Fundamentals

Principles of Complex Systems | @pocsvox
CSYS/MATH 300, Fall, 2017

Prof. Peter Dodds | @peterdodds

Dept. of Mathematics & Statistics | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont

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Outline


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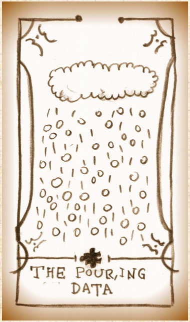
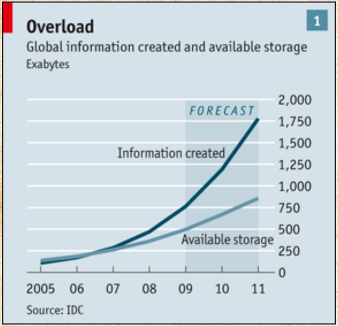

THE POURING DATA

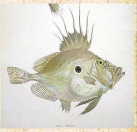
Data, Data, Everywhere—the Economist, Feb 25, 2010



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

Big Data Science:

- 2013: year traffic on Internet estimate to reach 2/3 Zettabytes (1ZB = 10^3EB = 10^6PB = 10^9TB)
- Large Hadron Collider: 40 TB/second.
- 2016—Large Synoptic Survey Telescope: 140 TB every 5 days.
- Facebook: $\sim$ 250 billion photos (mid 2013)
- Twitter: $\sim$ 500 billion tweets (mid 2013)



No really, that's a lot of data

Data inflation

2

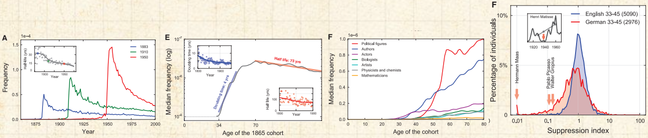
Unit	Size	What it means
Bit (b)	1 or 0	Short for "binary digit", after the binary code (1 or 0) computers use to store and process data
Byte (B)	8 bits	Enough information to create an English letter or number in computer code. It is the basic unit of computing
Kilobyte (KB)	1,000, or 2^{10}, bytes	From "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 [6]

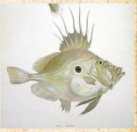


- http://www.culturomics.org/ and Google Books ngram viewer

Barney Rubble:

"Characterizing the Google Books corpus: Strong limits to inferences of socio-cultural and linguistic evolution"

Pechenick, Danforth, and Dodds, PLoS ONE, **10**, e0137041, 2015. [7]



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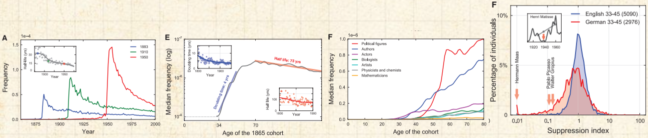

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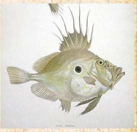

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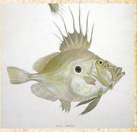
Lord Kelvin (possibly):

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

Bonus:



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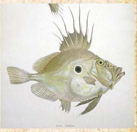

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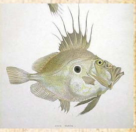

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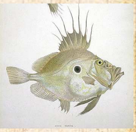

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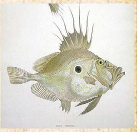

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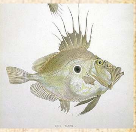

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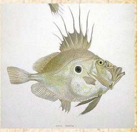
- "X-rays will prove to be a hoax."
- "There is nothing new to be discovered in physics now, All that remains is more and more precise measurement."

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THE CHARMS OF THE MANY WRONG PATHS


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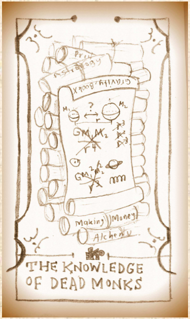
Astrology
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Making Money
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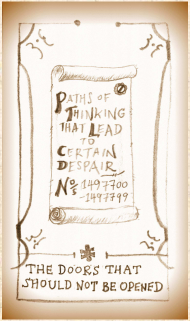
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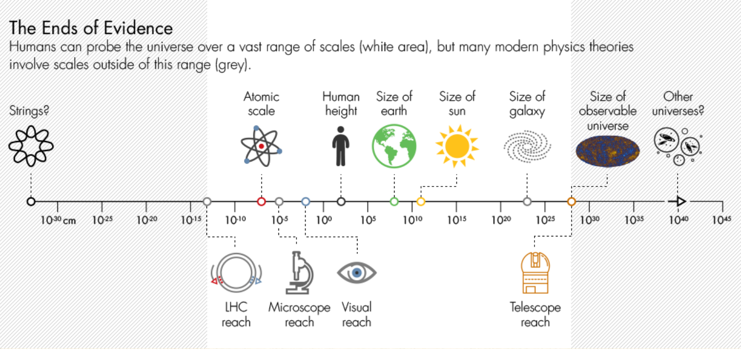
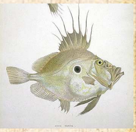
Limits of testability and happiness in Science:

From A Fight for the soul of Science in Quanta Magazine (2016/02):





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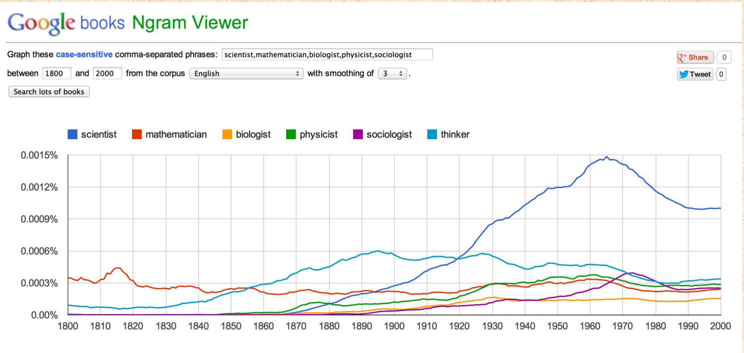

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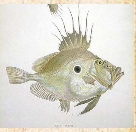

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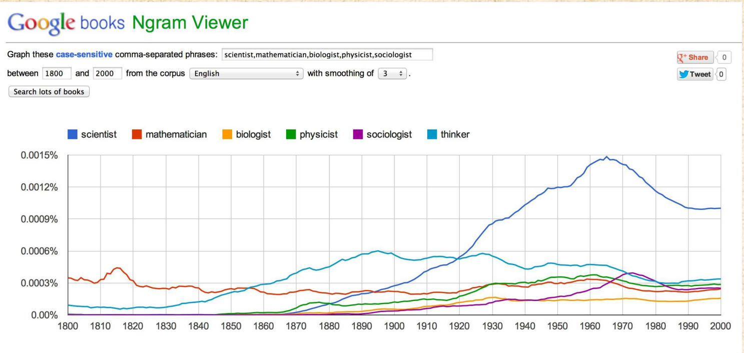

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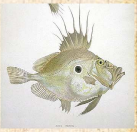


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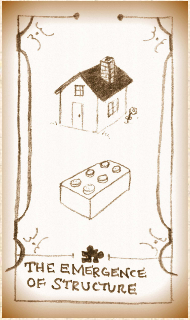
THE EMERGENCE OF STRUCTURE


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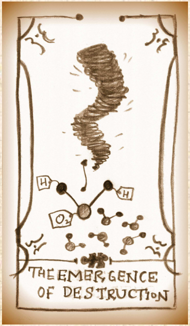
THE EMERGENCE OF DESTRUCTION


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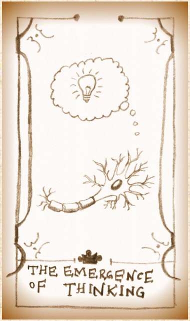
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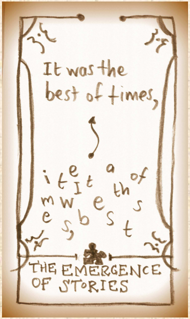
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The Wikipedia on Emergence (2006):

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Wikipedia, 2016:

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Fireflies ⇒ Synchronized Flashes:

Film: Sir David Attenborough, BBC.
Voiceover: Steve Strogatz on Radiolab's Emergence, S1E3.

Emergence:

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

Examples:

- Fundamental particles ⇒ Life, the Universe, and Everything
- Genes ⇒ Organisms
- Neurons etc. ⇒ Brain ⇒ Thoughts
- People ⇒ Religion, Collective behaviour
- People ⇒ The Web
- People ⇒ Language, and rules of language
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"The whole is more than the sum of its parts" –Aristotle

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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.[4]
- Decentralized structures help solve problems.
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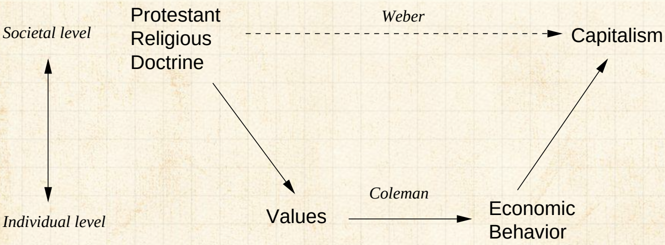

- Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena. [3]
- More on Coleman here.

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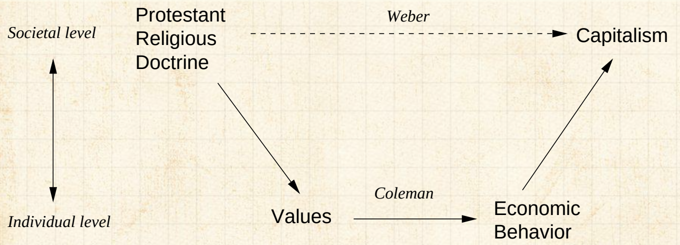

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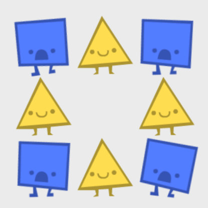
Emergence:

Thomas Schelling (Economist/Nobelist):

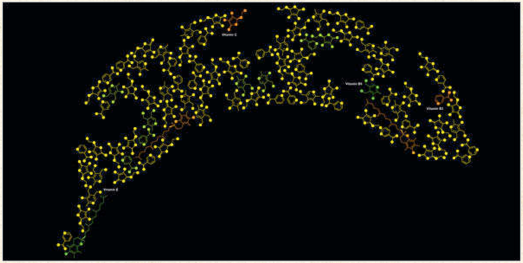
- "Micromotives and Macrobehavior"[10]
  - Segregation[8, 11]
  - Wearing hockey helmets[9]
  - Seating choices

Vi Hart and Nicky Case's Polygon-themed visualization:



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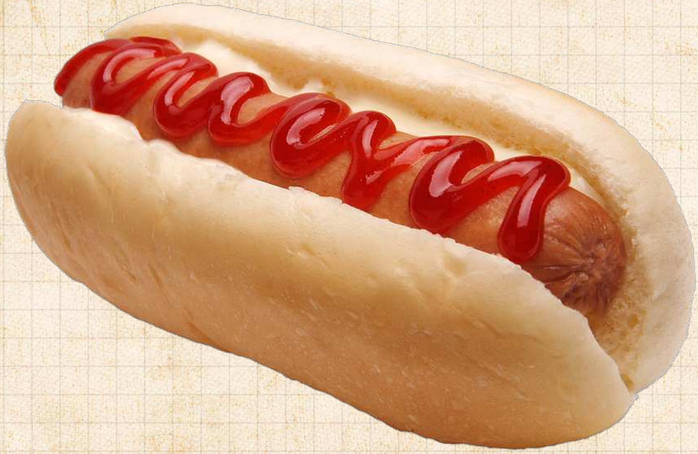
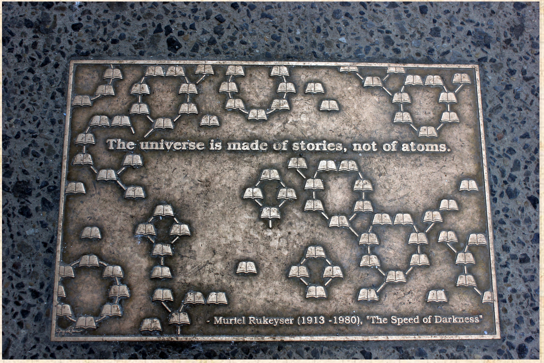
Gulf between theory and practice (see baseball and bumblebees).

This is a Collateralized Debt Obligation:



- “The Universe is made of stories, not of atoms.”



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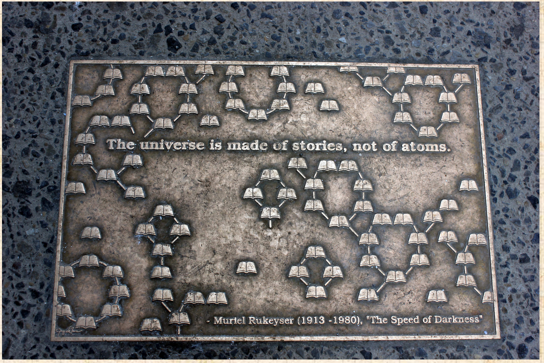

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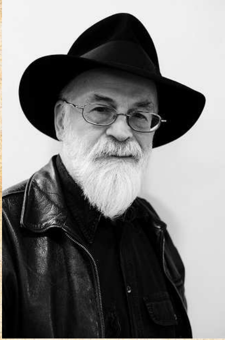

- "The most common element on the disc, although not included in the list of the standard five: earth, fire, air, water and surprise. It ensures that everything runs properly as a story."
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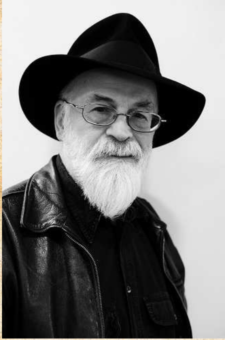

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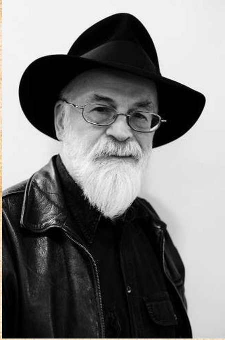

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Higher complexity:

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

Even mathematics:

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.

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

II. Strong emergence:

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- Magic explains strong emergence. [2]
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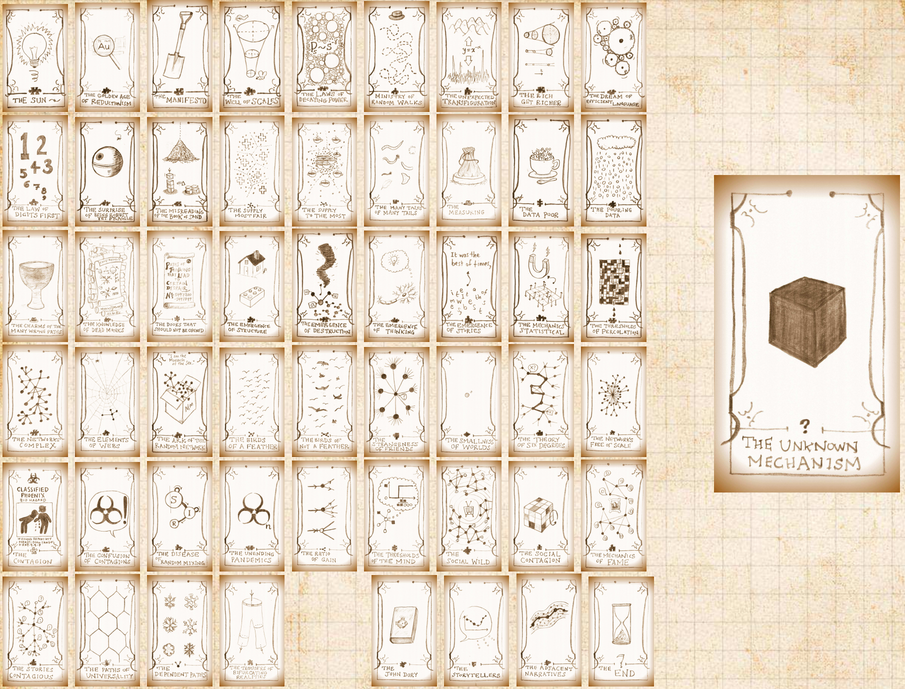
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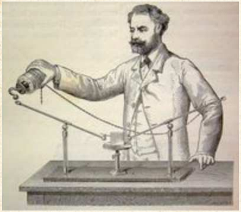
THE UNKNOWN MECHANISM

Limits of Science | Radiolab

Listen to Steve Strogatz, Hod Lipson, and Michael Schmidt (Cornell) in the last piece (11:16) on Radiolab's show 'Limits' (April 5, 2010).



(El Bibliomata/flickr)

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

TAGS: mind bending

Pair with some slow tv

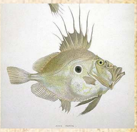
Bonus: Mike Schmidt's talk on Eureqa at UVM's 2011 TEDx event "Big Data, Big Stories."

Definitions

"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)

Examples:

- Molecules/Atoms liking each other → Gases, liquids, and solids.
- Spin alignment → Magnetization.
- Protein folding.
- Imitation → Herding, flocking, mobs, ...



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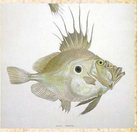

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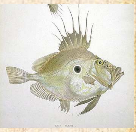

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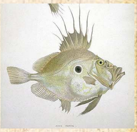
Fundamental question: how likely is 'complexification'?

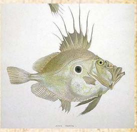


Tools and techniques:

- Differential equations, difference equations, linear algebra, stochastic models.
- Statistical techniques for comparisons and descriptions.
- Methods from statistical mechanics and computer science.
- Machine learning (but beware the black box).
- Computer modeling, everything from
  - Artisanal toy models
  - to kitchen sink models.

Key advance (more soon):

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



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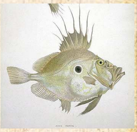

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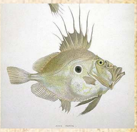

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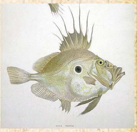

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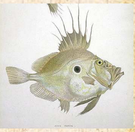

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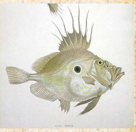

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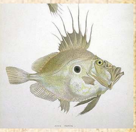

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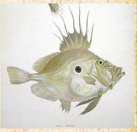
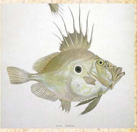


Rather silly but great example of real science:

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

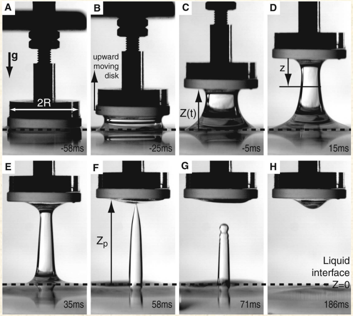
Amusing interview here

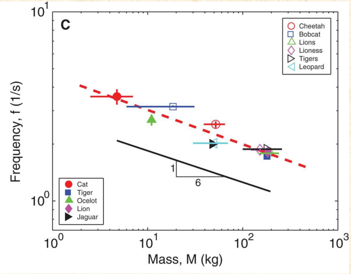


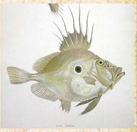
Another great, great moment in scaling:

$$f \sim M^{-1/6}$$

The balance of inertia and gravity yields a prediction for the lapping frequency of other felines. Assuming isometry within the Felidae family (i.e., that lapping height H scales linearly with tongue width R and animal mass M scales as R^3), the finding that Fr* is of order one translates to the prediction $f \sim R^{-1/2} \sim M^{-1/6}$. Isometry or marginally positive allomety among the Felidae has been demonstrated for skull (*20*, *21*) and limb bones (*22*). Although variability by function can lead to departures from isometry in interspecific scalings (*23*), reported variations within the Felidae (*23*, *24*) only minimally affect the predicted scaling $f \sim M^{-1/6}$. We tested this –1/6 power-law dependence by measuring the lapping frequency for eight species of felines, from videos acquired at the Zoo New England or available on YouTube (*16*). The lapping frequency was observed to decrease with animal mass as $f = 4.6\, M^{-0.181 \pm 0.024}$ (f in s^{-1}, M in kg) (Fig. 4C), close to the predicted $M^{-1/6}$. This close agreement suggests that the domestic cat's inertia- and gravity-controlled lapping mechanism is conserved among felines.








THE SUN
THE GOLDEN AGE OF REDUCTIONISM
THE MANIFESTO
THE WELL OF SCALES
THE LAWS OF DECAYING POWER
MINISTRY OF RANDOM WALKS
THE UNEXPECTED TRANSFIGURATION
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THE SURPRISE OF BEING ROBUST YET FRAGILE
THE MISREADING OF THE BOOK OF SAND
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THE CHARMS OF THE MANY WRONG PATHS
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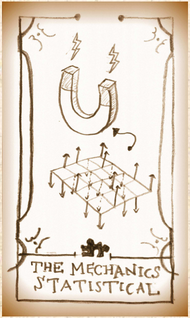
THE MECHANICS STATISTICAL


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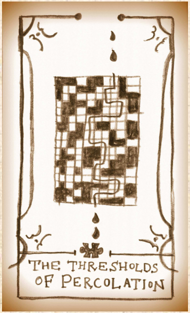
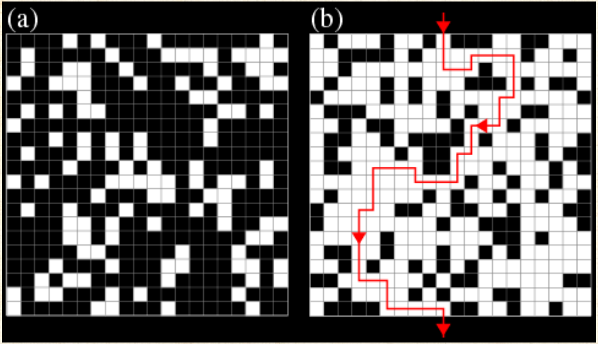
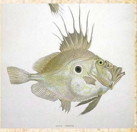

THE THRESHOLDS OF PERCOLATION

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

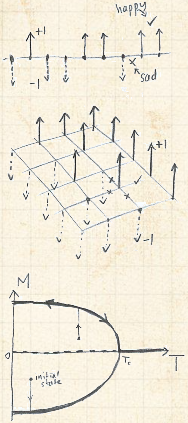
Percolation:



Snared from Michael Gastner’s page on percolation [no longer online]



The Ising Model of a ferromagnet:



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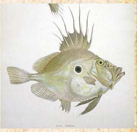
- Spins are assumed to be arranged on a lattice.
- In isolation, spins like to align with each other.
- Increasing temperature breaks these alignments.
- The drosophila of statistical mechanics.
- Criticality: Power-law distributions at critical points.

Example 2-d Ising model simulation:

http://dljohnson.net/projects/ising



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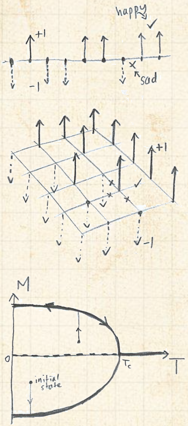

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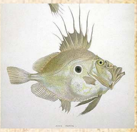

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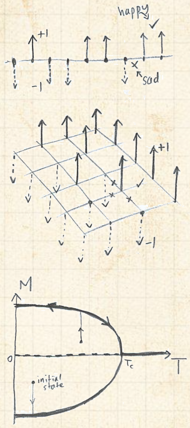

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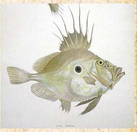

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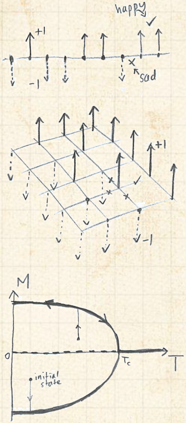

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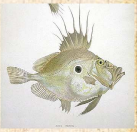

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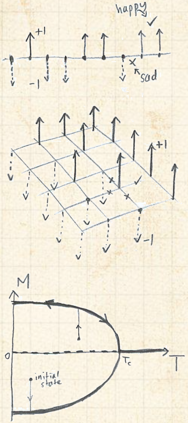

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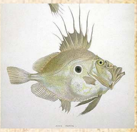

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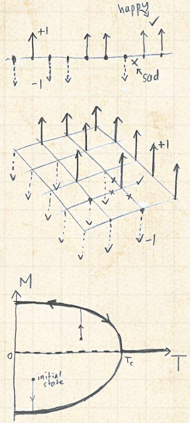

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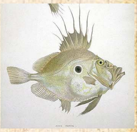

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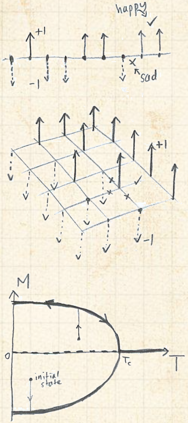

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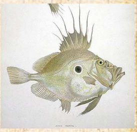
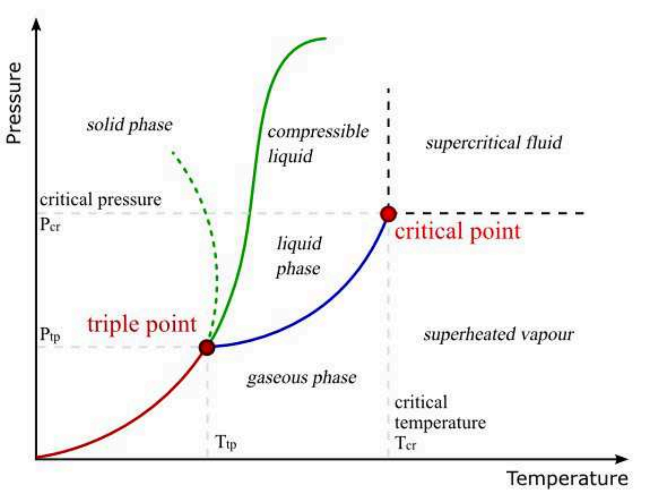
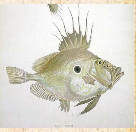


Phase diagrams

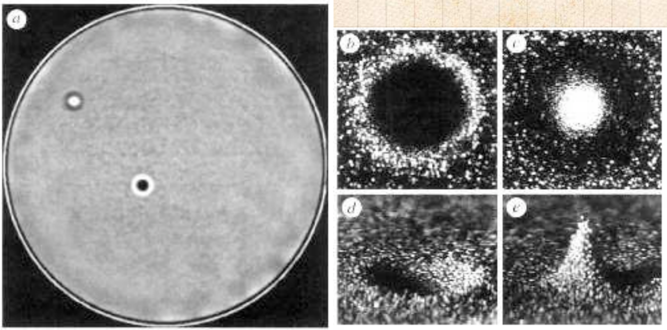


Qualitatively distinct macro states.

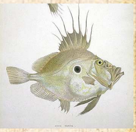


Phase diagrams

Oscillons, bacteria, traffic, snowflakes, ...



Umbanhowar et al., *Nature*, 1996 [12]



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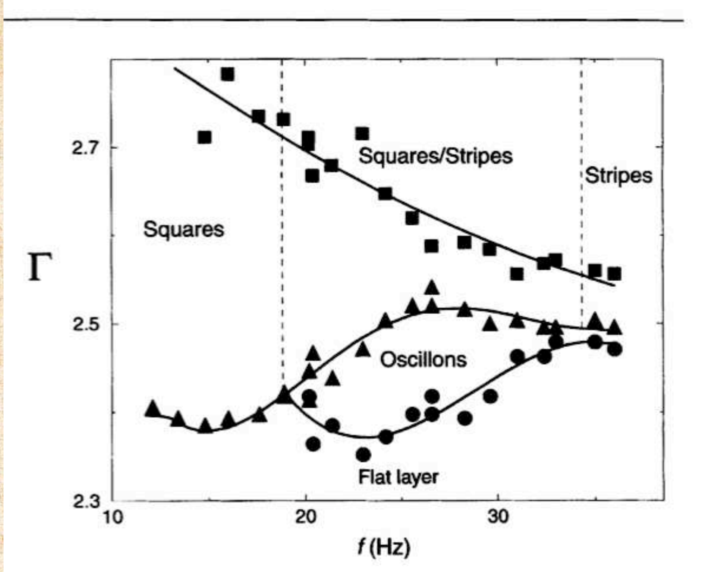

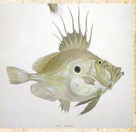

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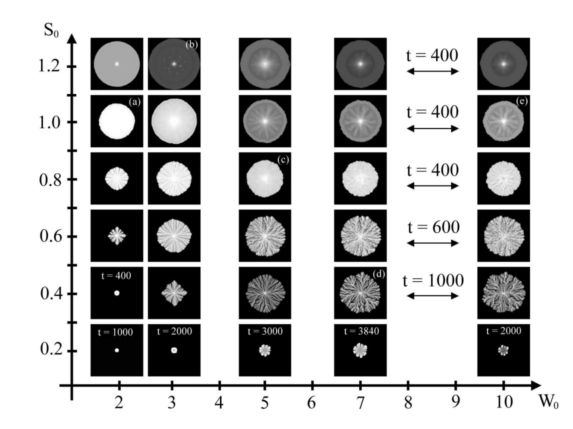
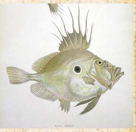


W_0 = initial wetness, S_0 = initial nutrient supply
http://math.arizona.edu/~lega/HydroBact.html



Ising model

Analytic issues:

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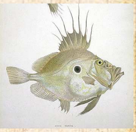

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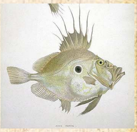

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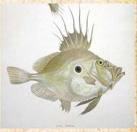

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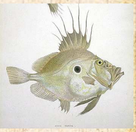


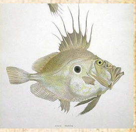
Statistics

Historical surprise:

- Origins of Statistical Mechanics are in the studies of people... (Maxwell and co.)
- Now physicists are using their techniques to study everything else including people...
- See Philip Ball's "Critical Mass"[1]

Beyond Statistical Mechanics:

- Analytic approaches have their limits, especially in evolutionary, algorithm-rich systems.
- Algorithmic methods and simulation techniques will continue to rise in importance.



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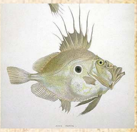

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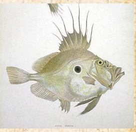

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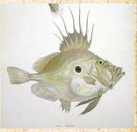

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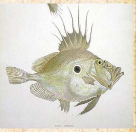

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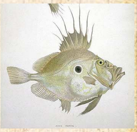
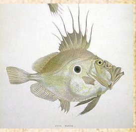
Data
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References



Nutshell

- The central concepts Complexity and Emergence are reasonably well defined.
- There is no general theory of Complex Systems.
- But the problems exist...
  Complex (Adaptive) Systems abound...
- And the observation of Universality of dynamical systems, statistical mechanics, and other quantitative areas means not everything is special and different.
- Framing from the Manifesto: Science's focus is moving to Complex Systems because it finally can.
- We use whatever tools we need.
- Science $\simeq$ Describe + Explain.



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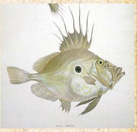

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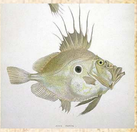

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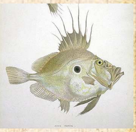

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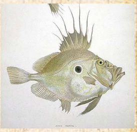

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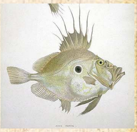

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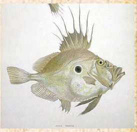

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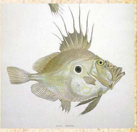

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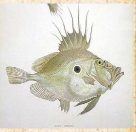

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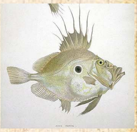

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