Overview of Complex Systems

Principles of Complex Systems
CSYS/MATH 300, Fall, 2010

Prof. Peter Dodds

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Center for Complex Systems
Vermont Advanced Computing Center
University of Vermont

Outline

Basics:

- Instructor: Prof. Peter Dodds
- Lecture room and meeting times: 010 Morrill Hall, Tuesday and Thursday, 1:00 pm to 2:15 pm
- Office: Farrell Hall, second floor, Trinity Campus
- E-mail: peter.dodds@uvm.edu
- Website: http://www.uvm.edu/~pdodds/teaching/courses/2010-08UVM-300 (⊞)
- Suggested Texts:
  - "Critical Phenomena in Natural Sciences: Chaos, Fractals, Selforganization and Disorder: Concepts and Tools" by Didier Sornette [12].
  - "Critical Mass: How One Thing Leads to Another" by Philip Ball [3]

Admin:

- CSYS/MATH 300 is one of two core requirements for UVM's Certificate of Graduate Study in Complex Systems (⊞).
- Five course requirement.

Admin:

Paper products:

1. Outline

Office hours:

- 1:00 pm to 4:00 pm, Wednesday,
  Farrell Hall, second floor, Trinity Campus

Exciting details regarding these slides:

- Three versions (all in pdf):
  1. Presentation,
  2. Flat Presentation,
  3. Handout (2x2).
- Presentation versions are navigable and hyperlinks are clickable.
- Web links look like this (⊞).
- References in slides link to full citation at end. [1]
- Citations contain links to papers in pdf (if available).
- Brought to you by a concoction of LaTeX (⊞), Beamer (⊞), perl (⊞), madness, and the indomitable emacs (⊞).

Grading breakdown:

- Projects/talks (50%)—Students will work on semester-long projects. Students will develop a proposal in the first few weeks of the course which will be discussed with the instructor for approval.

  Details: 14% for the first talk, 18% for the final talk, and 18% for the written project.
- Assignments (45%)—All assignments will be of equal weight and there will be five or six of them.
- General attendance/Class participation (5%)

How grading works:

Questions are worth 3 points according to the following scale:

- 3 = correct or very nearly so.
- 2 = acceptable but needs some revisions.
- 1 = needs major revisions.
- 0 = way off.

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Schedule:

Week # (dates)	Tuesday	Thursday
1 (8/31, 9/2)	overview	overview
2 (9/7, 9/9)	overview/projects	complex networks
3 (9/14, 9/16)	complex networks	lecture
4 (9/21, 9/23)	Project presentations	Project presentations
5 (9/28, 9/30)	lecture	lecture
6 (10/5, 10/7)	lecture	lecture
7 (10/12, 10/14)	lecture	lecture
8 (10/19, 10/21)	lecture	lecture
9 (10/26, 10/29)	lecture	lecture
10 (11/2, 11/4)	lecture	lecture
11 (11/9, 11/11)	lecture	lecture
12 (11/16, 11/18)	lecture	lecture
13 (11/23, 11/25)	Thanksgiving	Thanksgiving
14 (11/30, 12/2)	lecture	lecture
15 (12/7, 12/9)	Project Presentations	Project Presentations

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Important dates:

1. Classes run from Monday, August 30 to Thursday, December 9.
2. Add/Drop, Audit, Pass/No Pass deadline—Monday, September 13.
3. Last day to withdraw—Monday, November 1.
4. Reading and exam period—Friday, December 10 to Friday, December 17.

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More stuff:

Do check your zoo account for updates regarding the course.

Academic assistance: Anyone who requires assistance in any way (as per the ACCESS program or due to athletic endeavors), please see or contact me as soon as possible.

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Centers

- Santa Fe Institute (SFI)
- New England Complex Systems Institute (NECSI)
- Michigan's Center for the Study of Complex Systems (CSCS (⊞))
- Northwestern Institute on Complex Systems (NICO (⊞))
- Also: Indiana, Davis, Brandeis, University of Illinois, Duke, Warsaw, Melbourne, ...,
- UVM's Complex System Center (⊞)

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A few general books:

- "Micromotives and Macrobehavior" by Thomas Schelling [11]
- "Complex Adaptive Systems: An Introduction to Computational Models of Social Life," by John Miller and Scott Page [10]
- "Modeling Complex Systems" by Nino Boccara [7]
- "Dynamics of Complex Systems" by Yaneer Bar-Yam [4]

Useful online resources:

- Complexity Digest: http://www.comdig.org (⊞)
- Cosma Shalizi's notebooks: http://www.cscs.umich.edu/ crshalizi/notebooks/ (⊞)

Projects

- Semester-long projects.
- Develop proposal in first few weeks.
- May range from novel research to investigation of an established area of complex systems.
- We'll go through a list of possible projects soon.

Projects

The narrative hierarchy—explaining things on many scales:

- 1 to 3 word encapsulation, a soundbite,
- a sentence/title,
- a few sentences,
- a paragraph,
- a short paper,
- a long paper,
- a chapter,
- a book,
- . . .

Topics:

Measures of complexity

Scaling phenomena

- Zipf's law
- Non-Gaussian statistics and power law distributions
- Sample mechanisms for power law distributions
- Organisms and organizations
- Scaling of social phenomena: crime, creativity, and consumption.
- Renormalization techniques

Topics:

Multiscale complex systems

- Hierarchies and scaling
- Modularity
- Form and context in design

Complexity in abstract models

- The game of life
- Cellular automata
- Chaos and order—creation and maintenance

Topics:

Integrity of complex systems

- Generic failure mechanisms
- Network robustness
- Highly optimized tolerance: Robustness and fragility
- Normal accidents and high reliability theory

Complex networks

- Small-world networks
- Scale-free networks

Topics:

Collective behavior and contagion in social systems

- Percolation and phase transitions
- Disease spreading models
- Schelling's model of segregation
- Granovetter's model of imitation
- Contagion on networks
- Herding phenomena
- Cooperation
- Wars and conflicts

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Topics:

Large-scale Social patterns

- Movement of individuals

Collective decision making

- Theories of social choice
- The role of randomness and chance
- Systems of voting
- Juries
- Success inequality: superstardom

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Topics:

Information

- Search in networked systems (e.g., the WWW, social systems)
- Search on scale-free networks
- Knowledge trees, metadata and tagging

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Buzzword Definitions

Complex: (Latin = with + fold/weave (com + plex))

Adjective:

1. Made up of multiple parts; intricate or detailed.
2. Not simple or straightforward.

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Buzzword Definitions

Possible properties of a Complex System:

- Many interacting agents or entities
- Relationships are nonlinear
- Presence of feedback
- Complex systems are open (out of equilibrium)
- Presence of memory
- Modular/multiscale/hierarchical structure
- Evidence of emergence properties
- Evidence of self-organization

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Examples

Examples of Complex Systems:

- human societies
- cells
- organisms
- ant colonies
- weather systems
- ecosystems
- animal societies
- disease ecologies
- brains
- social insects
- geophysical systems
- the world wide web

Examples

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Relevant fields:

- Physics
- Economics
- Sociology
- Psychology
- Information Sciences
- Cognitive Sciences
- Biology
- Ecology
- Geosciences
- Geography
- Medical Sciences
- Systems Engineering
- Computer Science
- . . .

Buzzword Definitions

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Complicated versus Complex.

- Complicated: Mechanical watches, airplanes, ...
- Engineered systems can be made to be highly robust but not adaptable.
- But engineered systems can become complex (power grid, planes).
- They can also fail spectacularly.
- Explicit distinction: Complex Adaptive Systems.

Buzzword Definitions

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Nino Boccara in *Modeling Complex Systems*:

[7] "... there is no universally accepted definition of a complex system ... most researchers would describe a system of connected agents that exhibits an emergent global behavior not imposed by a central controller, but resulting from the interactions between the agents."

Buzzword Definitions

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The Wikipedia on Complex Systems:

"Complexity science is not a single theory: it encompasses more than one theoretical framework and is highly interdisciplinary, seeking the answers to some fundamental questions about living, adaptable, changeable systems."

Buzzword Definitions

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Philip Ball in *Critical Mass*:

[3] "...complexity theory seeks to understand how order and stability arise from the interactions of many components according to a few simple rules."

Buzzword Definitions

Cosma Shalizi:
“The "sciences of complexity" are very much a potpourri, and while the name has some justification—chaotic motion seems more complicated than harmonic oscillation, for instance—I think the fact that it is more dignified than "neat nonlinear nonsense" has not been the least reason for its success.—That opinion wasn’t exactly changed by working at the Santa Fe Institute for five years.”

Buzzword Definitions

Steve Strogatz in *Sync*:

“... every decade or so, a grandiose theory comes along, bearing similar aspirations and often brandishing an ominous-sounding C-name. In the 1960s it was cybernetics. In the ’70s it was catastrophe theory. Then came chaos theory in the ’80s and complexity theory in the ’90s.”

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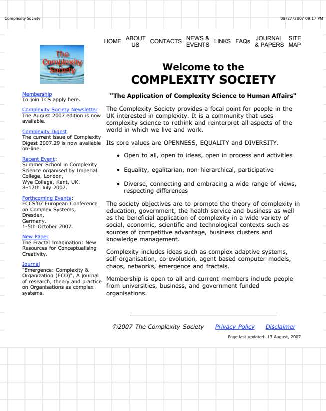
Outreach



Complexity Society 08/27/2007 09:17 PM

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Welcome to the
COMPLEXITY SOCIETY

"The Application of Complexity Science to Human Affairs"

Membership
To join TCS apply here.

Complexity Society Newsletter
The August 2007 edition is now available.

Complexity Digest
The current issue of Complexity Digest 2007.29 is now available on-line.

Recent Event:
Summer School in Complexity Science organised by Imperial College, London,
Wye College, Kent, UK.
8–17th July 2007.

Forthcoming Events:
ECCS’07 European Conference on Complex Systems,
Dresden,
Germany.
1-5th October 2007.

New Paper
The Fractal Imagination: New Resources for Conceptualising Creativity.

Journal
"Emergence: Complexity & Organization (ECO)", A journal of research, theory and practice on Organisations as complex systems.

The Complexity Society provides a focal point for people in the UK interested in complexity. It is a community that uses complexity science to rethink and reinterpret all aspects of the world in which we live and work.

Its core values are OPENNESS, EQUALITY and DIVERSITY.

- Open to all, open to ideas, open in process and activities
- Equality, egalitarian, non-hierarchical, participative
- Diverse, connecting and embracing a wide range of views, respecting differences

The society objectives are to promote the theory of complexity in education, government, the health service and business as well as the beneficial application of complexity in a wide variety of social, economic, scientific and technological contexts such as sources of competitive advantage, business clusters and knowledge management.

Complexity includes ideas such as complex adaptive systems, self-organisation, co-evolution, agent based computer models, chaos, networks, emergence and fractals.

Membership is open to all and current members include people from universities, business, and government funded organisations.

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Buzzword Definitions

The Wikipedia on Emergence:

“In philosophy, systems theory and the sciences, emergence refers to the way complex systems and patterns arise out of a multiplicity of relatively simple interactions. ... emergence is central to the physics of complex systems and yet very controversial.”

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Emergence:

Examples:

- Fundamental particles ⇒ Life, the Universe, and Everything
- Genes ⇒ Organisms
- Brains ⇒ Thoughts
- Fireflies ⇒ Synchronized Flashes [videos!]
- People ⇒ World Wide Web
- People ⇒ Behavior in games not specified by rules (e.g., bluffing in poker)
- People ⇒ Religion
- People ⇒ Language, and rules in language (e.g., -ed, -s).
- ? ⇒ time; ? ⇒ gravity; ? ⇒ reality.

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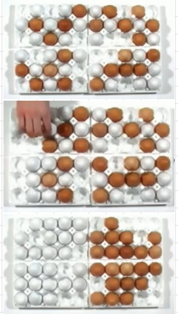
Emergence

Thomas Schelling (⊞) (Economist/Nobelist):



[youtube] (⊞)

- "Micromotives and Macrobehavior"[11]
  - Segregation
  - Wearing hockey helmets
  - Seating choices

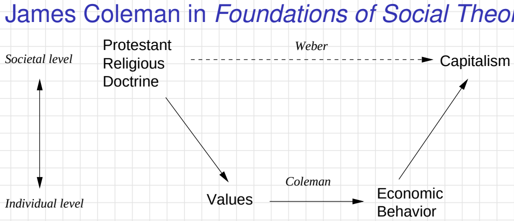
Emergence

Friedrich Hayek (⊞) (Economist/Philospher/Nobelist):

- Markets, legal systems, political systems are emergent and not designed.
- 'Taxis' = made order (by God, Sovereign, Government, ...)
- 'Cosmos' = grown order
- Archetypal limits of hierarchical and decentralized structures.
- Hierarchies arise once problems are solved.
- Decentralized structures help solve problems.
- Dewey Decimal System versus tagging.

Emergence

James Coleman in *Foundations of Social Theory*:



- Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena.[8]
- More on Coleman here (⊞).

Emergence

Higher complexity:

- Many system scales (or levels) that interact with each other.

Emergence

Even mathematics:[9]
Gödel's Theorem (roughly):
we can't prove every theorem that's true.

Suggests a strong form of emergence:

Some phenomena cannot be formally deduced from elementary aspects of a system.

Emergence

The idea of emergence is rather old...

"The whole is more than the sum of its parts" –Aristotle

Philosopher G. H. Lewes first used the word explicity in 1875.

Buzzword Definitions

There appear to be two types of emergence:

I. Weak emergence:

System-level phenomena is different from that of its constituent parts yet can be connected theoretically.

II. Strong emergence:

System-level phenomena fundamentally cannot be deduced from how parts interact.

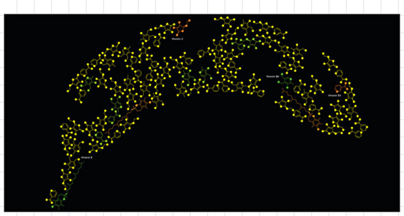
Strong emergence could be called magic...
See Bedau (1997) [5]

Buzzword Definitions

- Complex Systems enthusiasts often decry reductionist approaches . . .
- But reductionism seems to be misunderstood.
- Reductionist techniques can explain weak emergence (e.g., phase transitions).
- 'A Miracle Occurs' explains strong emergence.
- But: maybe miracle should be interpreted as an inscrutable yet real mechanism that cannot be simply described. Gulp.
- Listen to Steve Strogatz and Hod Lipson (Cornell) in the last piece on Radiolab's show 'Limits' (51:40): `http://blogs.wnyc.org/radiolab/2010/04/05/limits/`

The emergence of taste:

- Molecules ⇒ Ingredients ⇒ Taste
- See Michael Pollan's article on nutritionism (⊞) in the New York Times, January 28, 2007.



nytimes.com

Reductionism

Reductionism and food:

- Pollan: "even the simplest food is a hopelessly complex thing to study, a virtual wilderness of chemical compounds, many of which exist in complex and dynamic relation to one another..."
- "So ... break the thing down into its component parts and study those one by one, even if that means ignoring complex interactions and contexts, as well as the fact that the whole may be more than, or just different from, the sum of its parts. This is what we mean by reductionist science."

Reductionism

- "people don't eat nutrients, they eat foods, and foods can behave very differently than the nutrients they contain."
- Studies suggest diets high in fruits and vegetables help prevent cancer.
- So... find the nutrients responsible and eat more of them
- But "in the case of beta carotene ingested as a supplement, scientists have discovered that it actually increases the risk of certain cancers. Big oops."

Reductionism

Thyme's known antioxidants:

4-Terpineol, alanine, anethole, apigenin, ascorbic acid, beta carotene, caffeic acid, camphene, carvacrol, chlorogenic acid, chrysoeriol, eriodictyol, eugenol, ferulic acid, gallic acid, gamma-terpinene isochlorogenic acid, isoeugenol, isothymonin, kaempferol, labiatic acid, lauric acid, linalyl acetate, luteolin, methionine, myrcene, myristic acid, naringenin, oleanolic acid, p-coumoric acid, p-hydroxy-benzoic acid, palmitic acid, rosmarinic acid, selenium, tannin, thymol, tryptophan, ursolic acid, vanillic acid.

[cnn.com]

Reductionism

"It would be great to know how this all works, but in the meantime we can enjoy thyme in the knowledge that it probably doesn't do any harm (since people have been eating it forever) and that it may actually do some good (since people have been eating it forever) and that even if it does nothing, we like the way it tastes."

Gulf between theory and practice (see baseball and bumblebees).

Buzzword Definitions

Self-Organization

"Self-organization (⊞) is a process in which the internal organization of a system, normally an open system, increases in complexity without being guided or managed by an outside source."
(also: Self-assembly)

- Self-organization refers to a broad array of decentralized processes that lead to emergent phenomena.

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Examples of self-organization:

- Molecules/Atoms liking each other → Gas-liquid-solids
- Spin alignment → Magnetization
- Imitation → Herding, flocking, stampedes

Question: how likely is 'complexification'?

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Economics

Eric Beinhocker (*The Origin of Wealth*):[6]

Dynamic:

- Complexity Economics: Open, dynamic, non-linear systems, far from equilibrium
- Traditional Economics: Closed, static, linear systems in equilibrium

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Economics

Agents:

- Complexity Economics: Modelled individually; use inductive rules of thumb to make decisions; have incomplete information; are subject to errors and biases; learn to adapt over time
- Traditional Economics: Modelled collectively; use complex deductive calculations to make decisions; have complete information; make no errors and have no biases; have no need for learning or adaptation (are already perfect)

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Economics

Networks:

- Complexity Economics: Explicitly model bi-lateral interactions between individual agents; networks of relationships change over time
- Traditional Economics: Assume agents only interact indirectly through market mechanisms (e.g. auctions)

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Economics

Emergence:

- Complexity Economics: No distinction between micro/macro economics; macro patterns are emergent result of micro level behaviours and interactions
- Traditional Economics: Micro-and macroeconomics remain separate disciplines

Economics

Evolution:

- Complexity Economics:
  The evolutionary process of differentiation, selection and amplification provides the system with novelty and is responsible for its growth in order and complexity
- Traditional Economics:
  No mechanism for endogenously creating novelty, or growth in order and complexity

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Upshot

- The central concepts Complexity and Emergence are not precisely defined.
- There is as yet no general theory of Complex Systems.
- But the problems exist...
  Complex (Adaptive) Systems abound...
- Framing: Thinking about systems is essential today.
- We use whatever tools we need.

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Models

Nino Boccara in *Modeling Complex Systems*:

"Finding the emergent global behavior of a large system of interacting agents using methods is usually hopeless, and researchers therefore must rely on computer-based models."

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Approaches

Nino Boccara in *Modeling Complex Systems*:

Focus is on dynamical systems models:

- differential and difference equation models
- chaos theory
- cellular automata
- networks
- power-law distributions

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Models

Philip Ball in *Critical Mass*:

[3] "... very often what passes today for 'complexity science' is really something much older, dressed up in fashionable apparel. The main themes in complexity theory have been studied for more than a hundred years by physicists who evolved a tool kit of concepts and techniques to which complexity studies have barely added a handful of new items."

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Old School

- Statistical Mechanics is “a science of collective behavior.”
- Simple rules give rise to collective phenomena.

Statistical mechanics

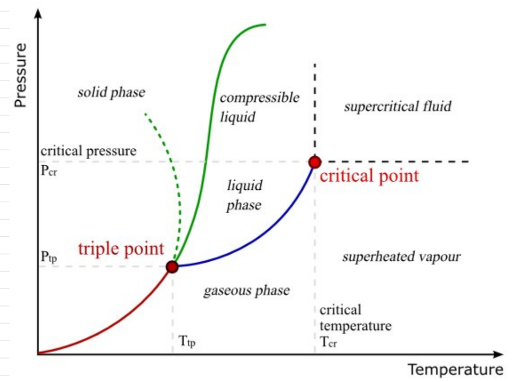
The Ising Model (⊞):

- Idealized model of a ferromagnet.
- Each atom is assumed to have a local spin that can be up or down: $S_i = \pm 1$.
- Spins are assumed arranged on a lattice (e.g. square lattice in 2-d).
- In isolation, spins like to align with each other.
- Increasing temperature breaks these alignments.
- The *drosophila* of statistical mechanics.

Ising model

2-d Ising model simulation:
http://www.pha.jhu.edu/ javalab/ising/ising.html (⊞)

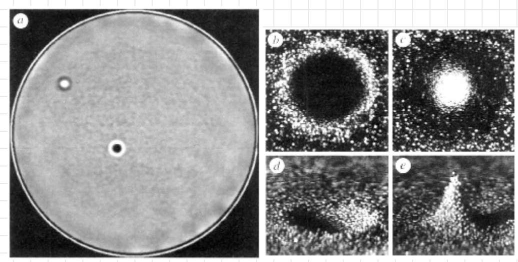
Phase diagrams



Qualitatively distinct macro states.

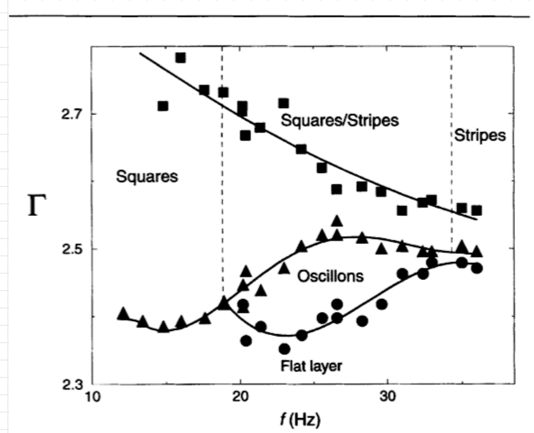
Phase diagrams

Oscillons, bacteria, traffic, snowflakes, ...

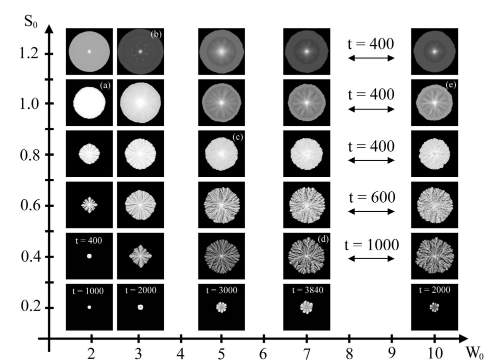


Umbanhowar et al., *Nature*, 1996 [15]

Phase diagrams



Phase diagrams



W_0 = initial wetness, S_0 = initial nutrient supply

http://math.arizona.edu/~lega/HydroBact.html

Ising model

Analytic issues:

- 1-d: simple (Ising & Lenz, 1925)
- 2-d: hard (Onsager, 1944)
- 3-d: extremely hard...
- 4-d and up: simple.

Statistics

- Origins of Statistical Mechanics are in the studies of people... (Maxwell and co.)
- Now physicists are using their techniques to study everything else including people...
- See Philip Ball's "Critical Mass"[3]

Limits to what is 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.

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?

Fluids

Fluid flow is modeled by the Navier-Stokes equations.

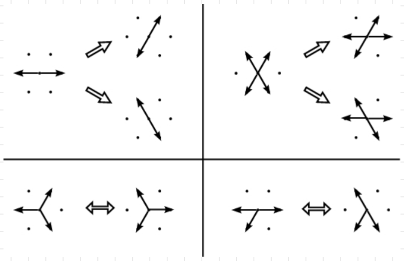
Works for many very different fluids:

- The atmosphere, oceans, blood, galaxies, the earth's mantle...

and ball bearings on lattices...?

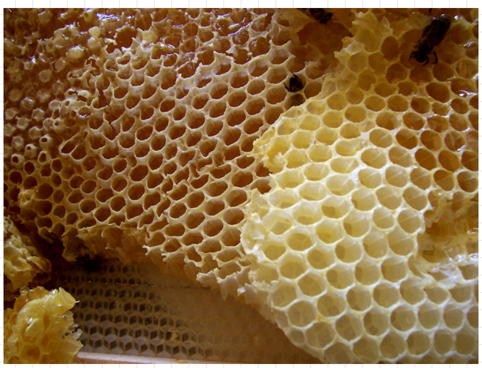
Lattice gas models

Collision rules in 2-d on a hexagonal lattice:



- Lattice matters...
- No 'good' lattice in 3-d.

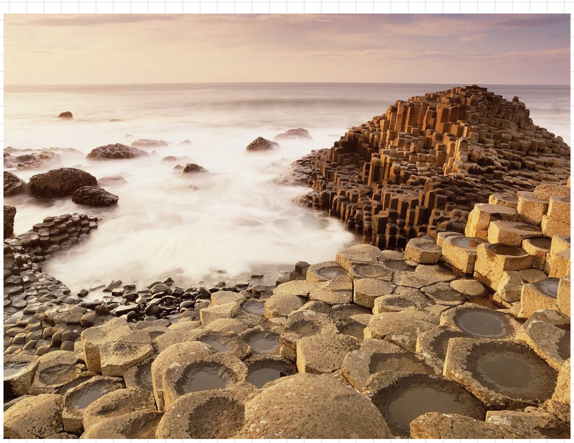
Hexagons—Honeycomb: (⊞)



- Orchestrated? Or an accident of bees working hard?
- See "On Growth and Form" by D'Arcy Wentworth Thompson (⊞).[13, 14]

Overview

Hexagons—Giant's Causeway: (⊞)



http://newdesktopwallpapers.info

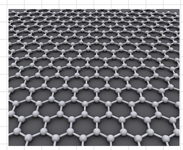
Overview

Hexagons—Giant's Causeway: (⊞)

http://www.physics.utoronto.ca/

Overview

Hexagons run amok:

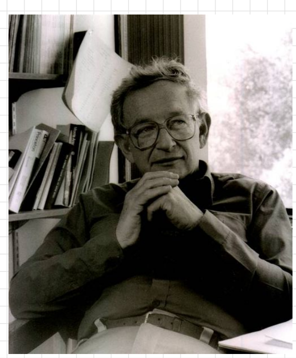


- Graphene (⊞): single layer of carbon molecules in a perfect hexagonal lattice (super strong).
- Chicken wire (⊞)...

Overview

Symmetry Breaking

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



- Argues against idea that the only real scientists are those working on the fundamental laws.
- Symmetry breaking ⇒ different laws/rules at different scales...

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

Overview

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

Symmetry Breaking

Anderson:
[the more we know about] "fundamental laws, the less relevance they seem to have to the very real problems of the rest of science."

Scale and complexity thwart the constructionist hypothesis.

Accidents of history and path dependence (⊞) matter.

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Symmetry Breaking

- Page 291–292 of Sornette[12]:
  Renormalization ≡ Anderson's hierarchy.
- But Anderson's hierarchy is not a simple one: the rules change.
- Crucial dichotomy between evolving systems following stochastic paths that lead to
  (a) inevitable or (b) particular destinations (states).

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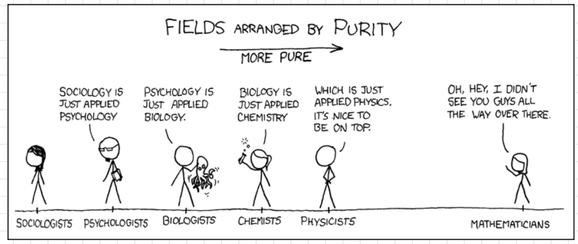
More is different:



http://xkcd.com/435/ (⊞)

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A real science of complexity:

A real theory of everything:

1. Is not just about the ridiculously small stuff...
2. It's about the increase of complexity

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?
- Another key: randomness can give order.

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Tools and techniques:

- Differential equations, difference equations, linear algebra.
- Statistical techniques for comparisons and descriptions.
- Methods from statistical mechanics and computer science.
- Computer modeling.

Key advance:

- Representation of complex interaction patterns as dynamic networks.
- The driver: Massive amounts of Data
- More later...

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The absolute basics:

Science in three steps:

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

Beware your assumptions

Don't use tools/models because they're there, or because everyone else does...

Measures of Complexity

How do we measure the complexity of a system?

(1) Entropy: number of microstates that could underlie a particular macrostate.

- Used in information theory and statistical mechanics/thermodynamics.
- Measures how uncertain we are about the details of a system.
- Problem: Randomness maximizes entropy, perfect order minimizes.
- Our idea of 'maximal complexity' is somewhere in between...

Hmmm

(Aside)

What about entropy and self-organization?

Isn't entropy supposed to always increase?

Hmmm

Two ways for order to appear in a system without offending the second law of thermodynamics:

(1) Entropy of the system decreases at the expense of entropy increasing in the environment.

(2) The system becomes more ordered macroscopically while becoming more disordered microscopically.

Measures of Complexity

(2) Various kinds of information complexity:

- Roughly, what is the size of a program required to reproduce a string of numbers?
- Again maximized by random strings.
- Very hard to measure.

Measures of Complexity

(3) Variation on (2): what is the size of a program required to reproduce members of an ensemble of a string of numbers?

Now: Random strings have very low complexity.

Measures of Complexity

Large problem: given any one example, how do we know what ensemble it belongs to?

One limited solution: divide the string up into subsequences to create an ensemble.

See *Complexity* by Badii & Politi [2]

Measures of Complexity

So maybe no one true measure of complexity exists.

Cosma Shalizi:

"Every few months seems to produce another paper proposing yet another measure of complexity, generally a quantity which can't be computed for anything you'd actually care to know about, if at all. These quantities are almost never related to any other variable, so they form no part of any theory telling us when or how things get complex, and are usually just quantification for quantification's own sweet sake."

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