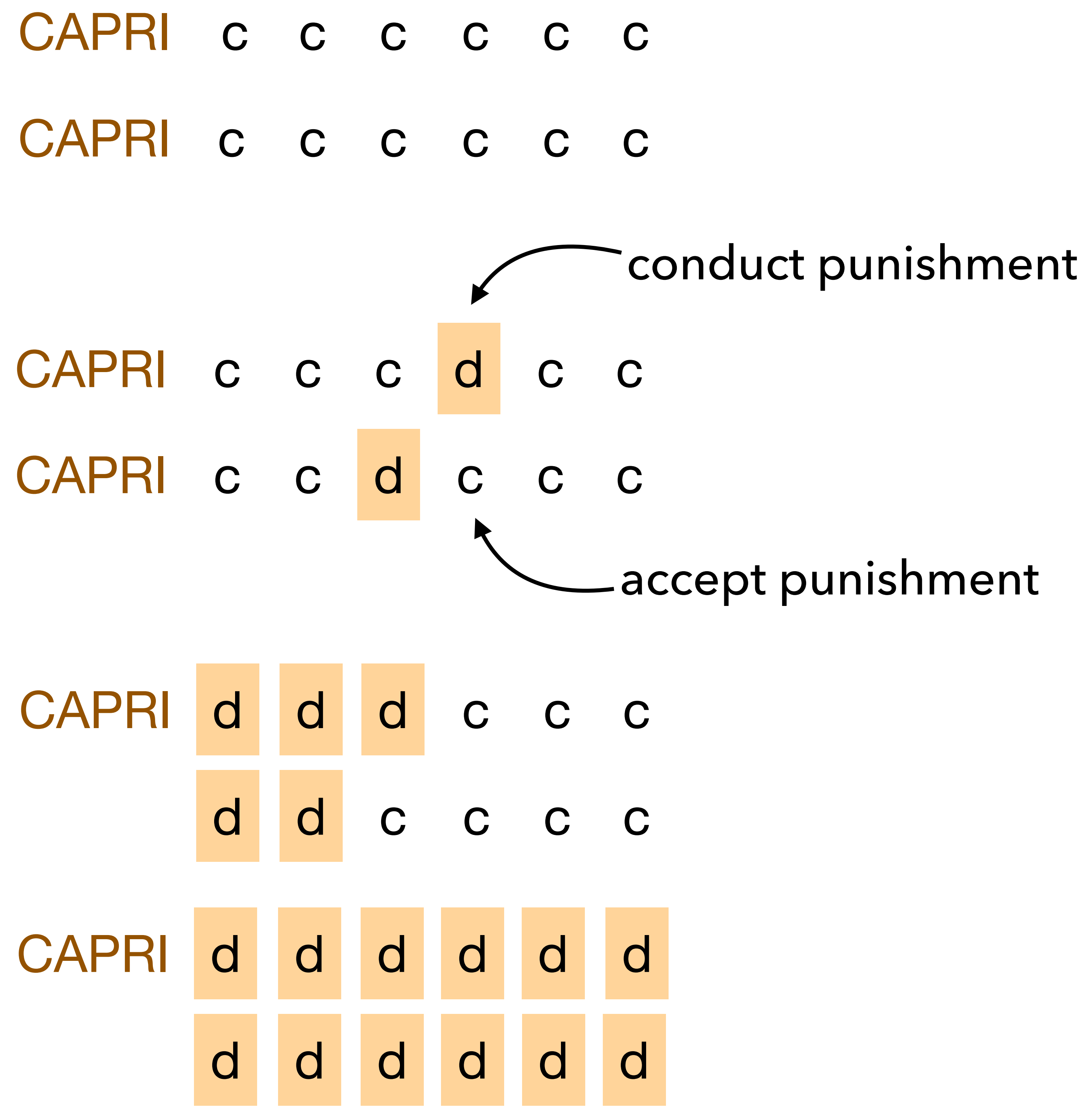
C ooperate at mutual cooperation.

A ccept punishment when you made a mistake.

P unish co-player and then forgive him.

R ecover cooperation when someone cooperated.

I n all the other cases, defect.



CAPRI-n: generalization to n-players game

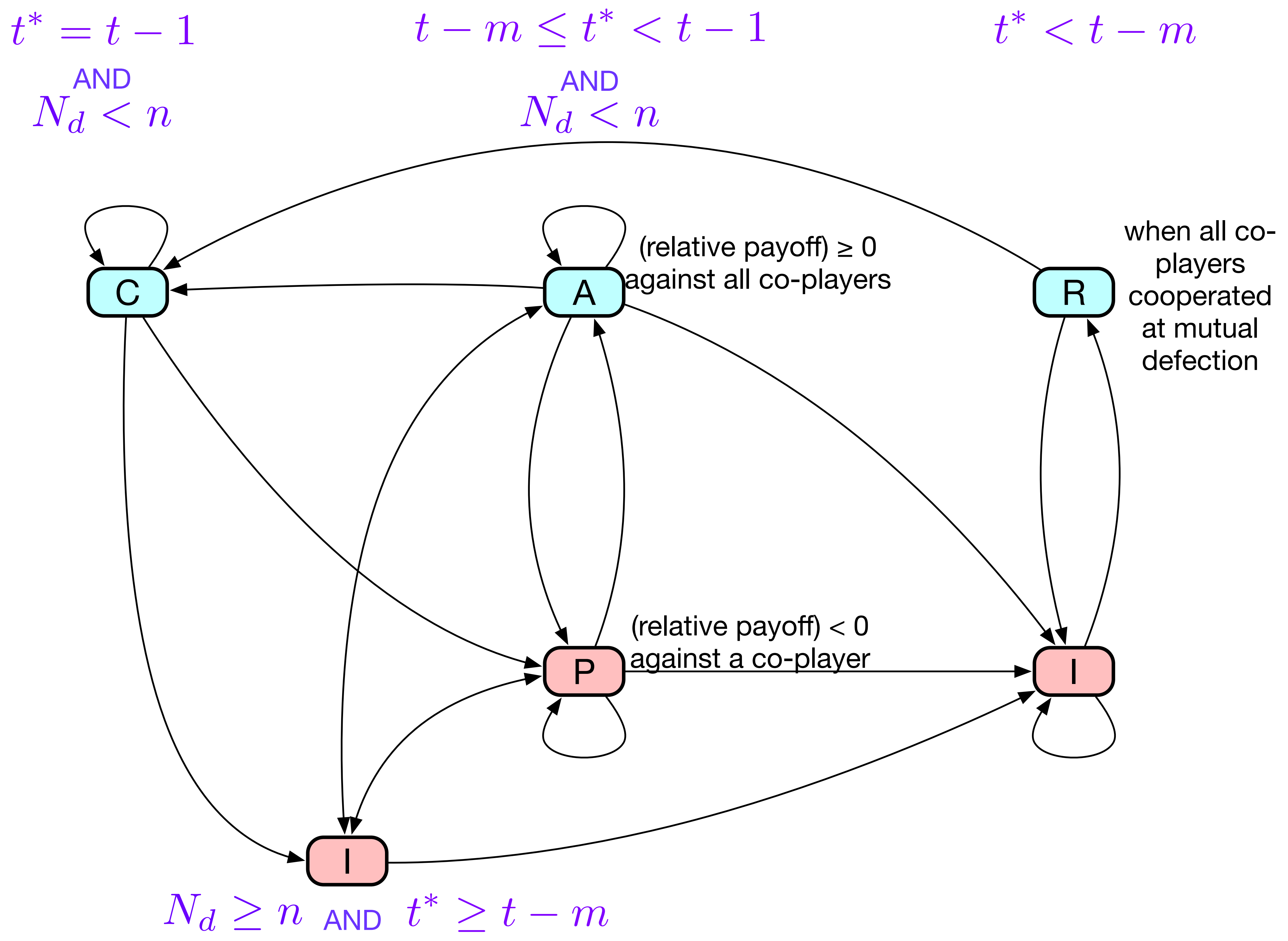
C ooperate at mutual cooperation

A ccept punishment when relative payoff is highest

P unish co-player when relative payoff is lower

R ecover cooperation when the others cooperated

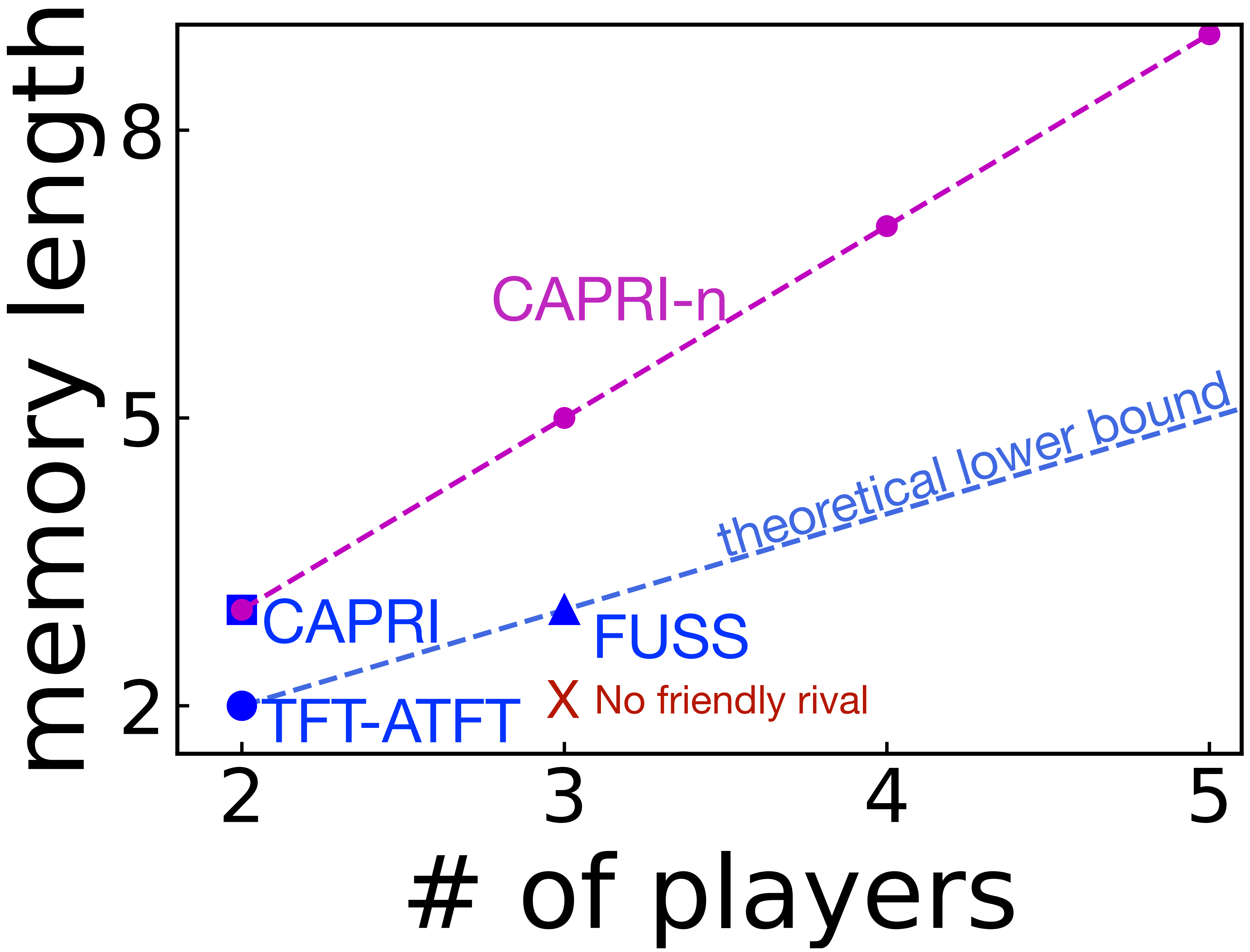
I n all the other cases, defect.



Y. Murase et al. Plos.Comp.Biol. (2021)

of players vs memory length

relationship between memory length *m* and the number of players *n*



$m = 2n - 1$

Y. Murase et al. Plos.Comp.Biol. (2021)

Y. Murase et al. J. Theor. Biol. (2018)

$m \geq n$

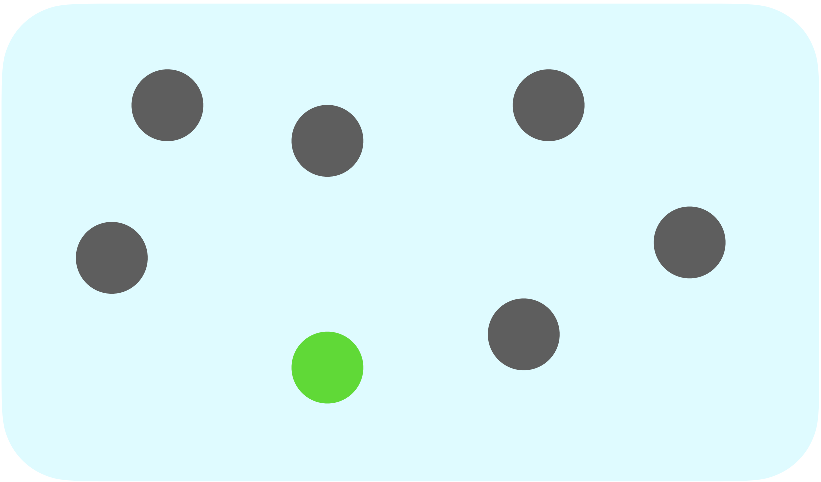
Y. Murase et al. Sci.Rep. (2020)

S.D. Yi et al. J. Theor. Biol. (2017)

Y. Murase et al., Sci. Rep. (2020)
Y. Murase et al., Plos Comp. Biol. (2023)

Do friendly rivals evolve?

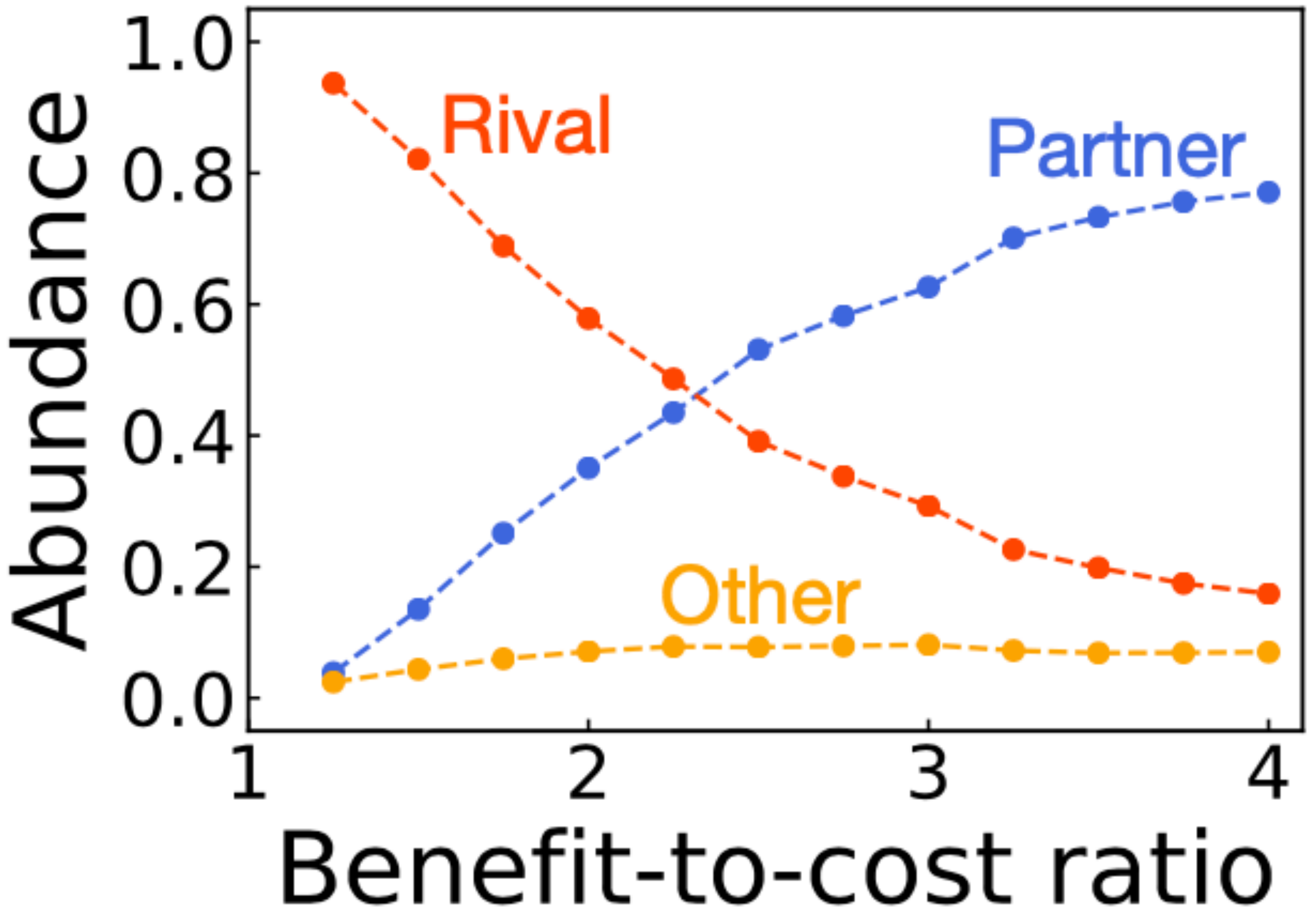
well-mixed population of **N** individuals updated by imitation process



$$f_{x \to y} = \frac{1}{1 + \exp\left[\sigma\left(s_x - s_y\right)\right]}$$

A mutant with a random strategy occasionally appears

simulation with reactive memory-1 species



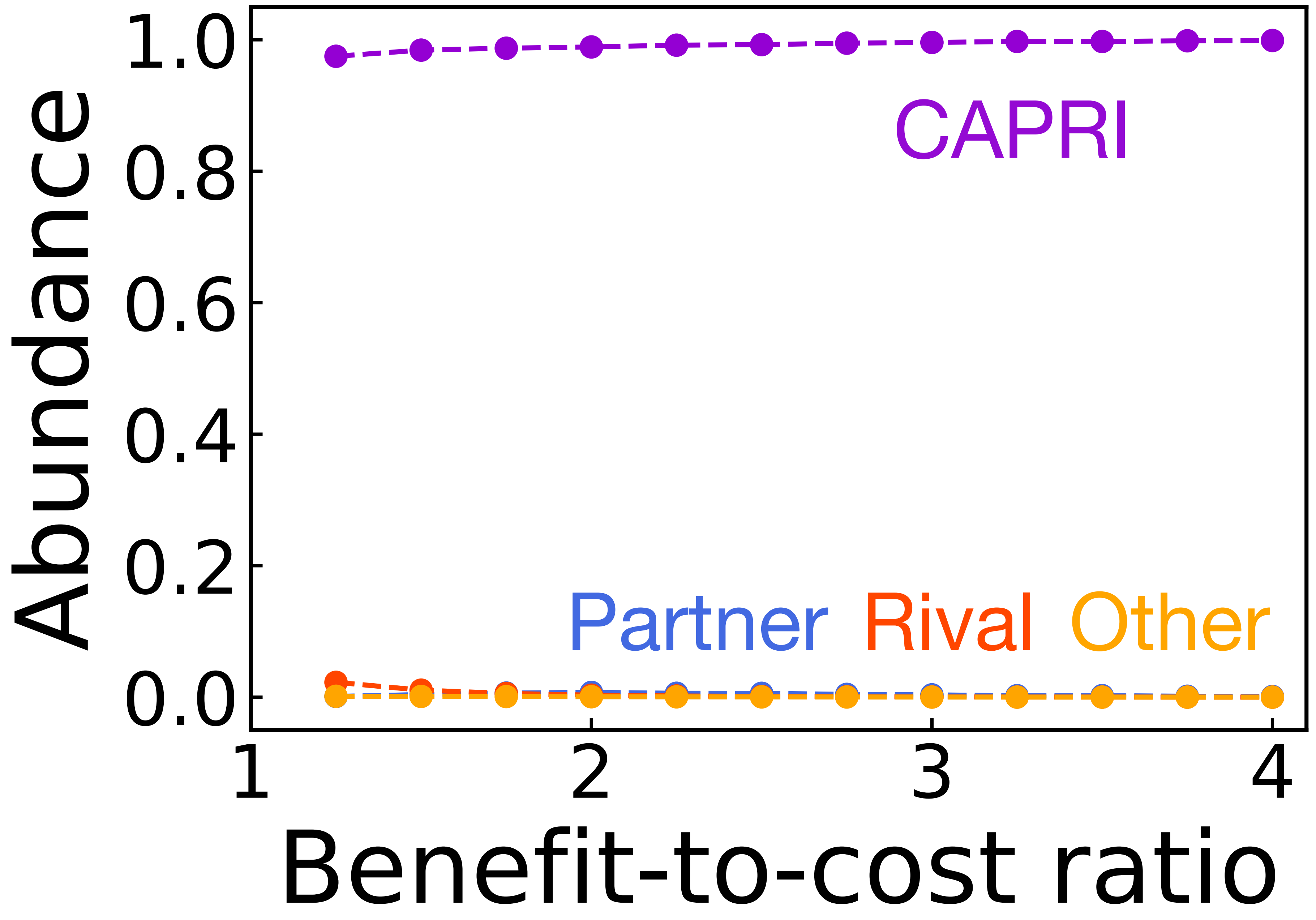
larger N, b/c → partners
smaller N, b/c → rivals

Hilbe et al., Nat.Hum.Behav. (2018)

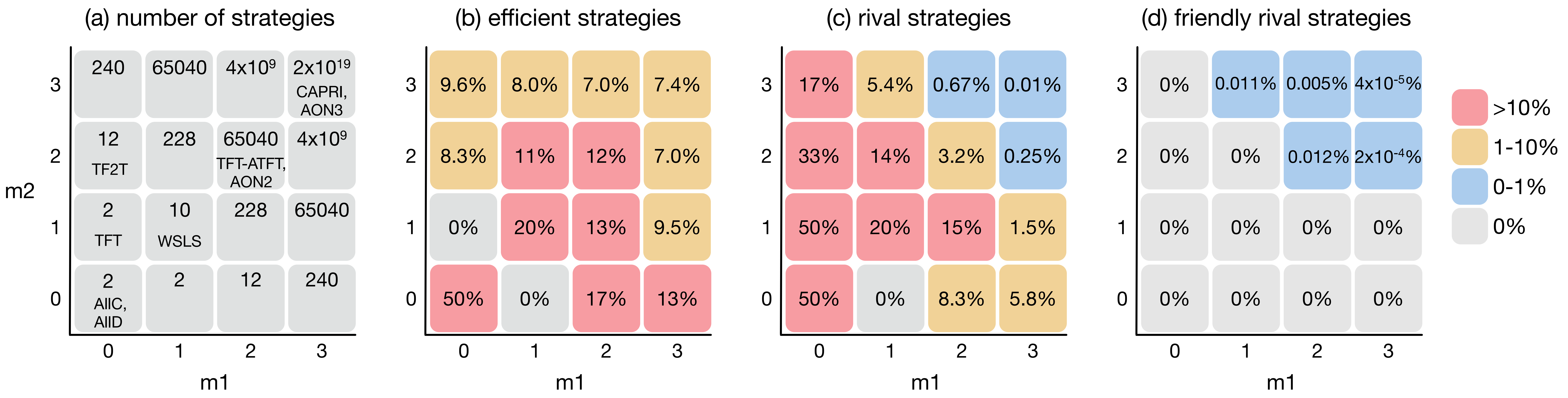
friendly rivals are evolutionarily robust for ***any*** N, b/c, and σ.

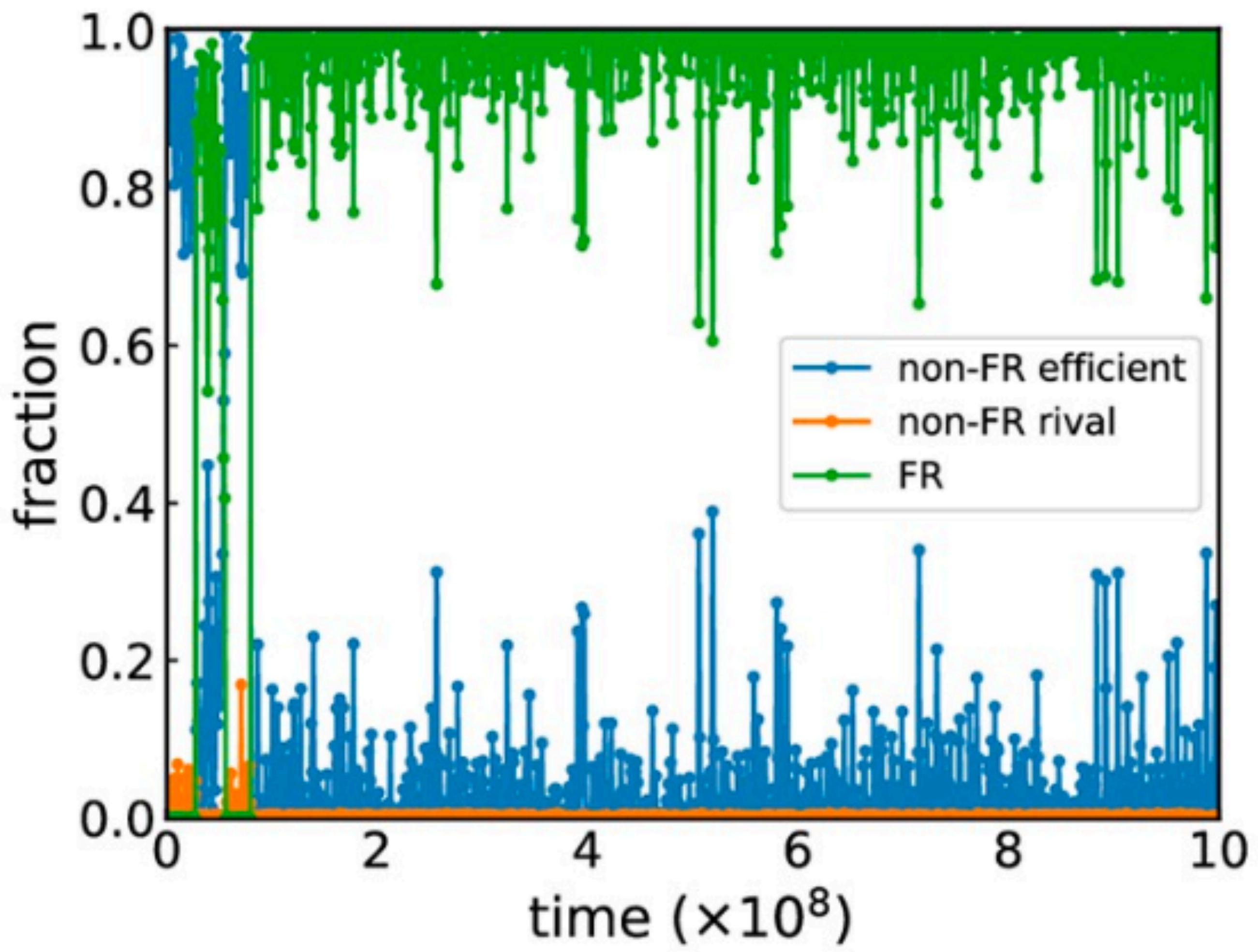
$$\rho \leq \frac{1}{N}$$ for any mutant

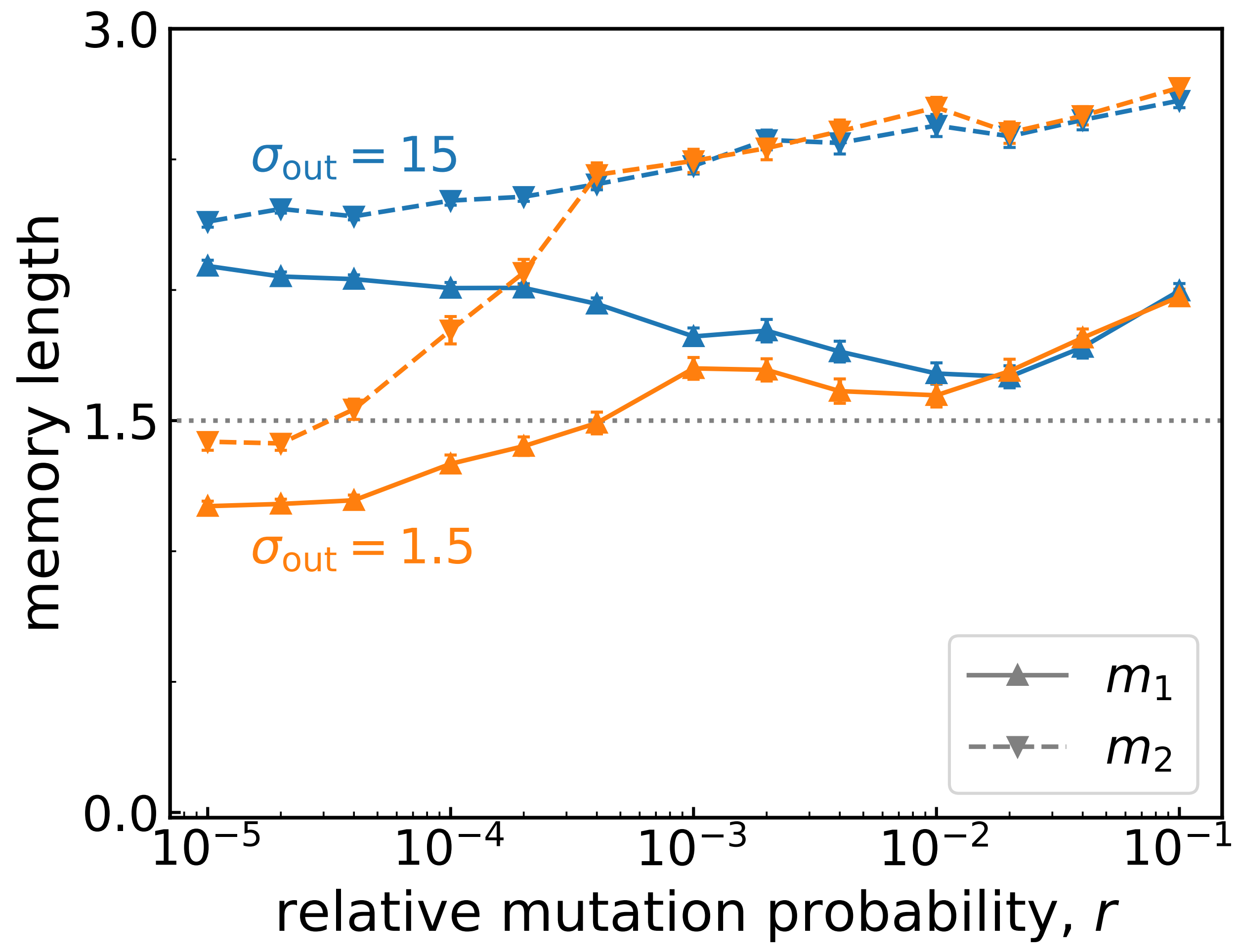
simulation with reactive memory-1 species and CAPRI



Y. Murase et al., Plos Comp. Biol. (2023)





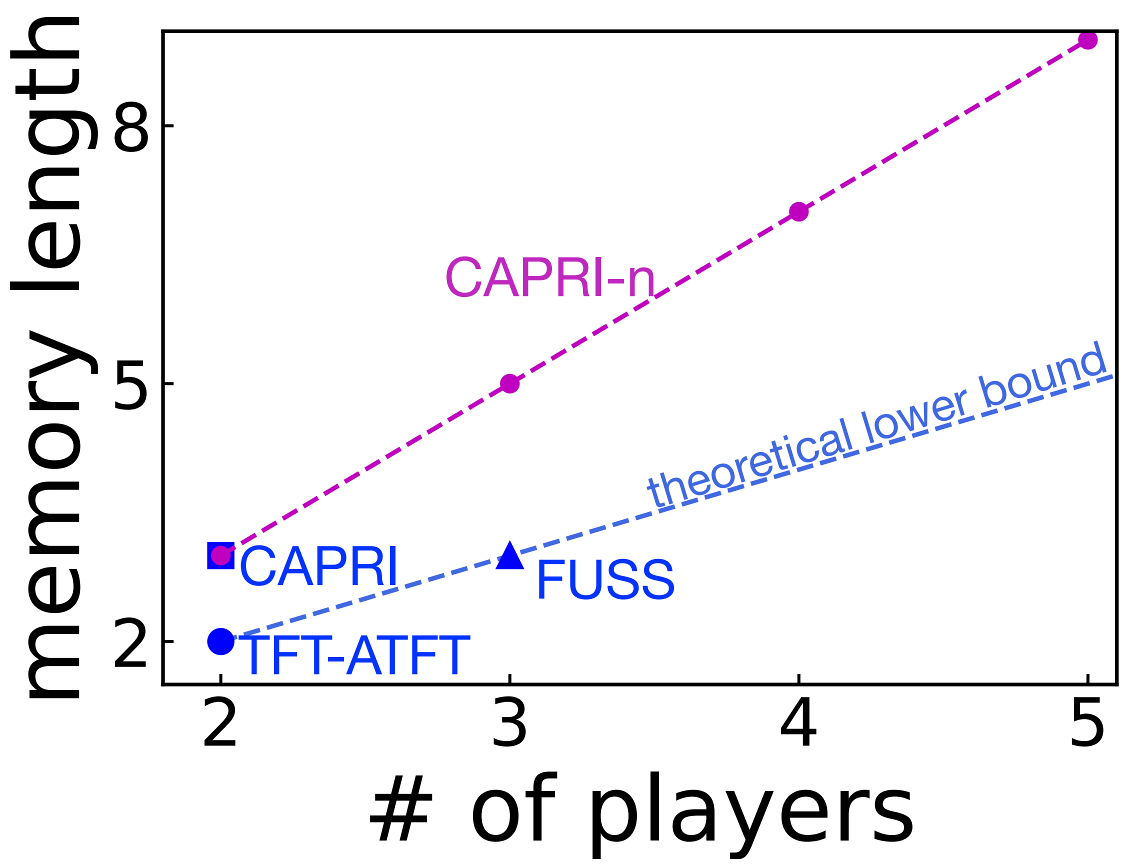


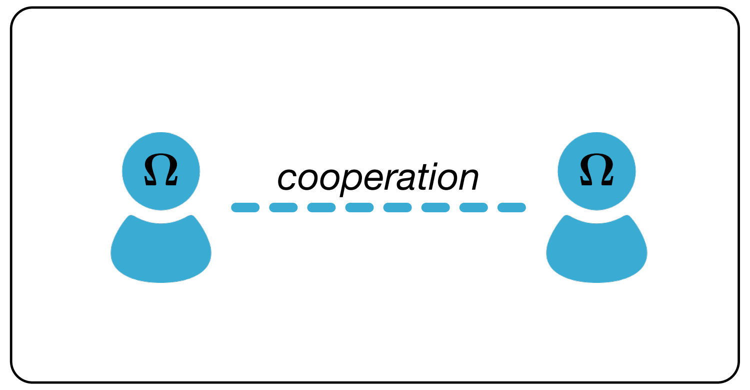
FR players remember the co-player's history better than his or her own.

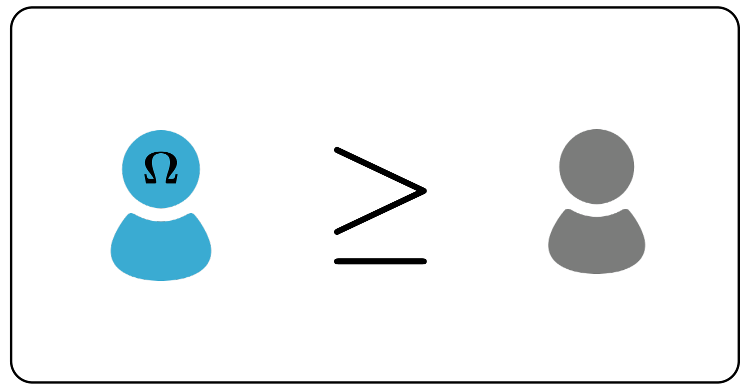
Conclusion

- We found friendly rival strategies in iterated Prisoner's dilemma and public-goods games.
- There is a critical memory lengths (strategic complexity) above which a fundamentally new class of strategies appear.

- Among them, we found ***CAPRI*** that is described by five simple rules. It has a number of desirable properties.
  - cooperation is robust against error (**partner**)
  - never allows any co-player to outperform you (**rivalry**)
  - **evolutionary robust** for any environmental conditions
  - exploit a broad range of strategies (AllC, WSLS), which prevents neutral drift
  - is a deterministic strategy whose actions are independent of the values of benefit or cost of the game
  - not only for PD but for the stag-hunt game and the snow-drift game
    - (2R > T+S, T > S)
  - generalizable to n-players public goods game







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HPCを用いたゲーム理論の将来展望

- これまでは解析的な理論研究や実験がメイン。いかに複雑な社会現象を単純な（手で解ける）数理モデルに落とし込むか
- HPCを用いることで解析可能な問題の範囲が広がる
  - 望ましい特徴を持つ戦略を大規模に探索する（公理的アプローチ）
  - 利得の計算が簡単でない場合の解析（進化的アプローチ）
- ありうる応用
  - 人間行動、心理的傾向や文化に見られるパターンを進化的観点から説明する
  - 社会システムのデザイン。（例：オンラインシステムで評判をどのように共有するべきか）
- 現状
  - まだ黎明期。手法が系統的に確立しているわけではなく、適切な問題を見つけ、個別に計算手法を開発
  - 基本的に embarrassingly parallel。単純な並列でも取り組むべき研究課題は多く、重要度の高い課題から取り組んでいる