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

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Sealie & Lambie Productions
What's the John Dory?

Computational Story Lab

Orientation
Course Information
Topics
Projects
Centers, Books, Resources

Fundamentals
Complexity
Emergence
Self-Organization
Our Framing
Modeling
Statistical Mechanics

References

Funding: NSF, NASA, MITRE.
To be clear, I work with this guy:
Outline

Computational Story Lab

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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 (田)
Potential paper products:

- The Syllabus (纣) and a Poster (纣).

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 (纣).
- 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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Exciting details regarding these slides:

- 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.

- References in slides link to full citation at end. [1]

- Citations contain links to pdfs for papers (if available).

- Some books will be linked to amazon.

- Brought to you by a frightening melange of \LaTeX (⊞), Beamer (⊞), perl (⊞), Perl\TeX (⊞), fevered command-line madness (⊞), and an almost fanatical devotion (⊞) to the indomitable emacs (⊞).

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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.
Important things:

1. Classes run from Tuesday, January 15 to Tuesday, April 30.
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.
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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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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
- Predictability

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;\textsuperscript{[17]}
- Granovetter’s model of imitation;\textsuperscript{[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:

<table>
<thead>
<tr>
<th>Week # (dates)</th>
<th>Tuesday</th>
<th>Thursday</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1/15 and 1/17)</td>
<td>Overview; Fundamentals: The Complexity Manifesto</td>
<td>Power-law size distributions</td>
</tr>
<tr>
<td>2 (1/22 and 1/24)</td>
<td>Zipf’s law; Fundamentals: Data, Emergence, Limits to Understanding</td>
<td>Power-law mechanisms: Randomness</td>
</tr>
<tr>
<td>4 (2/5 and 2/7)</td>
<td>Power-law mechanisms: Optimization</td>
<td>Fundamentals: Self-Organization; Projects</td>
</tr>
<tr>
<td>5 (2/12 and 2/14)</td>
<td>Robustness and Fragility</td>
<td>HOT vs. SOC</td>
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<tr>
<td>6 (2/19 and 2/21)</td>
<td>Fundamentals: Statistical Mechanics, Complex networks: Introduction</td>
<td>Complex networks: Key features</td>
</tr>
<tr>
<td>7 (2/26 and 2/28)</td>
<td>Project presentations†</td>
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</tr>
<tr>
<td>8 (3/5 and 3/7)</td>
<td>Spring recess</td>
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<tr>
<td>12 (4/2 and 4/4)</td>
<td>Social Contagion</td>
<td>Interesting Scaling</td>
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<tr>
<td>13 (4/9 and 4/11)</td>
<td>Interesting Scaling</td>
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<tr>
<td>14 (4/16 and 4/23)</td>
<td>Voting and Success</td>
<td>Happiness</td>
</tr>
<tr>
<td>15 (4/30)</td>
<td>The Big Story</td>
<td>—</td>
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</tbody>
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†: 3-4 minutes each + 1 or 2 questions;
Secrets of the Universe will be revealed:
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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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,
- ...
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Popular Science Books:

Historical artifact:

“Complexity: The Emerging Science at the Edge of Order and Chaos” (总书记在)

Shout-out: Dr. Andrew P. Morokoff (总书记在),
MBBS PhD FRACS D.Thau (Bug) (总书记在)
Popular Science Books:


“Complexity: A Guided Tour” [_field]

“The Information: A History, A Theory, A Flood” [_field]
On complex sociotechnical systems:

“Human Behaviour and the Principle of Least-Effort” (奋)

“Micromotives and Macrobehavior” (奮)

“Critical Mass: How One Thing Leads to Another” (奮)
A few textbooky books:


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/
Definitions

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

Adjective:
1. Made up of multiple parts; intricate or detailed.
2. Not simple or straightforward.
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**.
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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.”
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...
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Relevant fields:

- Physics
- Economics
- Sociology
- Psychology
- Information Sciences
- Cognitive Sciences
- Biology
- Ecology
- Geosciences
- Geography
- Medical Sciences
- Systems Engineering
- Computer Science
- ... i.e., everything that’s interesting...
Reductionism:

Democritus (יו) (ca. 460 BC – ca. 370 BC)
- Atomic hypothesis
- Atom $\sim$ a (not) – temnein (to cut)
- Plato allegedly wanted his books burned.

John Dalton (יו) 1766–1844
- Chemist, Scientist
- Developed atomic theory
- First estimates of atomic weights
Reductionism:

Albert Einstein (篙) 1879–1955
► Annus Mirabilis paper: (篙) “the Motion of Small Particles Suspended in a Stationary Liquid, as Required by the Molecular Kinetic Theory of Heat” [8, 9]
► Showed Brownian motion (篙) followed from an atomic model giving rise to diffusion.

Jean Perrin (篙) 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, ...

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Big Data Science:

- Exponential growth: ~ 60% per year.
- 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: ~ 100 billion photos
- Twitter: ~ 5 billion tweets
No really, that’s a lot of data

<table>
<thead>
<tr>
<th>Unit</th>
<th>Size</th>
<th>What it means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit (b)</td>
<td>1 or 0</td>
<td>Short for “binary digit”, after the binary code (1 or 0) computers use to store and process data</td>
</tr>
<tr>
<td>Kilobyte (KB)</td>
<td>$1,000, or $2^{10}$, bytes</td>
<td>From “thousand” in Greek. One page of typed text is 2KB</td>
</tr>
<tr>
<td>Megabyte (MB)</td>
<td>$1,000KB; $2^{20}$, bytes</td>
<td>From “large” in Greek. The complete works of Shakespeare total 5MB. A typical pop song is about 4MB</td>
</tr>
<tr>
<td>Gigabyte (GB)</td>
<td>$1,000MB; $2^{30}$, bytes</td>
<td>From “giant” in Greek. A two-hour film can be compressed into 1-2GB</td>
</tr>
<tr>
<td>Terabyte (TB)</td>
<td>$1,000GB; $2^{40}$, bytes</td>
<td>From “monster” in Greek. All the catalogued books in America’s Library of Congress total 15TB</td>
</tr>
<tr>
<td>Petabyte (PB)</td>
<td>$1,000TB; $2^{50}$, bytes</td>
<td>All letters delivered by America’s postal service this year will amount to around 5PB. Google processes around 1PB every hour</td>
</tr>
<tr>
<td>Exabyte (EB)</td>
<td>$1,000PB; $2^{60}$, bytes</td>
<td>Equivalent to 10 billion copies of <em>The Economist</em></td>
</tr>
<tr>
<td>Zettabyte (ZB)</td>
<td>$1,000EB; $2^{70}$, bytes</td>
<td>The total amount of information in existence this year is forecast to be around 1.2ZB</td>
</tr>
<tr>
<td>Yottabyte (YB)</td>
<td>$1,000ZB; $2^{80}$, bytes</td>
<td>Currently too big to imagine</td>
</tr>
</tbody>
</table>

Source: *The Economist*
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.
“Quantitative analysis of culture using millions of digitized books” by Michel et al., Science, 2011

[14]

http://www.culturomics.org/ (Books)
Google Books ngram viewer (Books)
Basic Science ∼ 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.”
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The Newness of being a Scientist:

![Google Books Ngram Viewer Graph](image)

Graph these case-sensitive comma-separated phrases: scientist, mathematician, biologist, physicist, sociologist

Between 1800 and 2000, from the corpus English with smoothing of 3.

- scientist
- mathematician
- biologist
- physicist
- sociologist
- thinker


Percent: 0.0000% 0.0003% 0.0006% 0.0009% 0.0012% 0.0015%
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“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.

The philosopher G. H. Lewes first used the word explicity in 1875.
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Emergence:
Tornadoes, financial collapses, human emotion aren’t found in water molecules, dollar bills, or carbon atoms.

Examples:
- Fundamental particles $\Rightarrow$ Life, the Universe, and Everything
- Genes $\Rightarrow$ Organisms
- Neurons etc. $\Rightarrow$ Brain $\Rightarrow$ Thoughts
- People $\Rightarrow$ Religion, Collective behaviour
- People $\Rightarrow$ The Web
- People $\Rightarrow$ Language, and rules of language
- $\text{?} \Rightarrow$ time; $\text{?} \Rightarrow$ gravity; $\text{?} \Rightarrow$ reality.

“The whole is more than the sum of its parts” – Aristotle
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[youtube] ( Econo...)

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Friedrich Hayek (經濟學家/哲學家/諾貝爾獎得主):

- 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. [7]
- Decentralized structures help solve problems.
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James Coleman (✝) in *Foundations of Social Theory*:

- **Weber**
- **Capitalism**
- **Protestant Religious Doctrine**
- **Societal level**
- **Individual level**
- **Values**
- **Economic Behavior**

Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena. [6]

More on Coleman [here](#).
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Even mathematics: [10]

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we can’t prove every theorem that’s true . . .

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► But: maybe magic should be interpreted as an inscrutable yet real mechanism that cannot ever be simply described.
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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).

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 $\Rightarrow$ Ingredients $\Rightarrow$ Taste

nytimes.com
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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- So... find the nutrients responsible and eat more of them.
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Thyme’s known antioxidants:
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[cnn.com]
“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).
Definitions

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“Self-organization ( amacı ) 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)

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There is no general theory of Complex Systems.

But the problems exist...

Complex (Adaptive) Systems abound...

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We use whatever tools we need.

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We use whatever tools we need.

Reality is theoretically weak.

Science \( \simeq \) Describe + Explain.
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Upshot

- The central concepts Complexity and Emergence are not precisely defined.
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- But the problems exist...
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- Framing: Science’s focus is moving to Complex Systems because it finally can.
- We use whatever tools we need.
- Reality is theoretically weak.
- Science \( \sim \) Describe + Explain.
Rather silly but great example of real science:

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

Amusing interview here (⊞)
Outline

Computational Story Lab

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Projects
Centers, Books, Resources

Fundamentals
Complexity
Emergence
Self-Organization
Our Framing
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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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[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.”

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The Ising Model (囲) 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 to be arranged on a lattice.
- In isolation, spins like to align with each other.
- Increasing temperature breaks these alignments.
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Example 2-d Ising model simulation: http://dtjohnson.net/projects/ising (囲)
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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

\[ W_0 = \text{initial wetness}, \ S_0 = \text{initial nutrient supply} \]

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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References I

More is different.

Critical Mass: How One Thing Leads to Another.

Weak emergence.

Modeling Complex Systems.
References II


pdf ((indent)
References III


References IV

The Information: A History, A Theory, A Flood.  
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References V


References VI

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