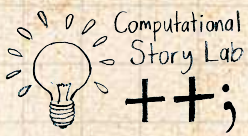
Fundamentals

Principles of Complex Systems | @pocsvox
CSYS/MATH 300, Fall, 2015 | #FallPoCS2015

Prof. Peter Dodds | @peterdodds

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



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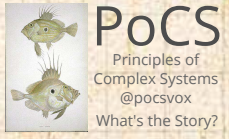

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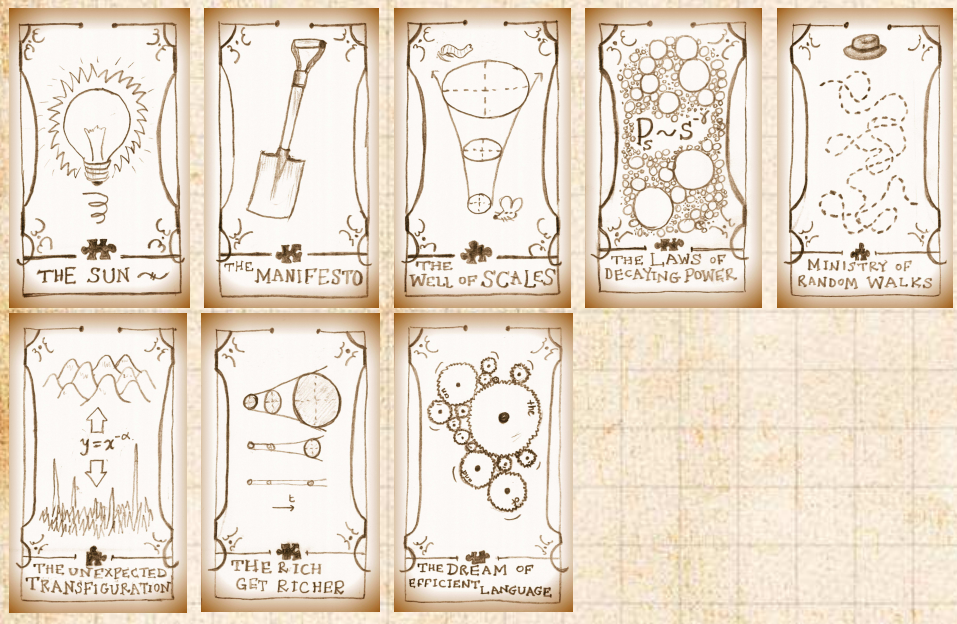

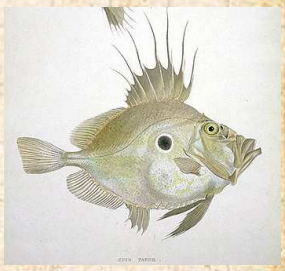

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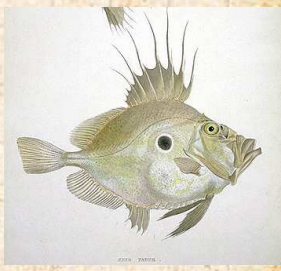

Data, Data, Everywhere—the Economist, Feb 25, 2010

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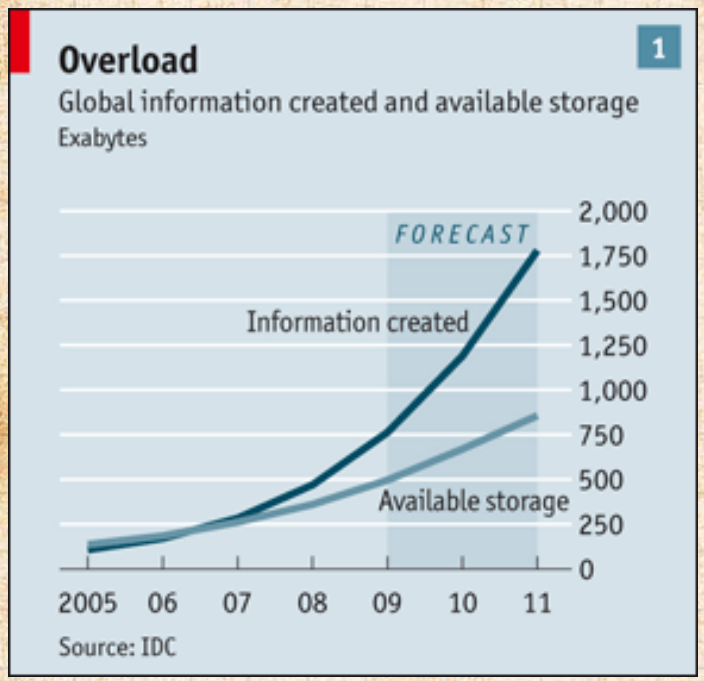
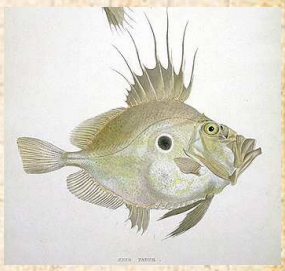


- Exponential growth: $\sim$ 60% per year.

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

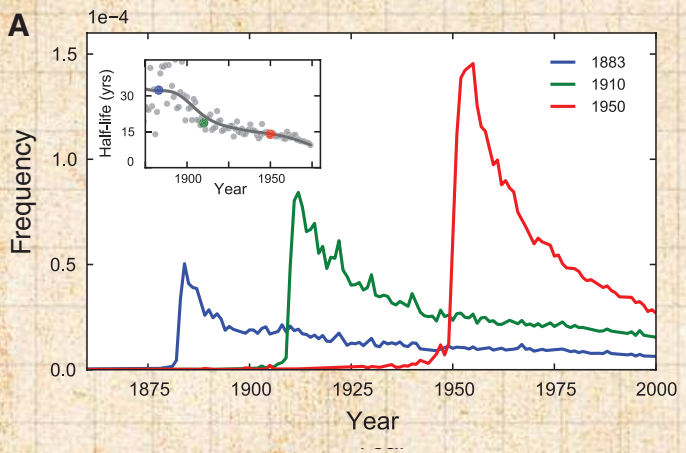
Unit	Size	What it means
Bit (b)	1 or 0	Short for "binary digit", after the binary code (1 or 0) computers use to store and process data
Byte (B)	8 bits	Enough information to create an English letter or number in computer code. It is the basic unit of computing
Kilobyte (KB)	1,000, or 2^{10}, bytes	From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

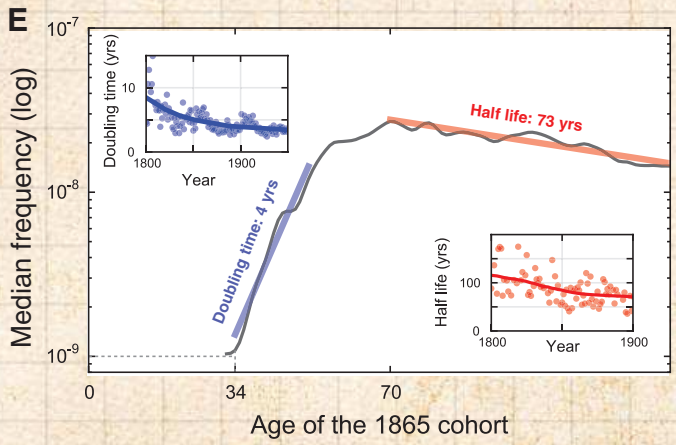
The prefixes are set by an intergovernmental group, the International Bureau of Weights and Measures. Yotta and Zetta were added in 1991; terms for larger amounts have yet to be established.

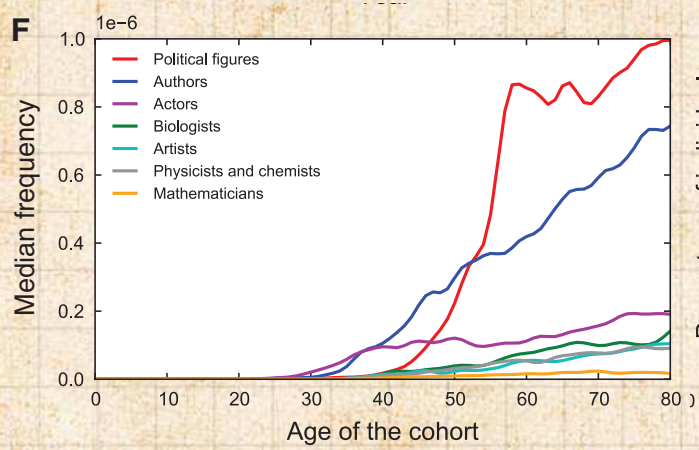
Source: *The Economist*

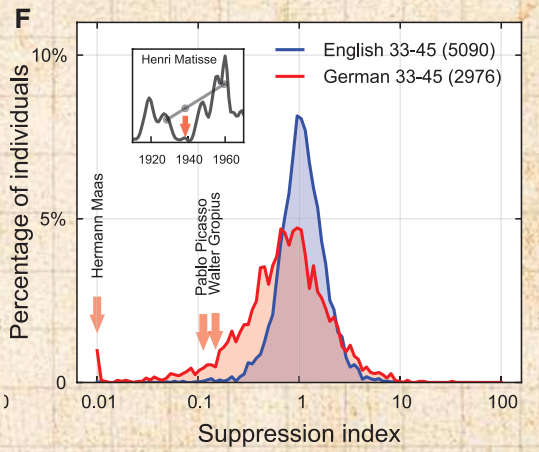
Big Data—Culturomics:

"Quantitative analysis of culture using millions of digitized books" by Michel et al., Science, 2011 [6]









http://www.culturomics.org/

Google Books ngram viewer

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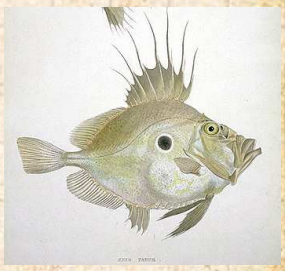

Basic Science ≃ Describe + Explain:

Lord Kelvin (possibly):

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

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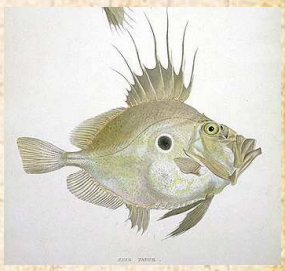

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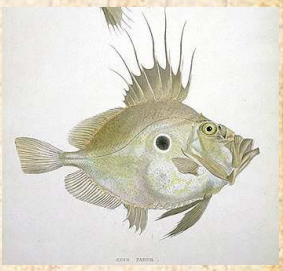

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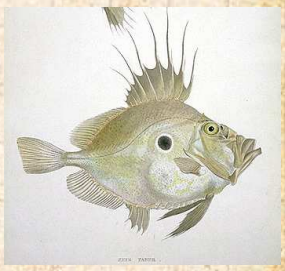

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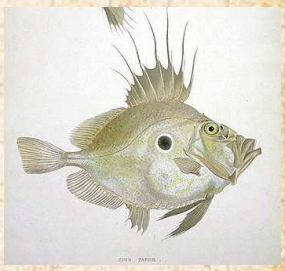

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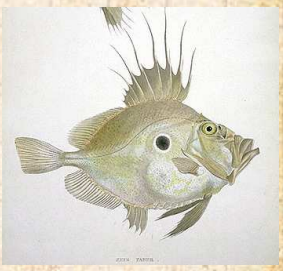
- “X-rays will prove to be a hoax.”



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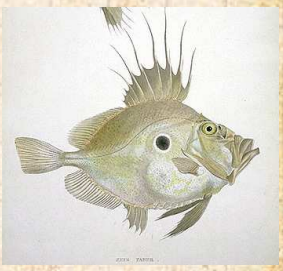

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Bonus:

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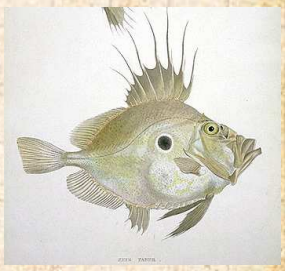
- "There is nothing new to be discovered in physics now, All that remains is more and more precise measurement."



The Newness of being a Scientist (1833 on):

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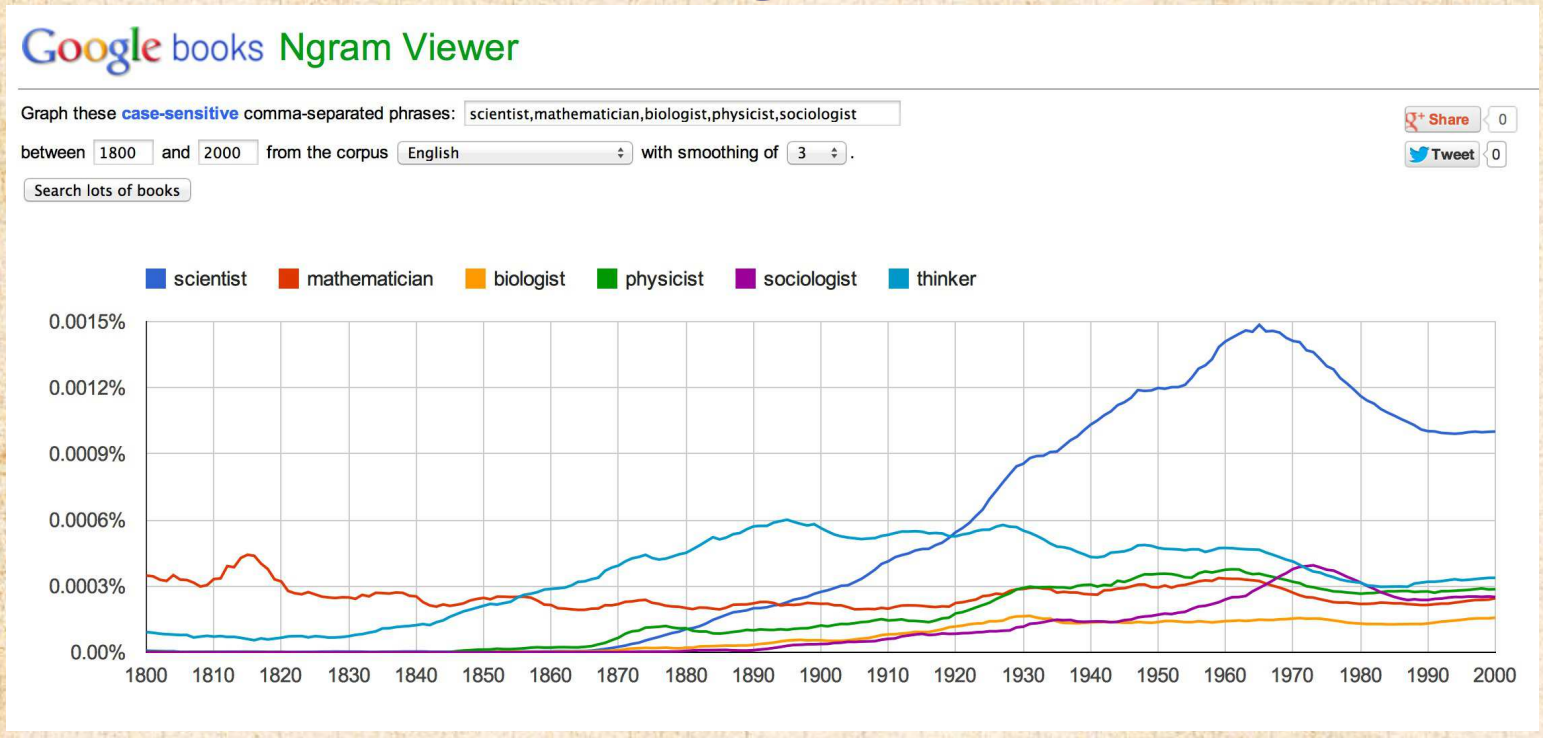
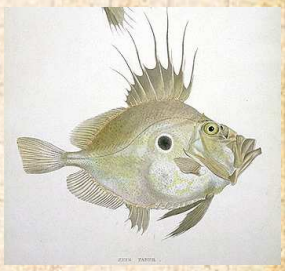


- Etymology here.
- "Scientists are the people who ask a question about a phenomenon and proceed to systematically go about answering the question themselves. They are by nature curious, creative and well organized."



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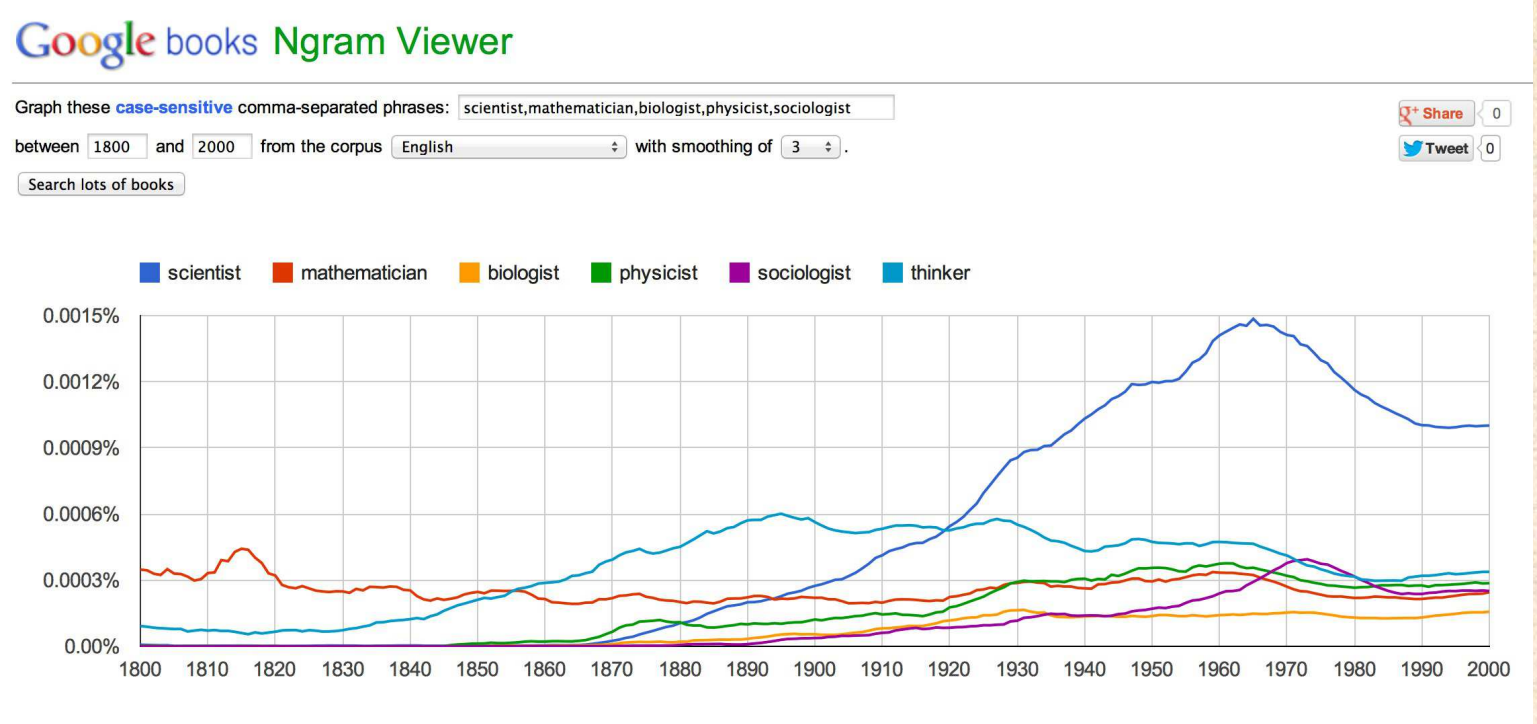

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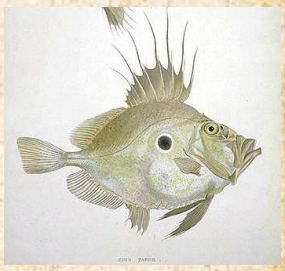

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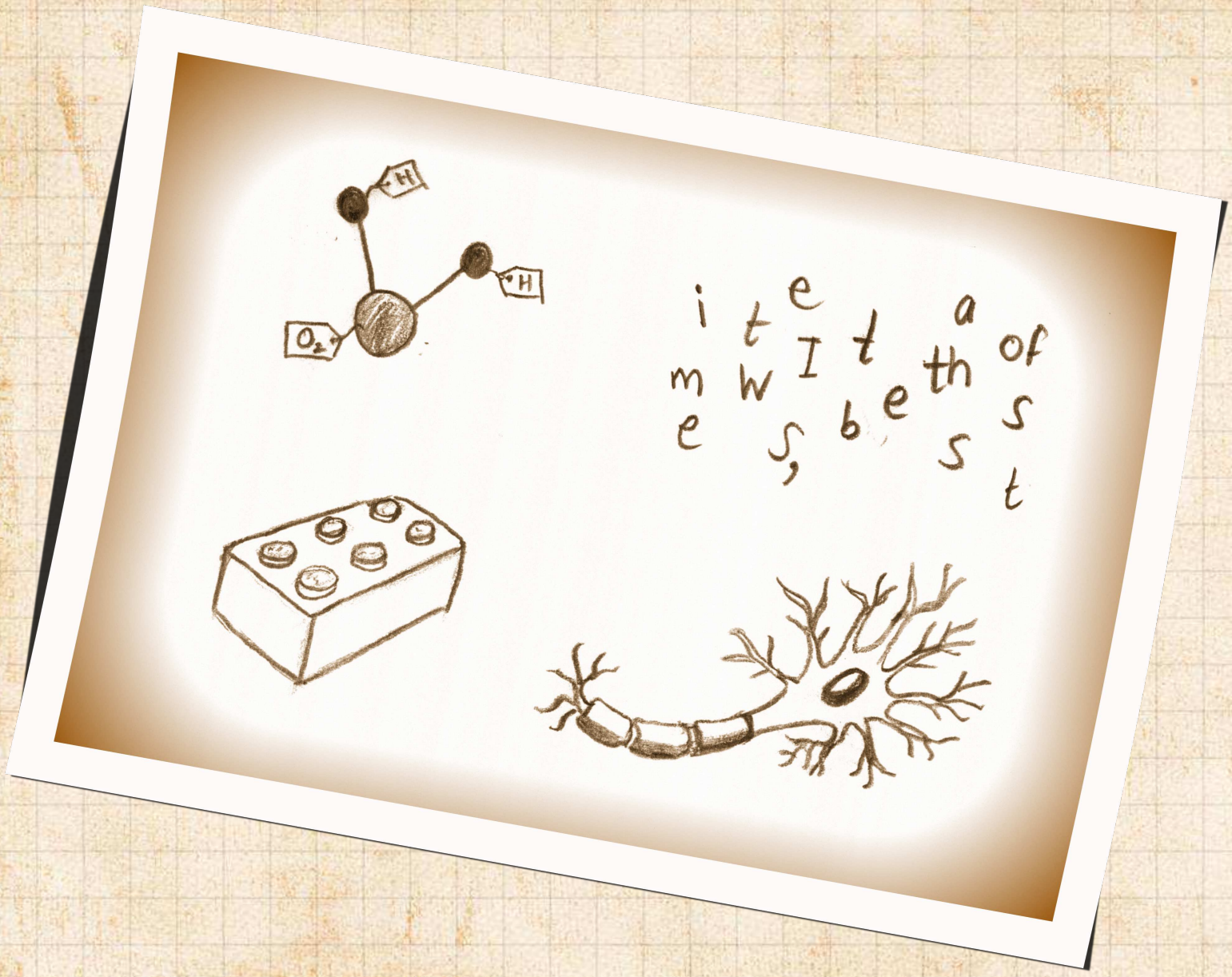

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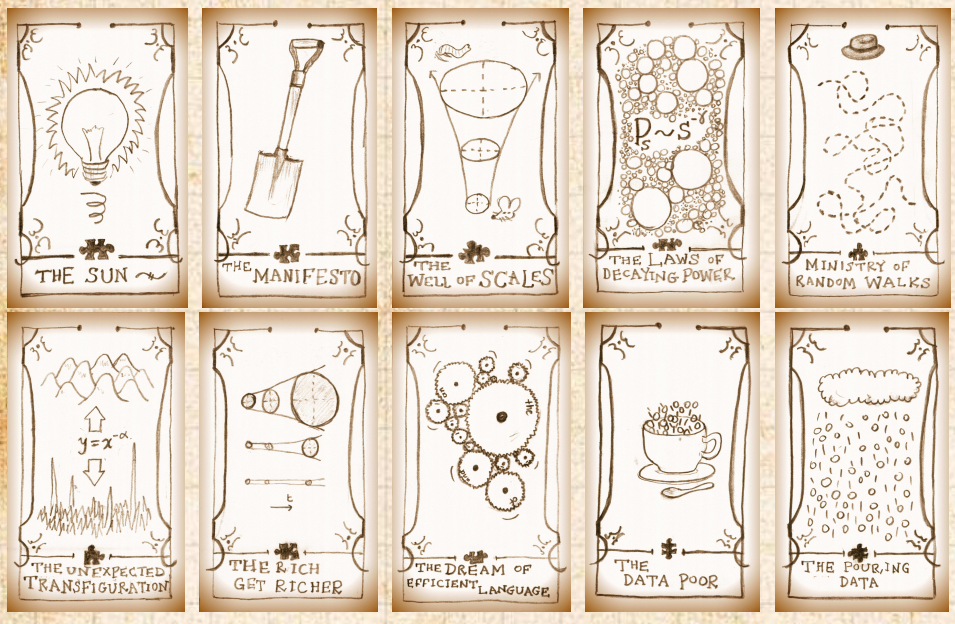

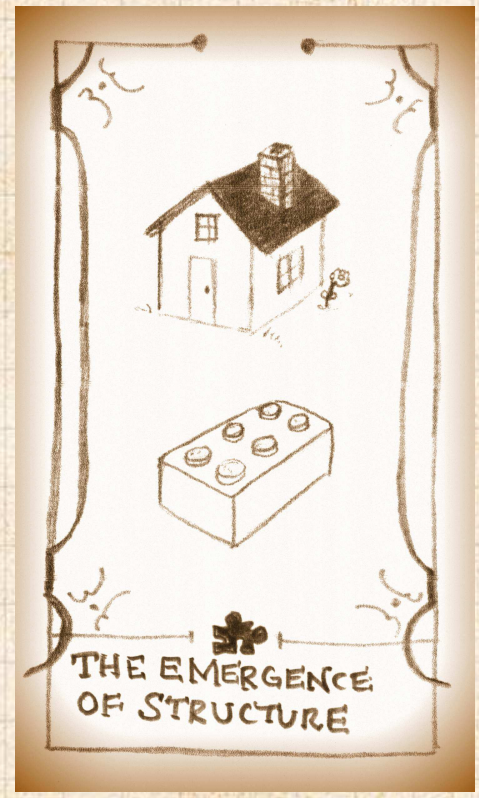

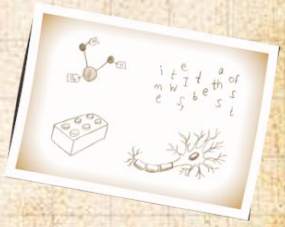

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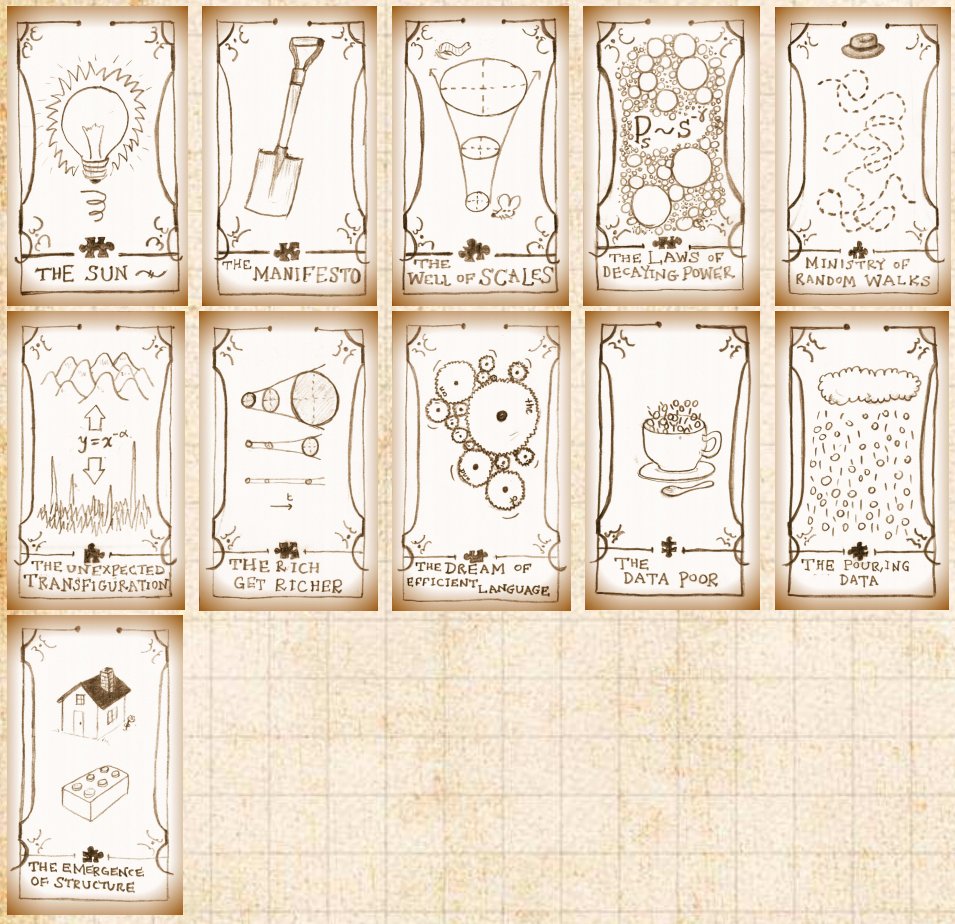

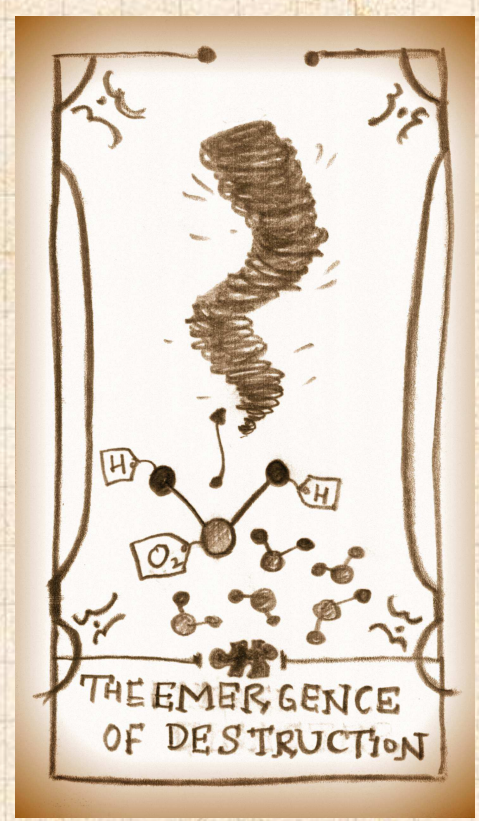

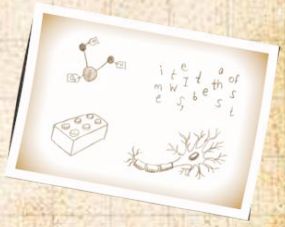

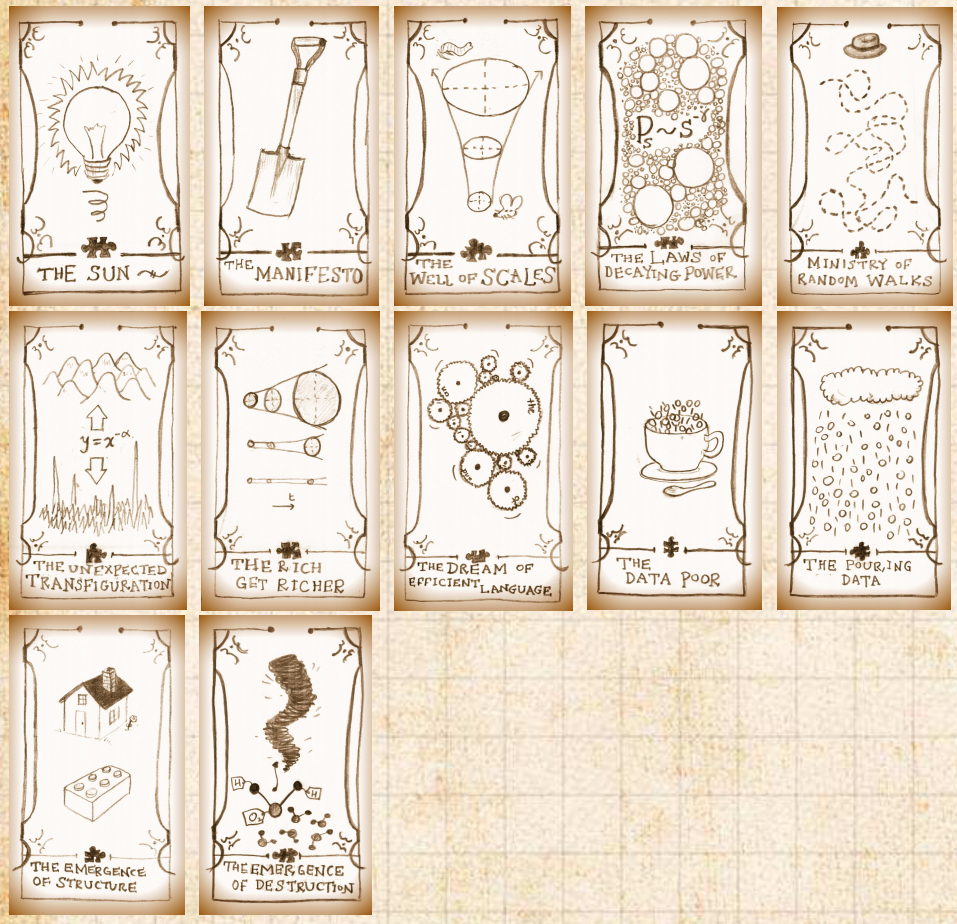

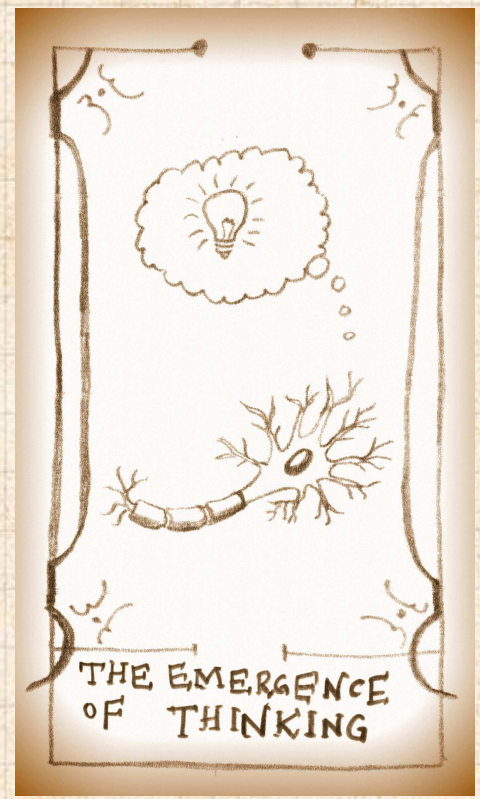

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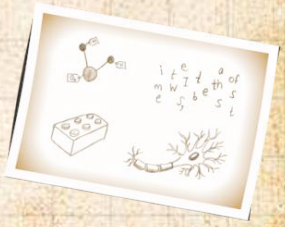

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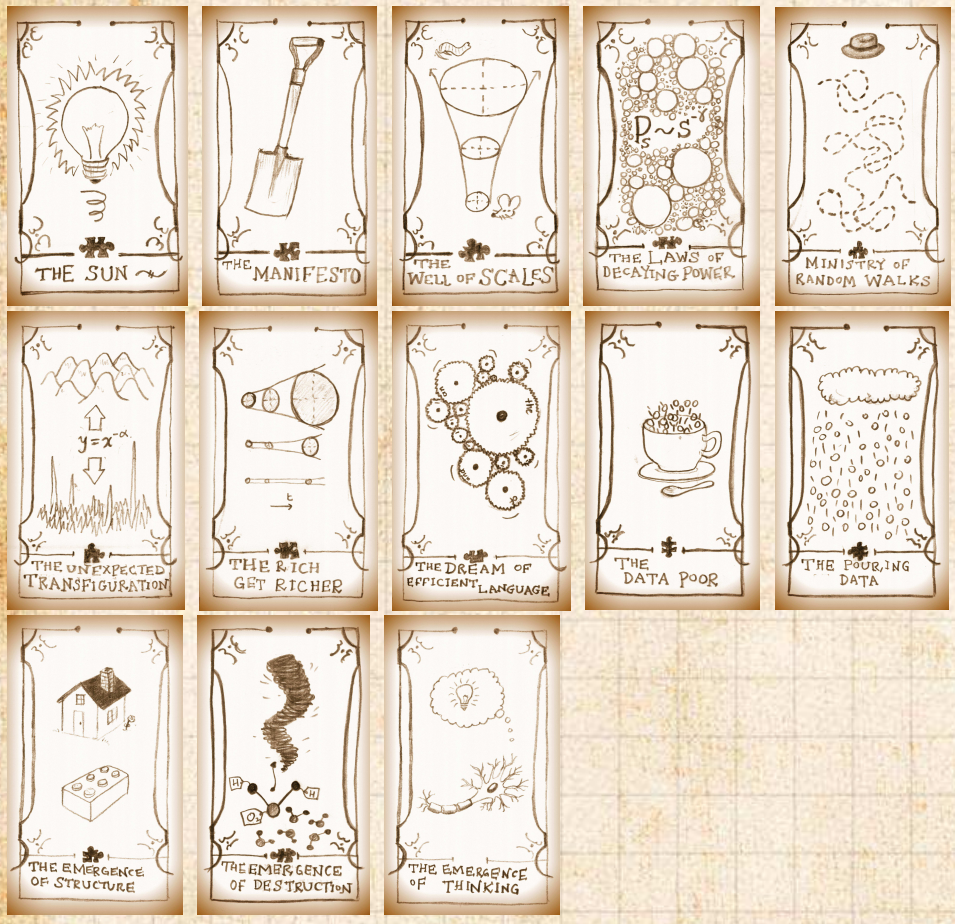

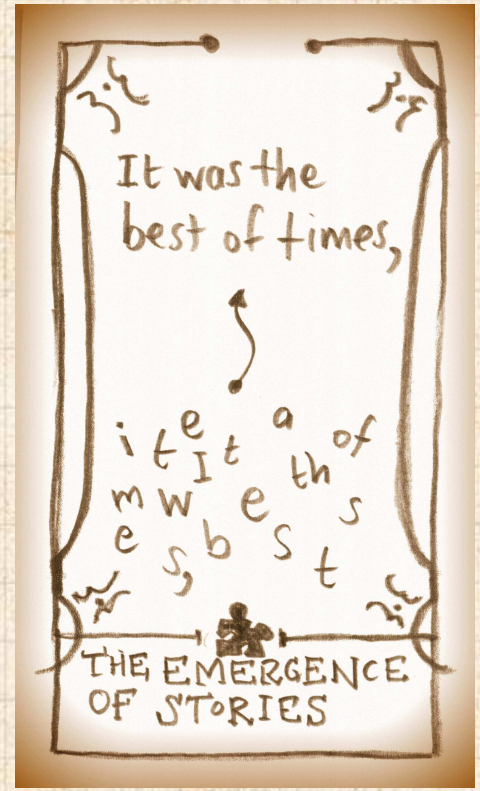

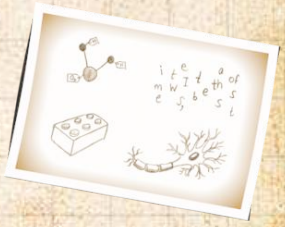

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The Wikipedia on Emergence:

"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.

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

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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
- ? ⇒ time; ? ⇒ gravity; ? ⇒ reality.

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

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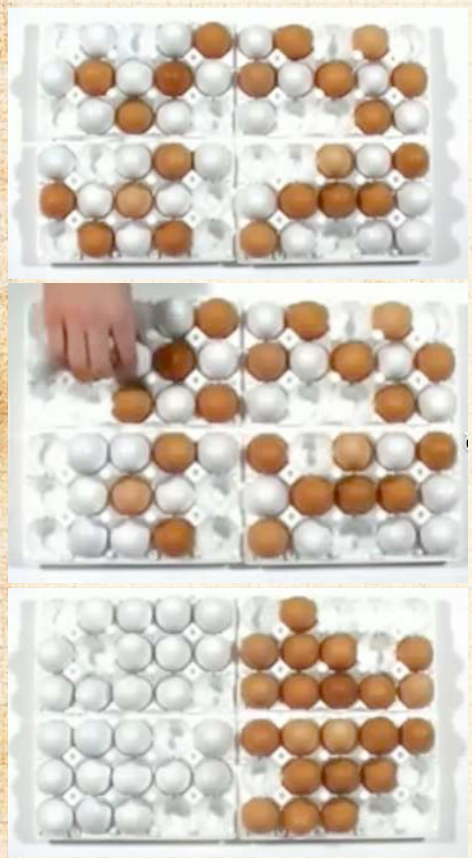
Emergence:

Thomas Schelling (Economist/Nobelist):



[youtube]

- "Micromotives and Macrobehavior" [9]
  - Segregation [7, 10]
  - Wearing hockey helmets [8]
  - Seating choices

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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. [1]
- Decentralized structures help solve problems.
- Dewey Decimal System versus tagging.

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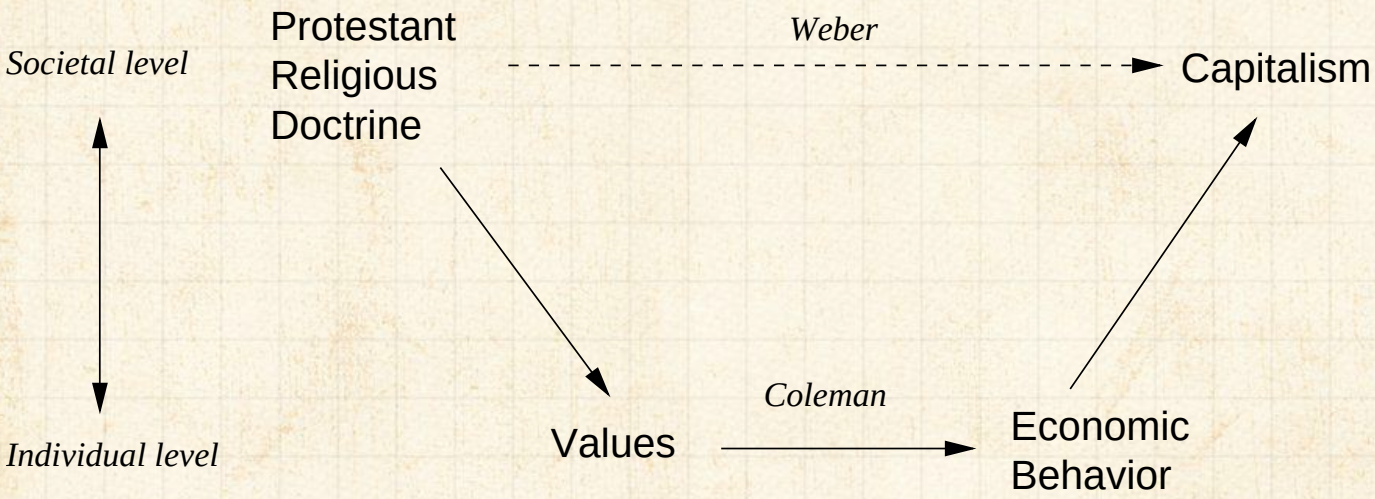

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- More on Coleman here.

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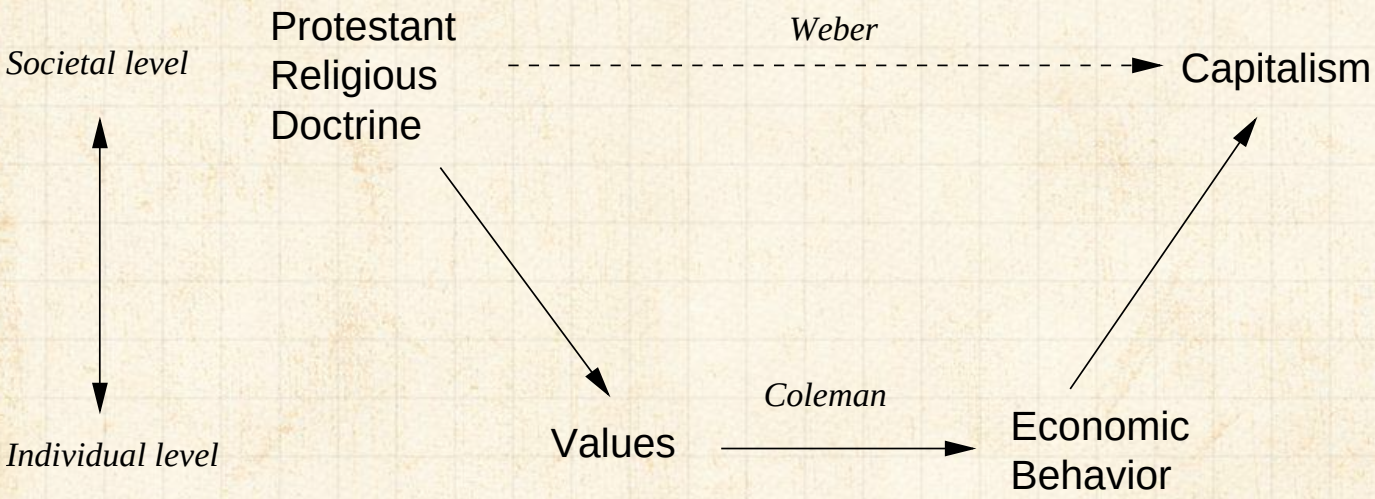

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The emergence of taste:

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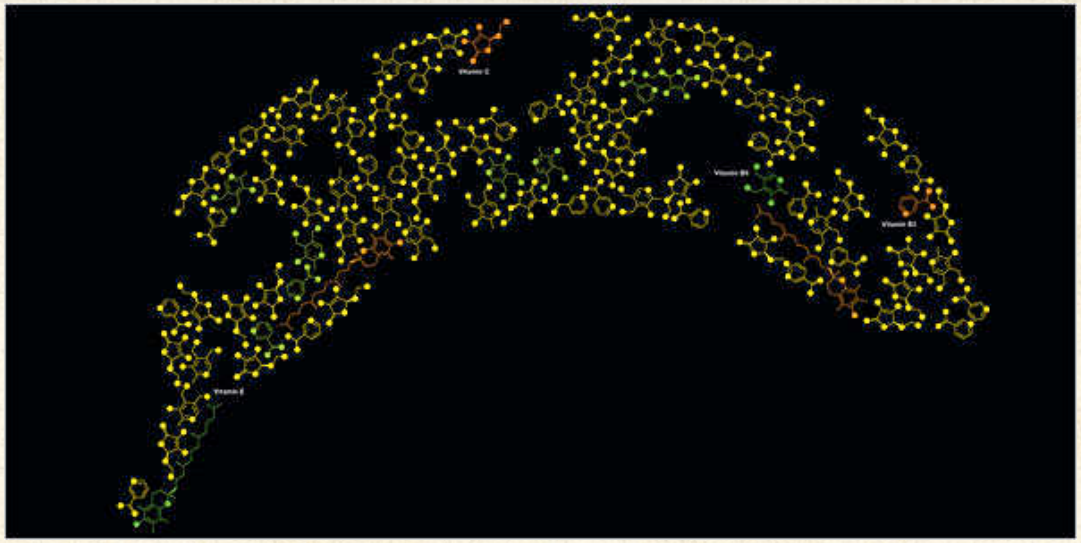
- Molecules ⇒ Ingredients ⇒ Taste
- See Michael Pollan's article on nutritionism in the New York Times, January 28, 2007.



nytimes.com

Reductionism

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Reductionism and food:

- Pollan: "even the simplest food is a hopelessly complex thing to study, a virtual wilderness of chemical compounds, many of which exist in complex and dynamic relation to one another…"
- "So … break the thing down into its component parts and study those one by one, even if that means ignoring complex interactions and contexts, as well as the fact that the whole may be more than, or just different from, the sum of its parts. This is what we mean by reductionist science."

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

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Reductionism

Thyme's known antioxidants:

4-Terpineol, alanine, anethole, apigenin, ascorbic acid, beta carotene, caffeic acid, camphene, carvacrol, chlorogenic acid, chrysoeriol, eriodictyol, eugenol, ferulic acid, gallic acid, gamma-terpinene isochlorogenic acid, isoeugenol, isothymonin, kaempferol, labiatic acid, lauric acid, linalyl acetate, luteolin, methionine, myrcene, myristic acid, naringenin, oleanolic acid, p-coumoric acid, p-hydroxy-benzoic acid, palmitic acid, rosmarinic acid, selenium, tannin, thymol, tryptophan, ursolic acid, vanillic acid.

[cnn.com]

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

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

This is a Collateralized Debt Obligation:

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

- From “The Speed of Darkness” (1968) by Muriel Rukeyser
- Quoted by Metatron in Supernatural, Meta Fiction, S9E18.

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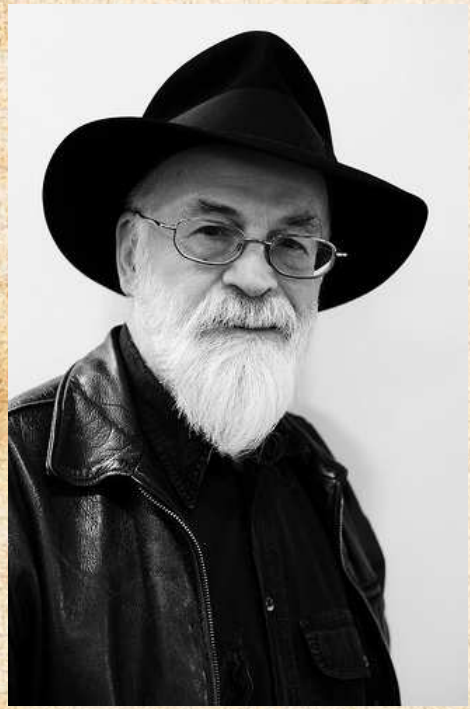

- "The most common element on the disc, although not included in the list of the standard five: earth, fire, air, water and surprise. It ensures that everything runs properly as a story."
- "A little narrativium goes a long way: the simpler the story, the better you understand it. Storytelling is the opposite of reductionism: 26 letters and some rules of grammar are no story at all."

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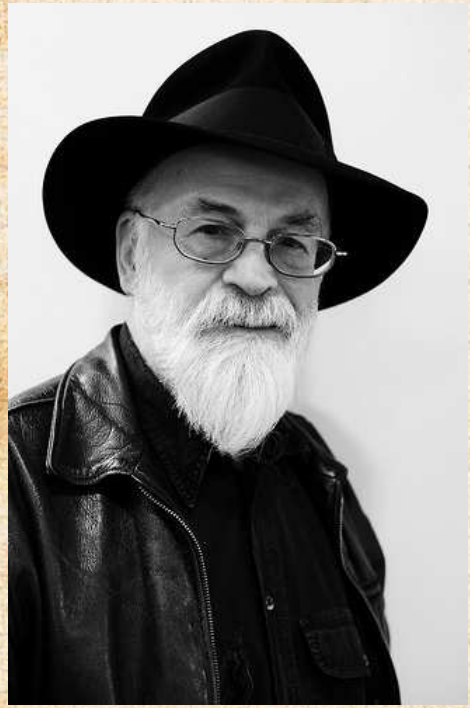

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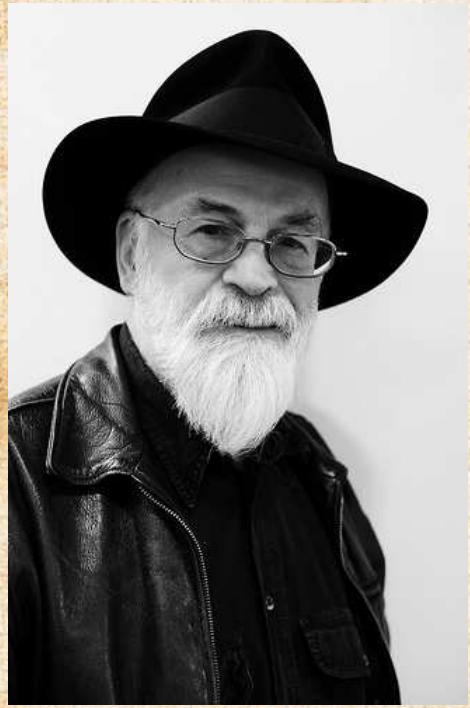

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Emergence:

Higher complexity:

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

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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Emergence:

Roughly speaking, there are two types of emergence:

I. Weak emergence:

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

II. Strong emergence:

System-level phenomena fundamentally cannot be deduced from how parts interact.

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- Reductionist techniques can explain weak emergence.
- Magic explains strong emergence. [2]
- But: maybe magic should be interpreted as an inscrutable yet real mechanism that cannot ever be simply described.
- Gulp.

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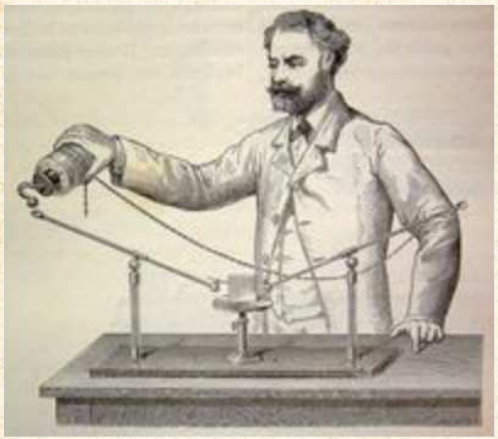
Listen to Steve Strogatz, Hod Lipson, and Michael Schmidt (Cornell) in the last piece (11:16) on Radiolab's show 'Limits' (April 5, 2010).



(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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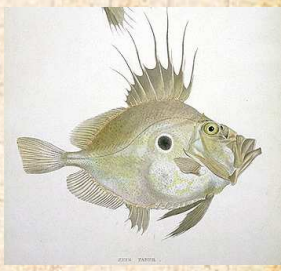

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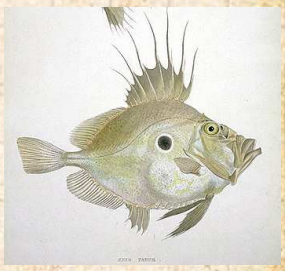

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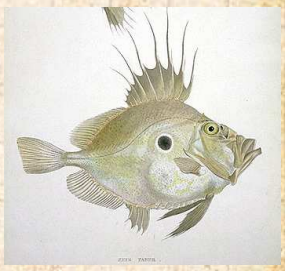

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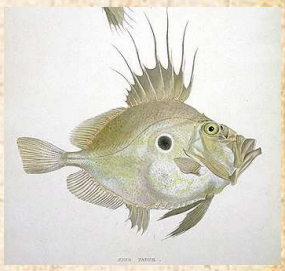
Fundamental question: how likely is 'complexification'?



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 (e.g., using Netlogo)
  - to kitchen sink models.

Key advance (to repeat):

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

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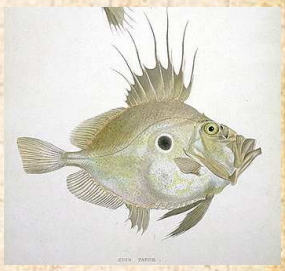

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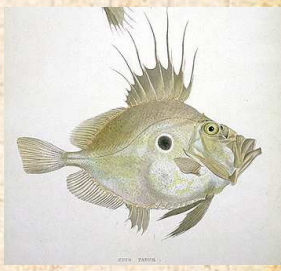

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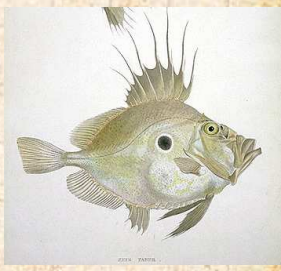

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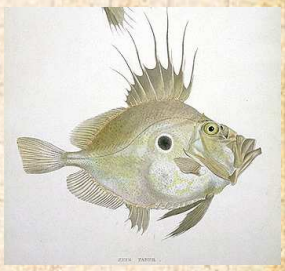

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Data
Emergence
Self-Organization
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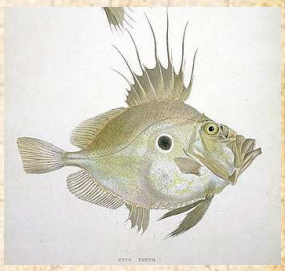

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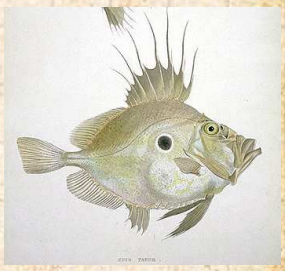

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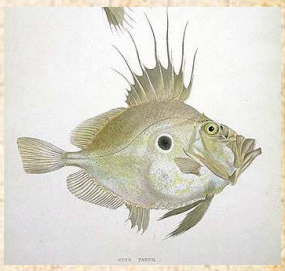

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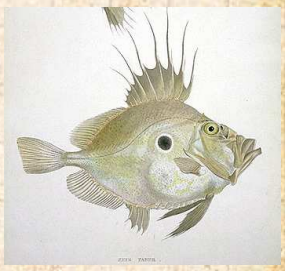

Rather silly but great example of real science:

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

Amusing interview here

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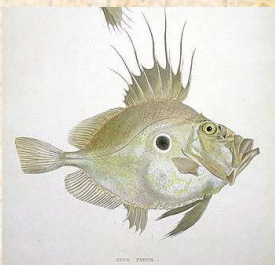

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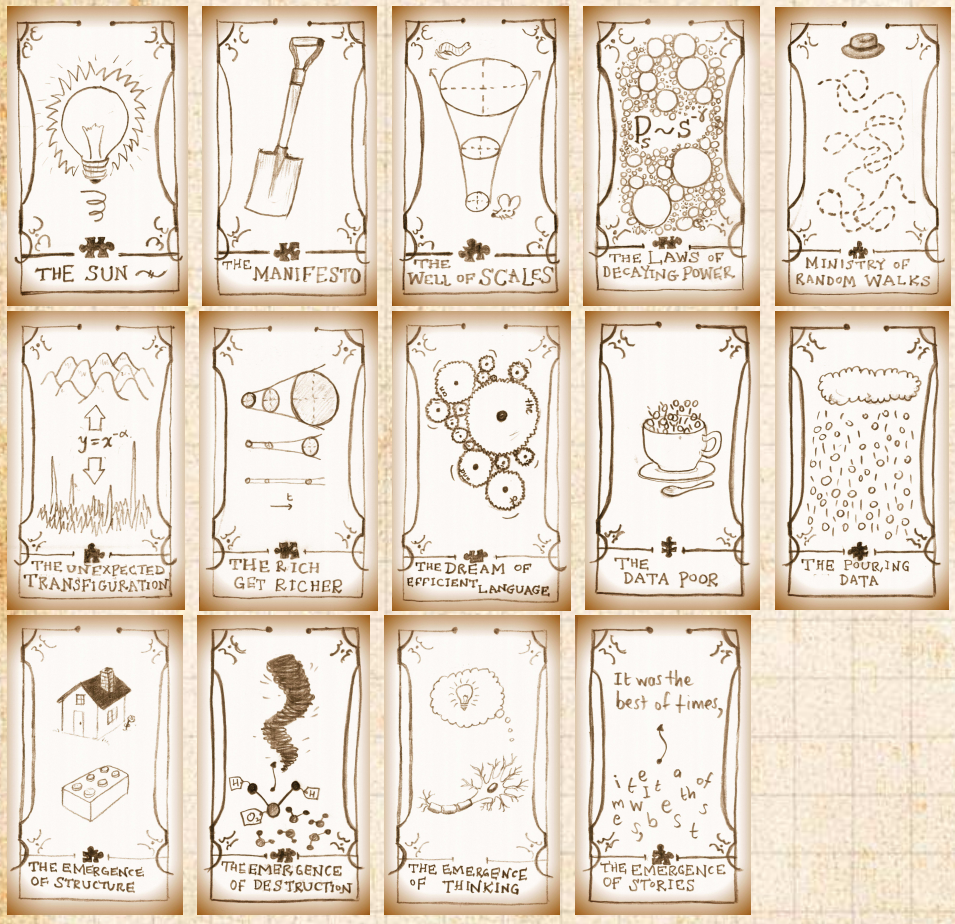

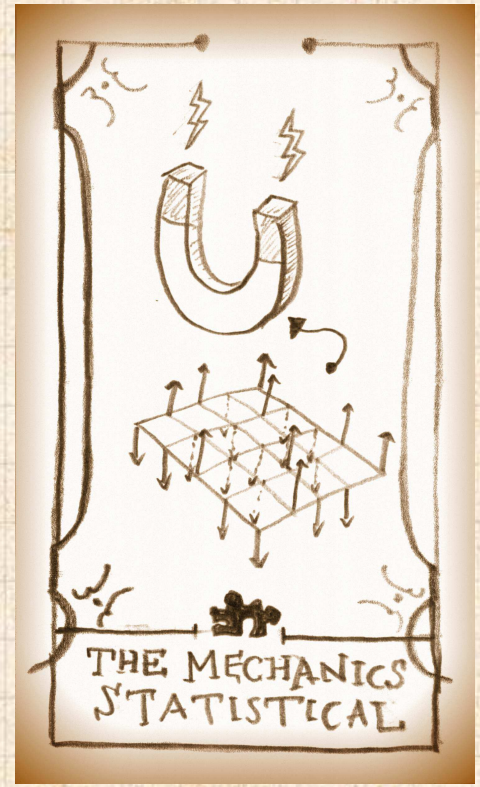

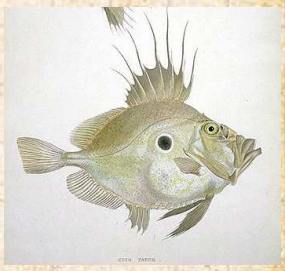

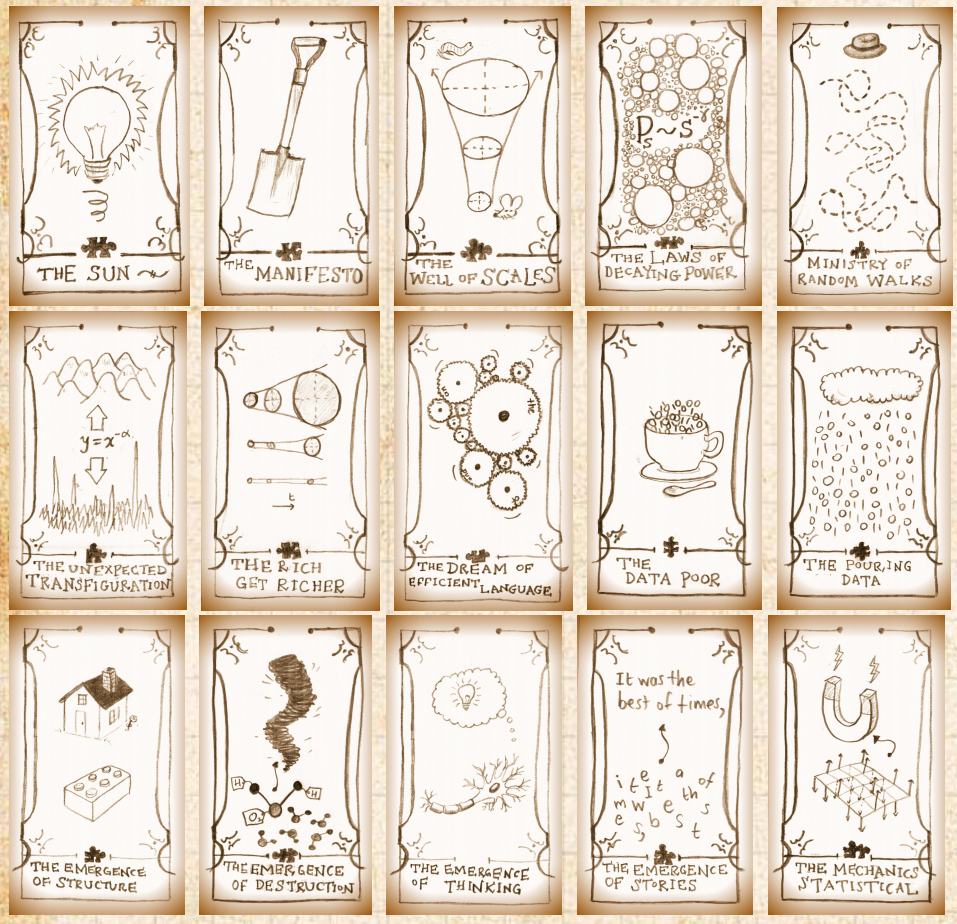

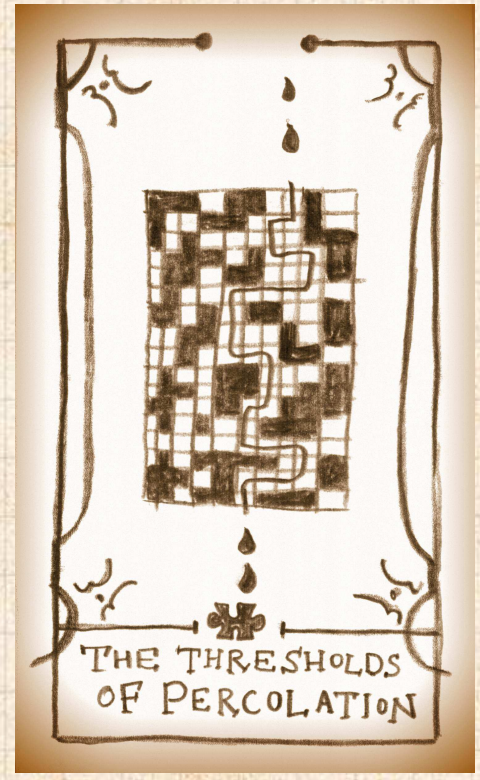

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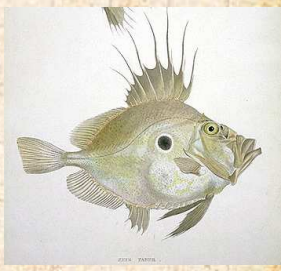
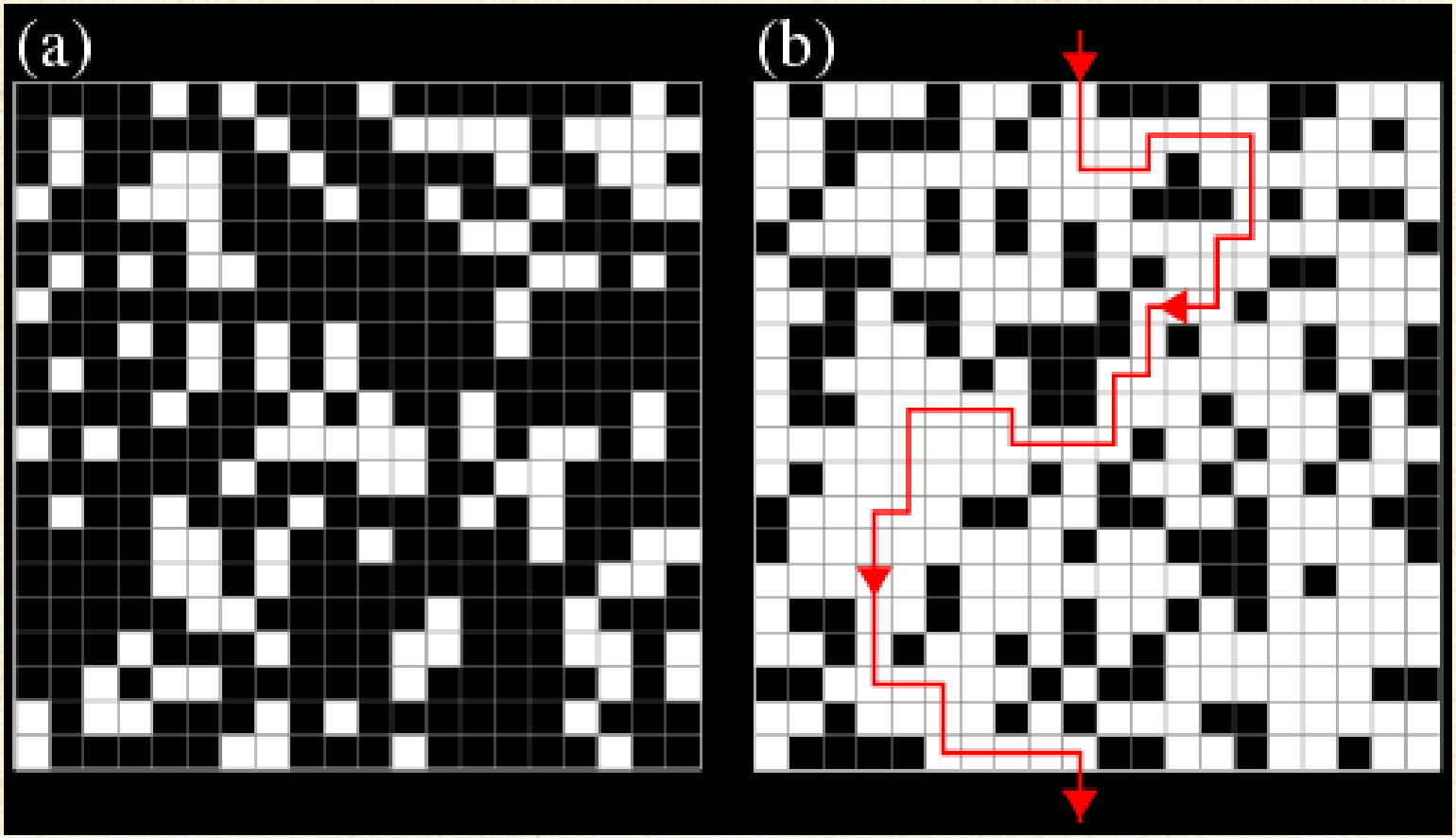
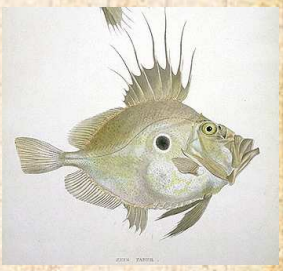


- Statistical Mechanics is "a science of collective behavior."
- Simple rules give rise to collective phenomena.

Percolation:



Snared from Michael Gastner's page on percolation



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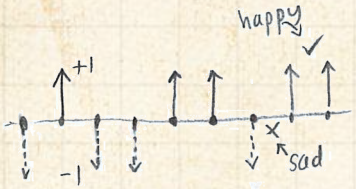

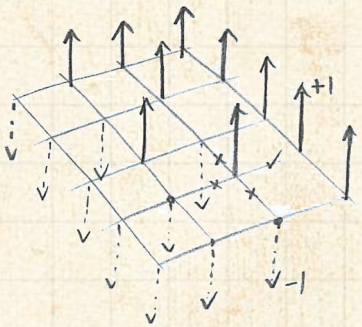

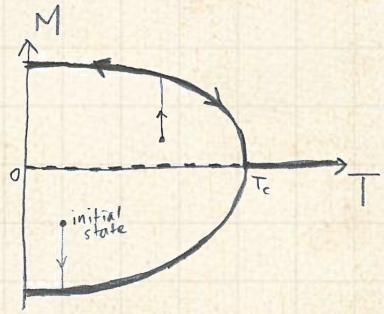

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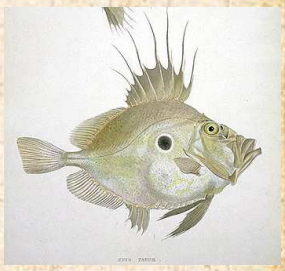
Example 2-d Ising model simulation:

http://dijohnson.net/projects/ising



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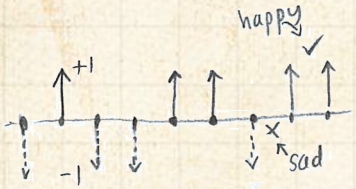

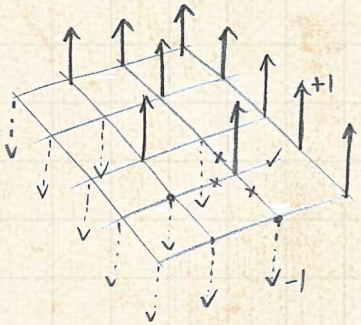

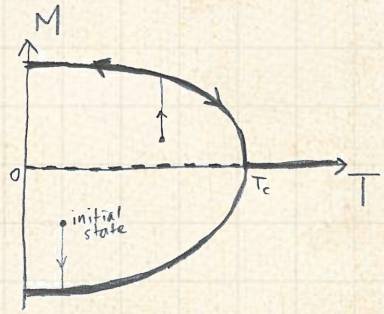

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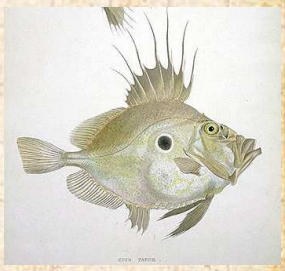

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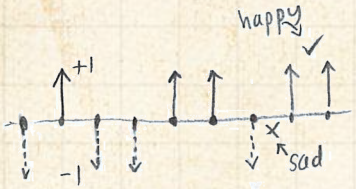

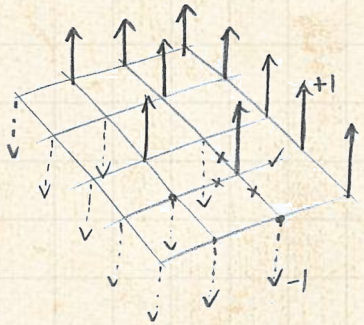

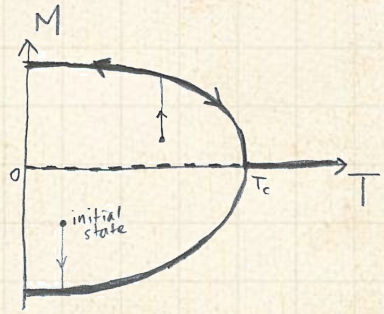

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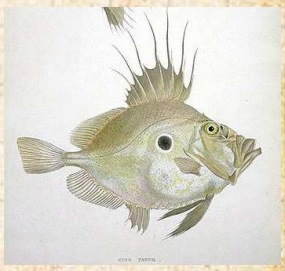

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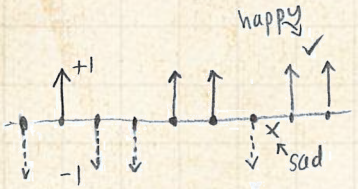

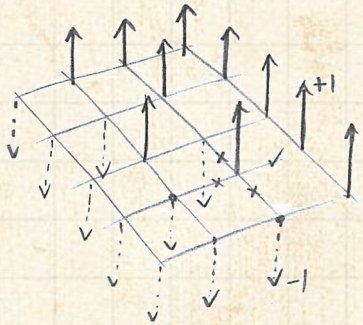

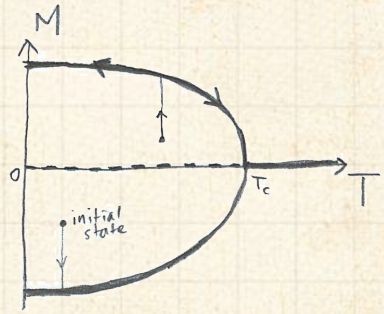

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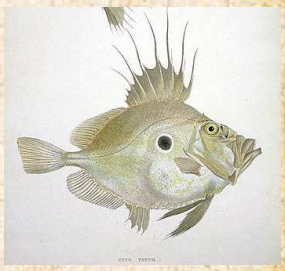

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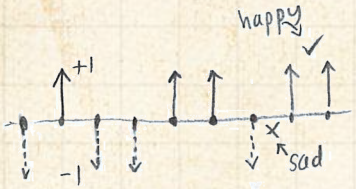

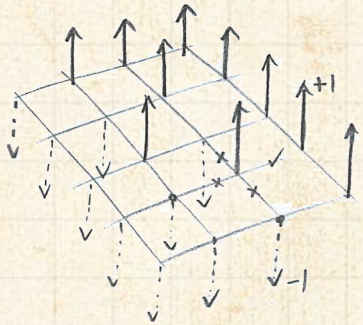

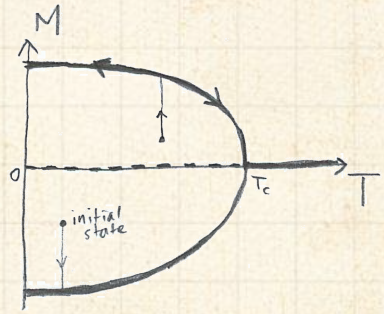

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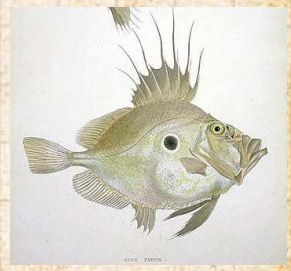

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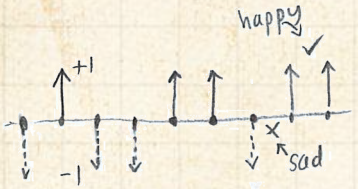

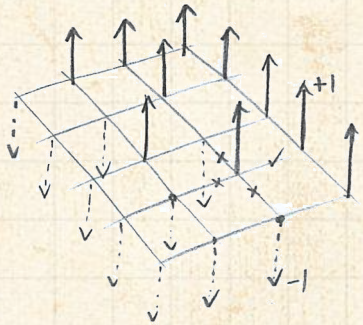

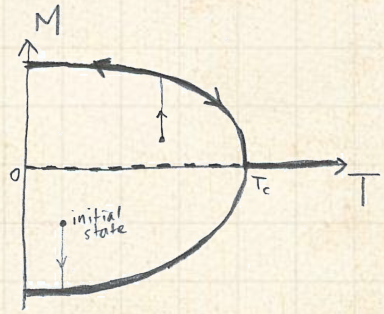

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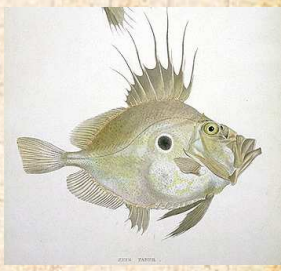

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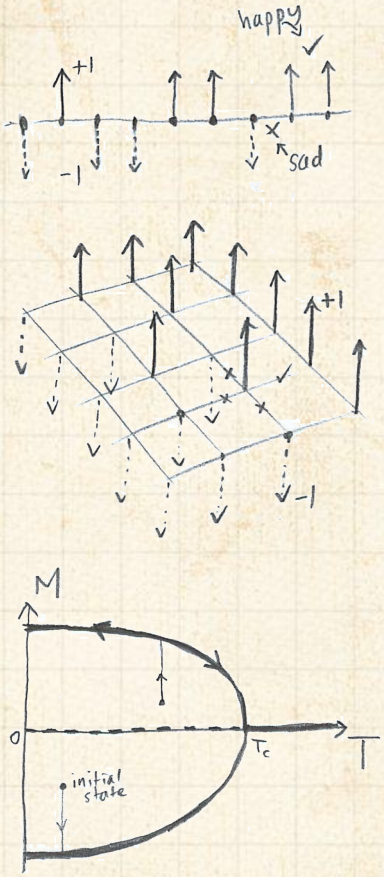

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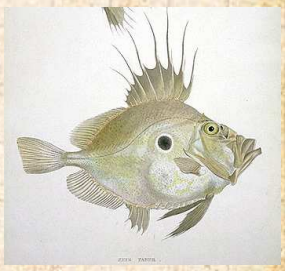

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Phase diagrams

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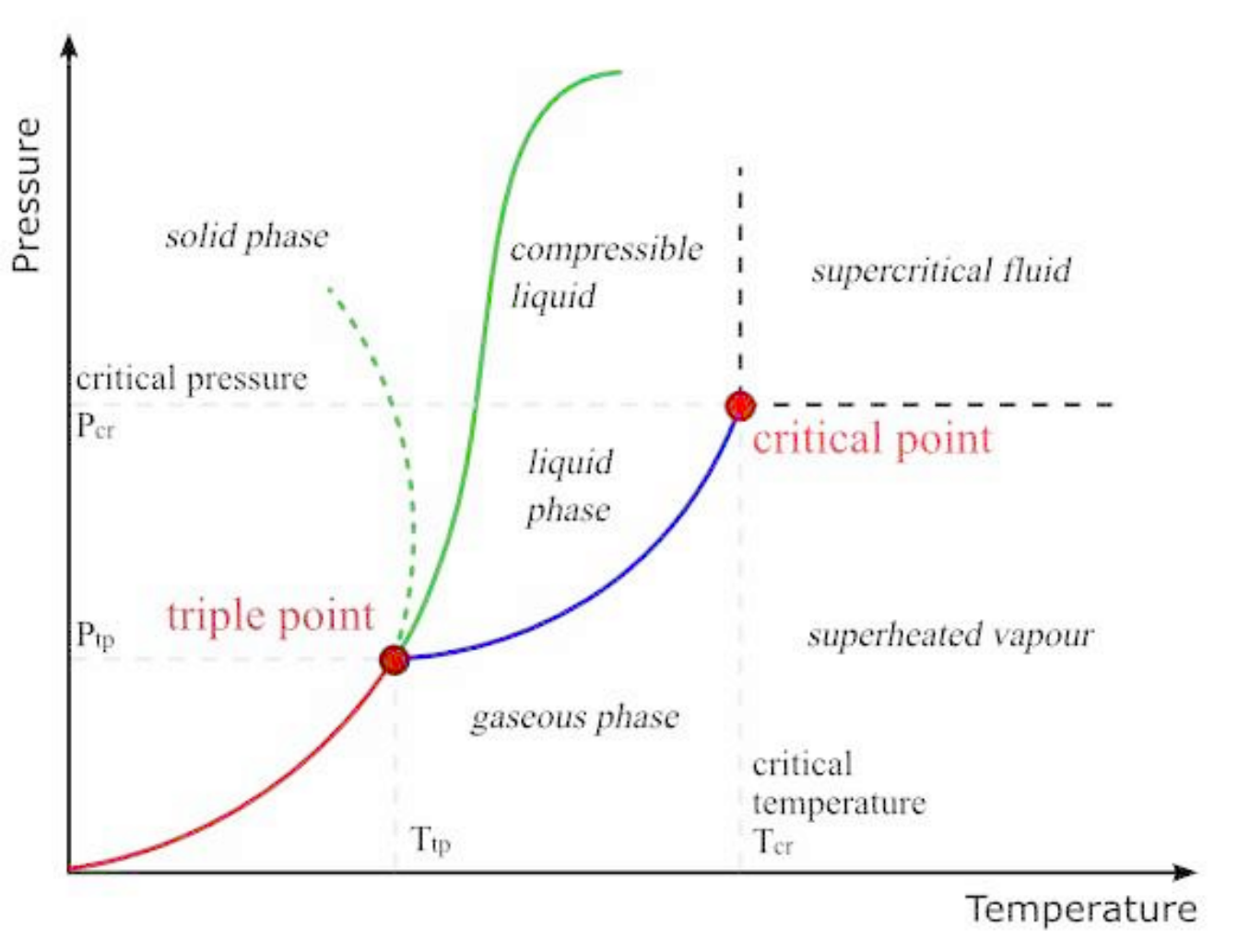

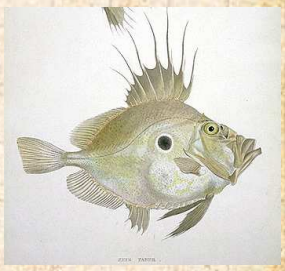

Qualitatively distinct macro states.

Phase diagrams

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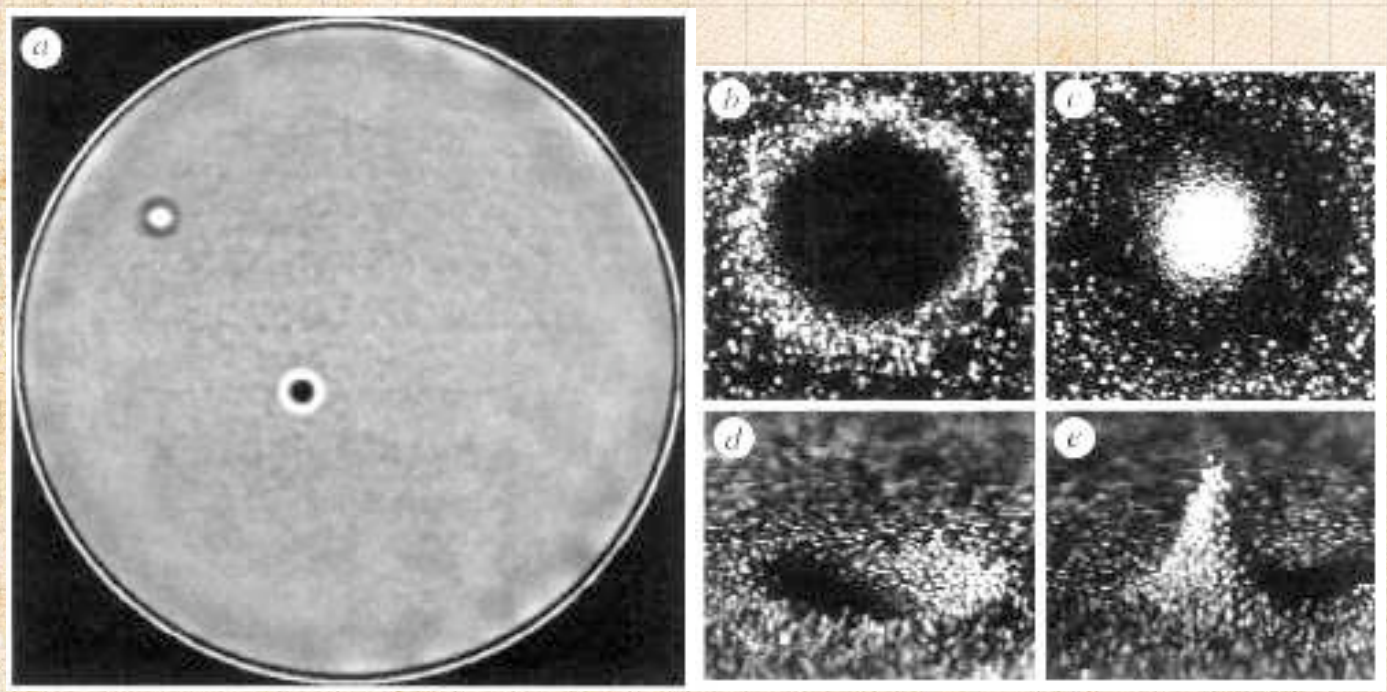
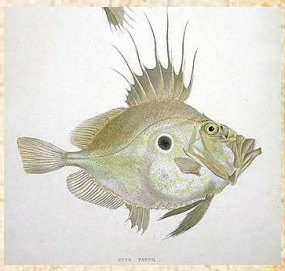
Oscillons, bacteria, traffic, snowflakes, ...



Umbanhowar et al., *Nature*, 1996 [11]



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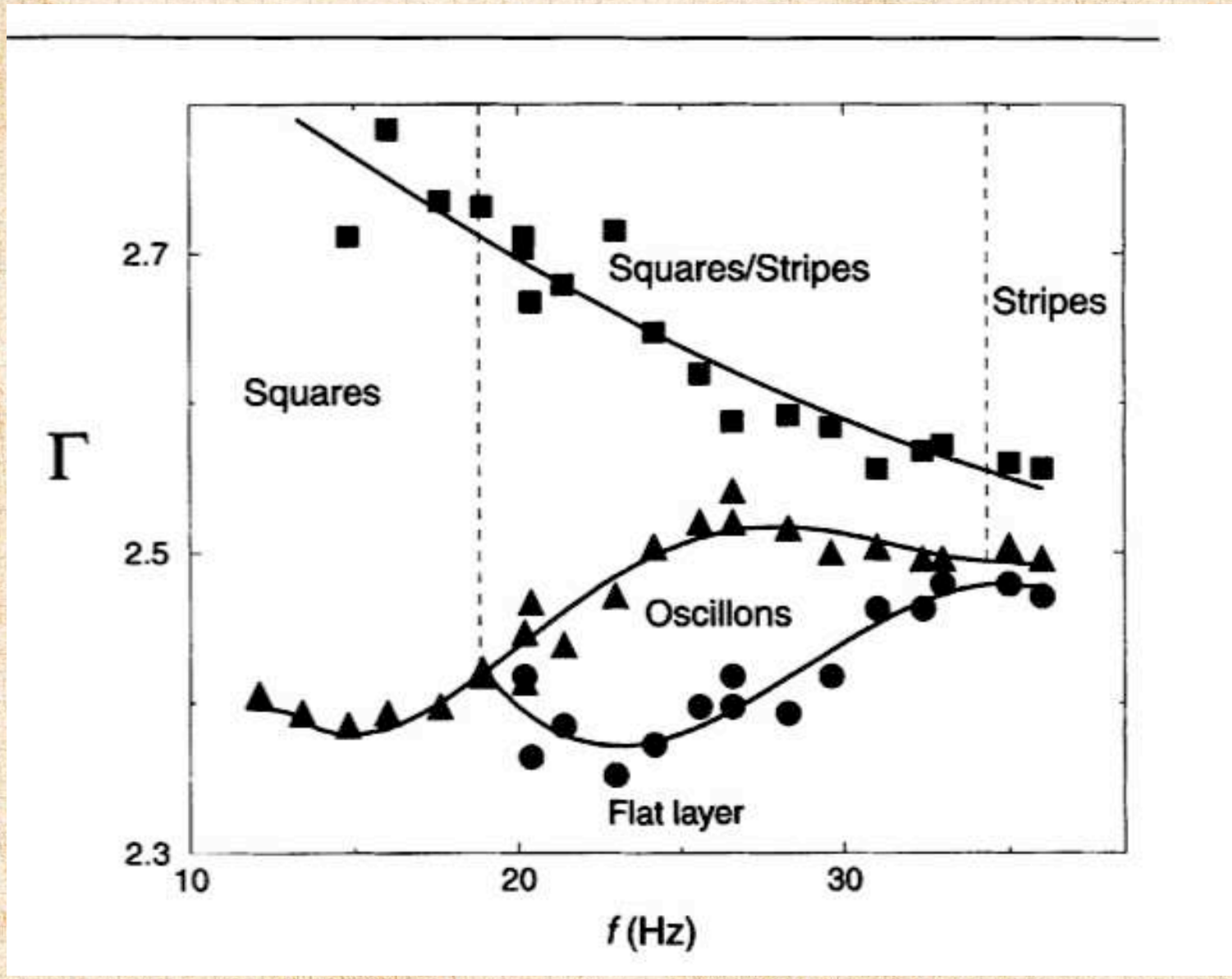
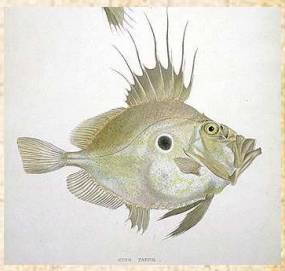
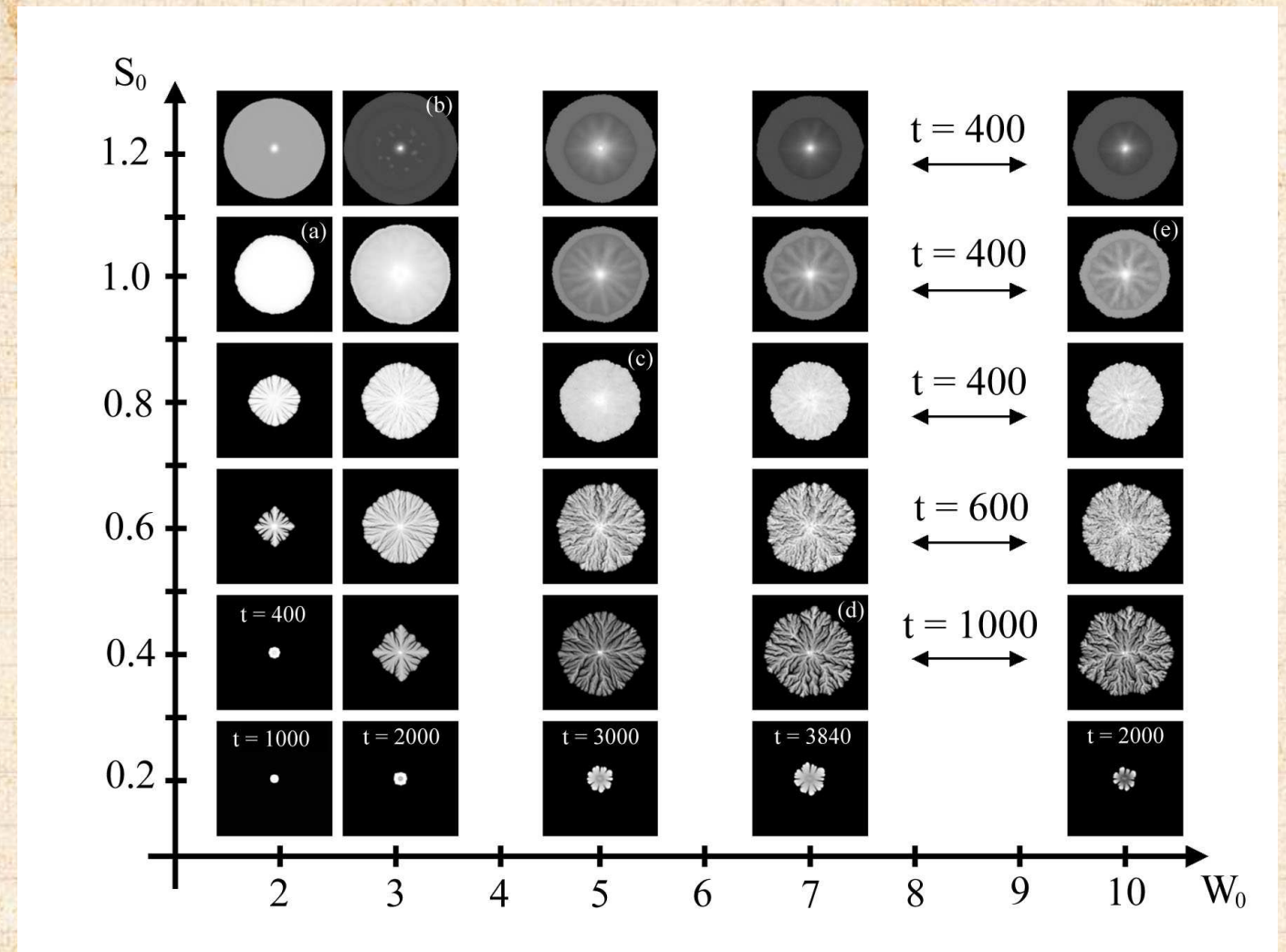
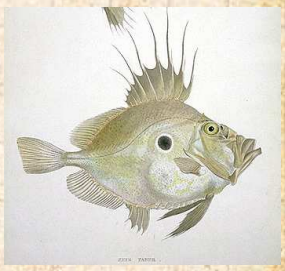




Phase diagrams





W_0 = initial wetness, S_0 = initial nutrient supply

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

Ising model

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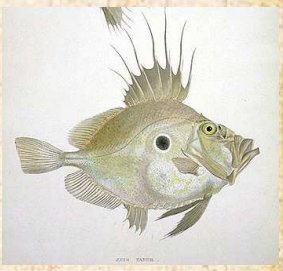
Analytic issues:

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



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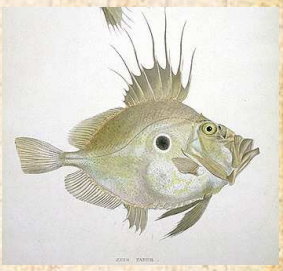

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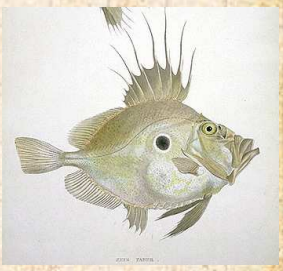

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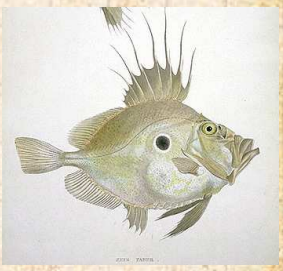

Statistics

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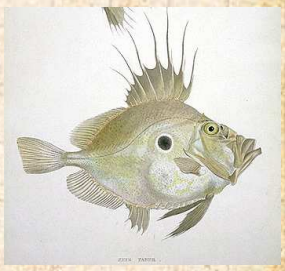
Historical surprise:

- 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" [11]

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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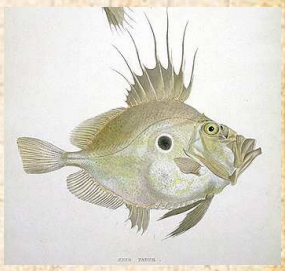

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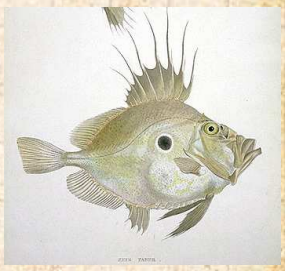

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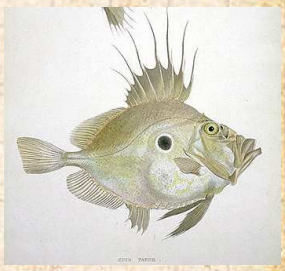

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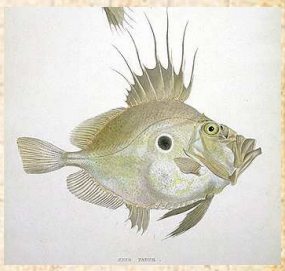

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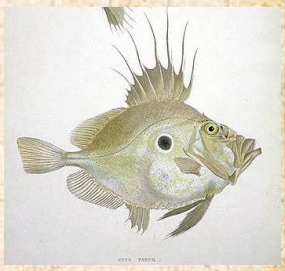

Nutshell

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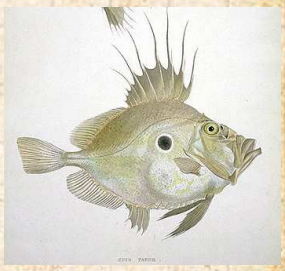
- The central concepts Complexity and Emergence are not precisely defined.
- There is no general theory of Complex Systems.
- But the problems exist...
  Complex (Adaptive) Systems abound...
- Framing from the Manifesto: Science's focus is moving to Complex Systems because it finally can.
- We use whatever tools we need.
- Science $\simeq$ Describe + Explain.



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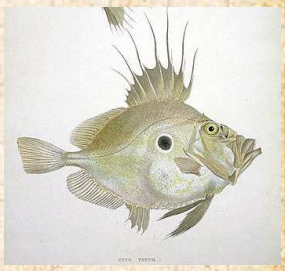

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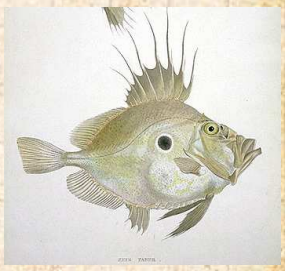

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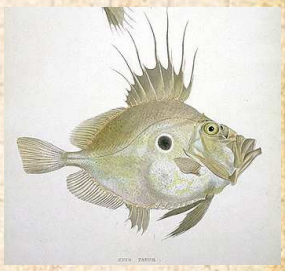

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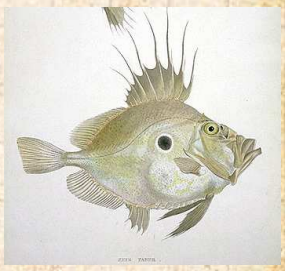

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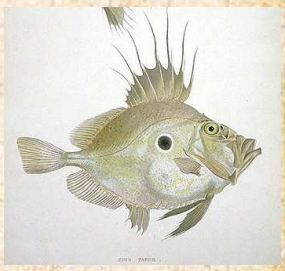

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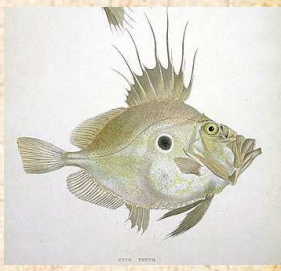

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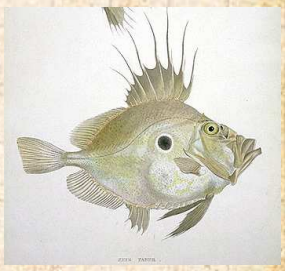

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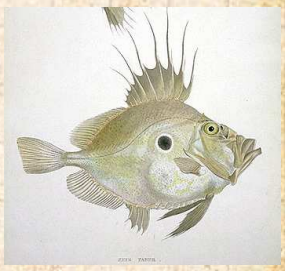

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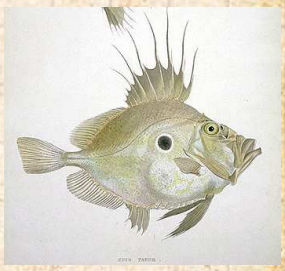
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