

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

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity
Emergence
Self-Organization
Our Framing
Modeling
Statistical Mechanics

References



Outline

Computational Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References

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



These slides brought to you by:

What's the John
Dory?

**Sealie &
Lambie
Productions**



Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity
Emergence
Self-Organization
Our Framing
Modeling
Statistical Mechanics

References





Peter Dodds



onehappybird.com



Lewis Mitchell



Nick Allgaier



Cathy Bliss



Chris Danforth

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



Jake Williams



Andy Reagan



Eitan Pechenik



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:

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



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)

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



Admin:

Potential paper products:

- ▶ The Syllabus (田) and a Poster (田).

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 (田).
- ▶ Other required course: Prof. Maggie Eppstein's "Modelling Complex Systems" (CSYS/CS 302).
- ▶ The Sequel to PoCS: "Complex Networks" (CSYS/MATH 303).

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



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 (⊞), PerLTeX (⊞), fevered command-line madnes (⊞), and an almost fanatical devotion (⊞) to the indomitable emacs (⊞).
#superpowers

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



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%)**

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



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.

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



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.

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



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?

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Topics:

What's the John Dory?

Complex networks:

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

Multiscale complex systems:

- ▶ Hierarchies and Scaling;
- ▶ Modularity;

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Topics:

What's the John Dory?

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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:

What's the John Dory?

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;

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Schedule:

What's the John Dory?

Computational
Story Lab

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:

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 (田) 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 (田). Add more!
- ▶ We'll go through a list of possible projects soon.

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



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,
- ▶ ...

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

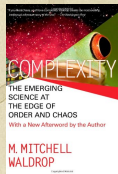
References



Popular Science Books:

What's the John Dory?

Historical artifact:



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

by M. Mitchell Waldrop (1993). [23]

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



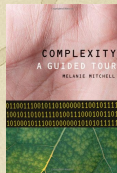
Popular Science Books:

What's the John Dory?



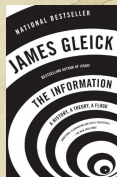
“Simply Complexity: A Clear Guide to Complexity Theory” (田)

by Neil F. Johnson (2009).^[13]



“Complexity: A Guided Tour” (田)

by Melanie Mitchell (2009).^[16]



“The Information: A History, A Theory, A Flood” (田)

by James Gleick (2011).^[11]

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



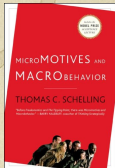
On complex sociotechnical systems:

What's the John Dory?



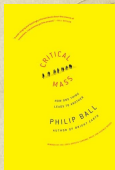
“Human Behaviour and the Principle of Least-Effort” (田)

by George K. Zipf (1949). [24]



“Micromotives and Macrobehavior” (田)

by Thomas C. Schelling (1978). [19]



“Critical Mass: How One Thing Leads to Another” (田)

by Philip Ball (2004). [2]

Computational
Story Lab

Orientation

Course Information
Topics

Projects

[Centers, Books, Resources](#)

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

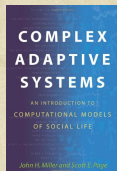
Modeling

Statistical Mechanics

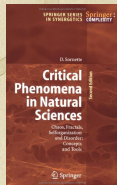
References



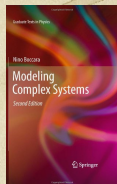
A few textbooky books:



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



“Critical Phenomena in Natural Sciences” (田) by Didier Sornette (2003). [21]



“Modeling Complex Systems” (田) by Nino Boccara (2004). [4]

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



Relevant online courses:

- ▶ **Melanie Mitchell (Santa Fe Institute):**
[Introduction to Complexity](#) (田)
- ▶ **Lada Adamic (Michigan):**
[Social Network Analysis](#) (田)

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



Centers:

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

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



Useful/amusing online resources:

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

- ▶ Complexity Digest:

<http://www.comdig.org> (田)

- ▶ Cosma Shalizi's notebooks:

<http://www.cscs.umich.edu/~crshalizi/notebooks/> (田)



Definitions

What's the John Dory?

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



Adjective:

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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**.



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.”

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Definitions

What's the John Dory?

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."

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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.”

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



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...

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



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...

What's the John Dory?

Computational Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

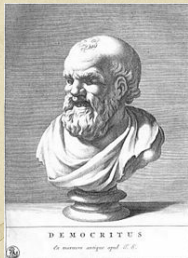
Statistical Mechanics

References



Reductionism:

What's the John Dory?



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

- ▶ Atomic hypothesis
- ▶ Atom ~ a (not) – temnein (to cut)
- ▶ Plato allegedly wanted his books burned.



John Dalton (田) 1766–1844

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

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

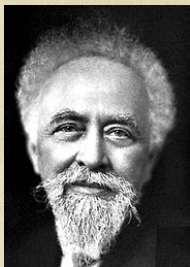
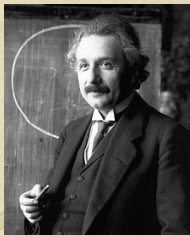
Modeling

Statistical Mechanics

References



Reductionism:



Albert Einstein (田) 1879–1955

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

Jean Perrin (田) 1870–1942

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

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



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.

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



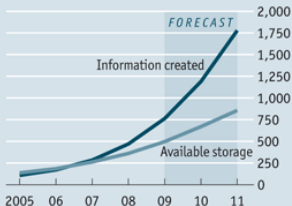


Big Data Science:

- ▶ 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: ~ 100 billion photos
- ▶ Twitter: ~ 5 billion tweets

Overload

Global information created and available storage
Exabytes



Source: IDC

- ▶ Exponential growth:
~ 60% per year.

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 <i>The Economist</i>
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

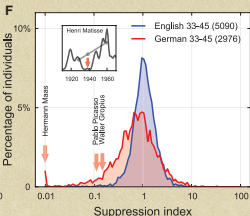
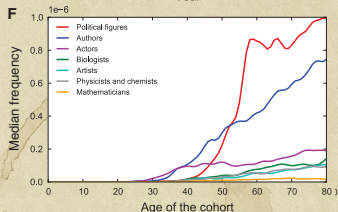
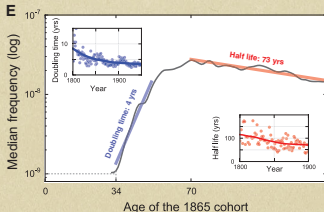
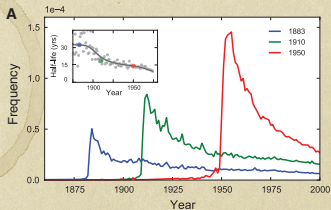
The prefixes are set by an intergovernmental group, the International Bureau of Weights and Measures. Yotta and Zetta were added in 1991; terms for larger amounts have yet to be established.

Source: *The Economist*

Big Data—Culturomics:

What's the John Dory?

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



Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



<http://www.culturomics.org/> (田)
[Google Books ngram viewer](#) (田)

Basic Science \simeq Describe + Explain:

What's the John Dory?



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.”

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



The Newness of being a Scientist:

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



Google books Ngram Viewer

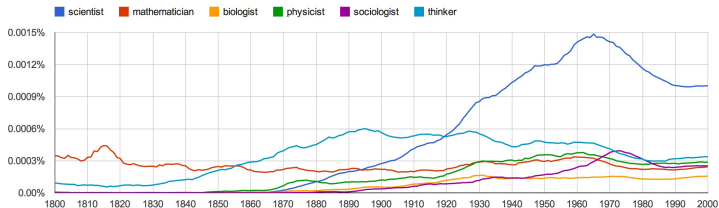
Graph these **case-sensitive** comma-separated phrases:

between and from the corpus with smoothing of

Share 0

Tweet 0

[Search lots of books](#)



Emergence:

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



The Wikipedia on Emergence:

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

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



Fireflies \Rightarrow Synchronized Flashes:

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



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
- ▶ ? \Rightarrow time; ? \Rightarrow gravity; ? \Rightarrow reality.

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

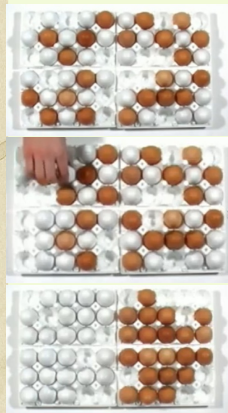
References



Emergence:

What's the John Dory?

Thomas Schelling (田) (Economist/Nobelist):



[youtube] (田)



- ▶ “Micromotives and Macrobehavior” [19]
 - ▶ Segregation [17, 20]
 - ▶ Wearing hockey helmets [18]
 - ▶ Seating choices

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Emergence:

Friedrich Hayek (田)

(Economist/Philosopher/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. [7]
- ▶ **Decentralized structures** help solve problems.
- ▶ Dewey Decimal System versus tagging.

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

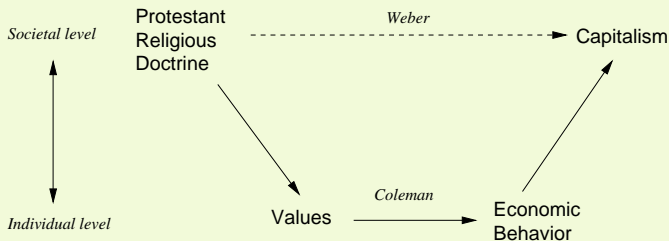
References



Emergence:

What's the John Dory?

James Coleman (田) in *Foundations of Social Theory*:



- ▶ Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena. [6]
- ▶ More on Coleman [here](#) (田).

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Emergence:

Higher complexity:

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

Even mathematics:^[10]



Gödel's Theorem (⊕):
we can't prove every theorem
that's true ...

- ▶ Suggests a **strong form of emergence**: Some phenomena cannot be analytically deduced from elementary aspects of a system.

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



Emergence:

What's the John Dory?

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.

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Emergence:

- ▶ 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 ever be simply described.
- ▶ Gulp.

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





Listen to Steve Strogatz, Hod Lipson, and Michael Schmidt (Cornell) in the last piece (田) on Radiolab's show 'Limits' (田) (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. Guro! 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 (田) at UVM's 2011 TEDx event "Big Data, Big Stories." (田)

The emergence of taste:

What's the John Dory?

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

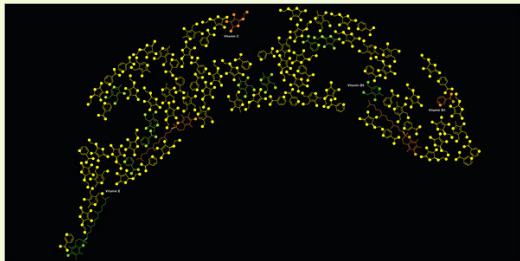
Modeling

Statistical Mechanics

References



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



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.”



Reductionism

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

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



Reductionism

What's the John Dory?

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]

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Reductionism

What's the John Dory?

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

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Self-Organization



“Self-organization (田) 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.

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Examples of self-organization:

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

Fundamental question: how likely is 'complexification'?

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



- ▶ 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.
- ▶ We use whatever tools we need.
- ▶ Reality is theoretically weak.
- ▶ Science \simeq Describe + Explain.

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Rather silly but great example of real science:

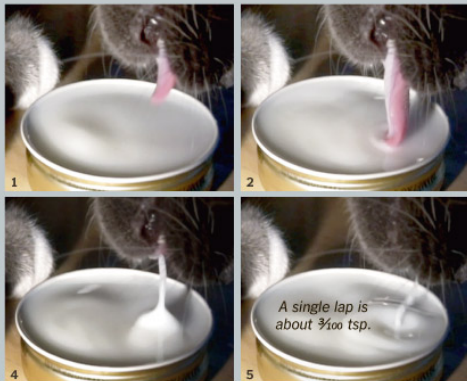
What's the John Dory?

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

Reis et al., *Science*, 2010.

A Study of Cat Lapping

Adult cats and dogs are unable to create suction in their mouths and must use their tongues to drink. A dog will scoop up liquid with the back of its tongue, but a cat will only touch the surface with the smooth tip of its tongue and pull a column of liquid into its mouth.



Source: Science

THE NEW YORK TIMES; IMAGES FROM VIDEO BY ROMAN STOCKER, SUNGHWAN JUNG, JEFFREY M. ARISTOFF AND PEDRO M. REIS

Amusing interview [here](#) (田)

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Nino Boccara in *Modeling Complex Systems*:

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

Focus is on dynamical systems models:

- ▶ differential and difference equation models
- ▶ dynamical systems theory
- ▶ cellular automata
- ▶ networks
- ▶ power-law distributions

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Tools and techniques:

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

Key advance:

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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



Philip Ball in *Critical Mass*:

[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.

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

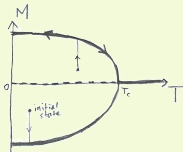
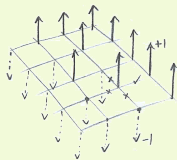
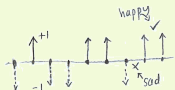
Modeling

Statistical Mechanics

References



The Ising Model (田) 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.
- ▶ The drosophila (田) of statistical mechanics.
- ▶ Criticality: Power-law distributions at critical points.

Example 2-d Ising model simulation:

<http://dtjohnson.net/projects/ising> (田)

What's the John Dory?

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity
Emergence

Self-Organization
Our Framing

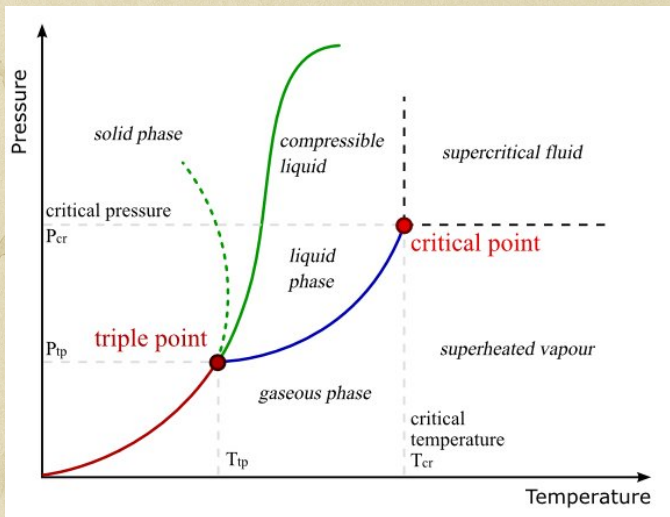
Modeling

Statistical Mechanics

References



Phase diagrams



Qualitatively distinct macro states.

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

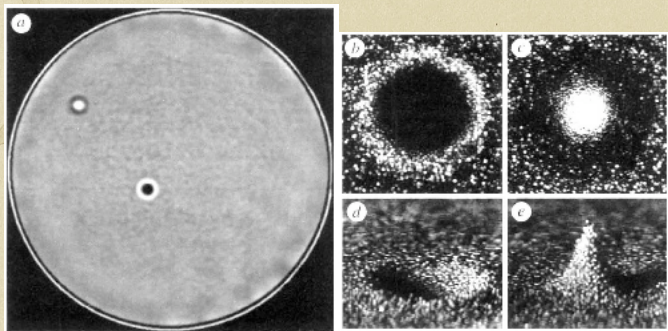
References



Phase diagrams

What's the John Dory?

Oscillons, bacteria, traffic, snowflakes, ...



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

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

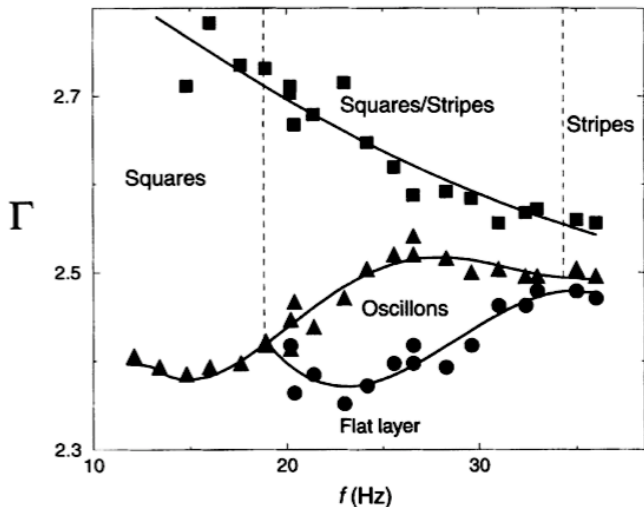
Statistical Mechanics

References



Phase diagrams

What's the John Dory?



Computational
Story Lab

Orientation

- Course Information
- Topics
- Projects
- Centers, Books, Resources

Fundamentals

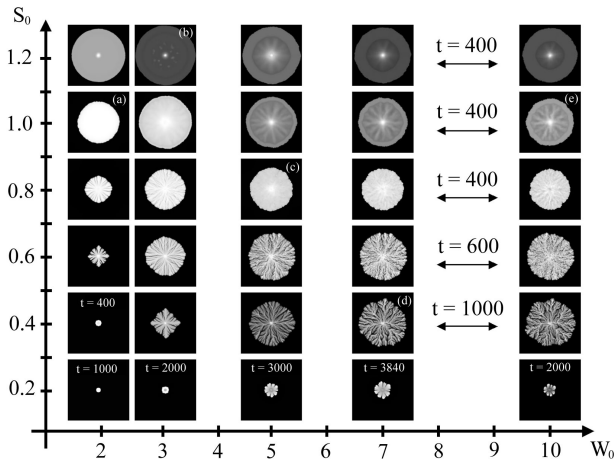
- Complexity
- Emergence
- Self-Organization
- Our Framing
- Modeling
- Statistical Mechanics

References



Phase diagrams

What's the John Dory?



W_0 = initial wetness, S_0 = initial nutrient supply

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

Computational
Story Lab

Orientation

Course Information
Topics

Projects
Centers, Books, Resources

Fundamentals

Complexity
Emergence
Self-Organization

Our Framing
Modeling

Statistical Mechanics

References



Ising model

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

Analytic issues:

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



Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References

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]



References I

- [1] P. W. Anderson.
More is different.
Science, 177(4047):393–396, 1972. pdf (田)
- [2] P. Ball.
Critical Mass: How One Thing Leads to Another.
Farra, Straus, and Giroux, New York, 2004.
- [3] M. A. Bedau.
Weak emergence.
In J. Tomberlin, editor, Philosophical Perspectives: Mind, Causation, and World, volume 11, pages 375–399. Blackwell, Malden, MA, 1997. pdf (田)
- [4] N. Boccarda.
Modeling Complex Systems.
Springer-Verlag, New York, 2nd edition, 2004.

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



References II

- [5] N. Boccarda.
Modeling Complex Systems.
Springer-Verlag, New York, 2004.
- [6] J. S. Coleman.
Foundations of Social Theory.
Belknap Press, Cambridge, MA, 1994.
- [7] P. S. Dodds, D. J. Watts, and C. F. Sabel.
Information exchange and the robustness of
organizational networks.
Proc. Natl. Acad. Sci., 100(21):12516–12521, 2003.
[pdf](#) (田)

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



References III

What's the John Dory?

[8] A. Einstein.

Über die von der molekularkinetischen theorie der wärme geforderte bewegung von in ruhenden flüssigkeiten suspendierten teilchen.

[Annalen der Physik](#), 322:549–560, 1905.

[9] A. Einstein.

On the movement of small particles suspended in a stationary liquid demanded by the molecular-kinetic theory of heat.

In R. Fürth, editor, [Investigations on the theory of the Brownian motion](#). Dover Publications, 1956. pdf (田)

[10] R. Foote.

Mathematics and complex systems.

[Science](#), 318:410–412, 2007. pdf (田)

Computational Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References



References IV

- [11] J. Gleick.
The Information: A History, A Theory, A Flood.
Pantheon, 2011.
- [12] M. Granovetter.
Threshold models of collective behavior.
Am. J. Sociol., 83(6):1420–1443, 1978. [pdf](#) (田)
- [13] N. F. Johnson.
Simply Complexity: A Clear Guide to Complexity Theory.
Oneworld Publications, London, UK, 2009. [pdf](#) (田)

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



References V

- [14] J.-B. Michel, Y. K. Shen, A. P. Aiden, A. Veres, M. K. Gray, The Google Books Team, J. P. Pickett, D. Hoiberg, D. Clancy, P. Norvig, J. Orwant, S. Pinker, M. A. Nowak, and E. A. Lieberman. Quantitative analysis of culture using millions of digitized books. [Science Magazine](#), 331:176–182, 2011. pdf (田)
- [15] J. H. Miller and S. E. Page. Complex Adaptive Systems: An introduction to computational models of social life. Princeton University Press, Princeton, NJ, 2007.
- [16] M. Mitchell. Complexity: A Guided Tour. Oxford University Press, New York, NY, 2009. pdf (田)

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



References VI

- [17] T. C. Schelling.
Dynamic models of segregation.
[J. Math. Sociol.](#), 1:143–186, 1971. [pdf](#) (田)
- [18] T. C. Schelling.
Hockey helmets, concealed weapons, and daylight saving: A study of binary choices with externalities.
[J. Conflict Resolut.](#), 17:381–428, 1973. [pdf](#) (田)
- [19] T. C. Schelling.
Micromotives and Macrobehavior.
Norton, New York, 1978.
- [20] T. C. Schelling.
Some fun, thirty-five years ago.
In L. Tesfatsion and K. L. Judd, editors, [Handbook of Computational Economics](#), volume 2, pages 1639–1644. Elsevier, 2006. [pdf](#) (田)

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



References VII

What's the John
Dory?

[21] D. Sornette.

Critical Phenomena in Natural Sciences.

Springer-Verlag, Berlin, 2nd edition, 2003.

[22] P. B. Umbanhowar, F. Melo, and H. L. Swinney.

Localized excitations in a vertically vibrated granular layer.

Nature, 382:793–6, 1996. pdf (田)

[23] M. M. Waldrop.

Complexity: The Emerging Science at the Edge of Order and Chaos.

Simon & Schuster, New York, NY, 1993.

[24] G. K. Zipf.

Human Behaviour and the Principle of Least-Effort.

Addison-Wesley, Cambridge, MA, 1949.

Computational
Story Lab

Orientation

Course Information

Topics

Projects

Centers, Books, Resources

Fundamentals

Complexity

Emergence

Self-Organization

Our Framing

Modeling

Statistical Mechanics

References

