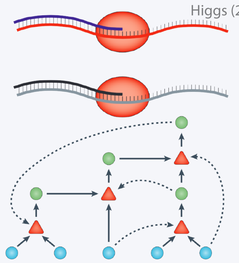
Alexandre Champagne-Ruel and Paul Charbonneau. **A Mutation Threshold for Cooperative Takeover**. 2021 – submitted for publication

Cooperation and the Origin of Life

In the RNA world theory, **polymerase ribozymes** replicating other unrelated strands can be considered a form of cooperation.

Likewise, catalysis of other components in an **autocatalytic set** represents a cooperative behavior.

Cooperation does not imply agency!



	Cooperate	Defect
Cooperate	R 3	S 0
Defect	T 5	P 1

ALLC : always cooperate
ALLD : always defect
TFT : reciprocal cooperation ("Tit-for-Tat")
RND : random

The **Prisoner's Dilemma** has been extensively studied — namely in a (micro)biological context.

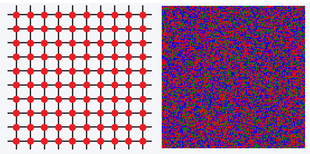
Its extension, the **Iterated PD**, can be used to model the repeated interaction of individuals.

While the PD's Nash equilibrium is to always defect, the **strategy "Tit-for-Tat"** has been shown to dominate against a wide range of opponents — but performs poorly in noisy environments.

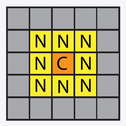
Modeling the emergence of cooperation

1

We can model the **dynamics of cooperative behavior** in an evolutionary framework using a Cartesian lattice, onto which we distribute players. Each player behaves according to one of the strategies outlined above.



	0	1	5	···	3	3	1	52
TFT	C	D	D	···	C	C	C	
RND	D	D	C	···	C	C	D	
	5	1	1	···	3	3	5	50

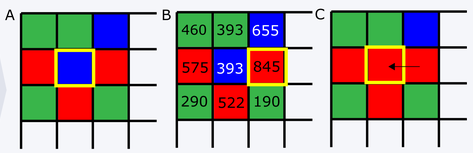


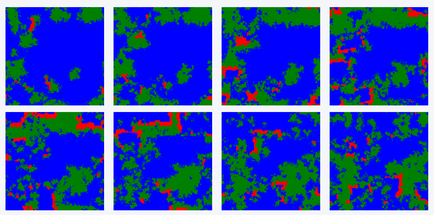
2

At each iteration of the model, every player gets to play **IPD games of *M* rounds** against each one of its neighbors. The score of each PD game is accounted for in the final score.

3

The score of each player is then **compared** against their neighbor's score. Players adopt the strategy of the highest scoring neighbor, or keep theirs otherwise.

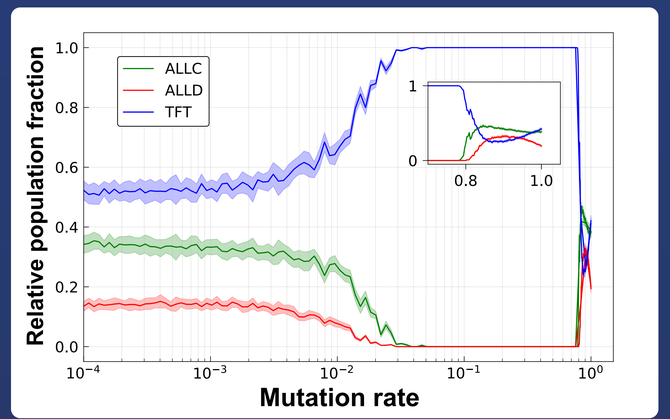




4

This results in a complex evolutionary dynamics over time. **Length of interaction** and **spatiality** are important parameters that impact the system's dynamics.

Mutations promote cooperation in an evolutionary setting.



Life could be more resilient than we assume,

and the habitable zone could be wider than we think.

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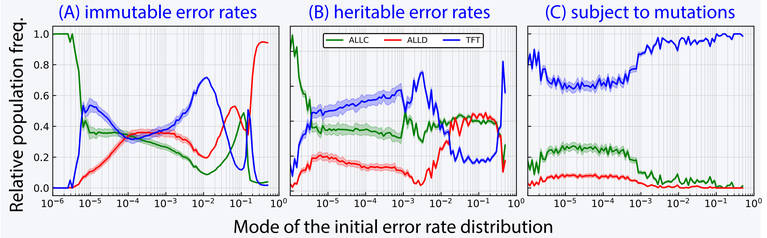
Error rate and the triad of evolutionary biology

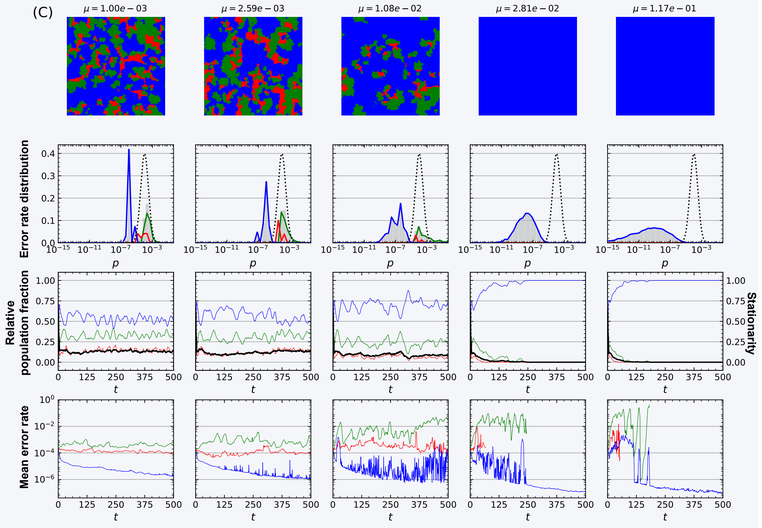
We can assume that prebiotic environments incur **stochastic perturbations**. We thus sought to investigate whether cooperation could emerge in an evolutionary, noisy environment. Introducing an **error rate** where the players make mistakes with a probability *p*, we carried out simulations that included various elements of evolutionary



While cooperators have a slight advantage in noisy environments when *p* is small (A), making the error rate heritable (B) increases the domination of the strategy TFT. However, when error rates are also subject to mutations, **TFT's predominance increases significantly**.

The transition towards a TFT-mediated cooperation

As we increase the mutation rate (central figure), the system reaches a critical point where TFT completely invades the lattice — **establishing a robust cooperative dynamics** — for a wide range of parameter space. Near the critical point, outlined below, the system experiences important fluctuations reminiscent of phase transitions.



A robust dominance of cooperation as soon as the evolutionary biology triad is included in the system suggests that **life could indeed emerge in stochastic, violent environments** — such as highly irradiated M-dwarfs, etc. These conclusions challenge our traditional **conception of the habitable zone**, and consequently the way we search for life in the Universe.

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