

Non-Equilibrium Statistical Mechanics and Evolution

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Non-Equilibrium Statistical Mechanics (NESM)

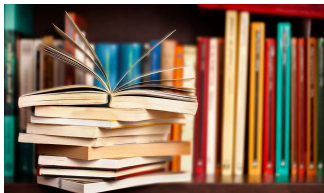
- 19th century → Statistical Mechanics (Equilibrium)
 - Time-independent observables, no external current/flux involved
 - Approximation and idealization on coarse-grained level
- Look at most of the systems around us...
 - we need non-equilibrium statistical mechanics!



<https://en.wikipedia.org/wiki/>

Non-Equilibrium Statistical Mechanics (NESM)

- Much harder to describe non-equilibrium systems
 - Temperature, free energy, partition functions etc. → not well defined anymore!
 - Time-dependent dynamics
- Still a work in progress...
 - E.g. Turbulence – “the last unsolved problem of classical physics”
 - No general solutions yet



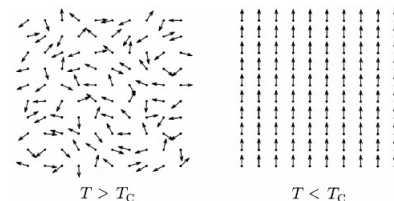
<https://www.hse.ru/en/ma/cogito/>



<http://bgr.com/2016/01/19/>

Main Approaches in NESM

- Near Equilibrium → Approximate to equilibrium
 - Linear Response
 - Boltzmann equation, fluctuation-dissipation theorem, Kramers-Kronig relations, Onsager reciprocal relations...
- Far From Equilibrium → Integrate (average) to equilibrium
 - Fluctuation Theorems
 - Extended the second law of thermodynamics
 - Calculate the irreversibility of a process based on entropy/energy dissipation
 - Jarzynski equality, Crook's equation...
- Emergent Properties
 - Non-equilibrium Phase Transitions
 - Order parameters, symmetry breaking...
 - Bifurcations, Different Universality Classes...



<https://www.researchgate.net/>

We can know evolution better with NESM!

- Evolution is also a physics problem
 - Self-organisation of matter
 - Use physics terms to explain distinctive features of life
- The physics methods are valuable
 - Emphasize collective phenomena (in contrast to reductionism)
 - Use deductive reasoning to overcome one sample bias
 - Theories can lead to new discoveries
 - E.g. the discovery of topoisomerases



<https://optinmonster.com/>

We can also know physics better!

- New physics law?
- Extend the frontier of physics
 - Draw analogy back to physics
 - E.g. predator-prey system and turbulence phase transitions*
 - Enrich physics descriptions
 - E.g. a new branch inspired by living systems→

ACTIVE MATTER



<http://www.iniciativamilenio.cl>

*H. Shih, T. Hsieh, N. Goldenfeld. Ecological collapse and the emergence of travelling waves at the onset of shear turbulence. *Nature Physics*, 2016

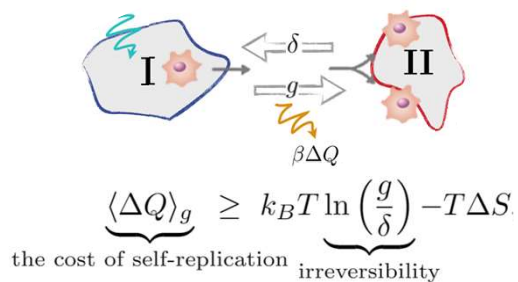
Use Phase Transitions

- Homochirality Emergence (order parameter: chirality)
 - In biological systems:
 - All amino acids are “left-handed”
 - Most carbohydrates in RNA and DNA are “right-handed”
 - Possible influence factor: enzymatic reactions
- Another example:
 - Genotype Selections (order parameter: genotype diversity)

S. Walker, *Rep Prog Phys*, 2017; M. Gleiser et al, *Orig Life Evol Biosph*, 2008; P. Sandars, *Orig Life Evol Biosph*, 2003; N. Goldenfeld et al, *Annu Rev of Con Mat Phys*, 2011; N. Goldenfeld et al, *Natures*, 2007;

Use the Extended 2nd Law of Thermodynamics

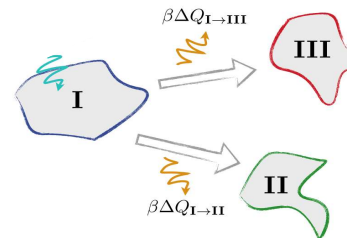
Self-replication



Higher net growth rate ($g-\delta$) if

1. Dissipates more energy (ΔQ)
2. Easily degradable (δ)
3. Simpler (ΔS)

Adaptation



Tends to evolve to the state that

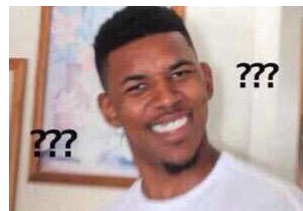
1. Closer to equilibrium
2. More accessible
3. **Reliably** dissipate more energy

T. Kachman et al, *Phys Rev Lett*, 2017; N. Perunov et al, *Phys Rev X*, 2016; J. England, *Nat Nanotech*, 2015; J. England, *J Chem Phys*, 2013

Combine with Geochemistry

- Numerous energy has been “trapped” when Earth cooled down
- Enzymatic reactions took over abiotic reactions
 - Life emerged as a relaxation channel for Earth to restore equilibrium (release its thermodynamic stress)

★ Can predict alien life in an environment with different chemistry 😊



<https://imgflip.com/meme/>



<https://www.pmel.noaa.gov>

E. Shock et al, *Elements*, 2015; M. Harold et al, *Complexity*, 2007

Looking forward to more stories in...
Non-Equilibrium Statistical Mechanics & *Evolution*

Thanks! 😊

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07/06/2018

P.S. NESM has very wide applications, e.g. condensed matter physics, quantum field theory, neuroscience, or even economics, sociology etc. It is a fascinating area!



<https://www.shutterstock.com/>