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Statistical mechanics and evolutionary biology: a few remarks

Mikhail Katsnelson

Is it possible to consider life as condensed matter/statistical physics phenomenon?

One of the possible answers: we should!

ANNUAL REVIEW OF CONDENSED MATTER PHYSICS Volume 2, 2011

Review Article

Life is Physics: Evolution as a Collective Phenomenon Far From Equilibrium

Nigel Goldenfeld[1] and Carl Woese[1,2]

View Affiliations and Author Notes

Vol. 2:375-399 (Volume publication date March 2011) | https://doi.org/10.1146/annurev-conmatphys-062910-140509

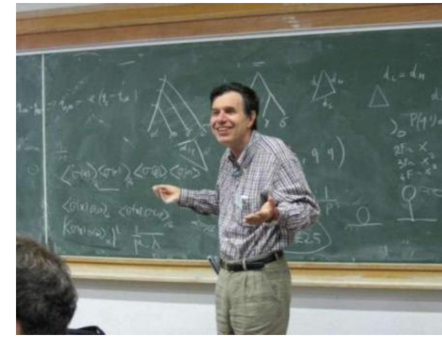
First published as a Review in Advance on January 03, 2011

The focus on “emergence”, “collective phenomena”, “universality classes”

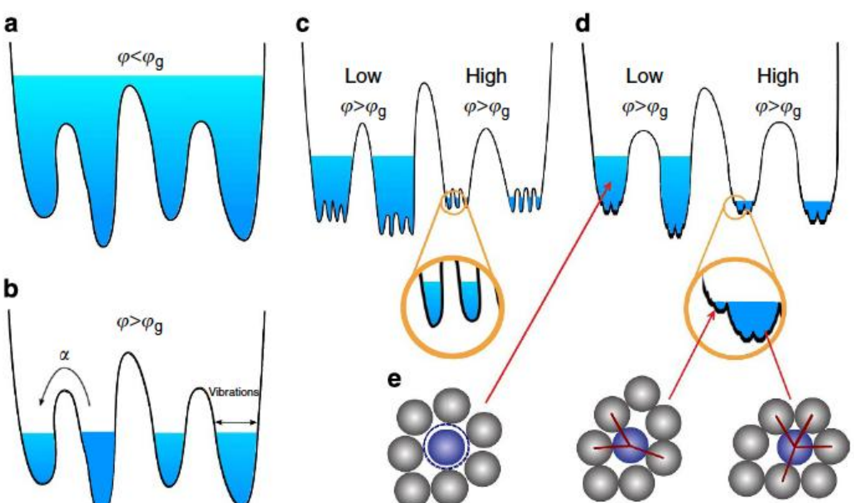
Two recent developments: spin glasses and machine learning

Giorgio Parisi, Nobel Prize in physics 2021

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."



Glass: **a system with an energy landscape characterizing by infinitely many local minima, with a broad distribution of barriers, relaxation at "any" time scale and aging (at thermal cycling you never go back to *exactly* the same state)**



Picture from P. Charbonneau et al,

DOI: 10.1038/ncomms4725

Intermediate state between equilibrium and non-equilibrium, opportunity for history and memory ("stamp collection")

Remarks on spin glasses

Disorder is not necessary: self-induced spin glasses

PHYSICAL REVIEW B **93**, 054410 (2016)

Stripe glasses in ferromagnetic thin films

Alessandro Principi* and Mikhail I. Katsnelson

PRL **117**, 137201 (2016) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2016

Self-Induced Glassiness and Pattern Formation in Spin Systems Subject to Long-Range Interactions

Alessandro Principi* and Mikhail I. Katsnelson

PHYSICAL REVIEW B **109**, 144414 (2024)

Frustrated magnets in the limit of infinite dimensions: Dynamics and disorder-free glass transition

Achille Mauri* and Mikhail I. Katsnelson†
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(Received 16 November 2023; accepted 27 March 2024; published 18 April 2024)

Frustrations (that is, competing interactions) are sufficient!

Experimental confirmation

Self-induced spin glass state in elemental and crystalline neodymium

Umut Kamber, Anders Bergman, Andreas Eich, Diana Iuşan, Manuel Steinbrecher, Nadine Hauptmann, Lars Nordström, Mikhail I. Katsnelson, Daniel Wegner*, Olle Eriksson, Alexander A. Khajetoorians*

Science **368**, 966 (2020)

Remarks on spin glasses II

IOP Publishing Physica Scripta
Phys. Scr. **93** (2018) 043001 (12pp) https://doi.org/10.1088/1402-4896/aaaba4

Invited Comment

Towards physical principles of biological evolution

Mikhail I Katsnelson[1], **Yuri I Wolf**[2] **and Eugene V Koonin**[2]

Physical foundations of biological complexity

E8678–E8687 | PNAS | vol. 115 | no. 37

Yuri I. Wolf[a], **Mikhail I. Katsnelson**[b], **and Eugene V. Koonin**[a,1]

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Contributed by Eugene V. Koonin, July 31, 2018 (sent for review May 21, 2018; reviewed by Sergei Maslov and Eörs Szathmáry)

Frustration caused by competing interactions in multidimensional systems could be the general driving force behind the emergence of complexity, within and beyond the domain of biology.

But spin glasses do not have long-term memory: too many local minima with too small basins of attraction – and biological evolution does (for billions of years!)

Search for state with smaller number of local minima (with some success)

Machine learning and all that

A fundamental question in the evolution: how to create novelty and complexity by trial-and-error approach? Is 4 billion years sufficient?

The answer is (we believe!) yes but it should be a trial-and-error within a very small part of configurational space

How do we know that this is physically and mathematically possible?

Well… otherwise AlphaGo would not be able to win the best human players in go (estimated total number of possible games in go is about 10^{700} in comparison with 10^{80} atoms in the Universe).

Both machine learning and Darwinian evolution are optimization problems

Analogies with biological evolution?

Toward a theory of evolution as multilevel learning

Vitaly Vanchurin[a,b,1], Yuri I. Wolf[a], Mikhail I. Katsnelson[c], and Eugene V. Koonin[a,1]

PNAS 2022 Vol. 119 No. 6 e2120037119

Thermodynamics of evolution and the origin of life

Vitaly Vanchurin[a,b,1], Yuri I. Wolf[a], Eugene V. Koonin[a,1], and Mikhail I. Katsnelson[c,1]

PNAS 2022 Vol. 119 No. 6 e2120042119

Table 1. Corresponding quantities in thermodynamics, machine learning, and evolutionary biology

	Thermodynamics	Machine learning	Evolutionary biology
$\mathbf{x}$	Microscopic physical degrees of freedom	Variables describing training dataset (nontrainable variables)	Variables describing environment
$\mathbf{q}$	Generalized coordinates (e.g., volume)	Weight matrix and bias vector (trainable variables)	Trainable variables (genotype, phenotype)
$H(\mathbf{x},\mathbf{q})$	Energy	Loss function	Additive fitness, $H(x,q) = -T \log f(q)$
$S(\mathbf{q})$	Entropy of physical system	Entropy of nontrainable variables	Entropy of biological system
$U(\mathbf{q})$	Internal energy	Average loss function	Average additive fitness
$Z(T,\mathbf{q})$	Partition function	Partition function	Macroscopic fitness
$F(T,\mathbf{q})$	Helmholtz free energy	Free energy	Adaptive potential (macroscopic additive fitness)
$\Omega(T,\mu)$	Grand potential, $\Omega_p(\mathscr{T},\mathscr{M})$	Grand potential	Grand potential, $\Omega_b(T,\mu)$
T or $\mathscr{T}$	Physical temperature, $\mathscr{T}$	Temperature	Evolutionary temperature, T
μ or $\mathscr{M}$	Chemical potential, $\mathscr{M}$	Absent in conventional machine learning	Evolutionary potential, μ
N_e or N	Number of molecules, N	Number of neurons, N	Effective population size, N_e
K	Absent in conventional physics	Number of trainable variables	Number of adaptable variables

Energy landscape in physics is similar to fitness landscape in biology

Analogies with biological evolution II

Can the change of e.g. biological temperature switch fitness landscape from a few well-defined peaks to a glassy-like with many directions of possible evolution?

Explaining the Cambrian "Explosion" of Animals

Charles R. Marshall

Annu. Rev. Earth Planet. Sci. 2006. 34:355–84

Australian Journal of Zoology
http://dx.doi.org/10.1071/ZO13052

The evolution of morphogenetic fitness landscapes: conceptualising the interplay between the developmental and ecological drivers of morphological innovation

Charles R. Marshall

Cambrian Explosion as an analog of magnetic phase transitions in neodymium?!

Difference with statistical physics: Two-level dynamics governed by different laws

Genotype-to-phenotype mapping: molecules governed by physical and chemical laws plus selection acting on macrolevel

What do we do in physics: We see pattern, we suggest Hamiltonian with competing interaction

PHYSICAL REVIEW B **69**, 064411 (2004)

Magnetization and domain structure of bcc $Fe_{81}Ni_{19}$/Co (001) superlattices

R. Bručas, H. Hafermann, M. I. Katsnelson, I. L. Soroka, O. Eriksson, and B. Hjörvarsson

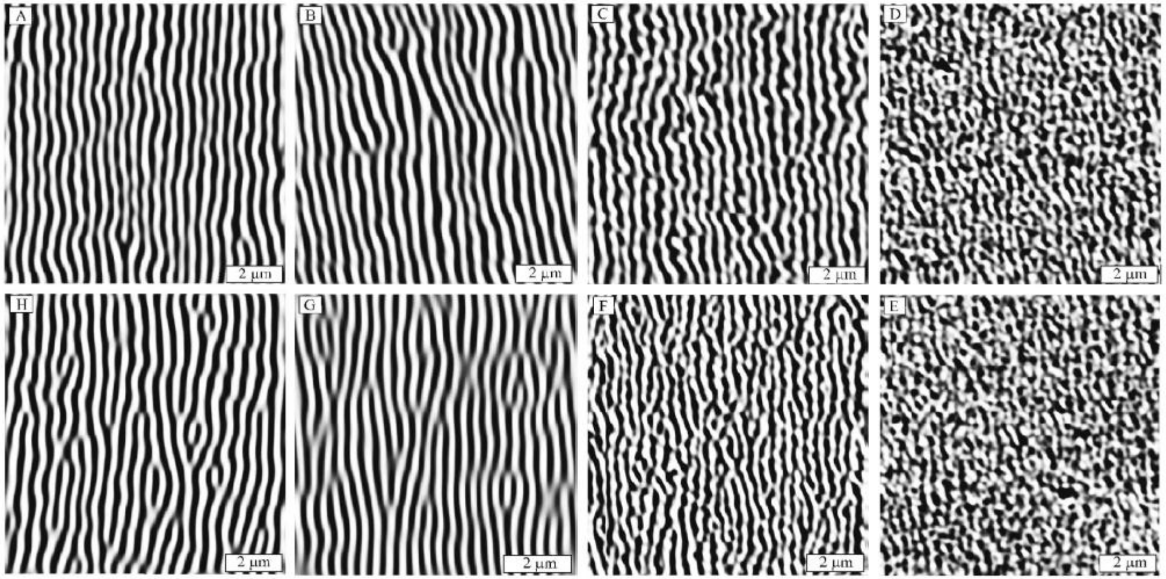


FIG. 2. The MFM images of the 420 nm thick $Fe_{81}Ni_{19}$/Co superlattice at different externally applied in-plane magnetic fields: (a)—virgin (nonmagnetized) state; (b), (c), (d)—increasing field 8.3, 30, and 50 mT; (e), (f), (g)—decreasing field 50, 30, 8.3 mT; (h)—in remanent state.

Difference with statistical physics: Two-level dynamics governed by different laws II

$$H = \int \left(\frac{J_x}{2} \left(\frac{\partial \boldsymbol{m}}{\partial x}\right)^2 + \frac{J_y}{2} \left(\frac{\partial \boldsymbol{m}}{\partial y}\right)^2 - \frac{K}{2} m_z^2 - h m_y \right) \mathrm{d}^2 r +$$

$$+ \frac{Q^2}{2} \int \int m_z(\boldsymbol{r}) \left(\frac{1}{|\boldsymbol{r}-\boldsymbol{r}'|} - \frac{1}{\sqrt{d^2 + (\boldsymbol{r}-\boldsymbol{r}')^2}} \right) m_z(\boldsymbol{r}')\mathrm{d}^2 r \mathrm{d}^2 r'.$$

Europhys. Lett., **73** (1), pp. 104–109 (2006)
DOI: 10.1209/epl/i2005-10367-8

Topological defects, pattern evolution, and hysteresis in thin magnetic films

P. A. Prudkovskii[1], A. N. Rubtsov[1] and M. I. Katsnelson[2]

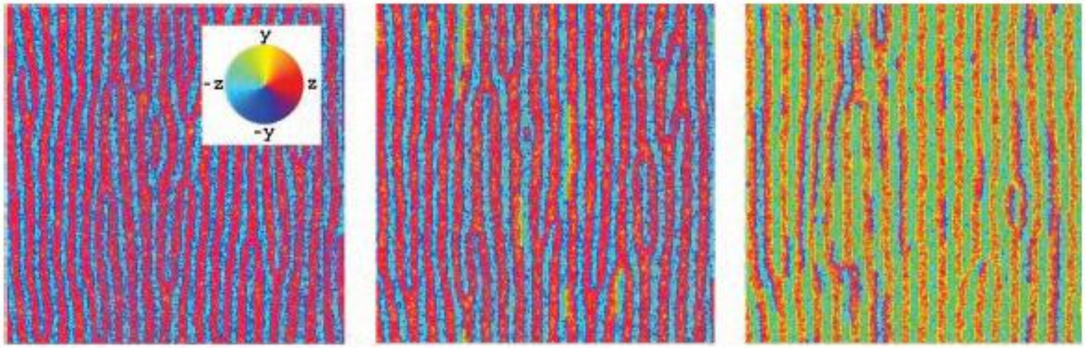


Fig. 2 – Snapshots of the stripe-domain system with the two-component order parameter at several points of the hysteresis loop for $\beta = 1$. The magnetic field is $h = 0$, $h = 0.3$, and $h = 0.6$, from left to right. The inset shows the color legend for the orientation of local magnetization.

Difference with statistical physics: Two-level dynamics governed by different laws III

But patterns in genome are not necessary based on chemistry of nucleic acids, they can follow from selection!

Nucleic Acids Research, 2024, **52**, 11045–11059
https://doi.org/10.1093/nar/gkae745
Advance access publication date: 28 August 2024
Genomics

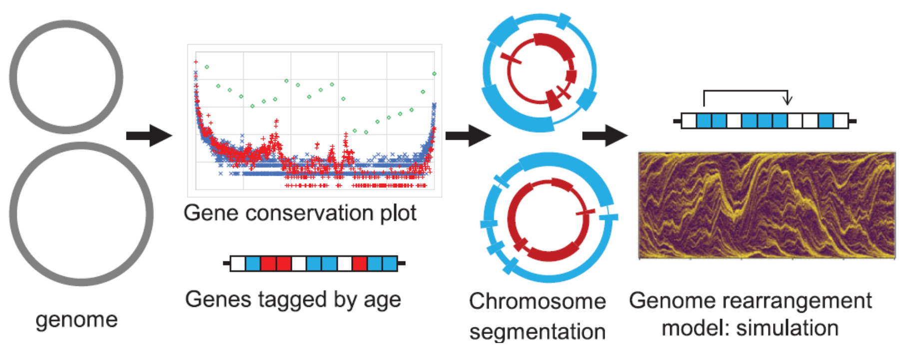
50TH ANNIVERSARY

OXFORD

Long range segmentation of prokaryotic genomes by gene age and functionality

Yuri I. Wolf [1], Ilya V. Schurov [2], Kira S. Makarova [1], Mikhail I. Katsnelson [2] and Eugene V. Koonin [1,*]

Graphical abstract



Existing language of statistical physics seems to be not suitable to describe this multilevel dynamics!