Overview of Complex Systems

Principles of Complex Systems
CSYS/MATH 300, Spring, 2013 | #SpringPoCS2013

Prof. Peter Dodds
@peterdodds

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

Outline

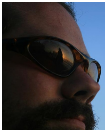
These slides brought to you by:

Computational Story Lab ++;

onehappybird.com

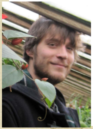

Peter Dodds

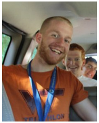

Lewis Mitchell


Nick Allgaier


Cathy Bliss


Chris Danforth


Jake Williams


Andy Reagan


Eitan Pechenick


Emily Cody

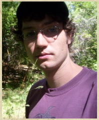

Morgan Frank


Lindsay Van Leir


Mike Foley


Ross Lieb-Lappen (Dartmouth)


Isabel Kloumann (Cornell)


Kameron Harris (Washington)


Paul Lessard (Colorado)

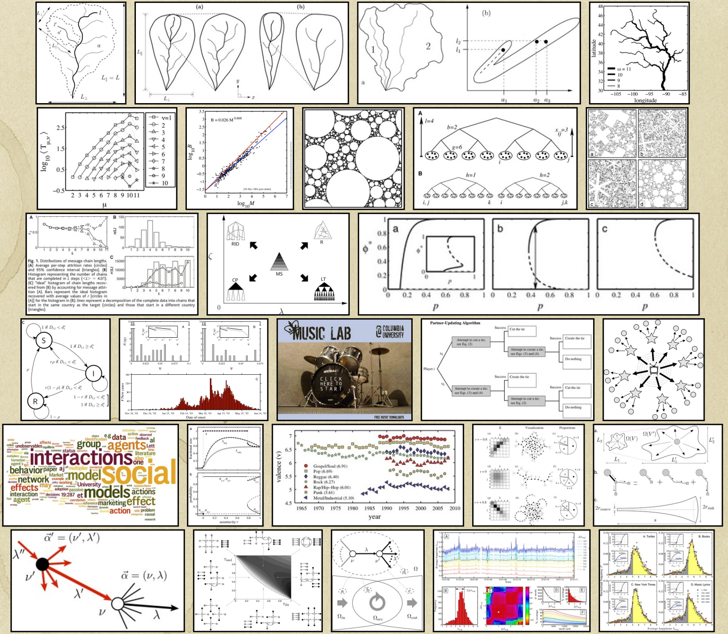

Tyler Gray (MIT)

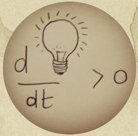

Suma Desu


Eric Clark

Funding: NSF, NASA, MITRE.

To be clear, I work with this guy:


MUSIC LAB
COLUMBIA UNIVERSITY
CLICK HERE TO START
Partner-Updating Algorithm
interactions
social
models
agents
network
behavior
group
data
effects
effect
marketing
actions
action
year
valence (v)
Gospel/Soul (6.91)
Pop (6.69)
Reggae (6.40)
Rock (6.27)
Rap/Hip-Hop (6.01)
Punk (5.61)
Metal/Industrial (5.10)
longitude
latitude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Outline

Basics:

- Instructor: Prof. Peter Dodds
- Lecture room and meeting times:
  102 Perkins, Tuesday and Thursday, 11:30 am to 12:45 pm
- Office: Farrell Hall, second floor, Trinity Campus
- email: peter.dodds@uvm.edu
- Course Website:
  http://www.uvm.edu/~pdodds/teaching/courses/2013-01UVM-300 (⊞)

Admin:

Potential paper products:

- The Syllabus (⊞) and a Poster (⊞).

Office hours:

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

Graduate Certificate:

- Principles of Complex Systems is one of two core requirements for UVM's five course Certificate of Graduate Study in Complex Systems (⊞).
- Other required course: Prof. Maggie Eppstein's "Modelling Complex Systems" (CSYS/CS 302).
- The Sequel to PoCS: "Complex Networks" (CSYS/MATH 303).

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- Three versions (all in pdf):
  1. Presentation,
  2. Flat Presentation,
  3. Handout (3x2 slides per page).
- Presentation versions are hyperly navigable: back + search + forward.
- Web links look like this (⊞) and are eminently clickable.
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Grading breakdown:

- Projects/talks (36%)—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: 12% for the first talk, 12% for the final talk, and 12% for the written project.

- Assignments (60%)—All assignments will be of equal weight and there will be six or seven of them.

- General attendance/Class participation (4%)

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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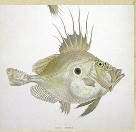
Important things:

1. Classes run from Tuesday, January 15 to Tuesday, April 30.
2. Add/Drop, Audit, Pass/No Pass deadline—Monday, January 28.
3. Last day to withdraw—Friday, March 29 (Sadness!).
4. Reading and Exam period—Thursday, May 2 to Friday, May 10.

Do check your zoo account for updates regarding the course.

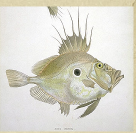
Academic assistance: Anyone who requires assistance in any way (as per the ACCESS program or due to athletic endeavors), please see or contact me as soon as possible.

Outline



Major themes:

- The Complexity Manifesto;
- Complex Systems $\equiv$ Modern, Normal Science;
- Roles and limits of Data, Theory, and Experiment;
- Emergence;
- Universality and Accidents of History;
- Structure and Stories: Micro-to-macro Mechanisms;
- Elements: Scaling, Surprise, Networks, Robustness, Failure, and Spreading.
- The Theory of Anything: Why Complexify?



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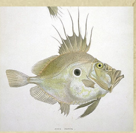

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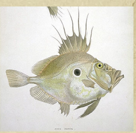

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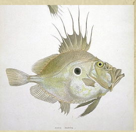

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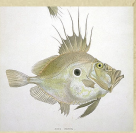

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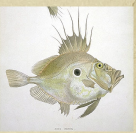

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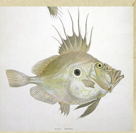

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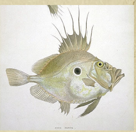
Topics:

Scaling phenomena:

- Allometry
- Scaling of social phenomena: crime, creativity, and consumption.
- Scaling in biology (elephants and platypuses).
- Non-Gaussian statistics and power law distributions
- Zipf's law
- Key mechanisms for power law distributions
- Renormalization techniques



Topics:

Complex networks:

- Structure and Dynamics;
- Statistical Mechanics;
- Phase transitions;
- Random Networks;
- Scale-free Networks;
- Small-world Networks.

Multiscale complex systems:

- Hierarchies and Scaling;
- Modularity;

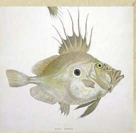
Topics:

Integrity of complex systems:

- Generic failure mechanisms
- Network robustness
- Highly Optimized Tolerance (HOT): Robustness and fragility
- Predictablity

Information and Language:

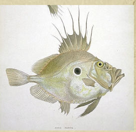
- Search in networked systems (e.g., the web, social systems)
- Search on scale-free networks
- Knowledge trees, metadata and tagging
- Evolution and structure of natural languages



Topics:

Sociotechnical Systems:

- Biological and social spreading models;
- Schelling's model of segregation; [17]
- Granovetter's model of imitation; [12]
- Collective behavior and Synchrony;
- Global cooperation from bad actors;
- Global conflicts from good actors.
- The Sociotechnocene.



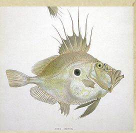
Topics:

Large-scale social patterns:

- Movement of individuals;
- Cities;
- Happiness;
- Twitter.

Collective decision making:

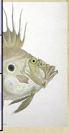
- Wisdom and madness of crowds;
- Systems of voting;
- The role of randomness and chance;
- Success inequality: superstardom;



Schedule:

Week # (dates)	Tuesday	Thursday
1 (1/15 and 1/17)	Overview; Fundamentals: The Complexity Manifesto	Power-law size distributions
2 (1/22 and 1/24)	Zipf's law; Fundamentals: Data, Emergence, Limits to Understanding	Power-law mechanisms: Randomness
3 (1/29 and 1/31)	Power-law mechanisms: Variable Transformation; Projects	Power-law mechanisms: The Rich-Get-Richer
4 (2/5 and 2/7)	Power-law mechanisms: Optimization	Fundamentals: Self-Organization; Projects
5 (2/12 and 2/14)	Robustness and Fragility	HOT vs. SOC
6 (2/19 and 2/21)	Fundamentals: Statistical Mechanics Complex networks: Introduction	Complex networks: Key features
7 (2/26 and 2/28)	Project presentations†	Project presentations†
8 (3/5 and 3/7)	Spring recess	Spring recess
9 (3/12 and 3/14)	Complex networks: Generalized random networks	Complex networks: Small-world networks
10 (3/19 and 3/21)	Complex networks: Scale-free networks	Complex networks: Modularity
11 (3/26 and 3/28)	Contagion: Introduction	Biological Contagion
12 (4/2 and 4/4)	Social Contagion	Interesting Scaling
13 (4/9 and 4/11)	Interesting Scaling	Interesting Scaling
14 (4/16 and 4/23)	Voting and Success	Happiness
15 (4/30)	The Big Story	—

†: 3-4 minutes each + 1 or 2 questions;



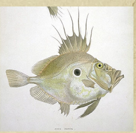
Secrets of the Universe will be revealed:

Outline

- Computational Story Lab
- Orientation
  - Course Information
  - Topics
  - Projects
  - Centers, Books, Resources
- Fundamentals
  - Complexity
  - Emergence
  - Self-Organization
  - Our Framing
  - Modeling
  - Statistical Mechanics
- References

Projects

- Semester-long projects.
- Develop proposal in first few weeks.
- May range from novel research to investigation of an established area of complex systems.
- Two talks + written piece.
- Usage of the VACC (⊞) is encouraged (ability to code well = super powers).
- Massive data sets available, including Twitter
- Academic output (journal papers) resulting from Principles of Complex Systems and Complex Networks can be found here (⊞). Add more!
- We'll go through a list of possible projects soon.



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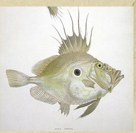

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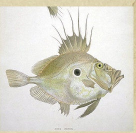

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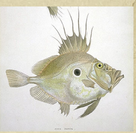

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- Usage of the VACC (⊞) is encouraged (ability to code well = super powers).
- Massive data sets available, including Twitter
- Academic output (journal papers) resulting from Principles of Complex Systems and Complex Networks can be found here (⊞). Add more!
- We'll go through a list of possible projects soon.

Projects

- Semester-long projects.
- Develop proposal in first few weeks.
- May range from novel research to investigation of an established area of complex systems.
- Two talks + written piece.
- Usage of the VACC (⊞) is encouraged (ability to code well = super powers).
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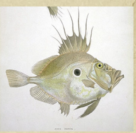


Projects

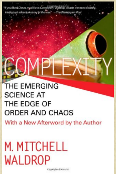
The narrative hierarchy—explaining things on many scales:

- 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,
- ...

Outline

Popular Science Books:

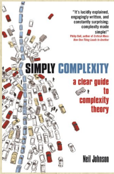
Historical artifact:



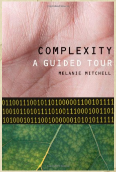
"Complexity: The Emerging Science at the Edge of Order and Chaos" (⊞) by M. Mitchell Waldrop (1993). [23]

Shout-out: Dr. Andrew P. Morokoff (⊞), MBBS PhD FRACS D.Thau (Bug) (⊞)

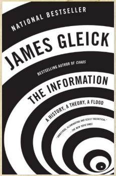
Popular Science Books:



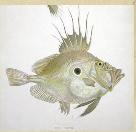
"Simply Complexity: A Clear Guide to Complexity Theory" (⊞)
by Neil F. Johnson (2009). [13]



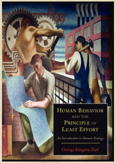
"Complexity: A Guided Tour" (⊞)
by Melanie Mitchell (2009). [16]



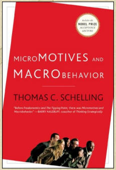
"The Information: A History, A Theory, A Flood" (⊞)
by James Gleick (2011). [11]



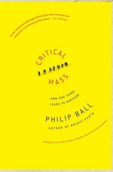
On complex sociotechnical systems:



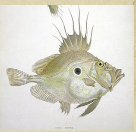
"Human Behaviour and the Principle of Least-Effort" (⊞) by George K. Zipf (1949). [24]



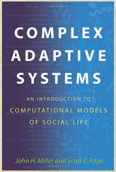
"Micromotives and Macrobehavior" (⊞) by Thomas C. Schelling (1978). [19]



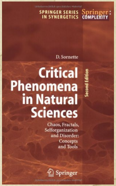
"Critical Mass: How One Thing Leads to Another" (⊞) by Philip Ball (2004). [2]



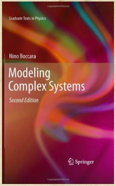
A few textbooky books:



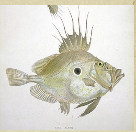
"Complex Adaptive Systems: An introduction to computational models of social life" (⊞) by John H. Miller and Scott E. Page and (2007). [15]



"Critical Phenomena in Natural Sciences" (⊞) by Didier Sornette (2003). [21]

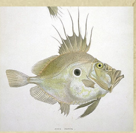


"Modeling Complex Systems" (⊞) by Nino Boccara (2004). [4]



Relevant online courses:

- Melanie Mitchell (Santa Fe Institute): Introduction to Complexity (⊞)
- Lada Adamic (Michigan): Social Network Analysis (⊞)



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 (⊞)

Useful/amusing online resources:

- Complexity Digest:
  http://www.comdig.org (⊞)

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

Outline

Definitions

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

Adjective:

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

Definitions

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.

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The UNIVERSITY of VERMONT

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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."

Nino Boccara in *Modeling Complex Systems*:

[5] "... 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."

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Philip Ball in *Critical Mass*:

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

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."

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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."

Definitions

A meaningful definition of a Complex System:

- Distributed system of many interrelated (possibly networked) parts with no centralized control exhibiting emergent behavior—'More is Different' [1]

A few optional features:

- Explicit nonlinear relationships
- Presence of feedback loops
- Being open or driven, opaque boundaries
- Presence of memory
- Modular (nested)/multiscale structure

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Examples of Complex Systems:

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

- i.e., everything that's interesting...

Relevant fields:

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

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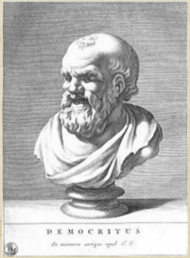
Reductionism:



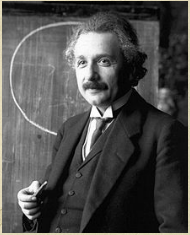
Democritus (⊞)
(ca. 460 BC – ca. 370 BC)

- Atomic hypothesis
- Atom $\sim$ a (not) – temnein (to cut)
- Plato allegedly wanted his books burned.

John Dalton (⊞)
1766–1844

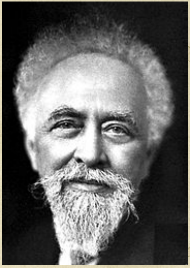
- Chemist, Scientist
- Developed atomic theory
- First estimates of atomic weights

Reductionism:



Albert Einstein (⊞) 1879–1955

- Annus Mirabilis paper: (⊞) "the Motion of Small Particles Suspended in a Stationary Liquid, as Required by the Molecular Kinetic Theory of Heat" [8, 9]
- Showed Brownian motion (⊞) followed from an atomic model giving rise to diffusion.



Jean Perrin (⊞) 1870–1942

- 1908: Experimentally verified Einstein's work and Atomic Theory.

Complexity Manifesto:

1. Systems are ubiquitous and systems matter.
2. Consequently, much of science is about understanding how pieces dynamically fit together.
3. 1700 to 2000 = Golden Age of Reductionism.
   - Atoms!, sub-atomic particles, DNA, genes, people, ...
4. Understanding and creating systems (including new 'atoms') is the greater part of science and engineering.
5. Universality: systems with quantitatively different micro details exhibit qualitatively similar macro behavior.
6. Computing advances make the Science of Complexity possible:
   6.1 We can measure and record enormous amounts of data, research areas continue to transition from data scarce to data rich.
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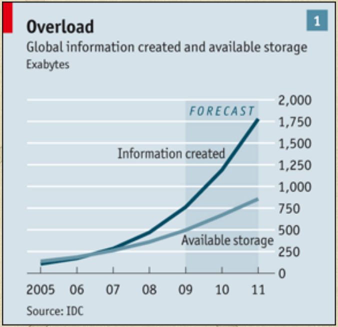
The University of Vermont

Data, Data, Everywhere—the Economist, Feb 25, 2010 (⊞)



- Exponential growth: $\sim$ 60% per year.

Big Data Science:

- 2013: year traffic on Internet estimate to reach 2/3 Zettabytes ($1\text{ZB} = 10^3\text{EB} = 10^6\text{PB} = 10^9\text{TB}$)
- Large Hadron Collider: 40 TB/second.
- 2016—Large Synoptic Survey Telescope: 140 TB every 5 days.
- Facebook: $\sim$ 100 billion photos
- Twitter: $\sim$ 5 billion tweets

No really, that's a lot of data

Data inflation

2

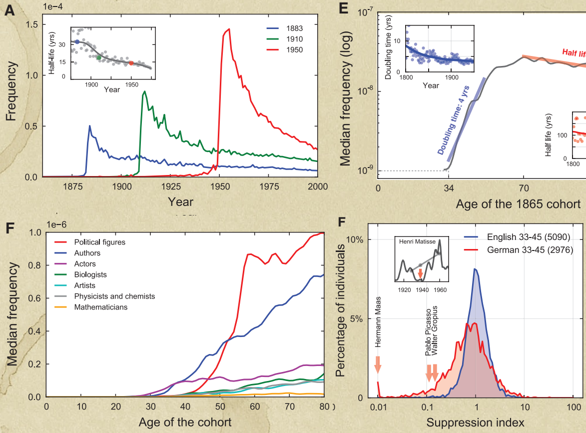
Unit	Size	What it means
Bit (b)	1 or 0	Short for "binary digit", after the binary code (1 or 0) computers use to store and process data
Byte (B)	8 bits	Enough information to create an English letter or number in computer code. It is the basic unit of computing
Kilobyte (KB)	1,000, or 2^{10}, bytes	From "thousand" in Greek. One page of typed text is 2KB
Megabyte (MB)	1,000KB; 2^{20} bytes	From "large" in Greek. The complete works of Shakespeare total 5MB. A typical pop song is about 4MB
Gigabyte (GB)	1,000MB; 2^{30} bytes	From "giant" in Greek. A two-hour film can be compressed into 1-2GB
Terabyte (TB)	1,000GB; 2^{40} bytes	From "monster" in Greek. All the catalogued books in America's Library of Congress total 15TB
Petabyte (PB)	1,000TB; 2^{50} bytes	All letters delivered by America's postal service this year will amount to around 5PB. Google processes around 1PB every hour
Exabyte (EB)	1,000PB; 2^{60} bytes	Equivalent to 10 billion copies of *The Economist*
Zettabyte (ZB)	1,000EB; 2^{70} bytes	The total amount of information in existence this year is forecast to be around 1.2ZB
Yottabyte (YB)	1,000ZB; 2^{80} bytes	Currently too big to imagine

The prefixes are set by an intergovernmental group, the International Bureau of Weights and Measures. Yotta and Zetta were added in 1991; terms for larger amounts have yet to be established.

Source: *The Economist*

Big Data—Culturomics:

"Quantitative analysis of culture using millions of digitized books" by Michel et al., Science, 2011 [14]



http://www.culturomics.org/ (⊞)

Google Books ngram viewer (⊞)

Basic Science $\simeq$ Describe + Explain:

Lord Kelvin (possibly):

- "To measure is to know."
- "If you cannot measure it, you cannot improve it."

Bonus:

- "X-rays will prove to be a hoax."
- "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

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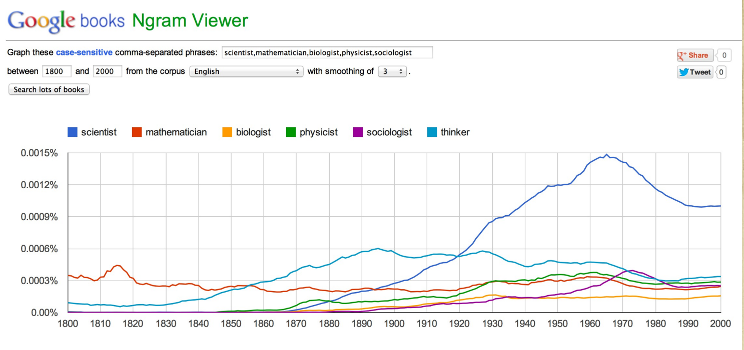
The Newness of being a Scientist:



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Emergence:

The Wikipedia on Emergence:

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The philosopher G. H. Lewes first used the word explicity in 1875.

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Fireflies ⇒ Synchronized Flashes:

Emergence:

Tornadoes, financial collapses, human emotion aren’t found in water molecules, dollar bills, or carbon atoms.

Examples:

- Fundamental particles ⇒ Life, the Universe, and Everything
- Genes ⇒ Organisms
- Neurons etc. ⇒ Brain ⇒ Thoughts
- People ⇒ Religion, Collective behaviour
- People ⇒ The Web
- People ⇒ Language, and rules of language
- ? ⇒ time; ? ⇒ gravity; ? ⇒ reality.

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

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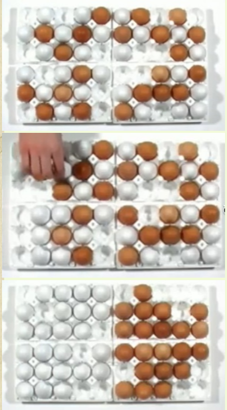
Emergence:

Thomas Schelling (⊞) (Economist/Nobelist):



[youtube] (⊞)

- "Micromotives and Macrobehavior" [19]
    - Segregation [17, 20]
    - Wearing hockey helmets [18]
    - 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, ...)
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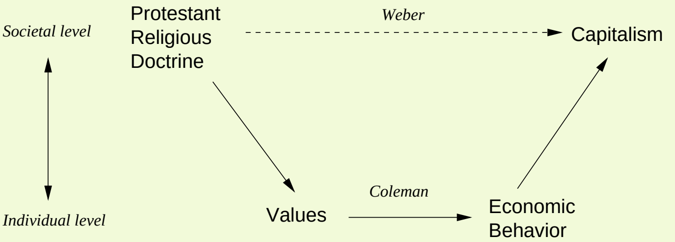

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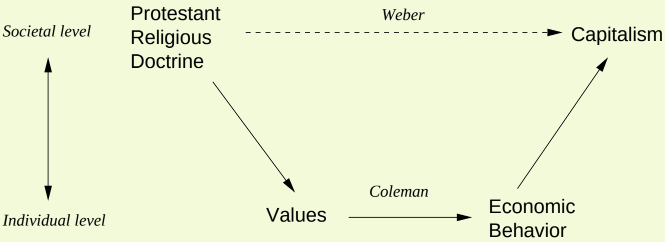

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Higher complexity:

- Many system scales (or levels) that interact with each other.
- Potentially much harder to explain/understand.

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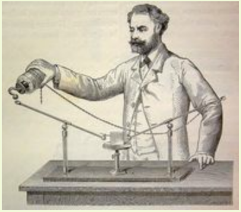
Listen to Steve Strogatz, Hod Lipson, and Michael Schmidt (Cornell) in the last piece (⊞) on Radiolab's show 'Limits' (⊞) (April 5, 2010).



(El Bibliomata/flickr)

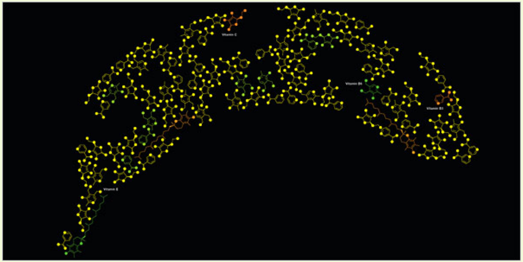
Dr. Steve Strogatz wonders if we've reached the limits of human scientific understanding, and should soon turn the reins of research over to robots. Cold, calculating robots. Then, Dr. Hod Lipson and Michael Schmidt walk us through the workings of a revolutionary computer program that they developed--a program that can deduce mathematical relationships in nature, through simple observation. The catch? As Dr. Gurol Suel explains, the program gives answers to complex biological questions that we humans have yet to ask, or even to understand.

TAGS: mind bending

Bonus: Mike Schmidt's talk on Eureka (⊞) at UVM's 2011 TEDx event "Big Data, Big Stories." (⊞)

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.”

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- "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
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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]

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"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."

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

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Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References

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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Fundamental question: how likely is ‘complexification’?

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Upshot

- The central concepts Complexity and Emergence are not precisely defined.
- There is no general theory of Complex Systems.
- But the problems exist...
  Complex (Adaptive) Systems abound...
- Framing: Science's focus is moving to Complex Systems because it finally can.
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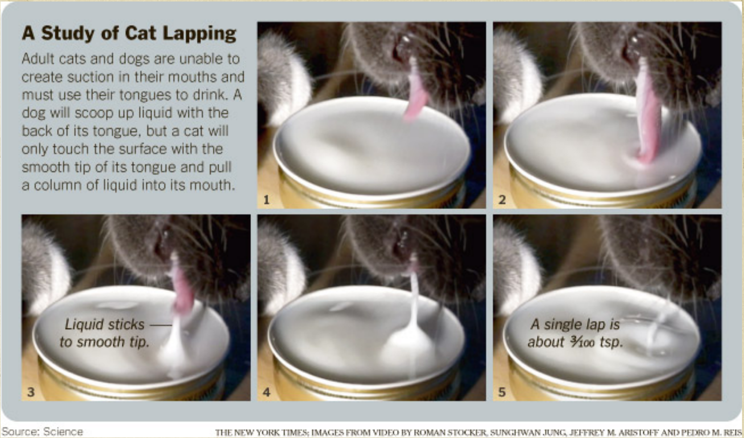
Rather silly but great example of real science:

"How Cats Lap: Water Uptake by *Felis catus*" (⊞)
Reis et al., *Science*, 2010.



Amusing interview here (⊞)

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"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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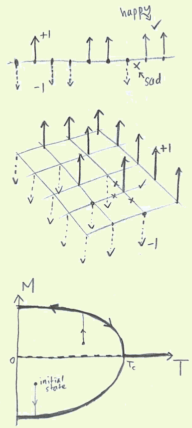

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- Spins are assumed to be arranged on a lattice.
- In isolation, spins like to align with each other.
- Increasing temperature breaks these alignments.
- The drosophila (⊞) of statistical mechanics.
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Example 2-d Ising model simulation:

http://dtjohnson.net/projects/ising (⊞)

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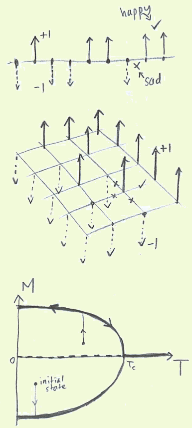

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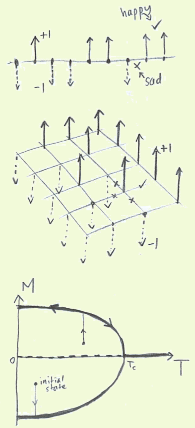

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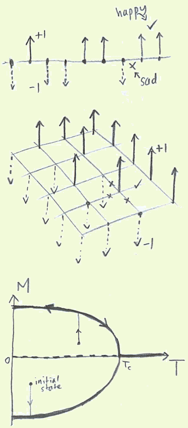

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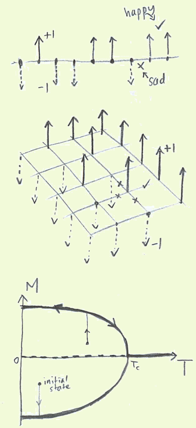

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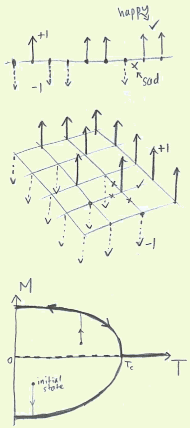

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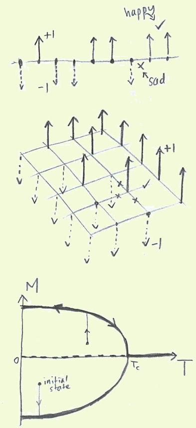

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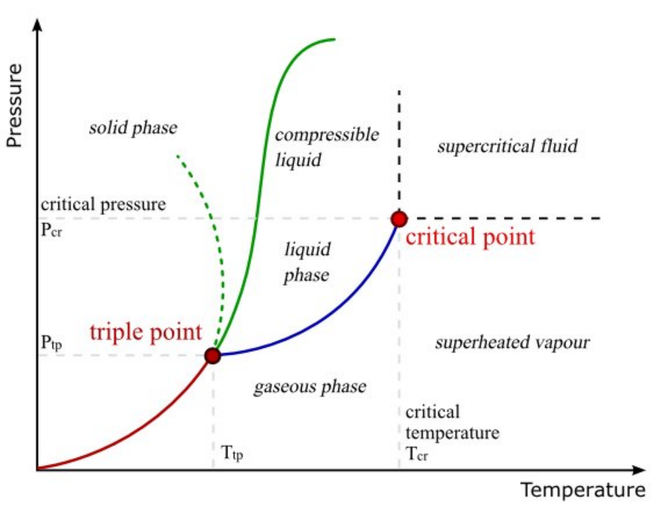
- The drosophila (⊞) of statistical mechanics.
- Criticality: Power-law distributions at critical points.

Example 2-d Ising model simulation:

http://dtjohnson.net/projects/ising (⊞)

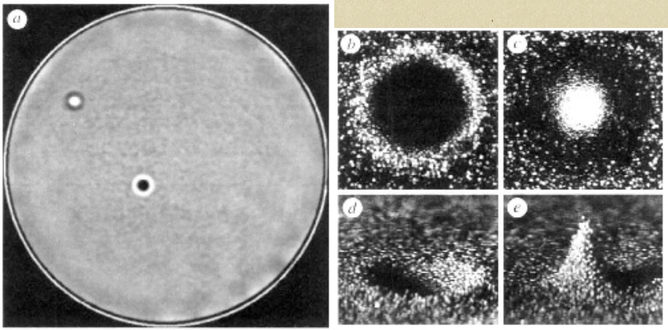
Phase diagrams



Qualitatively distinct macro states.

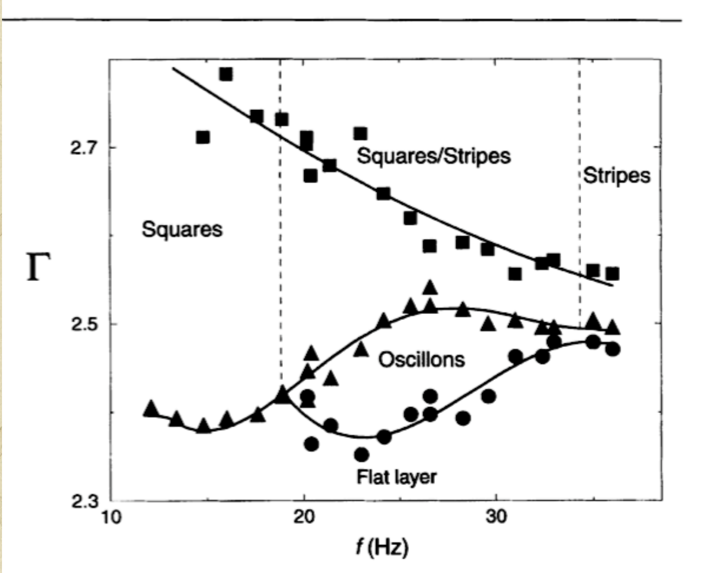
Phase diagrams

Oscillons, bacteria, traffic, snowflakes, ...

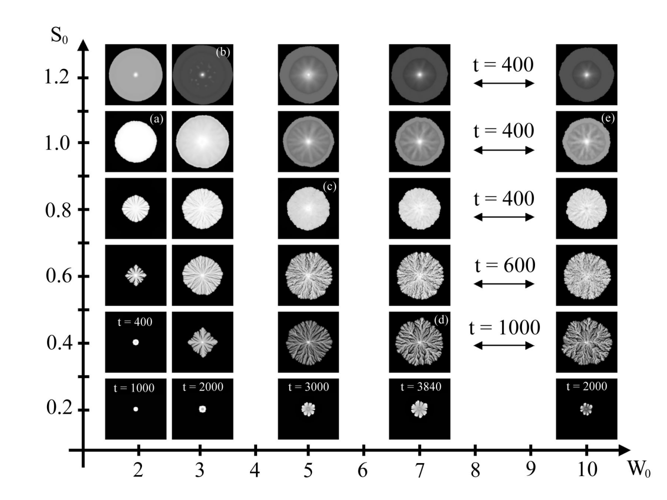


Umbanhowar et al., *Nature*, 1996 [22]

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.

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Statistics

Historical surprise:

- 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" [2]

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