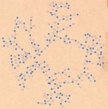
Overview of Complex Systems

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

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Orientation

Course Information
Major Complexity Centers
Resources
Projects
Topics

Fundamentals

Complexity
Emergence
Self-Organization
Modeling
Statistical Mechanics

References

Basics:

- Instructor: Prof. Peter Dodds
- Lecture room and meeting times:
  201 Torrey Hall, Tuesday and Thursday, 11:30 am to 12:45 pm
- Office: Farrell Hall, second floor, Trinity Campus
- E-mail: peter.dodds@uvm.edu
- Website: http://www.uvm.edu/~pdodds/teaching/courses/2011-08UVM-300 (⊞)

Admin:

Potential paper products:

1. Outline

Office hours:

- 12:50 pm to 3:50 pm, Wednesday, Farrell Hall, second floor, Trinity Campus

Graduate Certificate:

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

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Exciting details regarding these slides:

- Three versions (all in pdf):
  1. Presentation,
  2. Flat Presentation,
  3. Handout (3x2).
- 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 (⊞).

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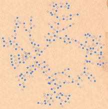

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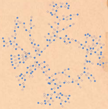

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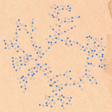

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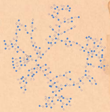

Grading breakdown:

- 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 five or six 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.

Schedule:

Week # (dates)	Tuesday	Thursday
1 (8/30, 9/1)	overview	overview
2 (9/6, 9/8)	overview/projects	lecture
3 (9/13, 9/15)	lecture	lecture
4 (9/20, 9/22)	Presentations	Presentations
5 (9/27, 9/29)	lecture	lecture
6 (10/4, 10/6)	lecture	lecture
7 (10/11, 10/13)	lecture	lecture
8 (10/18, 10/20)	lecture	lecture
9 (10/25, 10/27)	lecture	lecture
10 (11/1, 11/3)	lecture	lecture
11 (11/8, 11/10)	lecture	lecture
12 (11/15, 11/17)	lecture	lecture
13 (11/22, 11/24)	Thanksgiving	Thanksgiving
14 (11/29, 12/2)	lecture	Presentations
15 (12/6)	Presentations	—

Important dates:

1. Classes run from Monday, August 29 to Wednesday, December 7.
2. Add/Drop, Audit, Pass/No Pass deadline—Monday, September 12.
3. Last day to withdraw—Monday, October 31 (Boo).
4. Reading and Exam period—Thursday, December 8 to Friday, December 16.

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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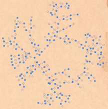
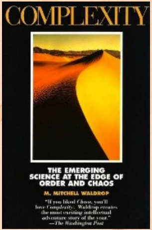


Popular Science Books:



Historical artifact:
Complexity—The Emerging Science at the Edge of Order and Chaos (⊞)
by M. Mitchell Waldrop

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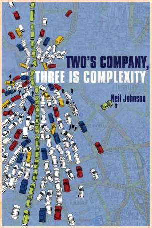
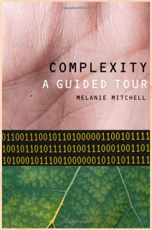
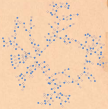


Simply Complexity: A Clear Guide to Complexity Theory (⊞)
by Neil Johnson.



Complexity—A Guided Tour (⊞)
by Melanie Mitchell.



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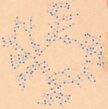
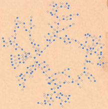
A few other relevant books:

- "Critical Phenomena in Natural Sciences: Chaos, Fractals, Self-organization and Disorder: Concepts and Tools" by Didier Sornette [13]
- "Micromotives and Macrobehavior" by Thomas Schelling [12]
- "Complex Adaptive Systems: An Introduction to Computational Models of Social Life," by John Miller and Scott Page [11]
- "Modeling Complex Systems" by Nino Boccara [4]
- "Critical Mass: How One Thing Leads to Another" by Philip Ball [2]
- "The Information" by James Gleick [9]



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/ (⊞)

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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.

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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

Topics:

Measures of complexity

Scaling phenomena

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

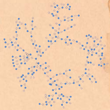
Topics:

Complex networks

- Structure and Dynamics
- Scale-free networks
- Small-world networks

Multiscale complex systems

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



Topics:

Integrity of complex systems

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

Information

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

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

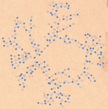
Topics:

Large-scale social patterns

- Movement of individuals
- Cities

Collective decision making

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



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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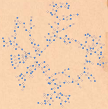


Definitions

Nino Boccara in *Modeling Complex Systems*:

[4] "... 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."

Definitions

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."

Definitions

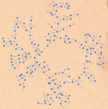
Philip Ball in *Critical Mass*:

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

Definitions

Cosma Shalizi:

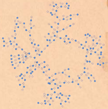
“The "sciences of complexity" are very much a potpourri, and while the name has some justification—chaotic motion seems more complicated than harmonic oscillation, for instance—I think the fact that it is more dignified than "neat nonlinear nonsense" has not been the least reason for its success.—That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



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."



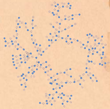
Definitions

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:

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



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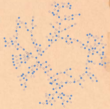
Examples

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...



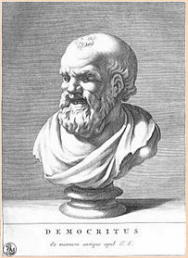
Examples

Relevant fields:

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

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

Reductionism:



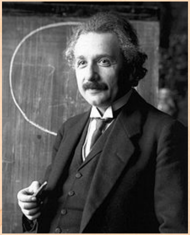
Democritus (⊞)
(ca. 460 BC – ca. 370 BC)

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

John Dalton (⊞)
1766–1844

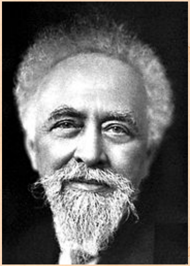
- Chemist, Scientist
- Developed atomic theory
- First estimates of atomic weights

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" [6, 7]
- 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.
   6.2 We can simulate, model, and create complex systems in extraordinary detail.

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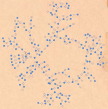

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    6.2 We can simulate, model, and create complex systems in extraordinary detail.

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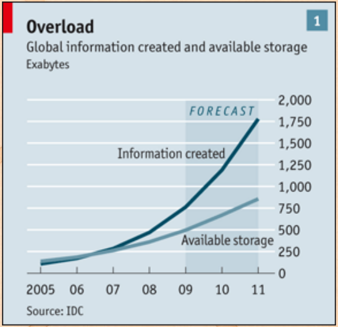
Data, Data, Everywhere—the Economist, Feb 25, 2010 (⊞)



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

Big Data Science:

- 2013: year traffic on Internet estimate to reach 2/3 Zettabytes ($1ZB = 10^3 EB = 10^6 PB = 10^9 TB$)
- 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

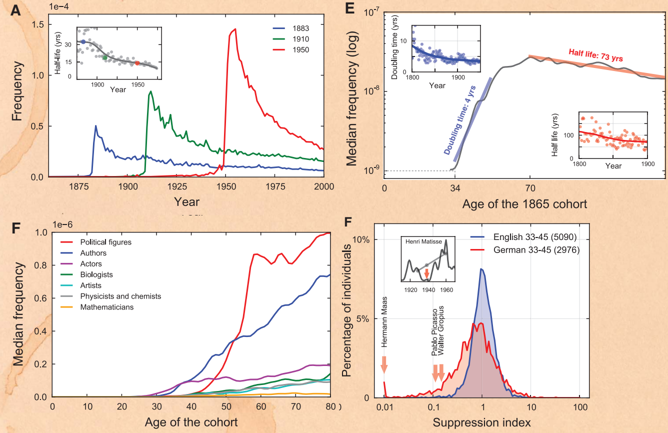
Unit	Size	What it means
Bit (b)	1 or 0	Short for "binary digit", after the binary code (1 or 0) computers use to store and process data
Byte (B)	8 bits	Enough information to create an English letter or number in computer code. It is the basic unit of computing
Kilobyte (KB)	1,000, or 2^{10}, bytes	From "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 [10]



http://www.culturomics.org/ (⊞)

Google Books ngram viewer (⊞)

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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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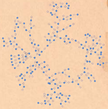

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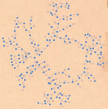

Outline

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.

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Fireflies ⇒ Synchronized Flashes:

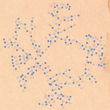
Emergence:

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
- Brains ⇒ Thoughts
- People ⇒ World Wide Web
- People ⇒ Religion
- People ⇒ Language, and rules in language (e.g., -ed, -s).
- ? ⇒ time; ? ⇒ gravity; ? ⇒ reality.

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



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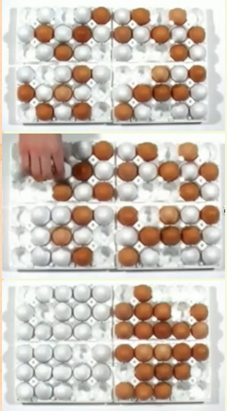

[youtube] (⊞)

- “Micromotives and Macrobehavior” [12]
  - 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.
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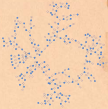

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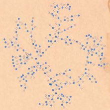

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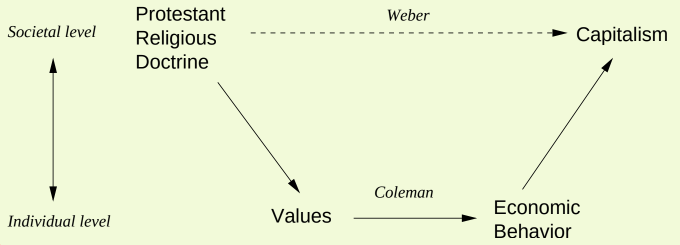
Emergence

James Coleman in *Foundations of Social Theory*:



- Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena. [5]
- More on Coleman here (⊞).

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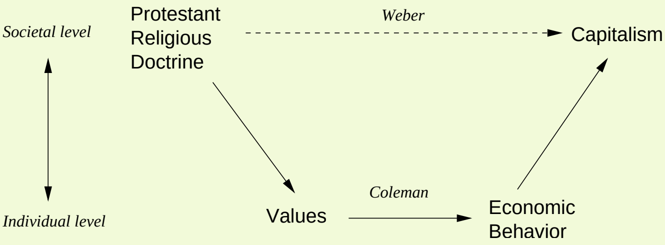

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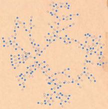
Emergence

Higher complexity:

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



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Even mathematics: [8]

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Suggests a strong form of emergence:

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

Emergence:

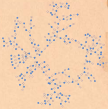
Roughly speaking, there are two types of emergence:

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.



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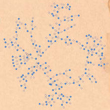

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- Reductionist techniques can explain weak emergence
- Magic explains strong emergence. [3]
- But: maybe magic should be interpreted as an inscrutable yet real mechanism that cannot be simply described.
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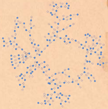

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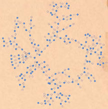

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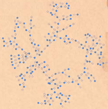

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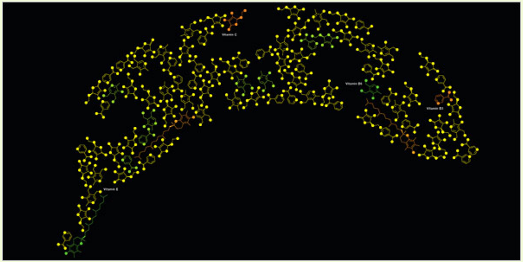
The emergence of taste:

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

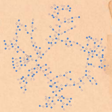


nytimes.com

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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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
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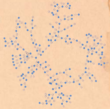

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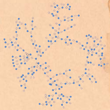

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Reductionism

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.”

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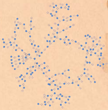
Gulf between theory and practice (see baseball and bumblebees).

Outline

Orientation
- Course Information
- Major Complexity Centers
- Resources
- Projects
- Topics

Fundamentals
- Complexity
- Emergence
- Self-Organization
- Modeling
- Statistical Mechanics

References



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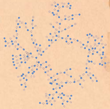
Definitions

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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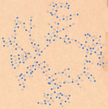
Fundamental question: how likely is ‘complexification’?



Upshot

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- There is as yet no general theory of Complex Systems.
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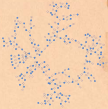

Upshot

- The central concepts Complexity and Emergence are not precisely defined.
- There is as yet no general theory of Complex Systems.
- But the problems exist...

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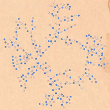

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  Course Information
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  Projects
  Topics

Fundamentals
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  Emergence
  Self-Organization
  Modeling
  Statistical Mechanics

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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."

Focus is on dynamical systems models:

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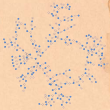

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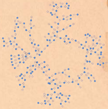

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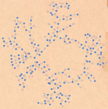

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- The driver: Massive amounts of Data
- More later...

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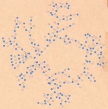

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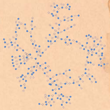

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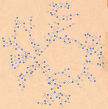

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[2] "... very often what passes today for 'complexity science' is really something much older, dressed up in fashionable apparel. The main themes in complexity theory have been studied for more than a hundred years by physicists who evolved a tool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

Old School:

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

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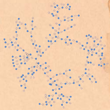

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- Idealized model of a ferromagnet.
- Each atom is assumed to have a local spin that can be up or down: $S_i = \pm 1$.
- Spins are assumed arranged on a lattice (e.g. square lattice in 2-d).
- In isolation, spins like to align with each other.
- Increasing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

2-d Ising model simulation:

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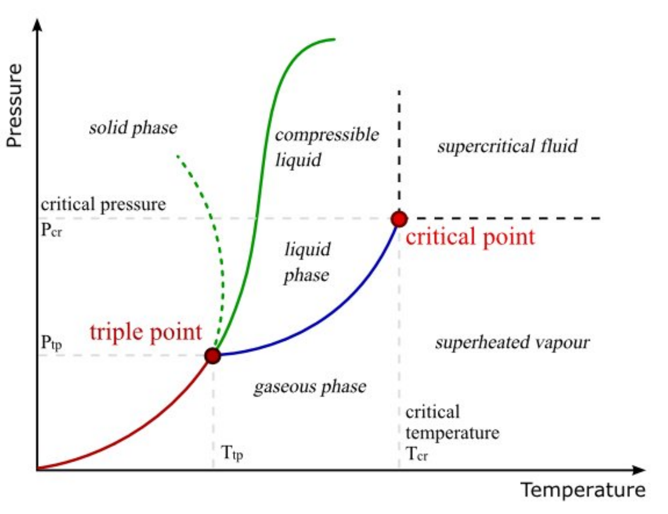
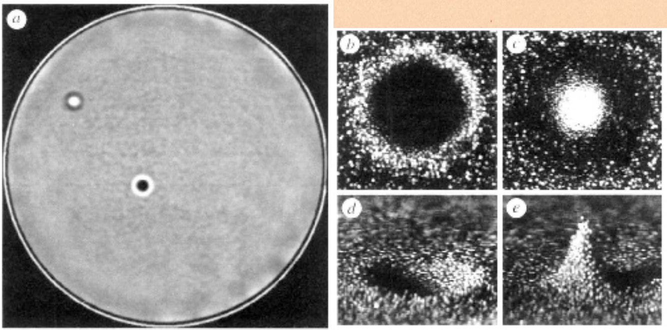
Phase diagrams



Qualitatively distinct macro states.

Phase diagrams

Oscillons, bacteria, traffic, snowflakes, ...



Umbanhowar et al., *Nature*, 1996 [14]

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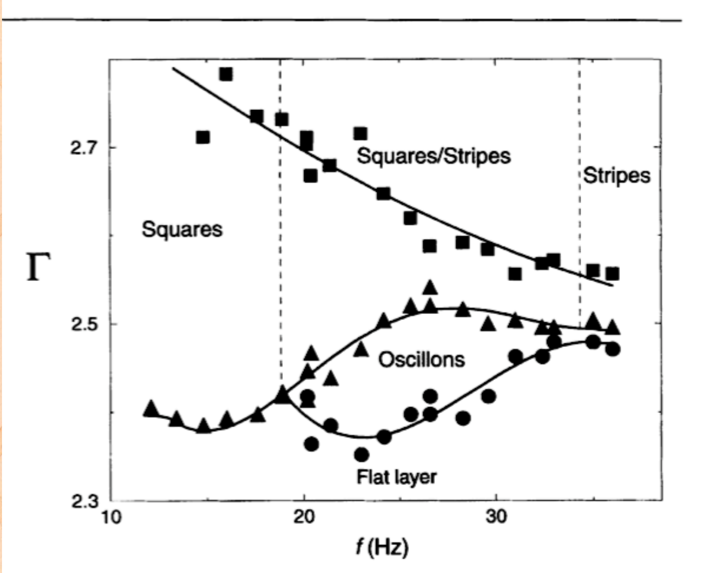

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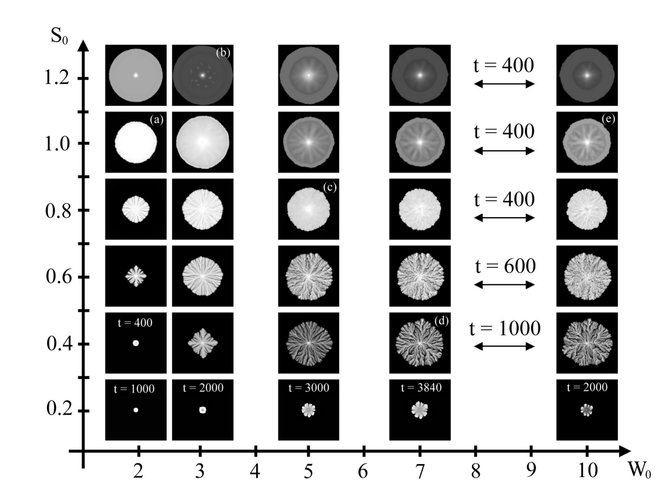

W_0 = initial wetness, S_0 = initial nutrient supply

`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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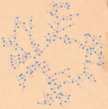
- See Philip Ball's "Critical Mass" [2]



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