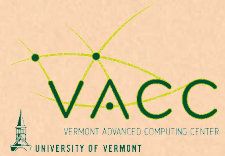
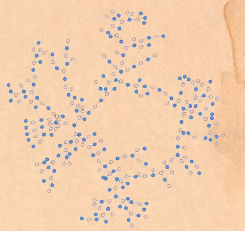
Why Complexify?

Principles of Complex Systems
CSYS/MATH 300, Fall, 2011

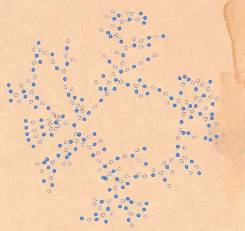
Prof. Peter Dodds

Department of Mathematics & Statistics | Center for Complex Systems | Vermont Advanced Computing Center | University of Vermont





Outline



Limits to what's possible:

Universality (⊞):

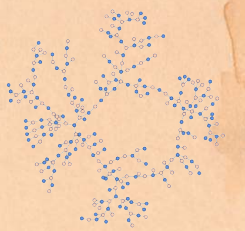
- The property that the macroscopic aspects of a system do not depend sensitively on the system's details.
- Key figure: Leo Kadanoff (⊞).

Examples:

- The Central Limit Theorem:

$$P(x;\mu,\sigma)\mathrm{d}x = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2}\mathrm{d}x\,.$$

- Navier Stokes equation for fluids.
- Nature of phase transitions in statistical mechanics.



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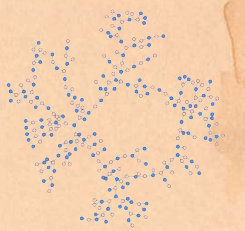

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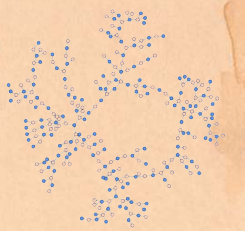

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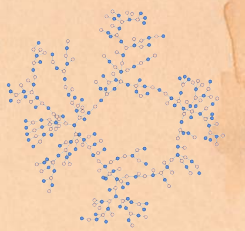

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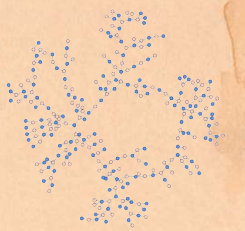
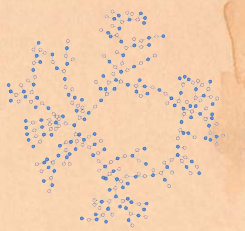


Universality

- Sometimes details don't matter too much.
- Many-to-one mapping from micro to macro
- Suggests not all possible behaviors are available at higher levels of complexity.

Large questions:

- How universal is universality?
- What are the possible of long-time states (attractors) for a universe?



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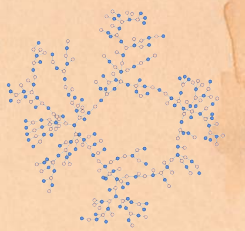

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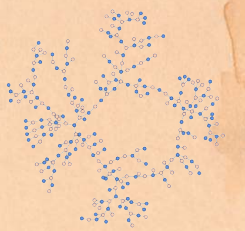

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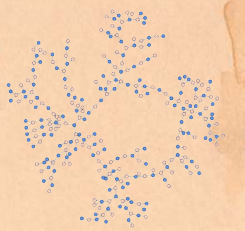

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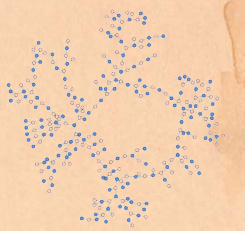

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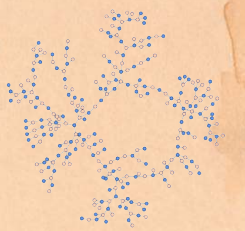
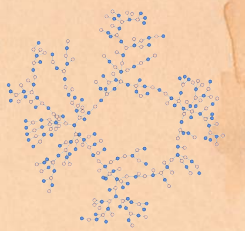


Fluids mechanics

- Fluid mechanics = One of the great successes of understanding complex systems.
- Navier-Stokes equations: micro-macro system evolution.
- The big three: Experiment + Theory + Simulations.
- Works for many very different ‘fluids’:
  - the atmosphere,
  - oceans,
  - blood,
  - galaxies,
  - the earth’s mantle...
  - and ball bearings on lattices...?



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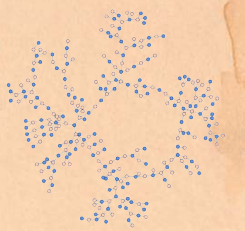

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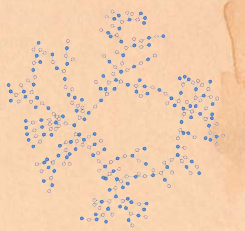

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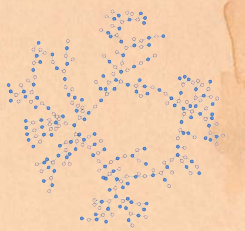

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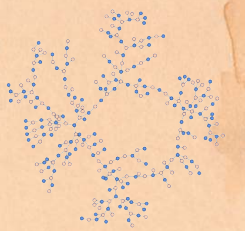
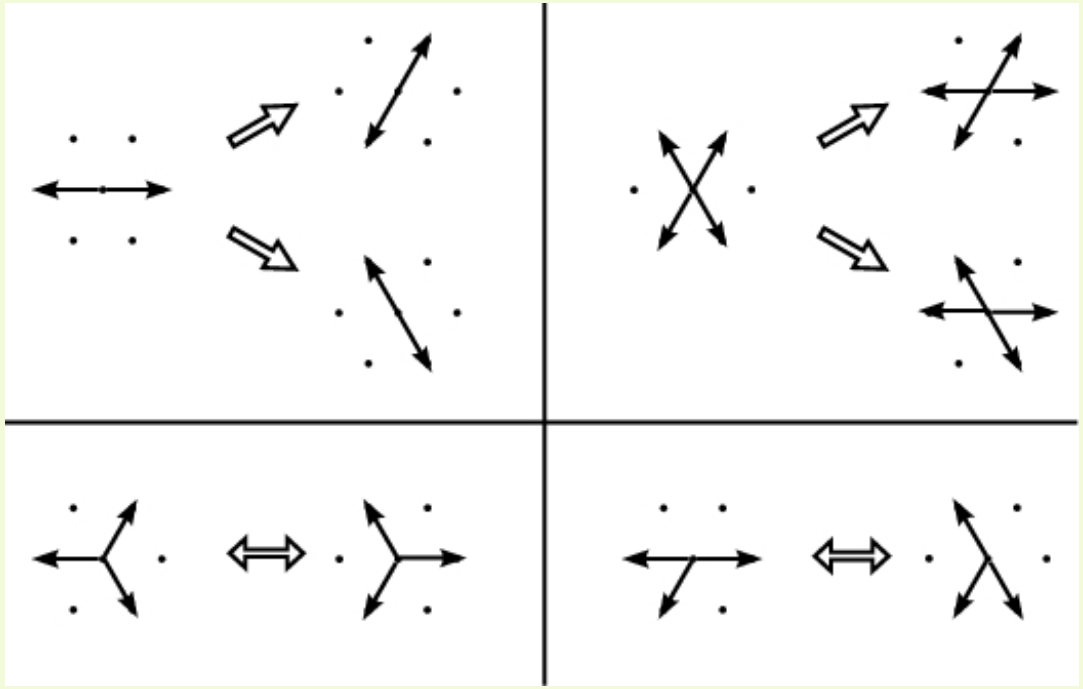


Lattice gas models

Collision rules in 2-d on a hexagonal lattice:



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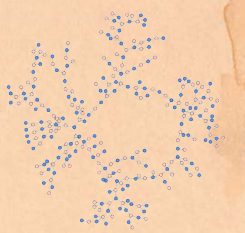
- No ‘good’ lattice in 3-d.
- Upshot: play with ‘particles’ of a system to obtain new or specific macro behaviours.



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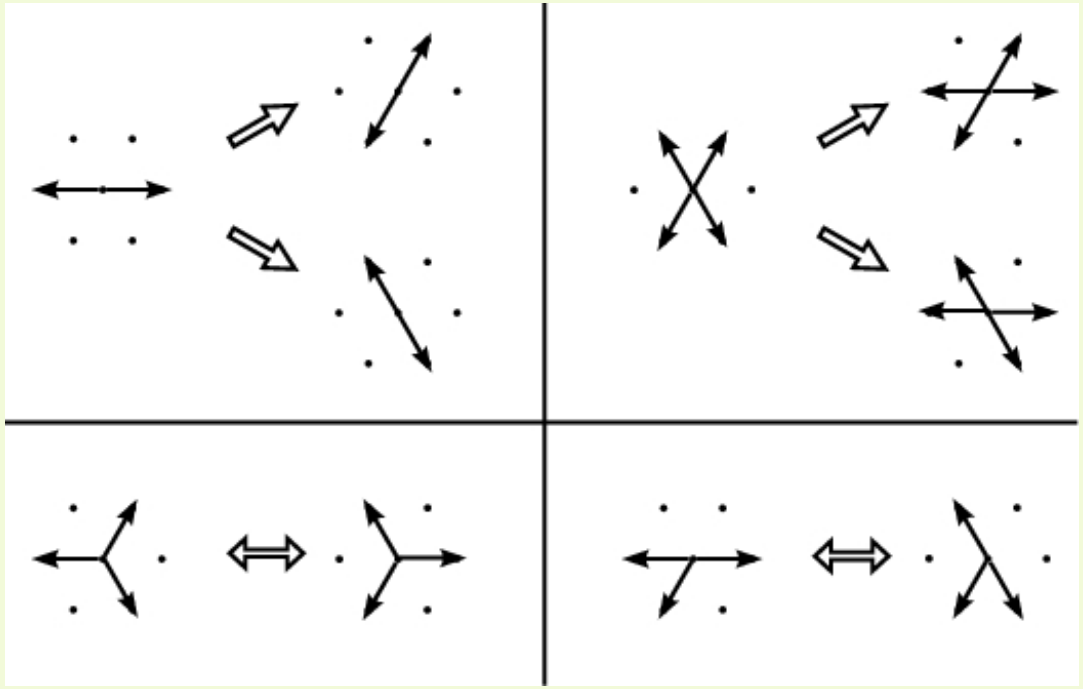

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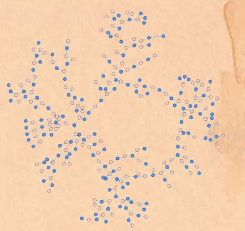

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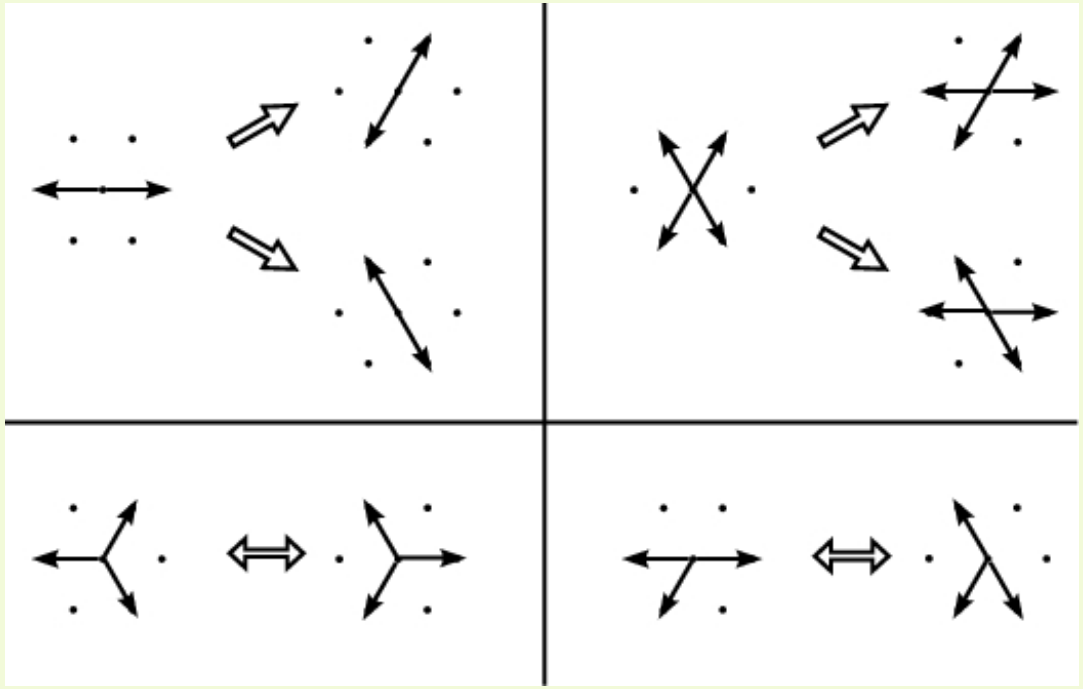

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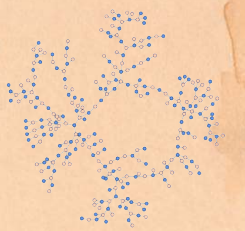

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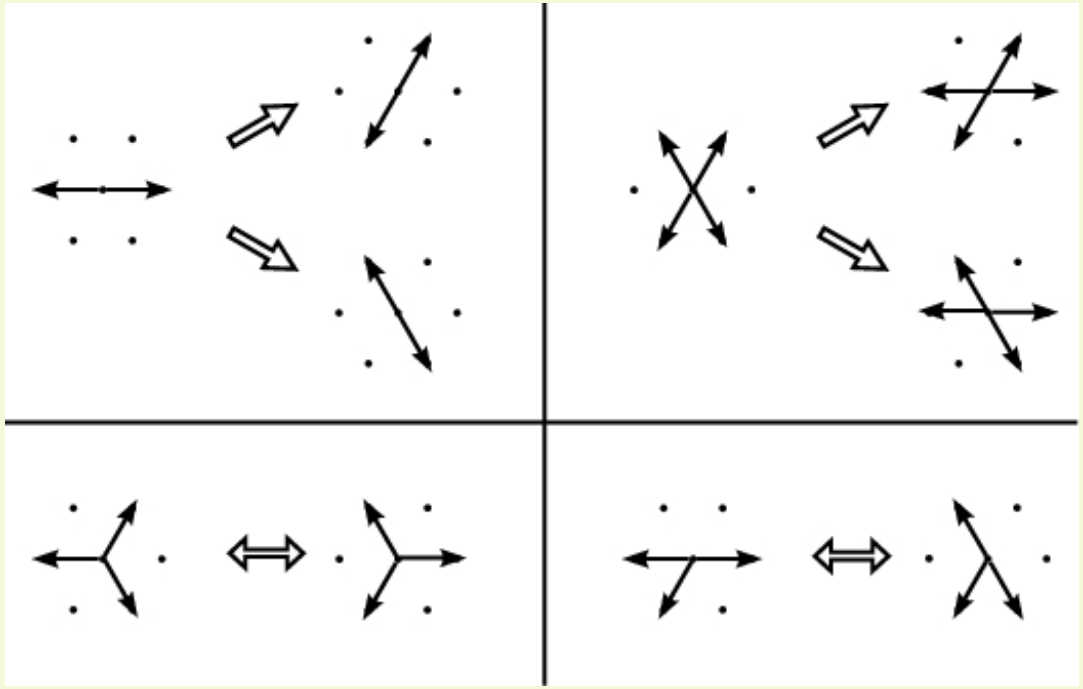

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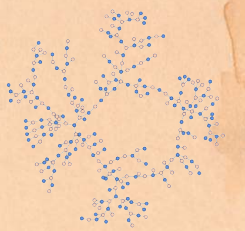
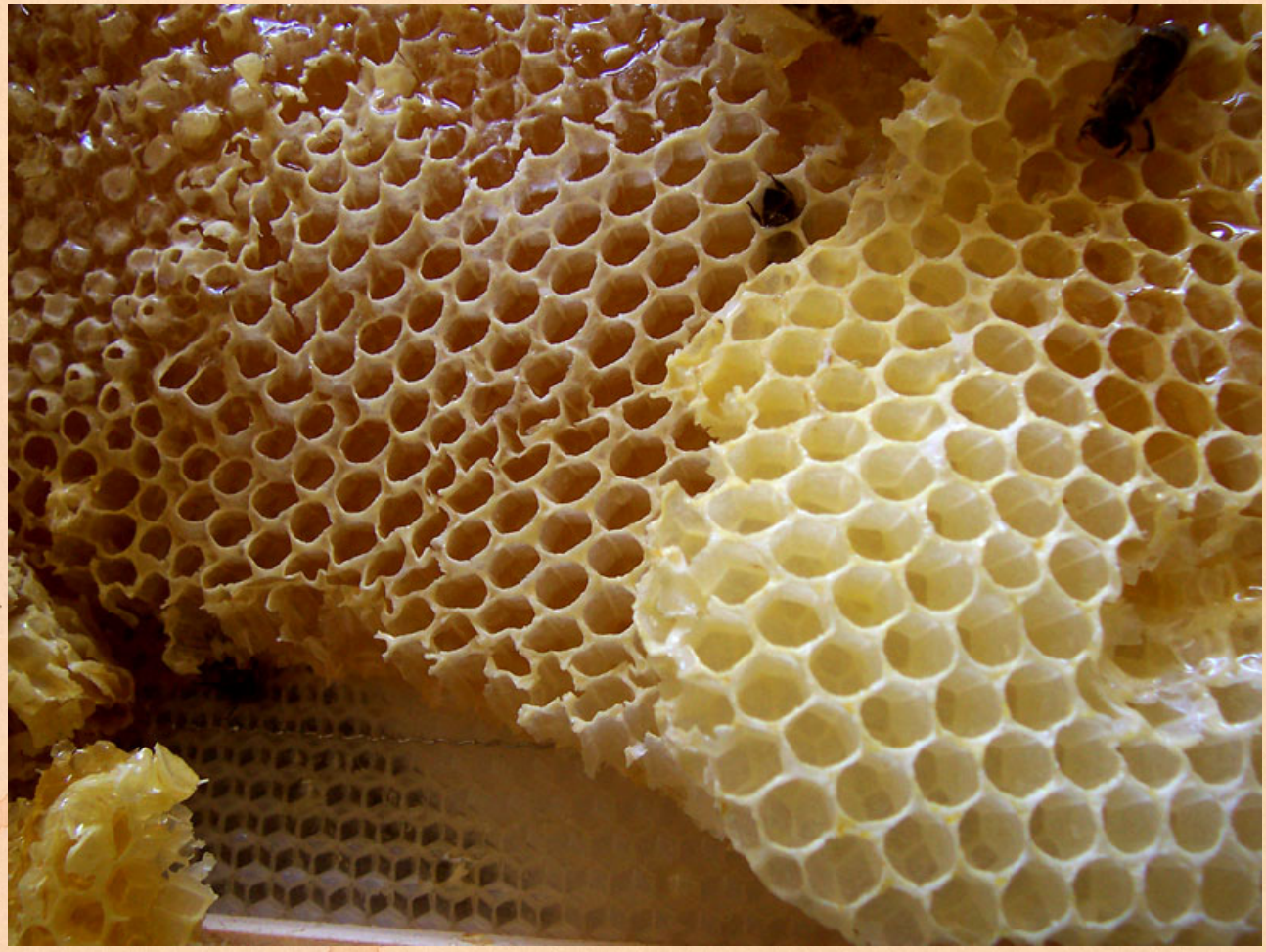
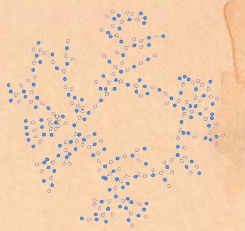


Hexagons—Honeycomb: (⊞)





- Orchestrated? Or an accident of bees working hard?
- See “On Growth and Form” by D’Arcy Wentworth Thompson (⊞). [4, 5]

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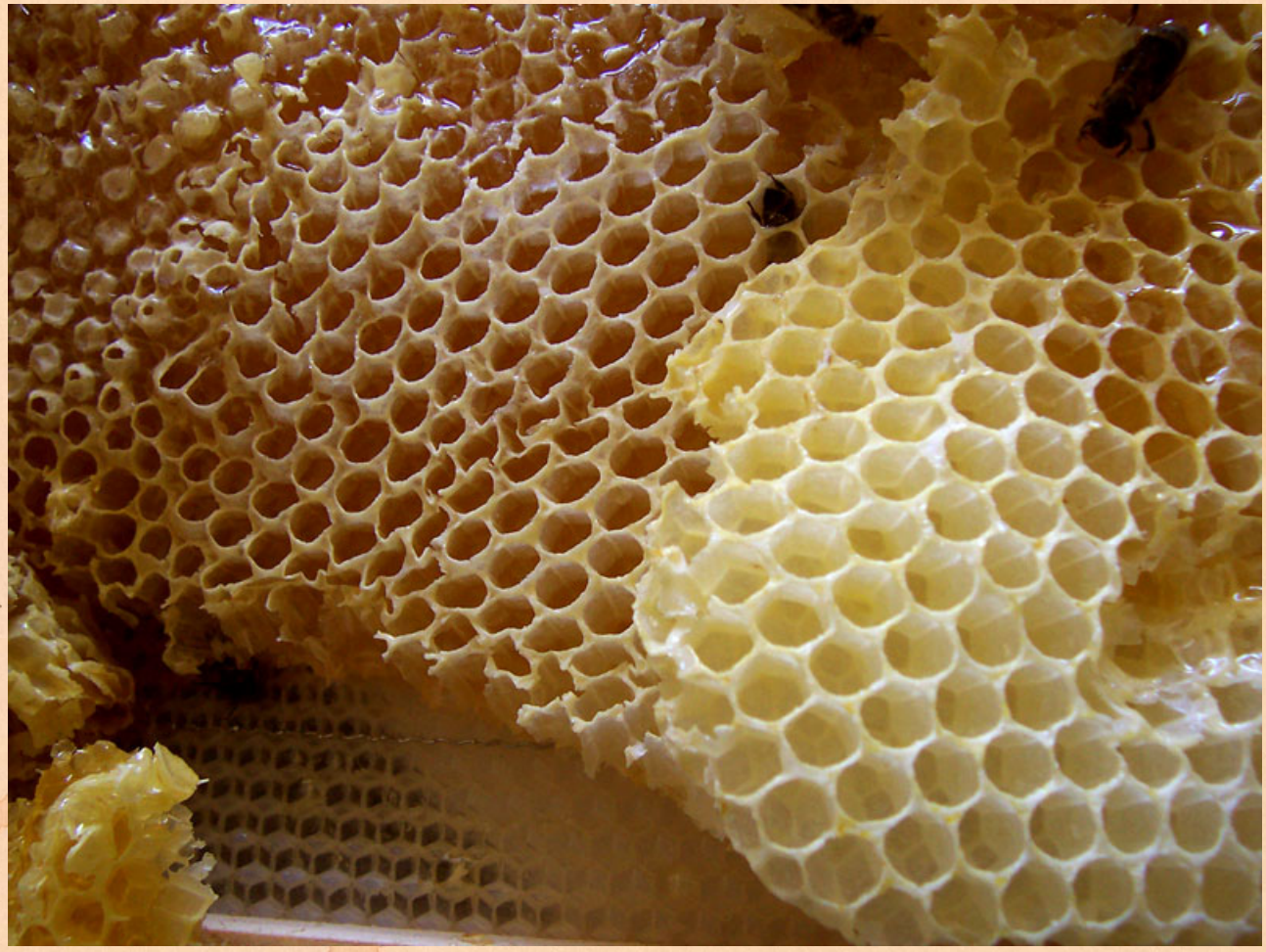

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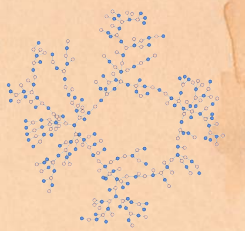
Hexagons—Giant's Causeway: (⊞)

http://newdesktopwallpapers.info



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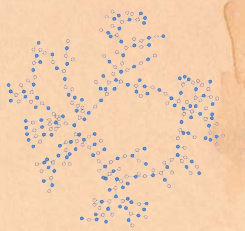
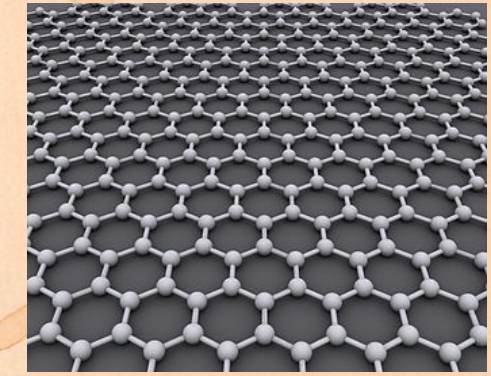
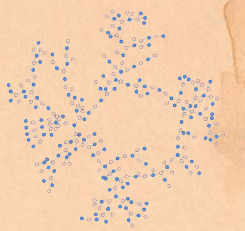


Hexagons run amok:



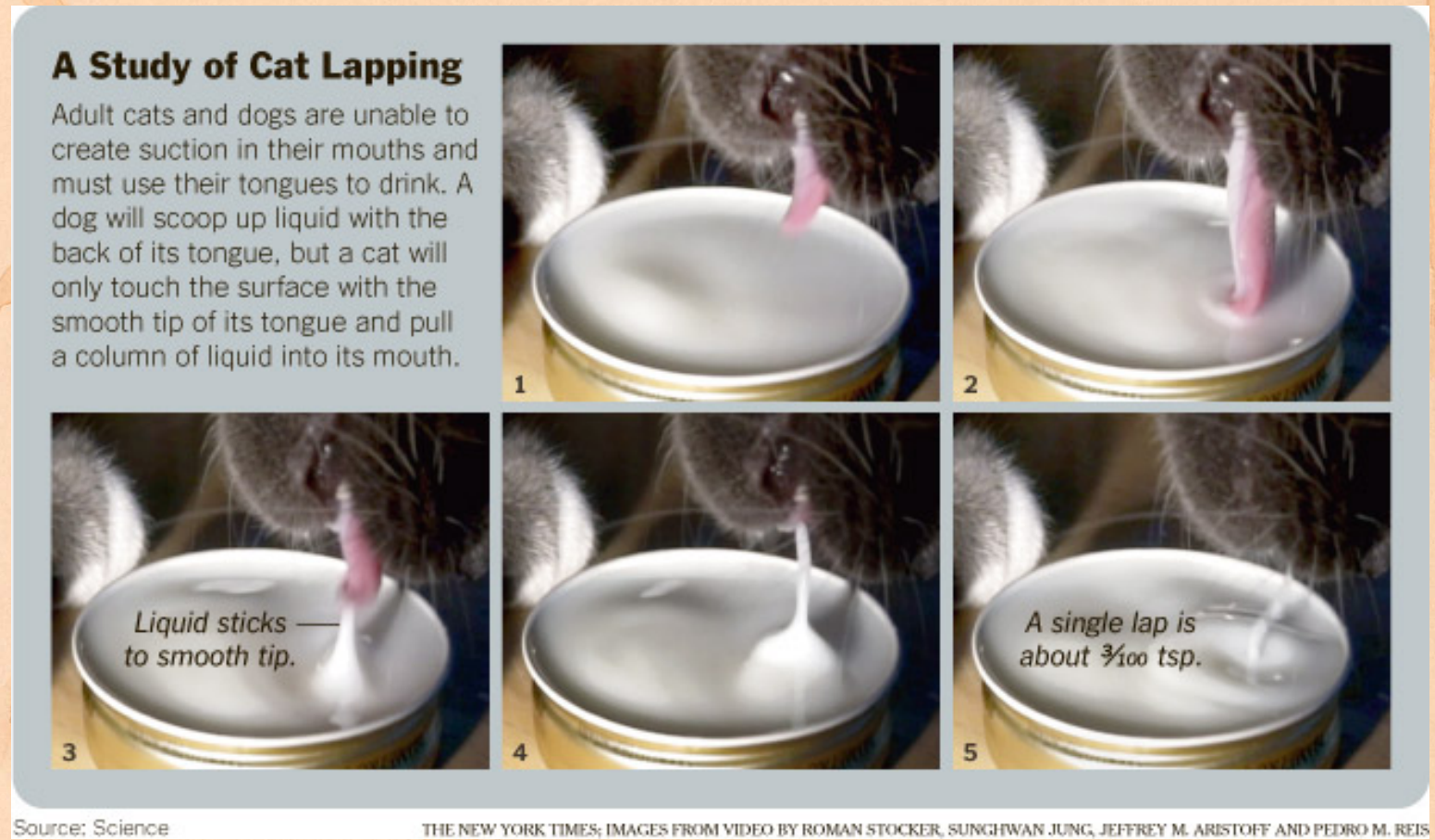
- Graphene (⊞): single layer of carbon molecules in a perfect hexagonal lattice (super strong).
- Chicken wire (⊞) . . .



Whimsical but great example of real science:

"How Cats Lap: Water Uptake by *Felis catus*" (⊞)

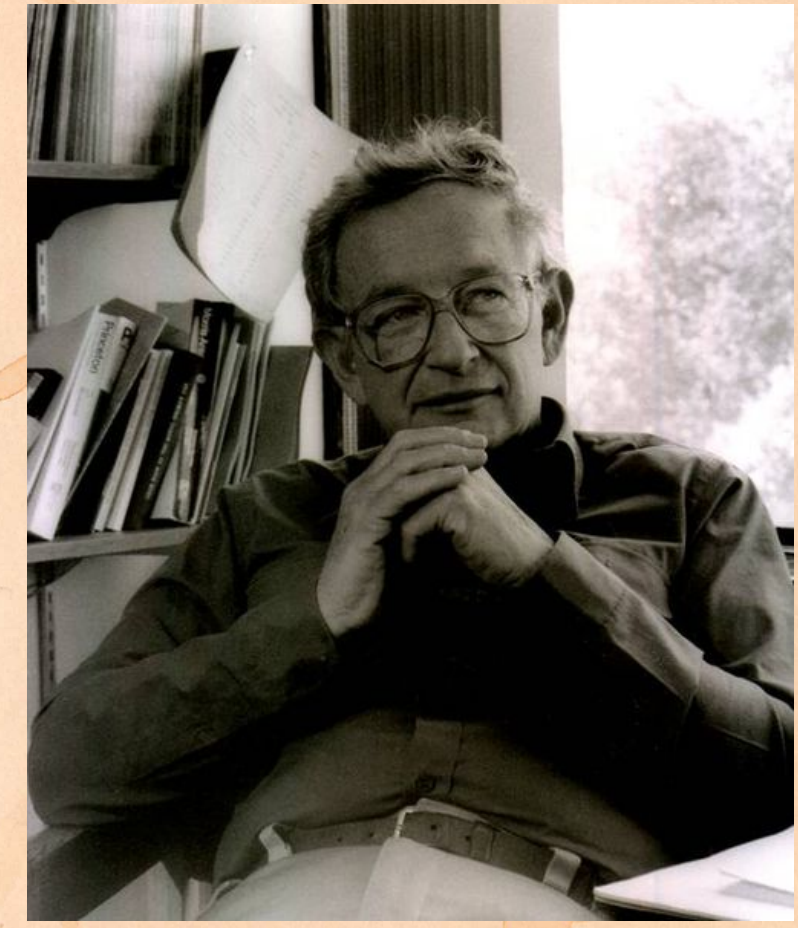
Reis et al., *Science*, 2010.



Amusing interview here (⊞)

Symmetry Breaking

Philip Anderson (⊞)—"More is Different," Science, 1972 [1]



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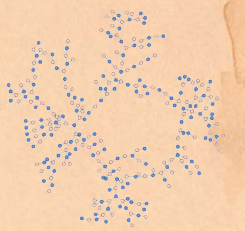
- Symmetry breaking → different laws/rules at different scales...



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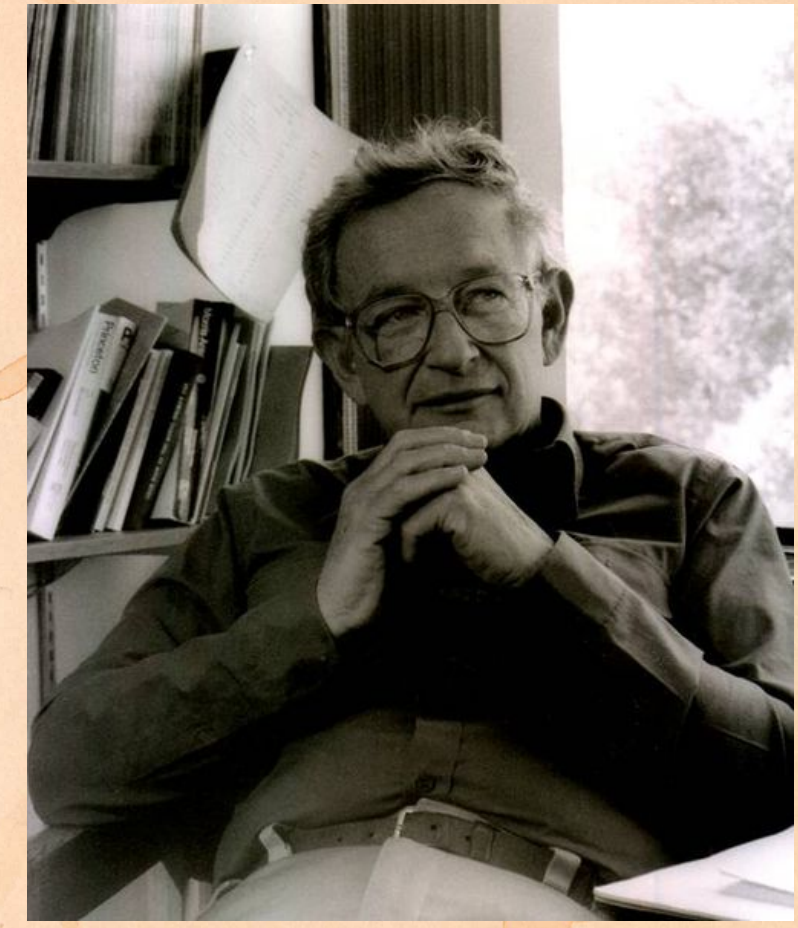

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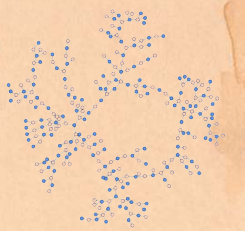

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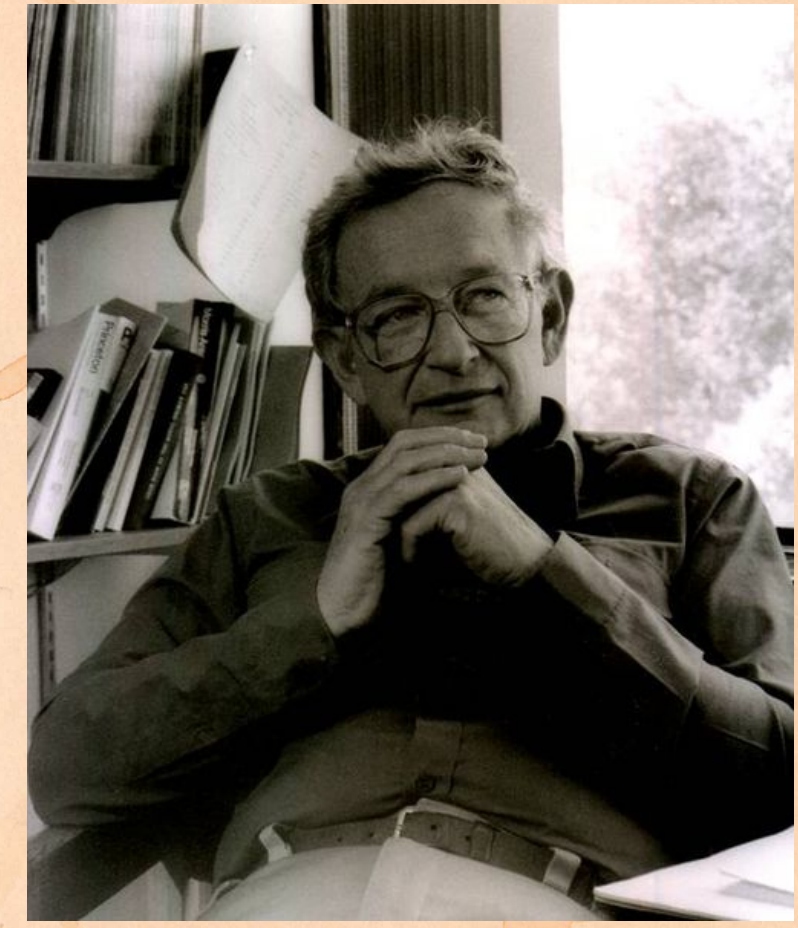

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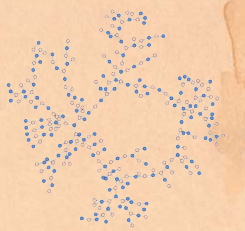

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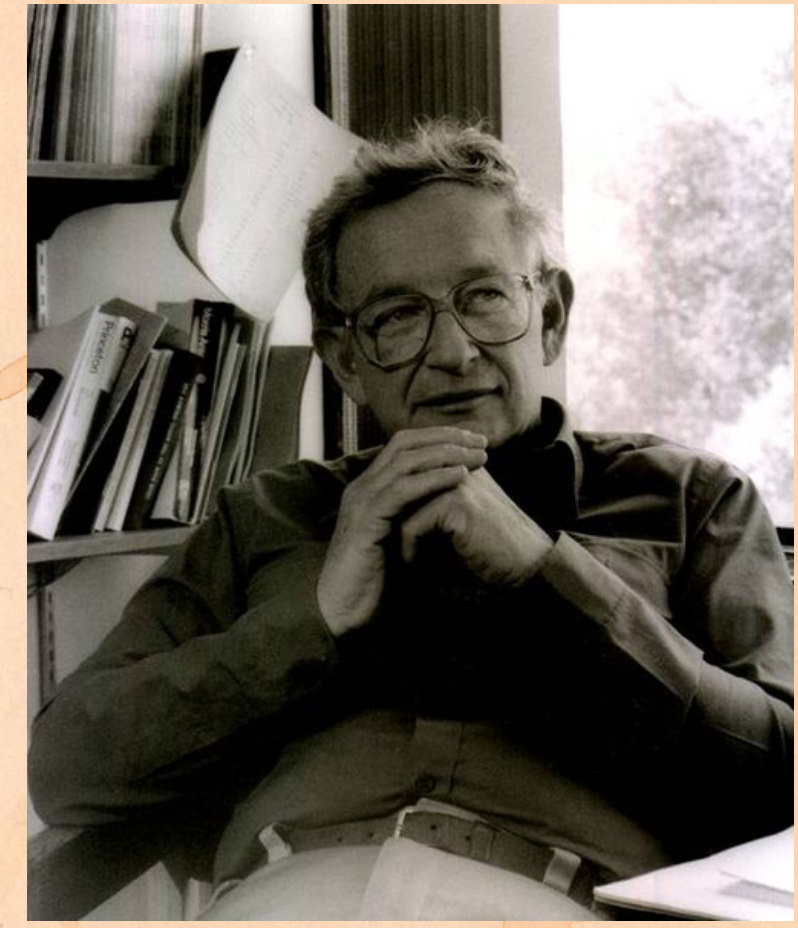

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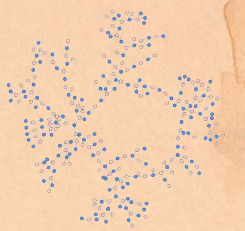
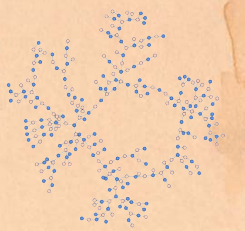
2006 study → "most creative physicist in the world" (⊞)



Symmetry Breaking

"Elementary entities of science X obey the laws of science Y"

X	Y
solid state or many-body physics	elementary particle physics
chemistry	solid state many-body physics
molecular biology	chemistry
cell biology	molecular biology
⋮	⋮
psychology	physiology
social sciences	psychology



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Anderson:

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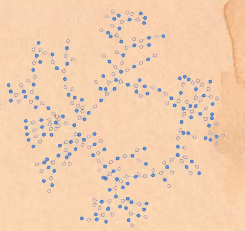

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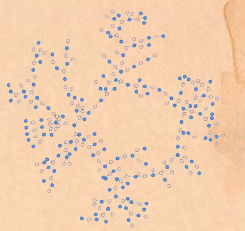

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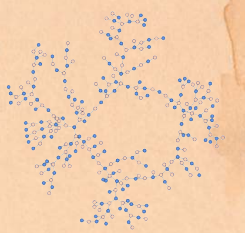

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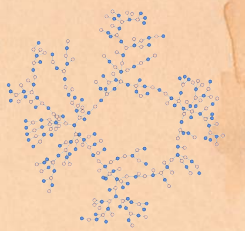

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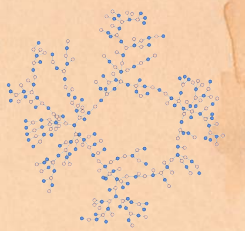

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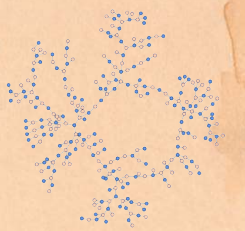

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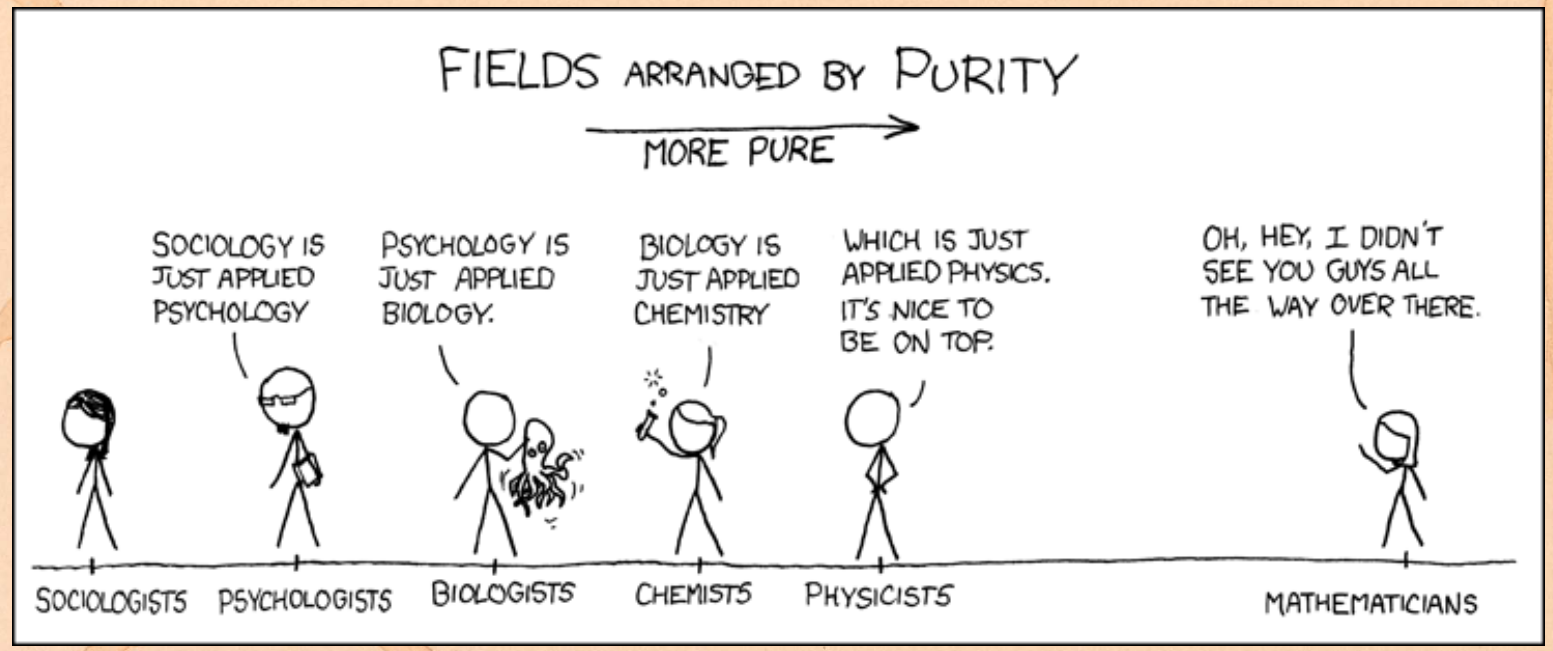
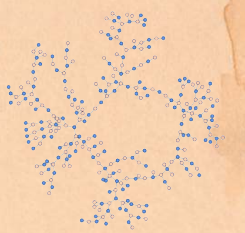


http://xkcd.com/435/ (⊞)



A real science of complexity:

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1. Is not just about the ridiculously small stuff...
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Symmetry breaking/ Accidents of history vs. Universality

- Second law of thermodynamics: we're toast in the long run.
- So how likely is the local complexification of structure we enjoy?
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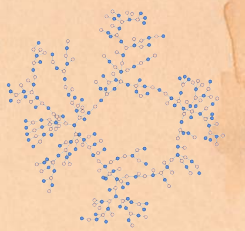

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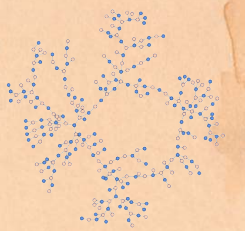

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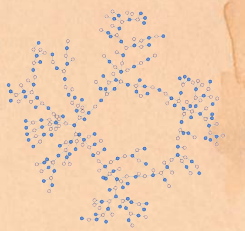

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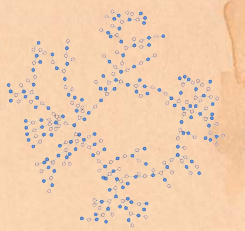

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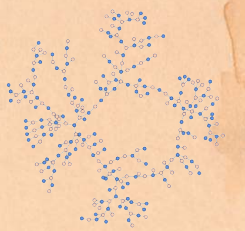

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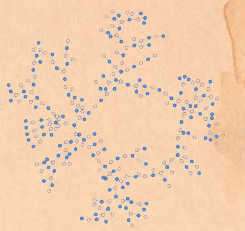

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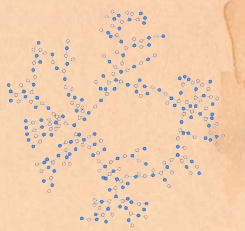
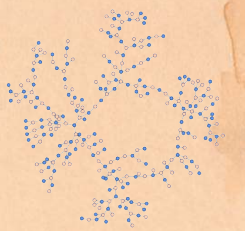


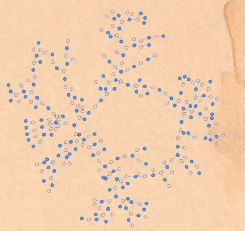
Complexification—the Big Transitions:

- Big Bang.
- Big Random-ness.
- Big Replicate.
- Big Life.
- Big Evolve.
- Big Word.
- Big Story.
- Big Number.
- Big God.
- Big Make.
- Big Science.
- Big Data.
- Big Information.
- Big Algorithm.
- Big Connection.
- Big Social.
- Big Awareness.



Why complexify?

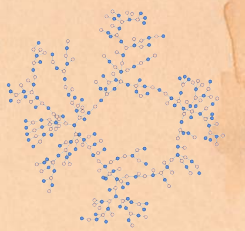
- "Why do things become more complex?" [2]
  Brian Arthur
  Scientific American, 268, 92, 1993.
- Complexification $\equiv$ evolution of algorithms?
- Differential equations and stories $\subset$ Algorithms.
- Life is a loaded word: The Search for Extraterrestrial Algorithms (SETA)?

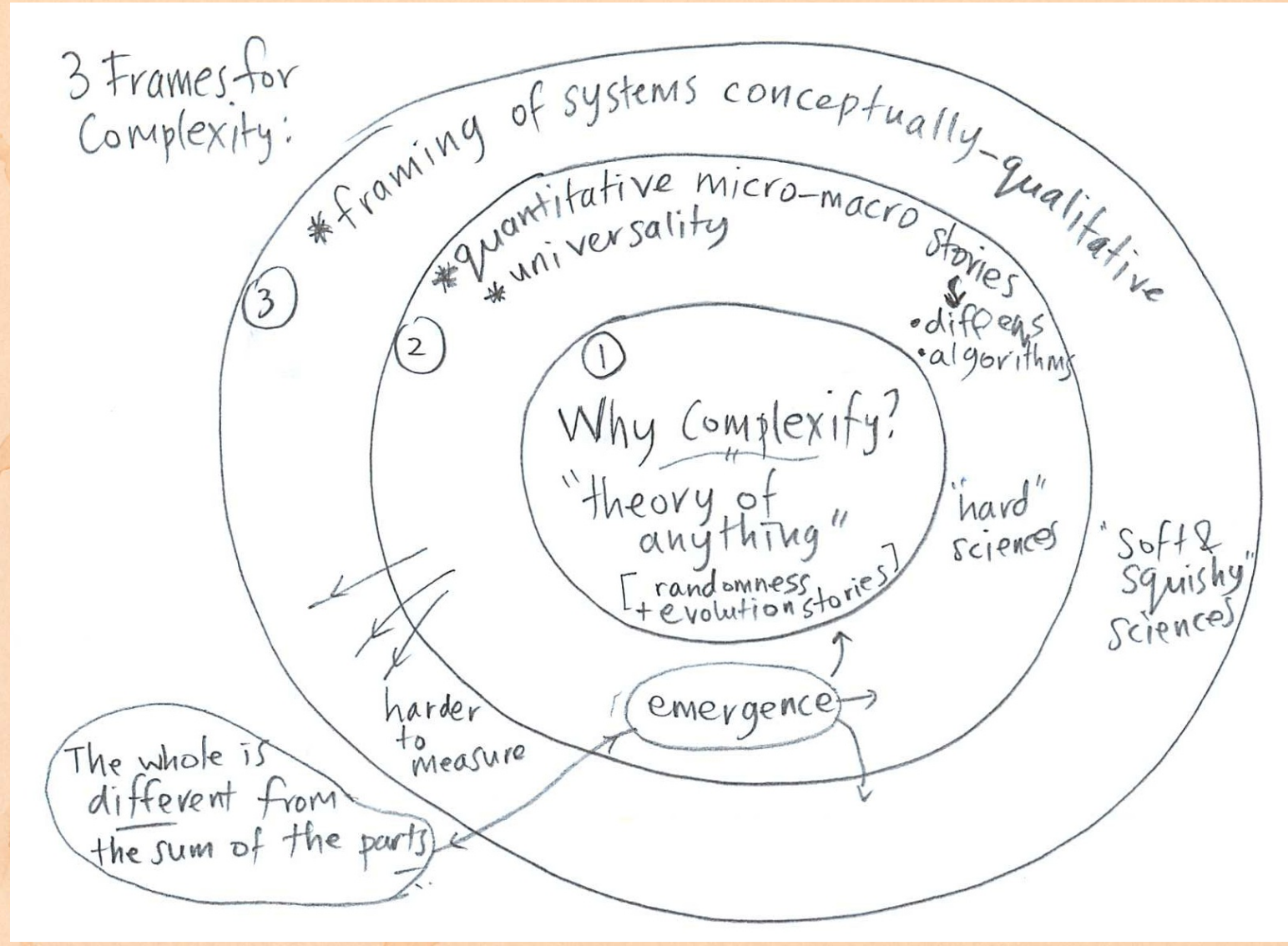


Why complexify?

Driving complexity's trajectory:

- Big Bang
- Randomness leads to replicating structures;
- Biological evolution;
- Sociocultural evolution;
- Technological evolution;
- Sociotechnological evolution.





Homo narrativus—What's the Story?:

http://xkcd.com/904/ (⊞)

- Mechanisms = Evolution equations, algorithms, stories, ...
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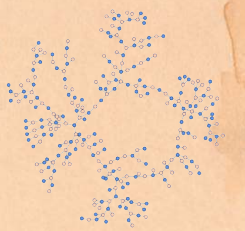
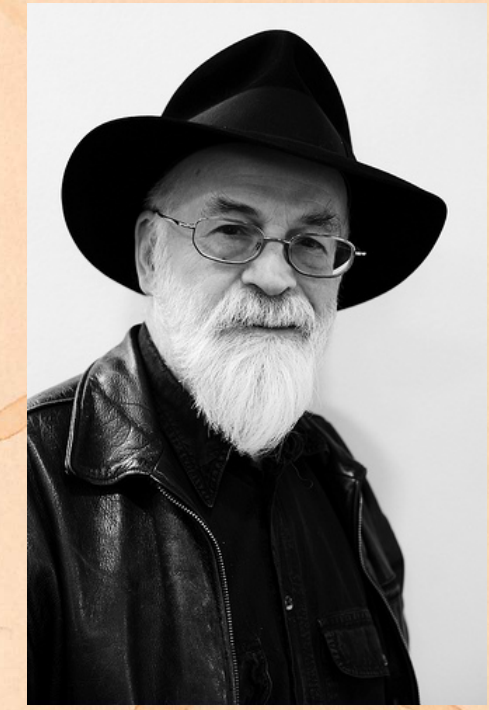
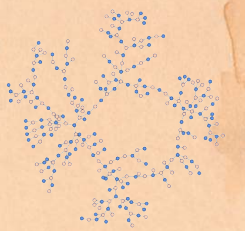


(Sir Terry) Pratchett's (⊞) Narrativium (⊞):



- "The most common element on the disc, although not included in the list of the standard five: earth, fire, air, water and surprise. It ensures that everything runs properly as a story."
- "A little narrativium goes a long way: the simpler the story, the better you understand it. Storytelling is the opposite of reductionism: 26 letters and some rules of grammar are no story at all."

- "Heroes only win when outnumbered, and things which have a one-in-a-million chance of succeeding often do so."



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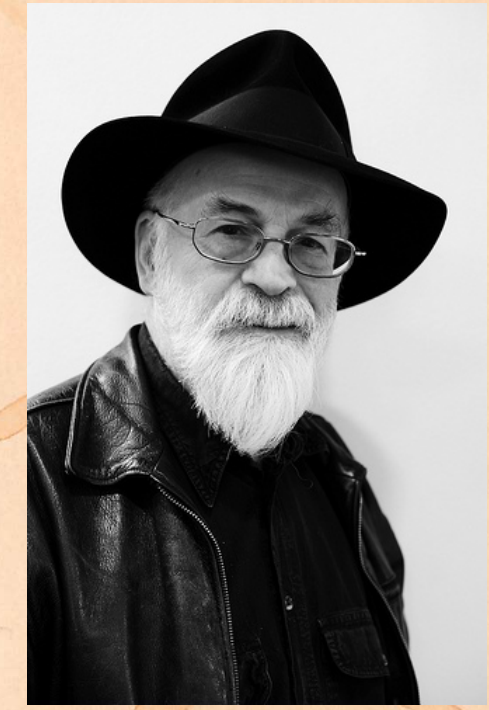

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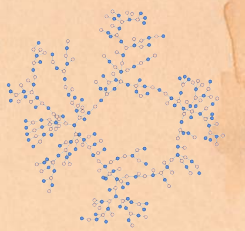

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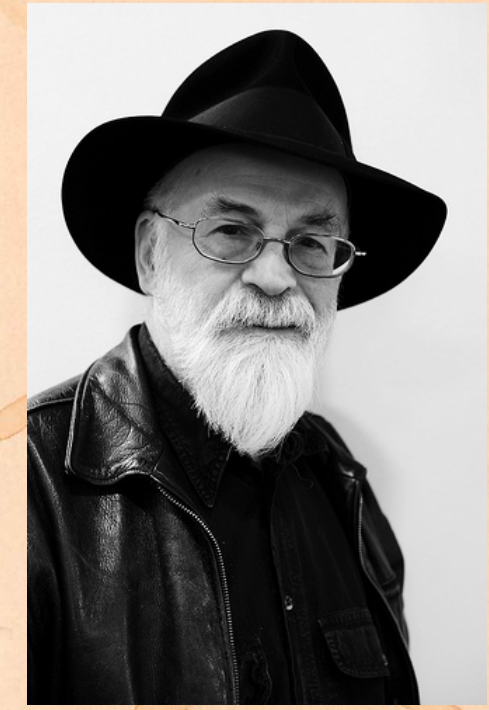

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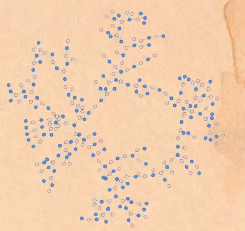

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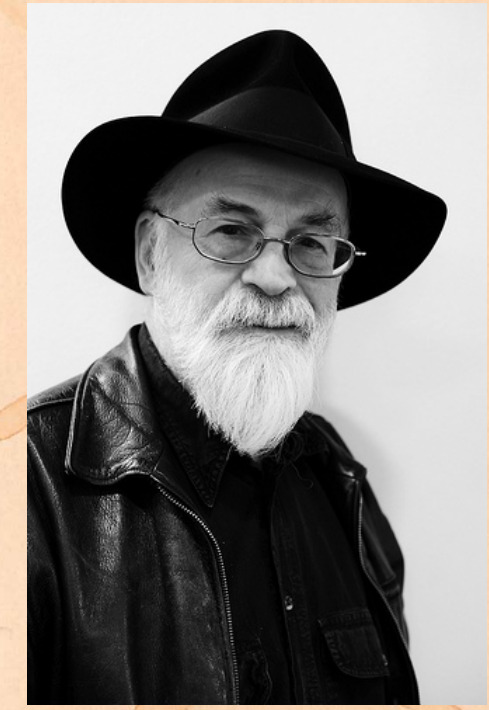

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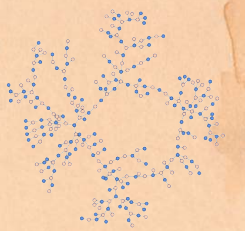

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1. Find interesting/meaningful/important phenomena involving spectacular amounts of data.
2. Describe what you see.
3. Explain it.

Beware your assumptions:

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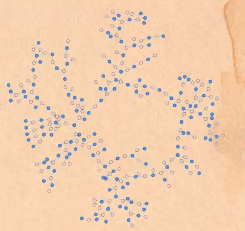

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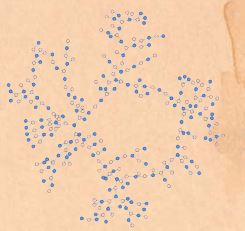

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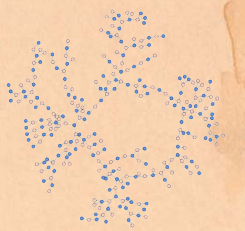

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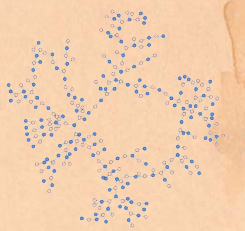

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Spring 2013: Complex Networks (CSYS/MATH 303)

- Branching networks (rivers, cardiovascular systems)
- Redistribution networks (airlines, post)
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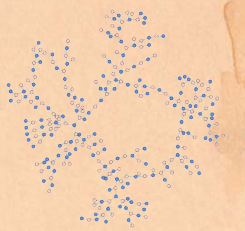
- Contagion
- Random networks-arama
- Distributed Search
- Organizational networks
- Deeper investigations of scale-free networks
- and more...



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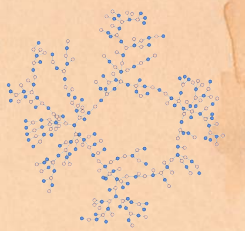

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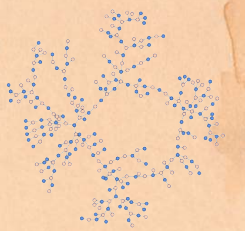

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[2] W. B. Arthur.
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[3] D. Sornette.
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[4] D. W. Thompson.
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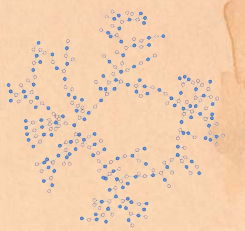

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