

INTERNSHIP PROPOSAL

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Internship location : ESPCI, 10 rue Vauquelin, 75005 Paris

Thesis possibility after internship: yes

Funding: maybe

Statistical physics of life-like chemical systems

How does life emerge from chemistry? The usual answer is Darwinian evolution, but this only shifts the question: how does Darwinian evolution itself emerge from simpler physical processes [1]? Evolution requires entities that reproduce, transmit their state (heredity) and vary. Nearly all origin-of-life scenarios obtain reproduction from autocatalysis, in which a set of molecules catalyzes its own formation. Autocatalysis, however, imposes demanding stoichiometric, dynamical and geometrical constraints [2]. It is rare in organic chemistry and, in biology, is achieved only through complex enzymes, making it more a phenomenon to be explained than a natural starting point. Moreover, it does not by itself provide extensive heritable diversity.

We have proposed an alternative mechanism based on three physical ingredients [3]:

- *Multistability*: a network of coupled reactions sustains a very large number of stable nonequilibrium steady states that differ only in their relative concentrations;
- *Spatial coupling* (diffusion): a state spreads to neighboring regions at the expense of other states;
- *Noise*: fluctuations cause stochastic transitions between states.

A region in a given state can convert its neighbors to the same state (reproduction with heredity), states diversify as they proliferate (variation), and they compete for space rather than for chemical resources (selection). With only 50 reactions, the model has over 500,000 heritable states, a number that grows exponentially with network size. The hallmarks of Darwinian dynamics thus emerge without autocatalysis. We further showed that these systems can learn and adapt to complex time-dependent environments [4].

The goal of the internship is to study whether the same mechanism can produce other hallmarks of life, including for instance:

- *Computation and memory*: can such systems perform computations on environmental inputs?
- *Cell-like organization*: can domains of different compositions form stable, compartment-like structures?
- *Morphogenesis*: can these systems form and exploit spatial patterns to adapt?

The work will combine analytical approaches (nonequilibrium statistical physics, stochastic processes, dynamical systems) with numerical simulations. The project is theoretical, but our models are designed with experimental realizations in mind, and the student may contribute to their implementation.

References:

- [1] N. Goldenfeld & C. Woese (2011). *Life is physics: evolution as a collective phenomenon far from equilibrium*. Annu. Rev. Condens. Matter Phys., 2 : 375-399.
- [2] Y. Sakref & O. Rivoire (2024). *Design principles, growth laws, and competition of minimal autocatalysts*. Comm. Chem. 7 : 239.
- [3] G. Bunin & O. Rivoire (2025). *Evolutionary features in a minimal physical system: diversity, selection, inheritance, and adaptation*. Proc. Natl. Acad. Sci. USA, 122 : e2425753122.
- [4] O. Rivoire & G. Bunin (2026). *Learning to outgrow the competition: Reaction–diffusion systems that adapt to time-dependent environments*. Proc. Natl. Acad. Sci. USA, 123 : e2605428123.