The PoCSverse
Fundamentals
1 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Fundamentals

Last updated: 2025/11/09, 12:52:30 EST

Principles of Complex Systems,
Vols. 1, 2, 3D, 4 Fourever, V for Vendetta

Prof. Peter Sheridan Dodds

Computational Story Lab | Vermont Complex Systems Institute
University of Vermont | Santa Fe Institute

PoCS
Principles of
Complex Systems
@pocsvox
What's the Story?

These slides are brought to you by:

Sealie & Lambie
Productions

The PoCSverse
Fundamentals
2 of 86
Data

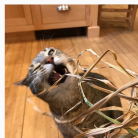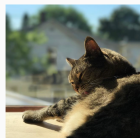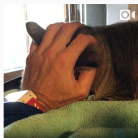Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

PoCS
Principles of
Complex Systems
@pocsvox
What's the Story?

These slides are also brought to you by:

The PoCSverse
Fundamentals
3 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Special Guest Executive Producer
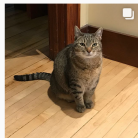
📷 On Instagram at pratchett_the_cat ↗

Outline

The PoCSverse
Fundamentals
4 of 86
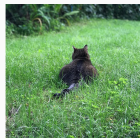Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

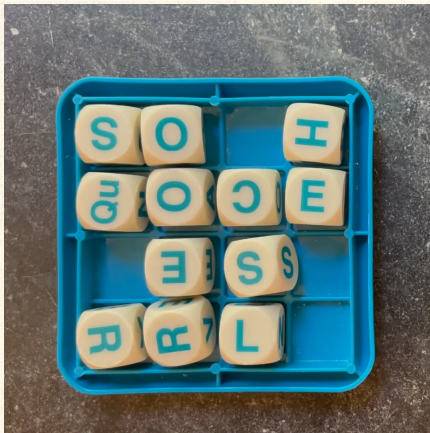References

Data

Measurement

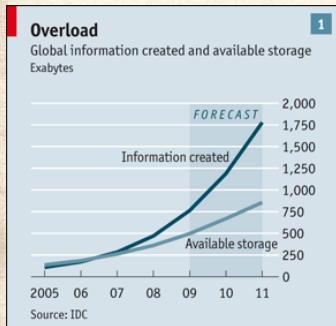Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

PoCS
Principles of
Complex Systems
@pocsvox
What's the Story?

The Boggoracle Speaks:

THE MEASURING

THE DATA POOR

THE POURING DATA

The PoCSverse
Fundamentals
9 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Around 2010: Data becomes Big Data 🔗 because it's about us:

Overload
Global information created and available storage
Exabytes

FORECAST

Information created

Available storage

2005 06 07 08 09 10 11
Source: IDC

🧩 Exponential growth: ∼ 60% per year.

Big Data Science over time:

🧩 Vera C. Rubin Observatory: 🔗 200,000 photos, 1.28 petabytes/year.

🧩 Large Hadron Collider, 2024: 1 petabye/second. 🔗

🧩 ∼ 2 trillion photos taken in 2024 🔗

🧩 Over 10 billion photos shared each day 🔗

🧩 Large language models 🔗, 2024: Up to 10^{13} tokens.

No really, that's a lot of data

Data inflation

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

Source: *The Economist*

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

Estimates of internet data, past, present, future:[1]

The PoCSverse
Fundamentals
11 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

Created:

- 2010: $\sim$ 2 zettabytes
- 2014: $\sim$ 12 zettabytes
- 2022: $\sim$ 97 zettabytes
- 2023: $\sim$ 120 zettabytes
- 2024: $\sim$ 150 zettabytes
- 2025: $\sim$ 180 zettabytes

- Video accounts for about 50% of all data.

---

[1] https://www.statista.com/statistics/871513/worldwide-data-created/ ⬀

Big Data—Culturomics:

The PoCSverse
Fundamentals
12 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

"Quantitative analysis of culture using millions of digitized books" by Michel et al., Science, 2011 [14]
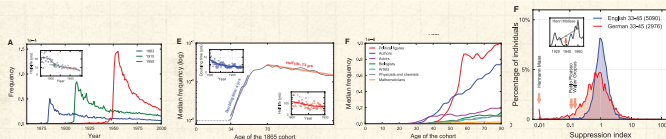
🔗 Google Books ngram viewer ⎘

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. [16]

Deceased: http://www.culturomics.org/ ⎘

Overboard

The PoCSverse
Fundamentals
13 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

🎲 Internet-scale data sets can be overly exciting.

Witness:

🎲 The End of Theory: The Data Deluge Makes the Scientific Theory Obsolete (Anderson, Wired) ⤢

🎲 "The Unreasonable Effectiveness of Data," Halevy et al. [10].

🎲 c.f. Wigner's "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" [25]

But:

🎲 For scientists, description is only part of the battle.

🎲 We still need to understand.

Basic Science $\simeq$ Describe + Explain:

The PoCSverse
Fundamentals
14 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

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."
- ♟ "My beard will always be cool."

A brief history of measuring time:

🎲 Megaliths for Big Time

🎲 Sundials, 1500 BC, Egypt (solid for over 2000 years)

🎲 Escapements (200s), Hourglasses (1300s?), Pendulum clocks (Galileo, 1500s)

🎲 Chronometers, 1700s:

"Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time" ⓐ ☑
by Dava Sobel (2007). [22]

🎲 Billionths of a second accuracy: Atomic clocks (Lord Kelvin, 1879)

The PoCSverse
Fundamentals
16 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Some very, very silly units of measurement courtesy of the Imperial system ⬀:

- 🎲 22 yards in a chain = 1 cricket pitch, 100 links in a chain, 10 chains in a furlong, 80 chains in a mile.
- 🎲 1 acre = 1 furlong × 1 chain = 43,560 square feet.
- 🎲 160 fluid ounces in a gallon.
- 🎲 14 pounds in a stone.
- 🎲 Hundredweight = 112 pounds.

Also:

- 🎲 Fahrenheit, Celcius, and Kelvin.
- 🎲 The entire metric system.

Our struggle to sensibly measure anything at all:

The PoCSverse
Fundamentals
17 of 86

Data
- - -

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

By 42CrMo4, Christoph Päper – English length units graph (PNG), CC BY-SA 4.0
https://commons.wikimedia.org/w/index.php?curid=61338012
From https://en.wikipedia.org/wiki/Barleycorn_(unit)

Measuring temperature was thought impossible:

The PoCSverse
Fundamentals
18 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The properties measured by our instruments usually begin as subjective judgments. Temperature is a good example. People were aware of variations in temperature long before there were any objective measurements of temperature. Judgments of temperature are imperfectly correlated among different persons, or even the same person at different times, depending on the humidity, the person's activity level and age, surrounding air currents, and so on. The idea that anything as subtle and complex as all the manifestations of changes in temperature could be measured and quantified on a single numerical scale was scoffed at as impossible, even by the leading philosophers of the sixteenth century.

The first thermometer invented by Galileo in 1592 did not go far in dispelling the notion that temperature was inherently unmeasurable, because the earliest thermometers, for about their first hundred years, were so imperfect as to make it possible for those who wished to do so to argue that no one could ever succeed in measuring temperature. Temperature was then confounded with all the subtleties of subjective judgment, which easily seem incompatible with a single numerical scale of measurement. How could the height of a column of mercury in a glass tube possibly reflect the rich varieties of temperature—damp cold, dank cold, frosty cold, crisp cold, humid heat, searing heat, scalding heat, dry heat, feverish heat, prickly heat, and so on?

From "Bias in Mental Testing", Arthur Jensen, 1980 [12]
per @SilverVVulpes ⟳: Also: Inventing Temperature, Hasok Chang, 2004 [5]

Measuring temperature was thought impossible:

The PoCSverse
Fundamentals
19 of 86

Data
- - -
Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The early thermometers were inconsistent, both with themselves and with each other. Because they consisted of open-ended glass tubes, they were sensitive to changes in barometric pressure as well as to temperature. And there were problems of calibration, such as where to locate the zero point and how to divide the column of mercury into units. It was believed, incorrectly, that all caves had the same temperature, so thermometers were calibrated in caves. The freezing and boiling points of water were also used in calibration, but, as these vary with impurities in the water and the barometric pressure, the calibration of different thermometers at different times and places resulted in thermometers that failed to correlate perfectly with one another in any given instance. They lacked reliability, as we now would say.

All the while, no one knew what temperature is in a theoretical or scientific sense. There was no theory of thermodynamics that could explain temperature phenomena and provide a complete scientific rationale for the construction and calibration of thermometers. Yet quite adequate and accurate thermometers, hardly differing from those we use today, were eventually developed by the middle of the eighteenth century. Thus the objective measurement of temperature considerably preceded the development of an adequate theory of temperature and heat, and necessarily so, as the science of thermodynamics could not possibly have developed without first having been able to quantify or measure the temperatures of liquids, gasses, and other substances independently of

From "Bias in Mental Testing", Arthur Jensen, 1980 [12]
per @SilverVVulpes 🔗: Also: Inventing Temperature, Hasok Chang, 2004 [5]

The PoCSverse
Fundamentals
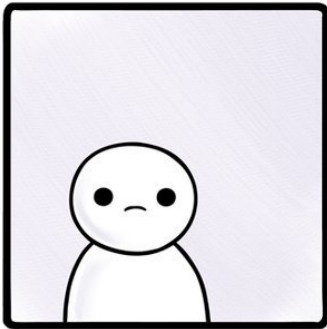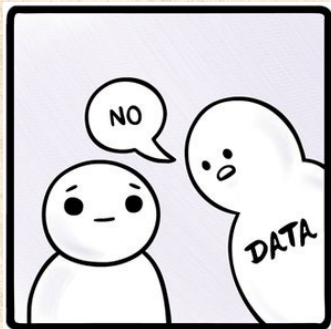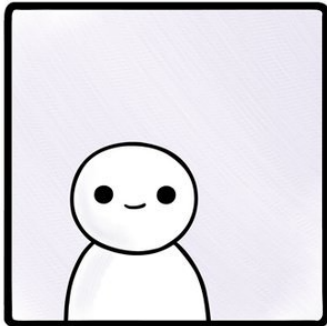20 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

THIS COMIC MADE POSSIBLE THANKS TO ADAM LINGELBACH

MRLOVENSTEIN.COM

The PoCSverse
Fundamentals
22 of 86
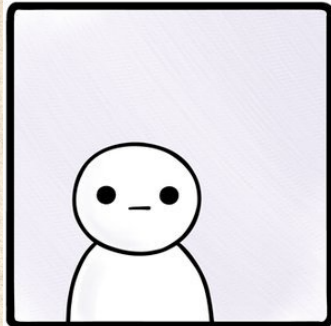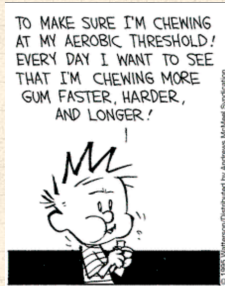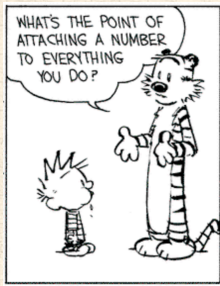
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Data Angry. Data Smash. ⬚↗
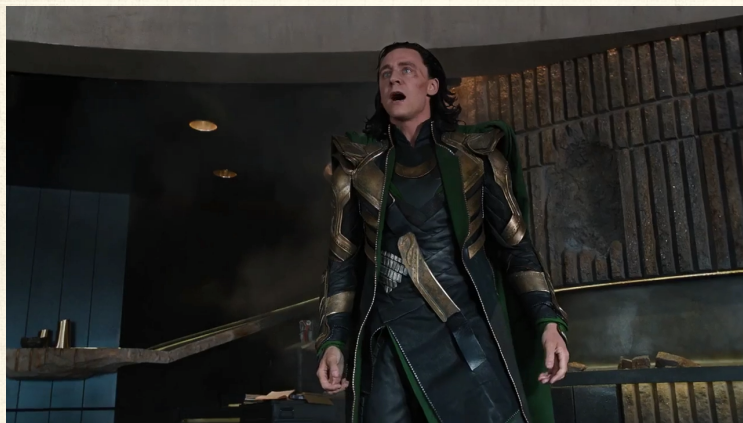
The PoCSverse
Fundamentals
23 of 86

Data
- - -

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The PoCSverse
Fundamentals
24 of 86

D̲a̲t̲a̲

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The PoCSverse
Fundamentals
25 of 86

Data
- - -
Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The PoCSverse
Fundamentals
26 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Analytically
Tractable
Mathematical
Models

Describable
Reality

Computational
Models

THE CHARMS OF THE MANY WRONG PATHS

PATHS OF
THINKING
THAT LEAD
TO
CERTAIN
DESPAIR

Nº 1497700
–1497799

THE DOORS THAT
SHOULD NOT BE OPENED
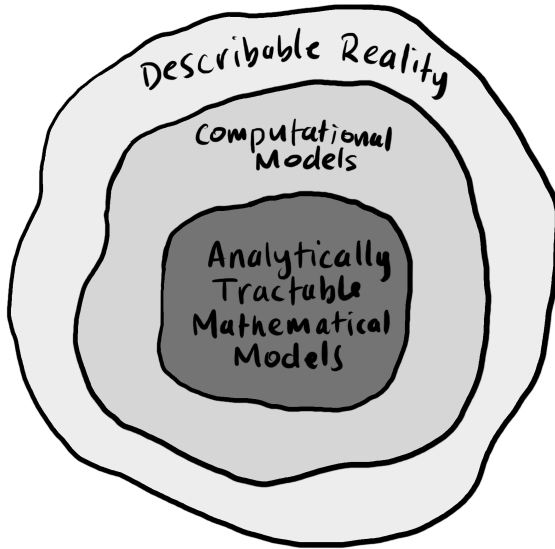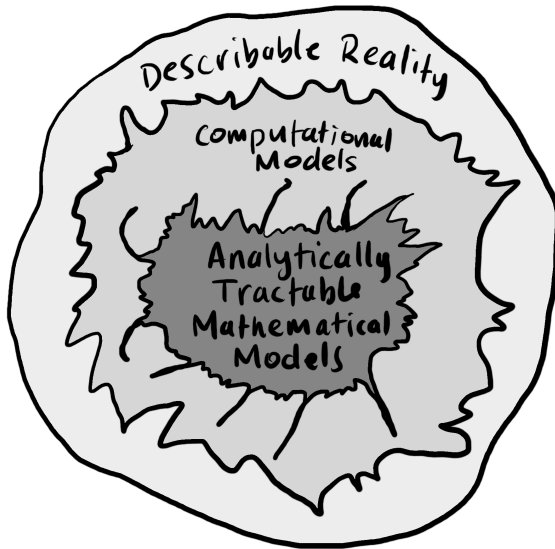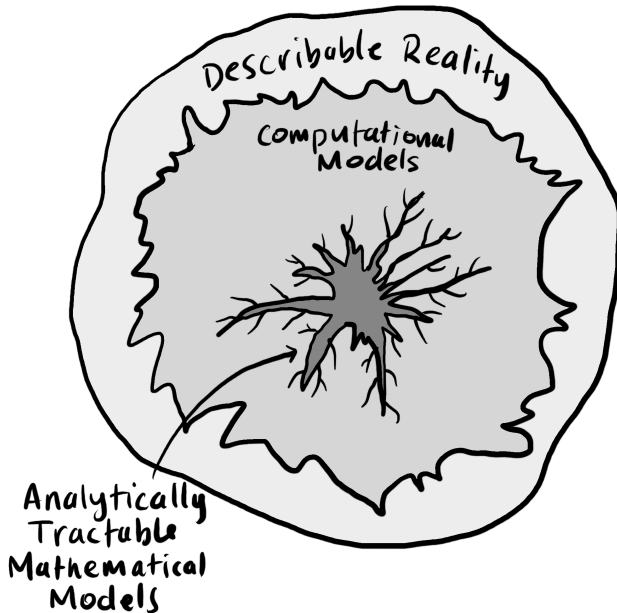
The PoCSverse
Fundamentals
30 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

Limits of testability and happiness in Science:
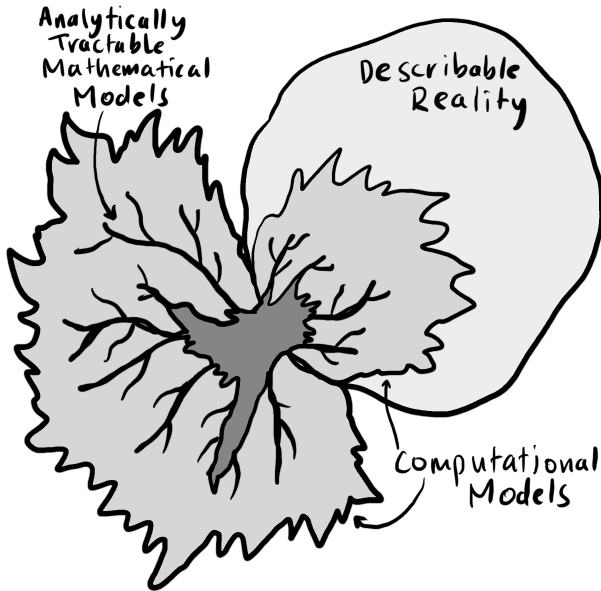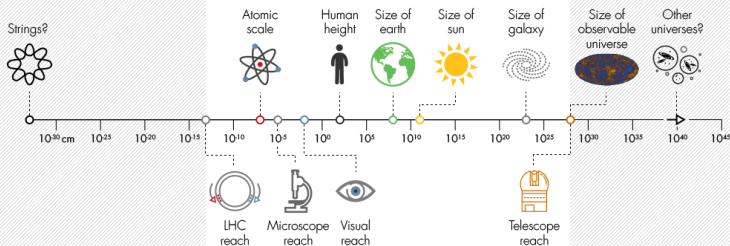
From A Fight for the soul of Science ⧉ in Quanta Magazine (2016/02):

The Ends of Evidence
Humans can probe the universe over a vast range of scales (white area), but many modern physics theories involve scales outside of this range (grey).
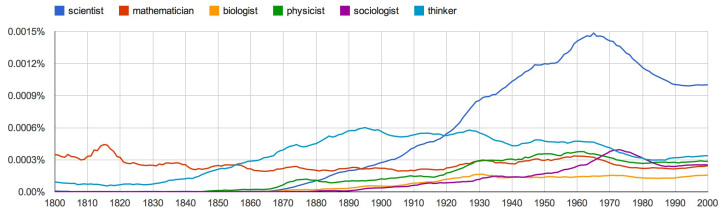
The Newness of being a Scientist (1833 on):

The PoCSverse
Fundamentals
31 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

Google books Ngram Viewer

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

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

Search lots of books

- 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."

_____

Consilience:
https://www.npr.org/2010/05/21/127037417/how-the-word-scientist-came-to-be

The PoCSverse
Fundamentals
32 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Please do not measure complex systems with one number:

NEW CUYAMA
Population   562
Ft. above sea level 2150
Established   1951
TOTAL   4663

- This is real ⎘—someone having some fun.
- Obtained from this tweet. ⎘
- Sadness for Buckingham (if Buckingham has no sense of humor).

The PoCSverse
Fundamentals
33 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The conceptual trapping pit ☑ of a single scale:

- 🎲 Lure of simplicity: Comparisons and rankings are easy.

- 🎲 A single scale measure is very appealing, very hard to resist ...
  ... and hard to push back against when widely adopted.

- 🎲 Examples:
  - 📦 Grade point average (GPA)
  - 📦 College rankings, City rankings, Country rankings, Wine scores, Michelin Guide ☑, Yelp scores, Amazon ratings ☑, ...
  - 📦 Body Mass Index (BMI)
  - 📦 Intelligence Quotient (IQ)[2]
  - 📦 Effective temperature
  - 📦 Price for all things: One dimension of belief
  - 📦 Salary!
  - 📦 stock market valuation for corporations
  - 📦 Complexity of civilizations [23]
  - 📦 A 1-d axis for political ideologies (a spatial metaphor trap, thanks France! ☑)

---

[2]Phrenology ☑ was at least a 2-d map; see also palmistry ☑

Personality distributions:

The PoCSverse
Fundamentals
34 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

"A Theory of the Emergence, Persistence, and Expression of Geographic Variation in Psychological Characteristics" 🗗
Rentfrow, Gosling, and Potter,
Perspectives on Psychological Science, **3**, 339–369, 2008. [17]

Five Factor Model (FFM):

- Extraversion [E]
- Agreeableness [A]
- Conscientiousness [C]
- Neuroticism [N]
- Openness [O]

"...a robust and widely accepted framework for conceptualizing the structure of personality... Although the FFM is not universally accepted in the field..." [17]

A concern: self-reported data.
Bigger concern: mass manipulation.

The PoCSverse
Fundamentals
35 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Openness

■ Top-10 States ■ 2nd Quintile ■ 3rd Quintile ■ 4th Quintile □ 5th Quintile

Conscientiousness

■ Top-10 States ■ 2nd Quintile ■ 3rd Quintile ■ 4th Quintile □ 5th Quintile

Extraversion

■ Top-10 States ■ 2nd Quintile ■ 3rd Quintile ■ 4th Quintile □ 5th Quintile

Agreeableness

■ Top-10 States ■ 2nd Quintile ■ 3rd Quintile ■ 4th Quintile □ 5th Quintile

Neuroticism

■ Top-10 States ■ 2nd Quintile ■ 3rd Quintile ■ 4th Quintile □ 5th Quintile
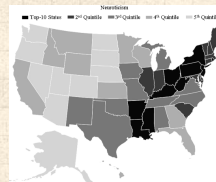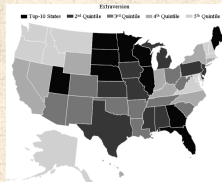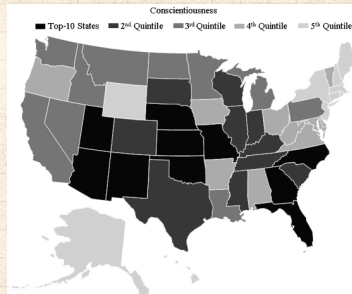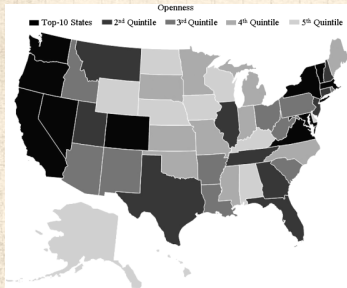
Dungeons & Dragons' full embrace of complexity:

The PoCSverse
Fundamentals
36 of 86

Data

Measurement
- - - - - - - -
Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

From here.

The PoCSverse
Fundamentals
37 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Dungeons & Dragons—Two alignment ⬈ axes for character:

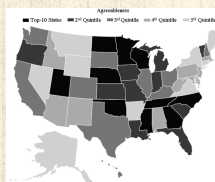| lawful good | lawful neutral | lawful evil |
Kind people are always kind, not just when it's easy.	You expect me to watch you doing that without telling on you?	Call me Craig, and call blackmail a day at the mall with Craig.
neutral good	true neutral	neutral evil
Some things are more connected than others, like tarantulas and me peeing my pants.	I don't believe in diibs, or love at first sight, or love, or best friends, or doing things.	I only entered this to get back at Vicki for not lending me a pencil.
chaotic good	chaotic neutral	chaotic evil
If loving worms is stupid I don't wanna be smart!	We're at the mercy of each other and ourselves.	I'm gonna deep fry your dog and eat your momma's face!

Law–Chaos
(vertical) and

Good–Evil
(horizontal).

---

[3]From this Reddit thread ⬈, where, naturally, the choices are enthusiastically debated.

The PoCSverse
Fundamentals
38 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Please just don't do it. ⊞ ↗

[door slams]

The Office
S7E15: The Search
February 3, 2011

The PoCSverse
Fundamentals
39 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The wisdom of Jason Mendoza ⧉ : ▦ ⧉

The Good Place
S2E04: Team Cockroach
October 5, 2017

Am I really that shallow?

Team Cockroach, S2E04, The Good Place ⧉

The PoCSverse
Fundamentals
40 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The Boggoracle Speaks: 🎞️⬈

THE EMERGENCE
OF STRUCTURE

THE EMERGENCE
OF DESTRUCTION

THE EMERGENCE
OF THINKING

It was the
best of times,

it e a of
i t It th s
m w e b t
e s b t

THE EMERGENCE
OF STORIES

Emergence:

The PoCSverse
Fundamentals
45 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References
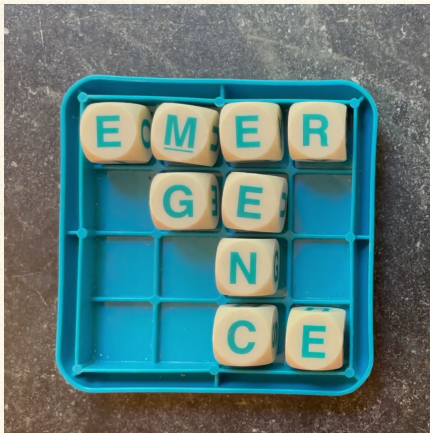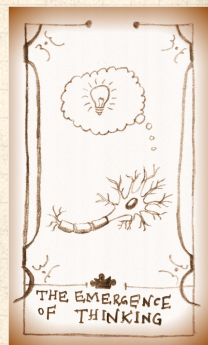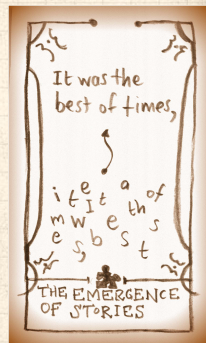
The Wikipedia on Emergence (2006):

"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."

Wikipedia, 2016:

In philosophy, systems theory, science, and art, emergence is a process whereby larger entities arise through interactions among smaller or simpler entities such that the larger entities exhibit properties the smaller/simpler entities do not exhibit.

The philosopher G. H. Lewes [13] is thought to have first described emergence in 1875.

The PoCSverse
Fundamentals
46 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Fireflies $\Rightarrow$ Synchronized Flashes: ⊞ ⬀

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

The PoCSverse
Fundamentals
47 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Emergence:

There's no tornado in a water molecule,
no financial collapse in a dollar bill,
no Dungeon Crawler Carl in the letters of the alhabet,
no love in a carbon atom.

Examples:

- Fundamental particles $\Rightarrow$ Life, the Universe, and Everything
- Genes $\Rightarrow$ Organisms
- Neurons etc. $\Rightarrow$ Brain $\Rightarrow$ Thoughts
- People $\Rightarrow$ Language, and rules of language
- People $\Rightarrow$ Religion, Society, Collective behavior
- People $\Rightarrow$ Internet
- ? $\Rightarrow$ space [?]
  - ? $\Rightarrow$ gravity
  - ? $\Rightarrow$ time [15, 2, 1]
  - ? $\Rightarrow$ reality

Emergence:

The PoCSverse
Fundamentals
48 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

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. [8]
- Decentralized structures help solve problems.
- Dewey Decimal System versus tagging.

Emergence:

The PoCSverse
Fundamentals
49 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

James Coleman ⬚ in *Foundations of Social Theory*:

Societal level

Protestant
Religious
Doctrine ....*Weber*........➤ Capitalism

Individual level

Values ——*Coleman*——➤ Economic
Behavior
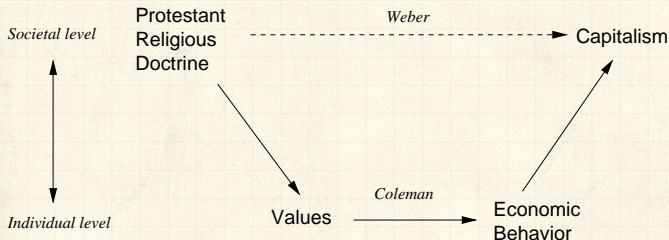
- Understand macrophenomena arises from microbehavior which in turn depends on macrophenomena. [6]
- More on Coleman here ⬚.

Emergence:

The PoCSverse
Fundamentals
50 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Thomas Schelling ⧉ (Economist/Nobelist):

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

▦ "Micromotives and Macrobehavior" [20]

⬢ Segregation [18, 21]
⬢ Wearing hockey helmets [19]
⬢ Seating choices
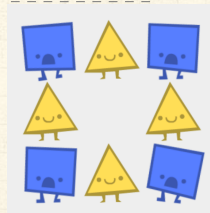
The emergence of taste:

The PoCSverse
Fundamentals
51 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

- Molecules $\Rightarrow$ Ingredients $\Rightarrow$ Taste
- See Michael Pollan's article on nutritionism $\boxed{\nearrow}$ in the New York Times, January 28, 2007.

nytimes.com $\boxed{\nearrow}$

Reductionism

The PoCSverse
Fundamentals
52 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

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

The PoCSverse
Fundamentals
53 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

- "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."

Reductionism

The PoCSverse
Fundamentals
54 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

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

The PoCSverse
Fundamentals
55 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

"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).

This is a Collateralized Debt Obligation:

The PoCSverse
Fundamentals
56 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

The PoCSverse
Fundamentals
57 of 86
Data

Measurement

Emergence

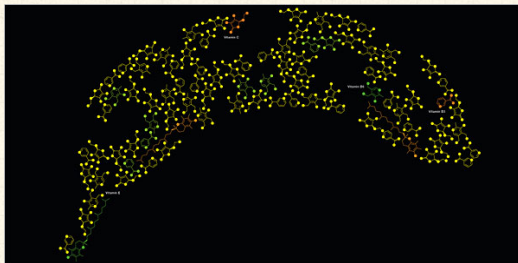Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

"The Universe is made of stories, not of atoms."

The universe is made of stories, not of atoms.

— Muriel Rukeyser (1913 -1980), "The Speed of Darkness"
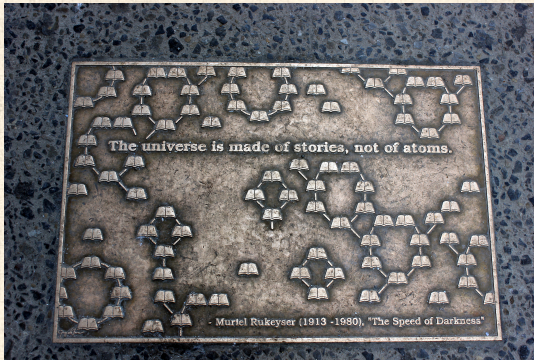
From "The Speed of Darkness" (1968) by Muriel Rukeyser 🔗

Quoted by Metatron in Supernatural, Meta Fiction, S9E18.

(Sir Terry) Pratchett's ⧉ Narrativium ⧉:

The PoCSverse
Fundamentals
58 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References
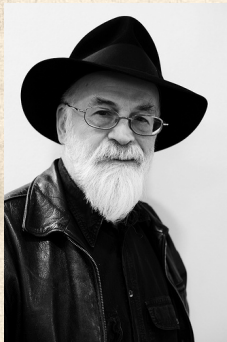
📦 "The most common element on the disc, although not included in the list of the standard five: earth, fire, air, water and surprise. It ensures that everything runs properly as a story."

📦 "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."

The PoCSverse
Fundamentals
59 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Higher complexity:

- 🧱 Many system scales (or levels)
  that interact with each other.

- 🧱 Potentially much harder to explain/understand.

Even mathematics: [9]

Gödel's Theorem 🔗:
we can't prove every
theorem that's true …
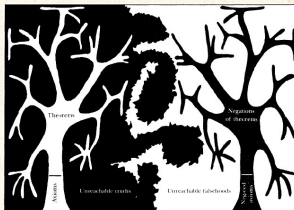
"Gödel, Escher, Bach" [11]

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

Emergence:

The PoCSverse
Fundamentals
60 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

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.

Emergence:

The PoCSverse
Fundamentals
61 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

- Reductionist techniques can explain weak emergence.
- Magic explains strong emergence. [4]
- But: maybe magic should be interpreted as an inscrutable yet real mechanism that cannot ever be simply described.
- Gulp.

THE UNKNOWN MECHANISM

?

The PoCSverse
Fundamentals
63 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Listen to Steve Strogatz, Hod Lipson, and Michael Schmidt (Cornell) in the last piece on Radiolab's show 'Limits' ⧉ (April 5, 2010). Starts at 50:30.

(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
VCSC's increasingly ancient 2011 TEDx event "Big Data, Big Stories." ⧉

Definitions

The PoCSverse
Fundamentals
64 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

"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, ...

Fundamental question: how likely is 'complexification'?

The PoCSverse
Fundamentals
65 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

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

A whimsical-powerful example of real science:

The PoCSverse
Fundamentals
66 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

"How Cats Lap: Water Uptake by *Felis catus*" 🔗
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.

Liquid sticks to smooth tip.

A single lap is about ³⁄₁₀₀ tsp.

Source: Science

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

Amusing interview here 🔗

The PoCSverse
Fundamentals
67 of 86

Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

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 allometry 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 MECHANICS STATISTICAL

THE SUN · "THE GOLDEN EGG" OF REDISTRIBUTION · THE MANIFESTO · MALL OF SOULS · "THE LAMP OF SPREADING FIRES" · THE DISPOSITES OF INTERNMENT · BEAUTY OF RANDOM WALKS · THE RICH GET RICHER · "THE BREATH OF WANDERING" · THE ELM OF WINTER'S START · THE DOORWAY OF THE SPINE

· THE LIGHTING OF THE MIND · "THE MANY FACES" OF BERRY FELD · THE MESSENGER · THE DATA FIELD · THE PRIMING DATA · THE COURAGE OF BRAVE MANOEUVRES · THE DEAD END OF RELATION · THE BLIND SPOT OF WISDOM · THE WHIRLWIND OF STRUGGLE · THE ASYMMETRY OF OUTCOMES · THE OVERSIGHT OF OVERSIGHT

· IT ALL THE FLOW OF TRUTH · THE ROUGHNESS OF POWER · THE NETWORK COMPLEX · THE ELEMENTS OF WIRING · THE KINGS OF A FEATHER · THE KINGS OF A FEATHER · THE SELECTION OF RANDOM OUTCOMES · THE MASTERHOOD OF WISDOM · THE SMALLEST OF WORLDS · THE TRAGEDY OF SIX DEGREES

· THE HOLLOWED FIRE OF SCALE · CLASHED PRIORITY ACCORDS · THE SCIENCE OF CONTAGION · THE SPREAD OF RANDOM WISDOM · THE UNIVERSAL EXPERIENCE · THE THRESHOLD OF THE MINDS · THE SOCIAL WILDS · THE SOCIAL CONTAGION · THE BATH OF RISK · THE ENGINE OF FAME · THE TALE OF FAME

· THE SPOKES UNTANGLING · THE THIN VEIL · THE MEDIATOR'S PARADOX · THE STORYTELLERS · THE INVERSE · THE SIGNS OF UNIVERSALITY · THE PRESIDENT · THE MECHANICS OF RESONANCE · THE UNKNOWN MECHANICS · THE LANGUAGE OF SOCIAL PATHS · THE NETWORK OF BLOOD

· THE TREES OF REALITY · THE HUMBLE DREAMS · THE TREE OF BRANCHES · THE OUTLINE ROOTS WANDERING · THE SPIRIT · THE LINE OF OPTIMAL PLACE · THE FAMINE OF QUARTERLIES · THE CROSSFIRE · THE FAMILY OF FRACTALS · THE MERIDIAN OF MOUNTAINS

· THE HOLDING · THE AWRY MINDFIELD · THE LABOR OF COMMONS AND · FREEDOM ART OF OPTIMIZATION · THE TRADERS WORLDS · THE STURGEON OF DESTINY · THE DEPTH OF NETWORKING · THE SCATTER OF STARS · THE LORDS OF PERCOLATION

The PoCSverse
Fundamentals
70 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

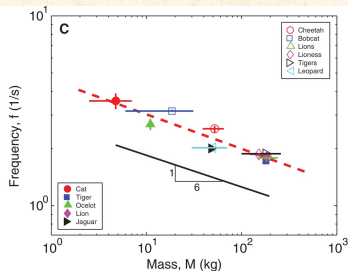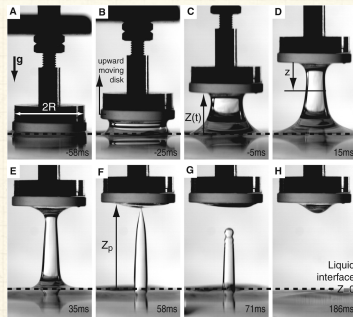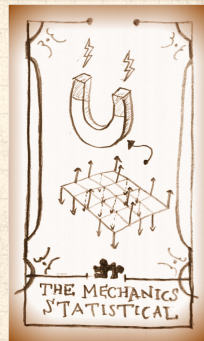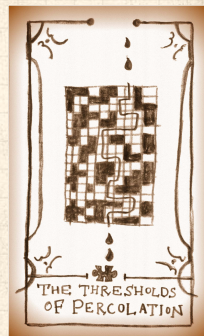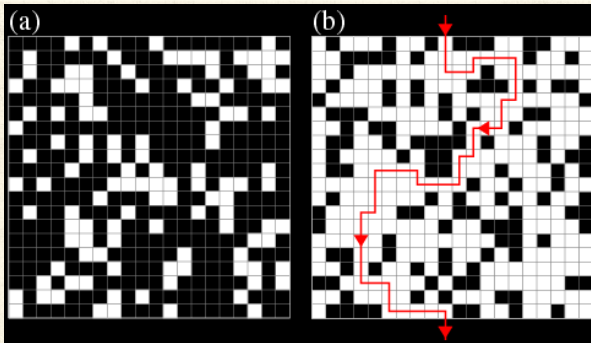- Statistical Mechanics is "a science of collective behavior."

- Simple rules give rise to collective phenomena.

Percolation:

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

The PoCSverse
Fundamentals
71 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

The Ising Model ⬀ of a ferromagnet:

- Each atom is assumed to have a local spin that can be up or down: $S_i = \pm 1$.
- Spins are assumed 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.
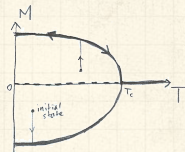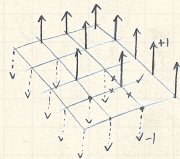
Example 2-d Ising model simulation:

https://mattbierbaum.github.io/ising.js/ ⬀

Phase diagrams

The PoCSverse
Fundamentals
72 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

Qualitatively distinct macro states.

Phase diagrams

The PoCSverse
Fundamentals
73 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Oscillons, bacteria, traffic, snowflakes, ...
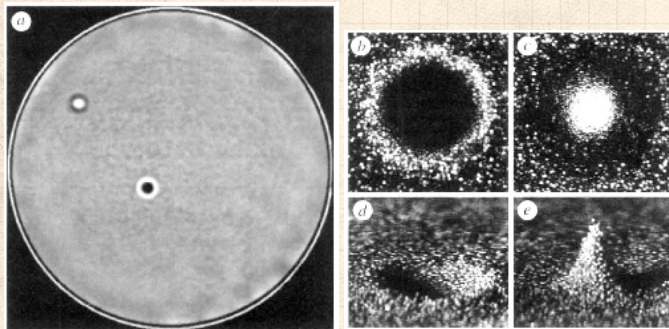
Umbanhowar et al., *Nature*, 1996 [24]

Phase diagrams

The PoCSverse
Fundamentals
74 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics
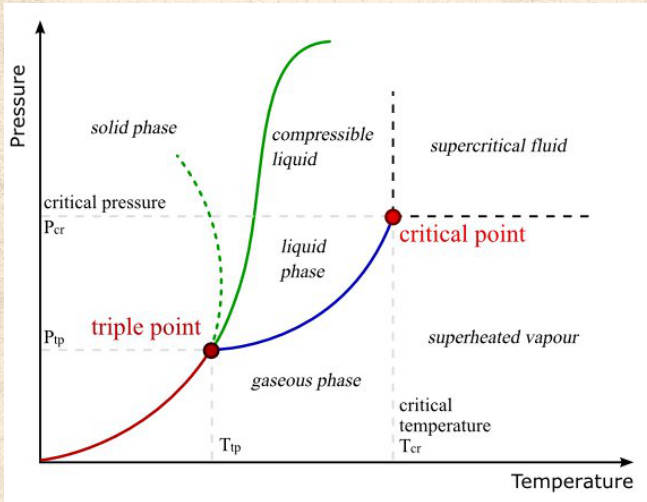
Nutshell
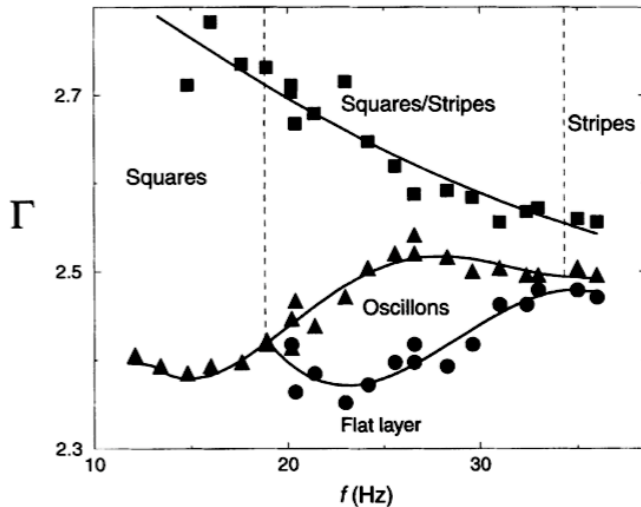
References

Phase diagrams

The PoCSverse
Fundamentals
75 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell
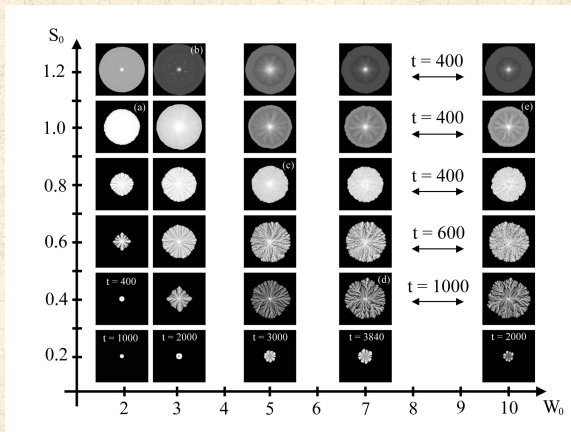
References

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

Ising model

The PoCSverse
Fundamentals
76 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

Analytic issues:

- 1-d: simple (Ising & Lenz, 1925)

- 2-d: hard (Onsager, 1944)

- 3-d: extremely hard...

- 4-d and up: simple.

- See lower and upper critical dimension ⬈ in statistical physics.

- Also: Curse and Blessing of Dimensionality ⬈

Statistics

The PoCSverse
Fundamentals
77 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

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" [3]

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.

Nutshell

The PoCSverse
Fundamentals
78 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

- Complex systems are everywhere.

- The central concepts Complexity and Emergence are reasonably well defined.

- There is no single unified general theory of Complex Systems but there are big stories that cover giant spaces (fluids, rich-get-richer).

- 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. [7]

- We use whatever tools we need.

- Science $\simeq$ Describe + Explain.

References I

The PoCSverse
Fundamentals
79 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

[1] A. Albrecht.
     The clock ambiguity: Implications and new developments.
     arXiv preprint, 2008.

[2] A. Albrecht and A. Iglesias.
     The clock ambiguity and the emergence of physical laws.
     Physical Review D, 77(6):063506, 2008.

[3] P. Ball.
     Critical Mass: How One Thing Leads to Another.
     Farra, Straus, and Giroux, New York, 2004.

[4] 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

References II

The PoCSverse
Fundamentals
80 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

[5] H. Chang.
     Inventing temperature: Measurement and scientific progress.
     Oxford University Press, 2004.

[6] J. S. Coleman.
     Foundations of Social Theory.
     Belknap Press, Cambridge, MA, 1994.

[7] P. S. Dodds.
     The three books of science, 2025. pdf🡕

[8] 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🡕

References III

The PoCSverse
Fundamentals
81 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

[9]   R. Foote.
      Mathematics and complex systems.
      Science, 318:410–412, 2007. pdf ☑

[10] A. Halevy, P. Norvig, and F. Pereira.
      The unreasonable effectiveness of data.
      IEEE Intelligent Systems, 24:8–12, 2009. pdf ☑

[11] D. R. Hofstadter.
      Gödel, Escher, Bach.
      Vintage Books, New York, 1980.

[12] A. R. Jensen.
      Bias in mental testing.
      ERIC, 1980.

The PoCSverse
Fundamentals
82 of 86
Data

Measurement

Emergence

Self-Organization

Modeling

Statistical Mechanics

Nutshell

References

References IV

[13] G. H. Lewes.
Problems of Life and Mind, Vol. II: The Physical Basis of
Mind.
Trübner and Co., London, 1875.
See Chapter V, "The Nature of Emergent Effects".

[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

The PoCSverse
Fundamentals
83 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

References V

[15] D. N. Page and W. K. Wootters.
Evolution without evolution: Dynamics described by
stationary observables.
Physical Review D, 27(12):2885–2892, 1983.

[16] E. A. Pechenick, C. M. Danforth, and P. S. Dodds.
Characterizing the Google Books corpus: Strong limits to
inferences of socio-cultural and linguistic evolution.
PLoS ONE, 10:e0137041, 2015. pdf ⬀

[17] P. J. Rentfrow, S. D. Gosling, and J. Potter.
A theory of the emergence, persistence, and expression of
geographic variation in psychological characteristics.
Perspectives on Psychological Science, 3:339–369, 2008.
pdf ⬀

The PoCSverse
Fundamentals
84 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

References VI

[18] T. C. Schelling.
Dynamic models of segregation.
J. Math. Sociol., 1:143–186, 1971. pdf 🔗

[19] 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 🔗

[20] T. C. Schelling.
Micromotives and Macrobehavior.
Norton, New York, 1978.

[21] 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 🔗

The PoCSverse
Fundamentals
85 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

References VII

[22] D. Sobel.
Longitude: The True Story of a Lone Genius Who Solved the
Greatest Scientific Problem of His Time.
Bloomsbury Publishing, US, 2007.

[23] P. Turchin, T. E. Currie, H. Whitehouse, P. François,
K. Feeney, D. Mullins, D. Hoyer, C. Collins, S. Grohmann,
P. Savage, et al.
Quantitative historical analysis uncovers a single dimension
of complexity that structures global variation in human social
organization.
Proceedings of the National Academy of Sciences,
115:E144–E151, 2018. pdf

[24] P. B. Umbanhowar, F. Melo, and H. L. Swinney.
Localized excitations in a vertically vibrated granular layer.
Nature, 382:793–6, 1996. pdf

References VIII

The PoCSverse
Fundamentals
86 of 86
Data
Measurement
Emergence
Self-Organization
Modeling
Statistical Mechanics
Nutshell
References

[25] E. Wigner.
The unreasonable effectivenss of mathematics in the natural sciences.
Communications on Pure and Applied Mathematics, 13:1–14, 1960. pdf ⬀