Evolution of complexity… New biology? New physics?

Concluding (rambling) thoughts

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Evolution of Complexity from the Statistical Physics Perspective

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- ***All science is either physics or stamp collection***

  Attributed to Ernest Rutherford
- ***Life is physics: evolution as a collective phenomenon far from equilibrium***

  Nigel Goldenfeld, Carl Woese 2010
- ***Ask not what physics can do for biology:***

  Ask what biology can do for physics

  Stanislaw Ulam (from Nigel Goldenfeld's talk)

- ***The fact that the world is comprehensible is a miracle***

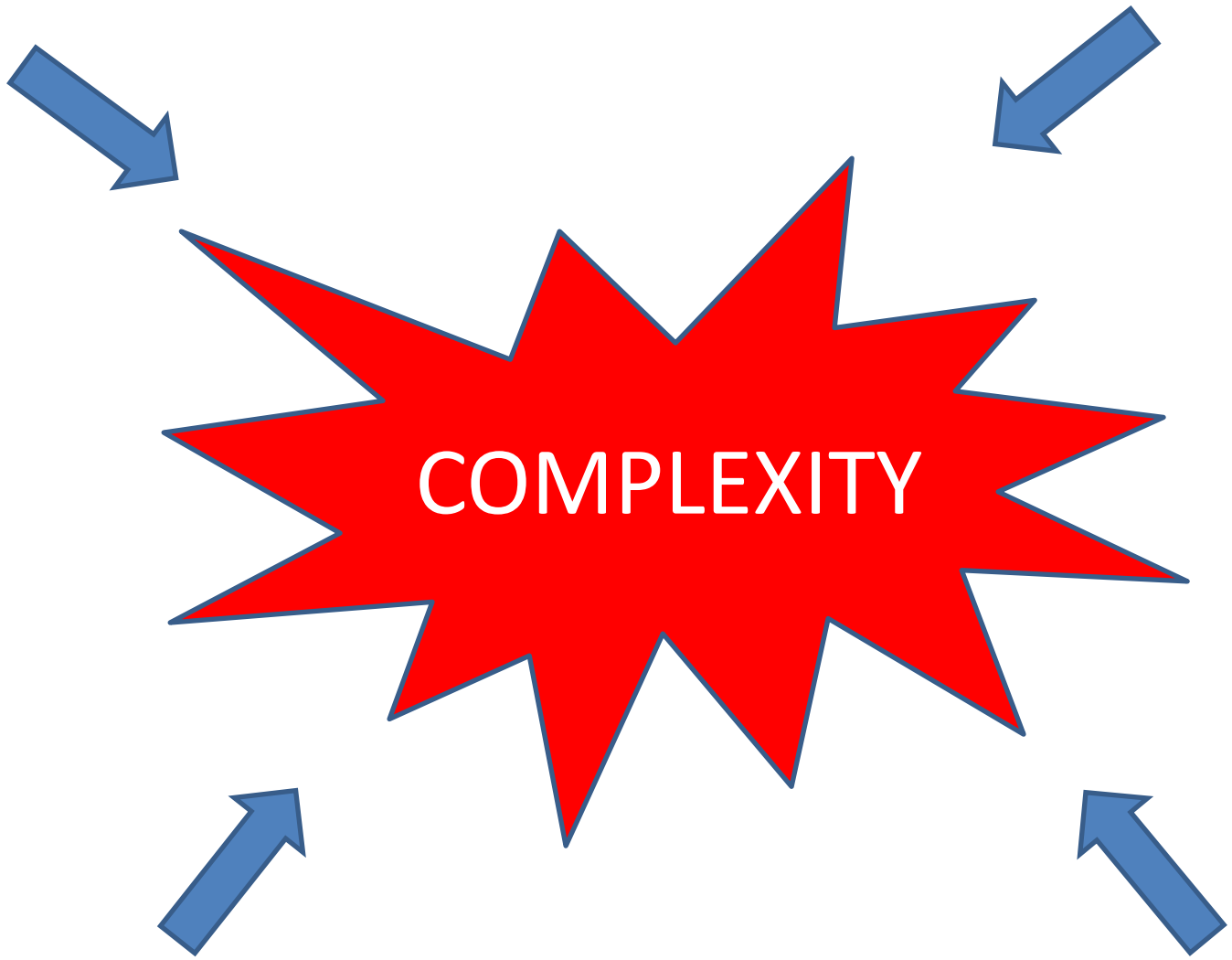
  Albert Einstein

Different dimensions of complexity

- Organizational: structure of biological entities at all levels – nucleic acids/proteins-cells-organisms-populations-biocenoses
- Functional: regulatory circuits, resource allocation, phenotypic plasticity…
- Evolutionary: multiple paths, complex fitness landscapes, biological conflicts, cooperation…
- **Renormalizability – same principles – and often, formalisms - across scales**

Physics – thermodynamics/stat mechanics/spin glasses…

Game theory



Biology/evolution

Learning

General principles of system evolution/ learning: Why is the World comprehensible?

- P1. **Loss function (optimization)**. In any evolving/learning system, there exists a loss function of time-dependent variables that is minimized during evolution.
- P2. Hierarchy of scales. Evolving systems encompass multiple dynamical variables that change on different temporal scales.
- P3. Frequency gaps. Dynamical variables are split among distinct levels of organization separated by sufficiently wide frequency gaps - substantially different characteristic time scales/change rate.
- P4. Renormalizability. Across the entire range of organization levels of evolving systems, a statistical description of faster-changing (higher-frequency) variables is feasible through the slower-changing (lower-frequency) variables.
- ***P1-P4 – conditions for a universe observability; P5-P7 – high complexity/life***
- P5. Extension. Evolving systems have the capacity to recruit additional variables that can be utilized to sustain the system and the ability to exclude variables that could destabilize the system.
- P6. Replication and elimination. Evolving systems replicate and eliminate information-processing units (IPUs) on every level of organization.
- P7. Information flow. In evolving systems, slower-changing levels absorb information from faster-changing levels during learning and pass information down to the faster levels for prediction of the state of the environment and the system itself.

Vanchurin, Wolf, Katsnelson, EK, PNAS 2022

Conjecture

Given P1-P4, any observable universe will show substantial complexity

Thus, an observable universe will never be boring!

(Daniel Czegel)

Conjecture

Is P1 sufficient to explain all evolution – life and beyond?
That is, are all principles of evolution emergent with respect to the existence of a loss function/optimization?

Universality in Biology

- Collective phenomena
- Multilevel learning/selection – hierarchy
- Renormalizability
- Maximum entropy principle
- Frustration/conflict/trade-offs
- Phase transitions

Complexity vs Universality

- Universality simplifies
- But… there is **A LOT** of stochasticity in nature in general and in biology in particular, and it can make “constructive” contributions to the evolution of complexity
- Moreover, optimization over many variables can be efficient **ONLY** through stochastic algorithms (eg stochastic gradient descent) – randomness of mutations and recombination is essential for evolution

Stochastic thermodynamics of systems far from equilibrium

(David Wolpert)

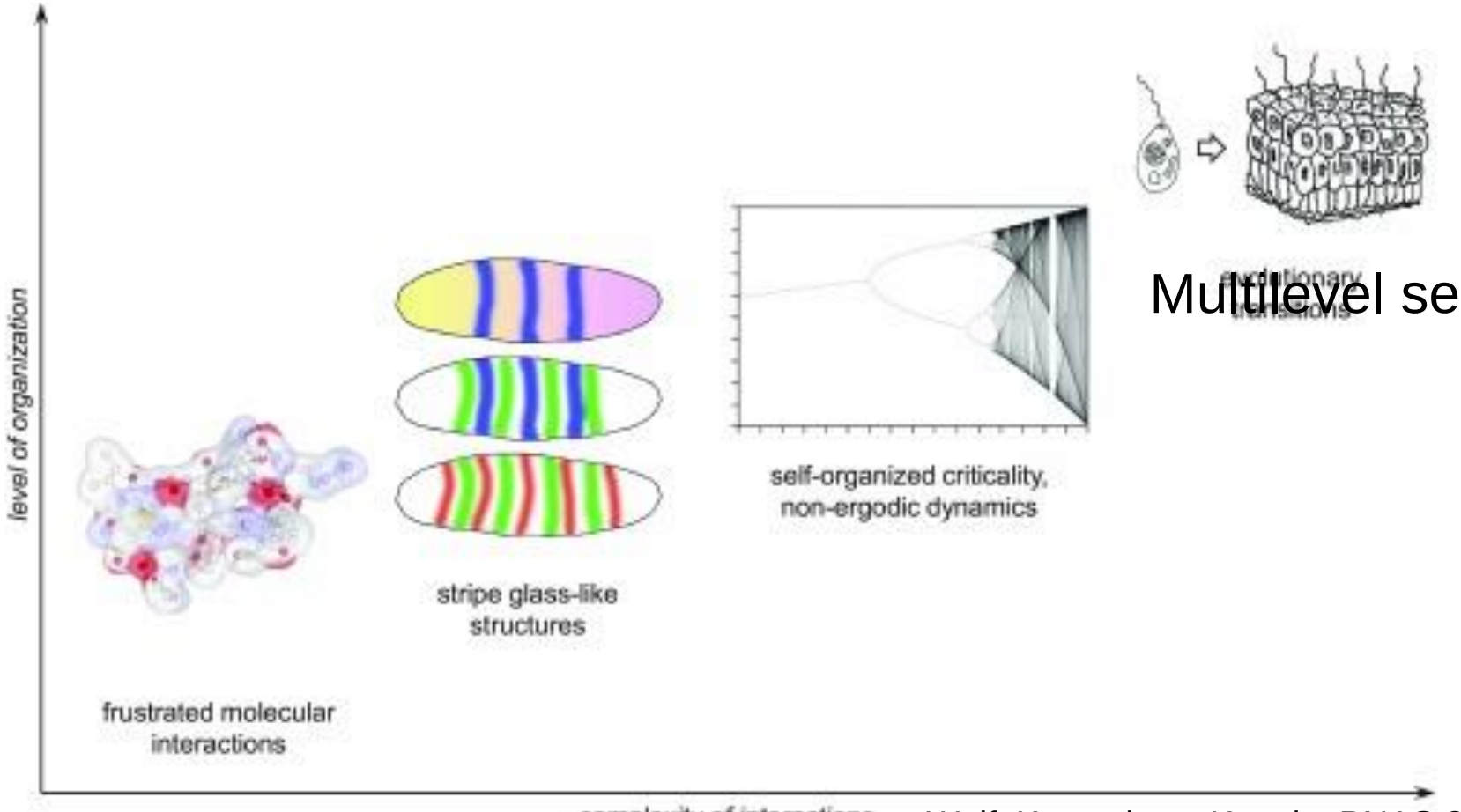
entropy flow
entropy production

New kind of non-equilibrium thermodynamics

Frustration: different optimization criteria at different levels

From frustrated states to complexity

Frustration as a necessary and sufficient condition for emergence of (biological) complexity?!



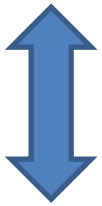
Wolf, Katsnelson, Koonin, PNAS 2018

Self-organized criticality

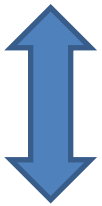
- Appears naturally in learning processes
- However, is it sufficient to explain biological complexity?
- Self-similarity is simple but… different levels of organization are not **exactly** self-similar

Isomorphism

evolution



learning

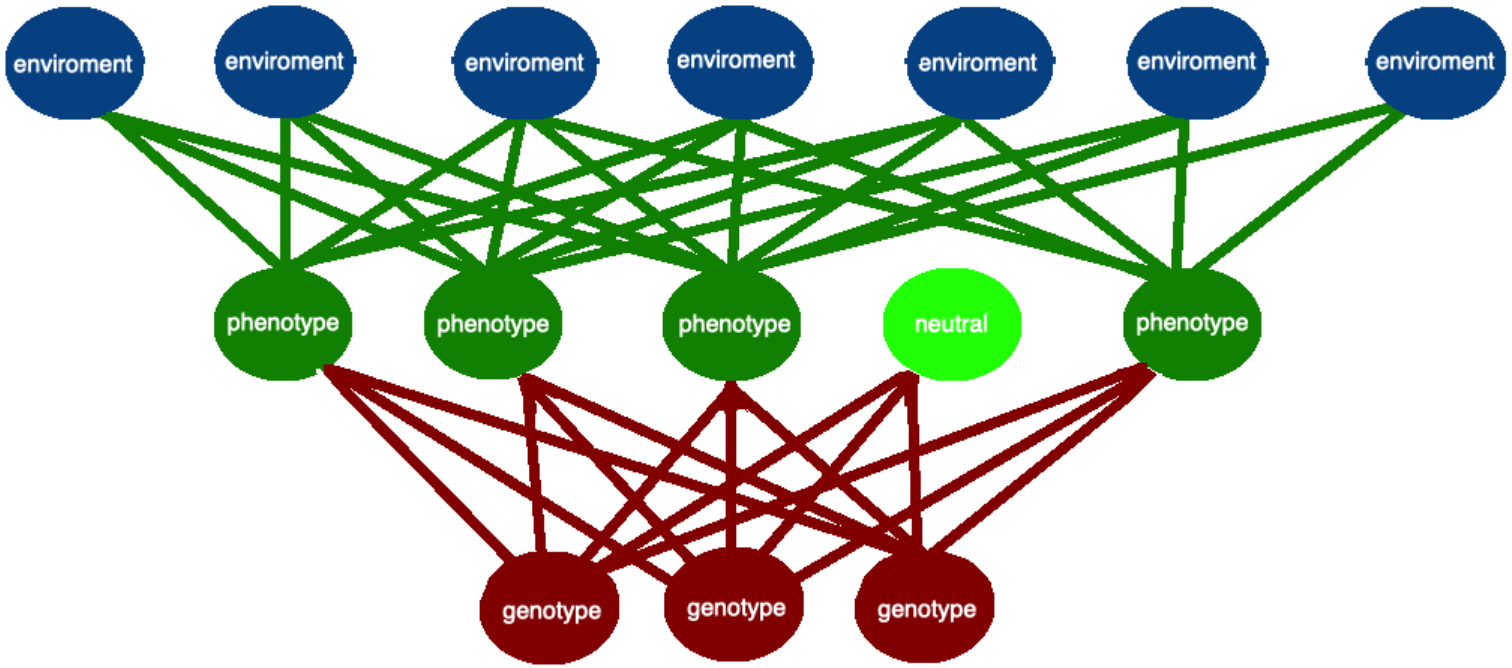


thermodynamics

This goes beyond analogy! Beginnings of new physics?

So what can biology do for physics?

Neural networks!



…and neural networks can be "everything"

Vanchurin V. 2020. **The World as a Neural Network.** *Entropy* 22(11):1210

closing:

"Of course, at present, the claim that natural selection may be relevant on all scales is very speculative, but it seems that neural networks do offer an interesting new perspective on the problem of observers"

So what can biology do for physics?

Evolution/selection!

Because the Universe evolves, "Nothing in physics makes sense except in light of evolution"