lecture 13: complex systems under limits

evaluation

- Participation: 20%.
  - class discussion, everybody reads and discusses every paper
  - engagement in class
- Paper Presentation and Discussion: 20%
  - **SSIE501** students are assigned to papers individually or as group lead presenters and discussants
    - all students are supposed to read and participate in discussion of every paper.
  - Presenter prepares short summary of assigned paper (15 minutes)
    - no formal presentations or PowerPoint unless figures are indispensable.
  - Summary should:
    - 1) Identify the key goals of the paper (not go in detail over every section)
    - 2) What discussant liked and did not like
    - 3) What authors achieved and did not
    - 4) Any other relevant connections to other class readings and beyond.
  - **ISE440** students chose one of the presented papers to participate as lead discussant
    - not to present the paper, but to comment on points 2-3) above
  - Class discussion is opened to all
    - lead discussant ensures we important paper contributions and failures are addressed
- Black Box: 60%
  - Group Project (2 parts)
    - Assignment I (25%) and Assignment II (35%)

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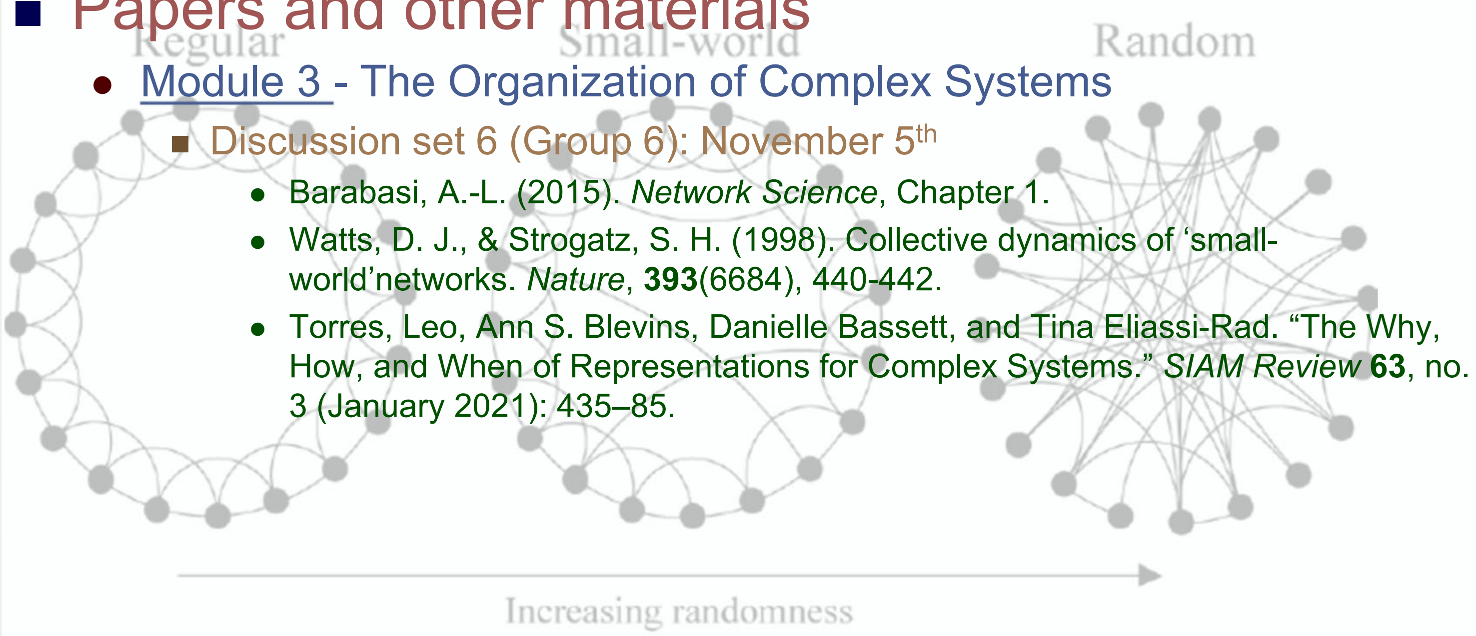
readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 3 - The Organization of Complex Systems
    - Discussion set 6 (Group 6): November 5th
      - Barabasi, A.-L. (2015). *Network Science*, Chapter 1.
      - Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world'networks. *Nature*, **393**(6684), 440-442.
      - Torres, Leo, Ann S. Blevins, Danielle Bassett, and Tina Eliassi-Rad. "The Why, How, and When of Representations for Complex Systems." *SIAM Review* **63**, no. 3 (January 2021): 435–85.



readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 3 - The Organization of Complex Systems
    - Discussion set 7 (Group 1): November 7th
      - Ashby, W. Ross. “Principles of the Self-Organizing System.” In *Principles of Self-Organization*: Transactions of the University of Illinois Symposium, edited by H. Von Foerster and G. W. Zopf, Jr., 255–78. London: Pergamon Press, 1962.
      - Kauffman, Stuart A. “Emergent Properties in Random Complex Automata.” Physica D: Nonlinear Phenomena 10, no. 1–2 (January 1984): 145–56.
        - Optional: Kauffman, S.A. “Metabolic Stability and Epigenesis in Randomly Constructed Genetic Nets.” Journal of Theoretical Biology 22, no. 3 (March 1969): 437–67.
    - Discussion Set 8 – Part I (Group 2): November 7th
      - Prigogine, I. “New Perspectives on Complexity.” In *The Science and Praxis of Complexity*, 107–18. United Nations University Press, 1985.
        - Optional: Rocha, L M. “Selected Self-Organization and the Semiotics of Evolutionary Systems.” In *Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-Organization*, edited by S Salthe, G VandeVijver, and M Delpos, 341–58.Kluwer Academic Publishers., 1998

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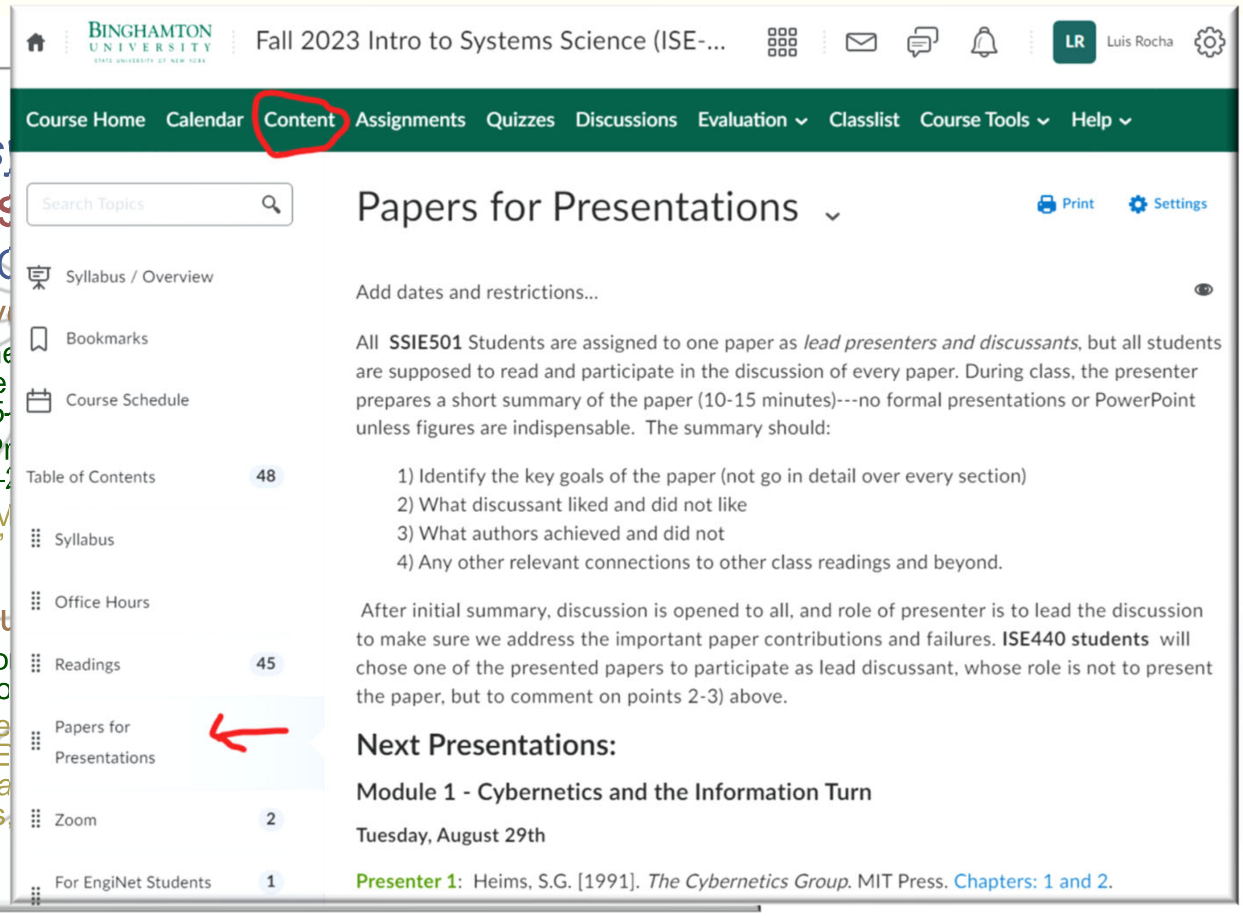
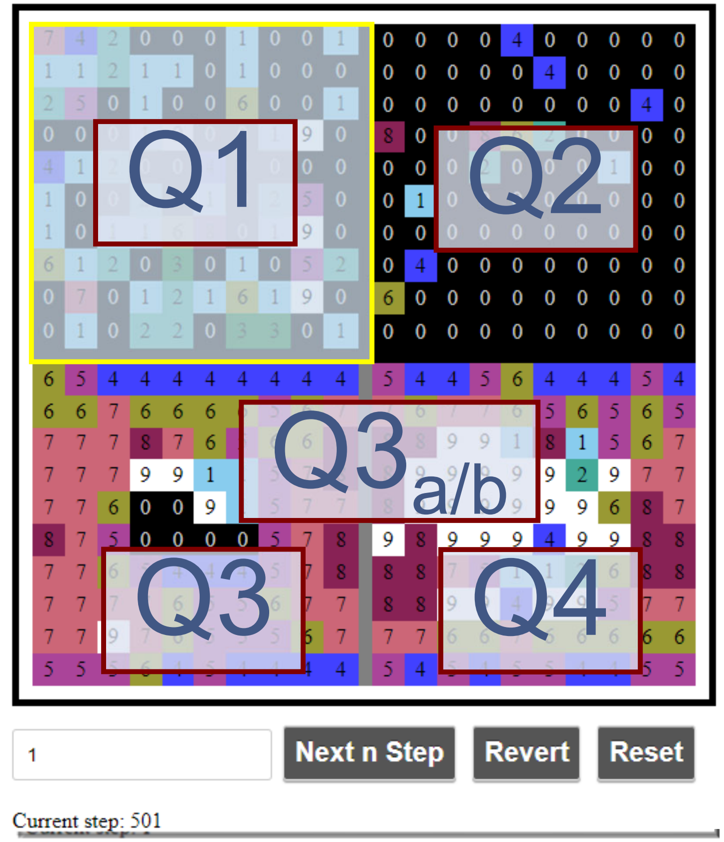


The Black Box II: Due: **November 22nd, 2024**

Herbert Simon: Law discovery means only finding **pattern** in the data; whether the pattern will continue to hold for new data that are observed subsequently will be decided in the course of **testing the law**, not discovering it. The **discovery process** runs from particular facts to general laws that are somehow induced from them; the **process of testing** discoveries runs from the laws to predictions of particular facts from them [...] To explain why the patterns we extract from observations frequently lead to correct predictions (when they do) requires us to face again the problem of **induction**, and perhaps to make some hypothesis about the uniformity of nature. But that hypothesis is neither required for, nor relevant to, the theory of discovery processes. […] By separating the question of pattern detection from the question of prediction, we can construct a **true normative theory of discovery**-a logic of discovery.



- Focus on uncovering quadrants
  - using data collection, descriptive patterns & statistics, and induction.
- Propose a formal model or algorithm of what each quadrant is doing.
  - Analyze, using deduction, the behavior of this algorithm.
- Maximum 20 pages!!!
  - 4 per quadrant + 4
  - Supporting information in separate file

What is it!!??

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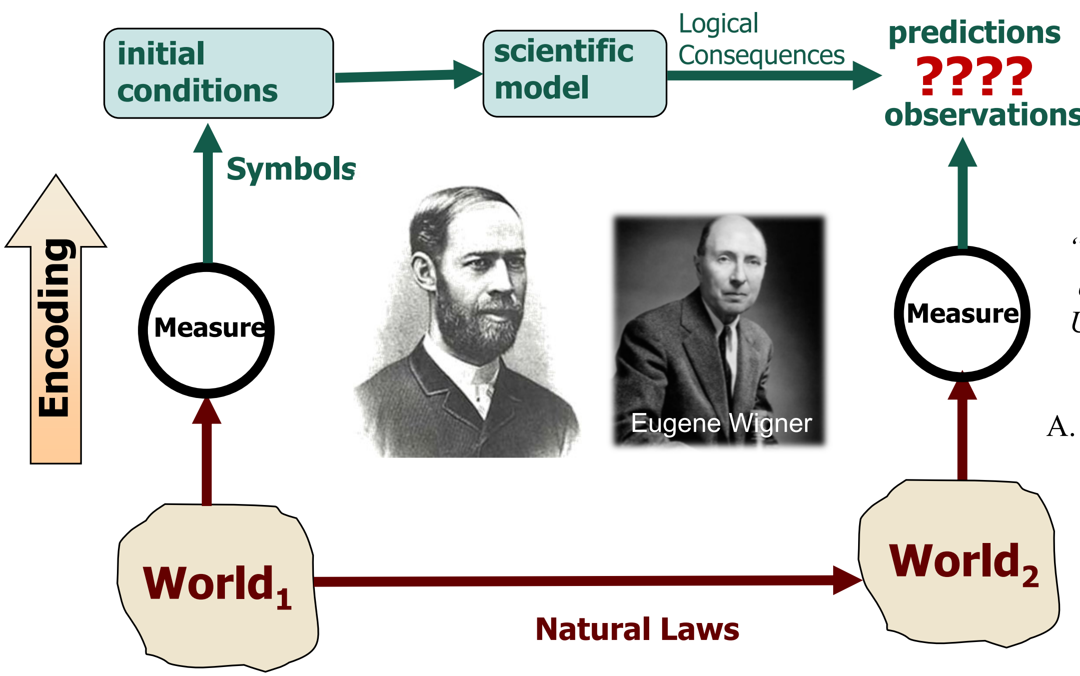
Hertzian scientific modeling paradigm



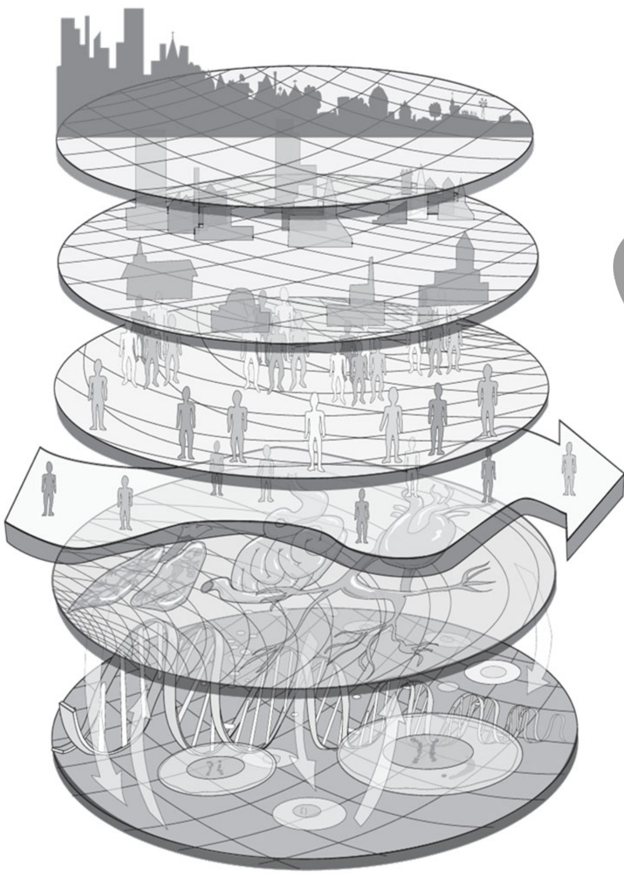
*"**Every empirical law has the disquieting quality that one does not know its limitations**." E. Wigner [1957] in "The Unreasonable Effectiveness of Mathematics in the Natural Sciences"*

A. Rosenblueth and N. Wiener [1945] "The role of models in science." *Philosophy of Science*. **12**(4): 316-321."

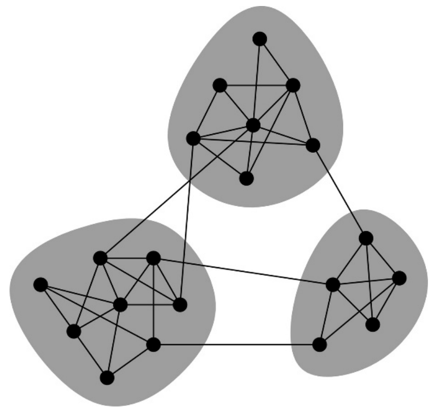
C. Shalizi [2024] "Opening a closed box." In: *Foundational Papers in Complexity Science, D.C.* Krakauer (Ed). pp. 149–169

"The most direct and in a sense the most important problem which our conscious knowledge of nature should enable us to solve is the ***anticipation of future events***, so that we may arrange our present affairs in accordance with such anticipation". (Hertz, 1894)

Good news I: Simon's "architecture of complexity" (near-decomposability)

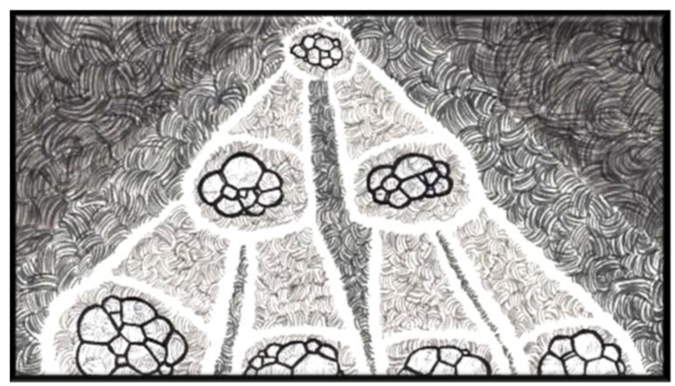


Pescosolido, B.A. 2006. Journal of Health and Social Behavior 47: 189-208.



Newman, M.E.J. (2006). "Modularity and community structure in networks." *PNAS* **103** (23): 8577-8582.

Simon, H.A. [1962]. "The Architecture of Complexity". *Proc. Am. Phil. Soc.*, **106**: pp. 467-482.



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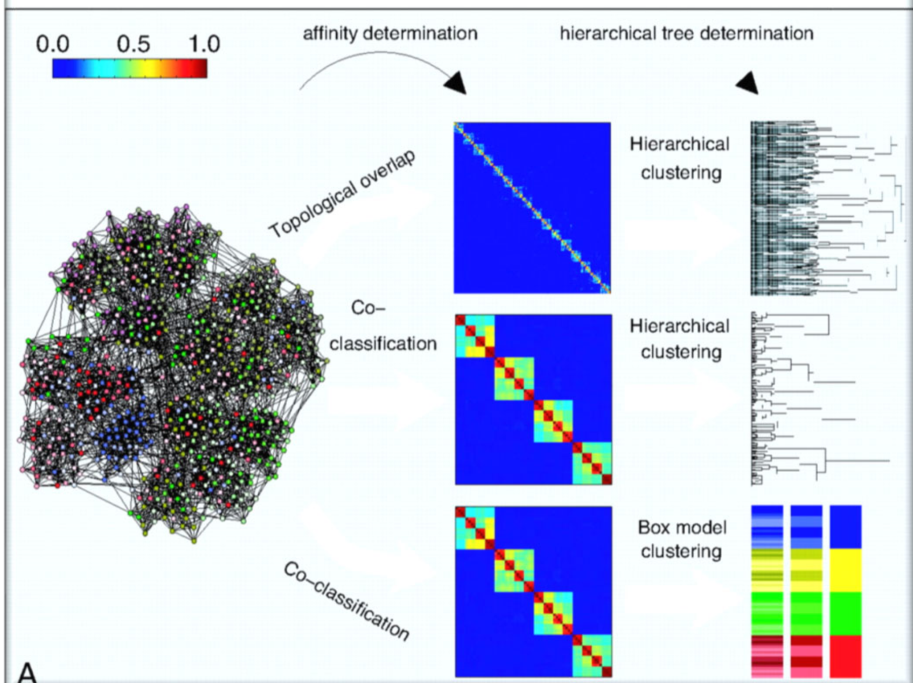

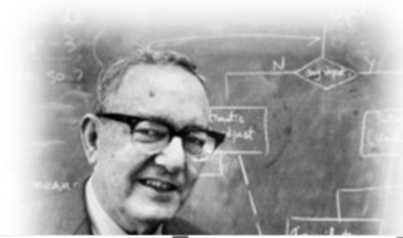

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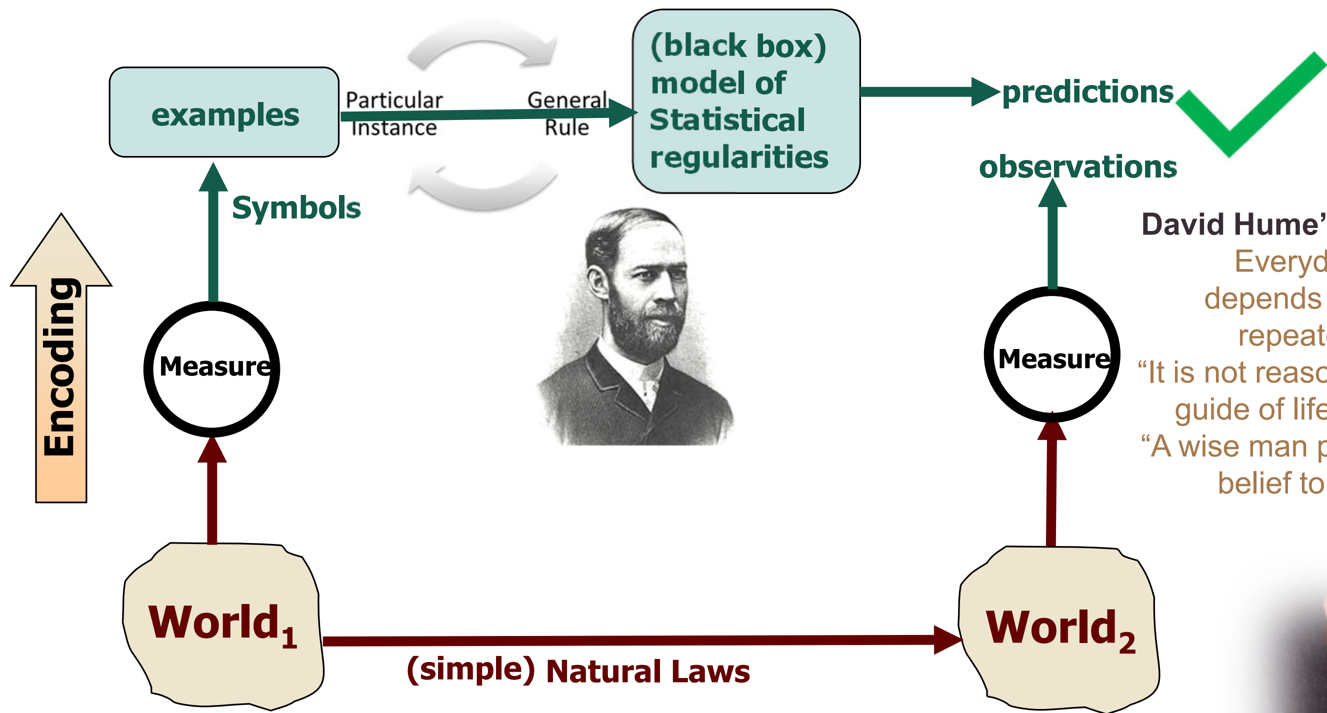
good news II: induction

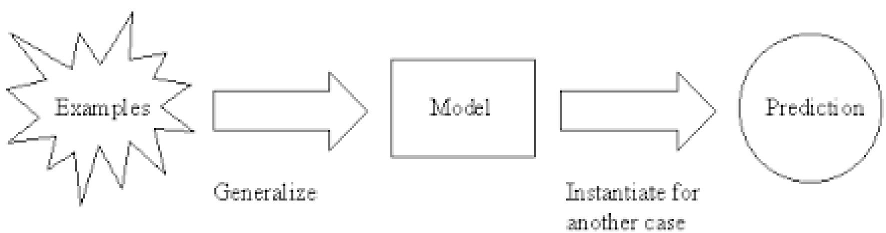


David Hume’s Empiricism

Everyday knowledge depends on patterns of repeated experience

“It is not reason which is the guide of life, but custom.”

“A wise man proportions his belief to the evidence”



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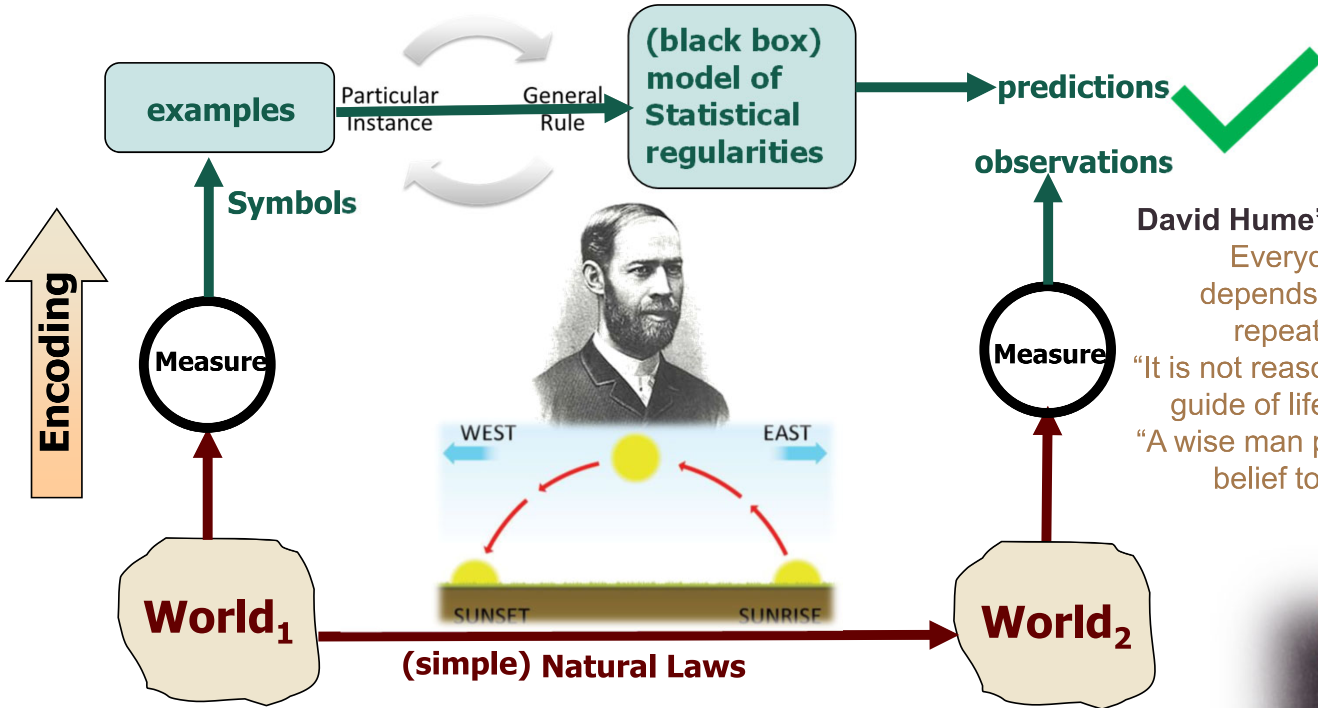

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good news II: induction

examples

Particular Instance → General Rule

(black box) model of Statistical regularities

predictions

observations

Symbols

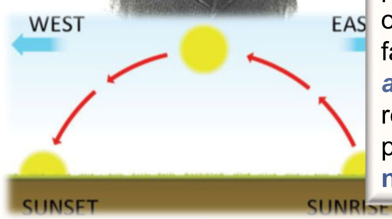
Encoding

Measure

World$_1$

(simple) Natural Laws

World$_2$



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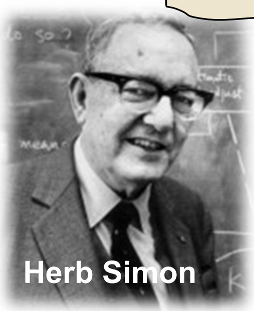

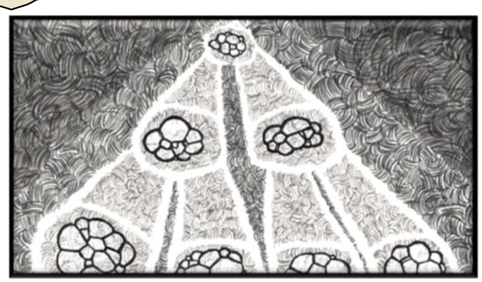

Studying (multilayered, contextual) complexity possible if world is near-decomposable and predictable from past examples

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good news II: induction

examples

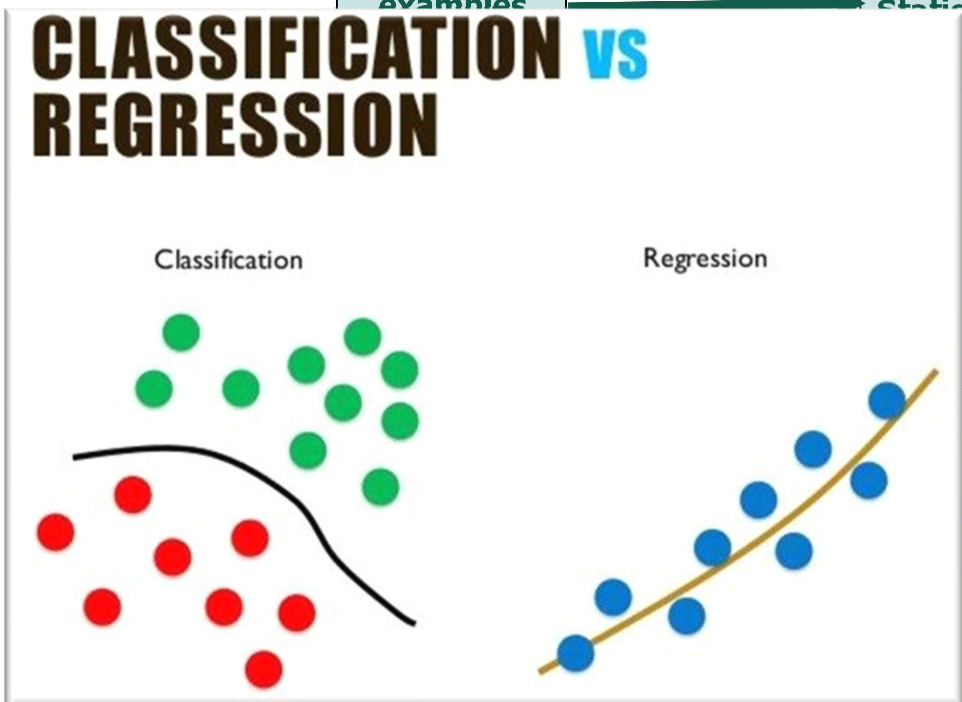
Particular

General

(black box) model of Statistical ...arities

predictions

observations



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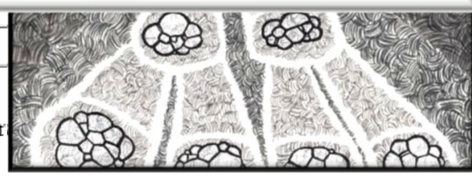
world_2



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are all "models" equally acceptable/useful?

- No!
- William Ockham (c. 1285–1349):
  - "entia non sunt multiplicanda praeter necessitatem"
    - Loosely paraphrased as "make no unnecessary assumptions", or "of two competing theories: simplest is often best"
- Explanatory "power" (cf. discussion on "beauty")
- Generality
  - Example: model of lightning? "Thor gets mad."
- Karl Popper (1902-1994): notion of Falsifiability
  - model/theories/assertions can not be confirmed by any number of empirical tests (Blackbox modeling)
    - but information gained when falsified
      - logical asymmetry between verification and falsification: many observations do not derive (universal) theories, a single observation can falsify it: scientific theories (deduced) from induction are testable.
  - falsifiability hard requirement for scientific models
    - tremendously important in science
- All of these matter in complex systems modeling
  - existing intuitive notions fail in complex systems
  - falsifiability: praxis/logistic problems

Popper (1972) Objective Knowledge

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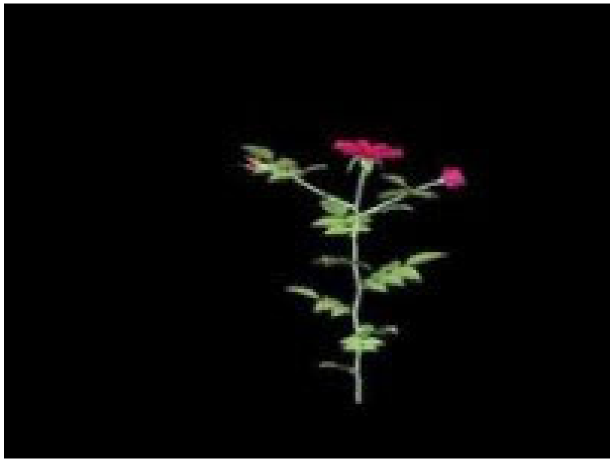
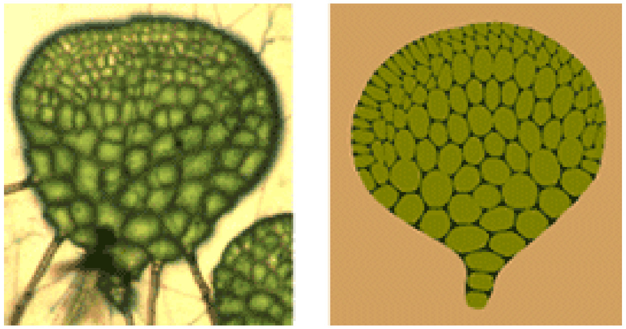
models or realistic imitations?

- Common features (design principle) between artificial and real plants
  - Development of (macro-level) morphology from local (micro-level) logic
  - Parallel application of simple rules
  - Recursion
- But are the algorithms the same as the biological *mechanism*?
  - Real organisms need to economize information for coding complex phenotypes
    - The genome cannot encode every ripple of the brain or lungs
    - Organisms need to encode **compact procedures** for producing the same pattern (with randomness) again and again
- But recursion alone does not explain form and morphogenesis
  - One of the design principles involved
  - There are others
    - Selection, genetic variation, self-organization, epigenetics

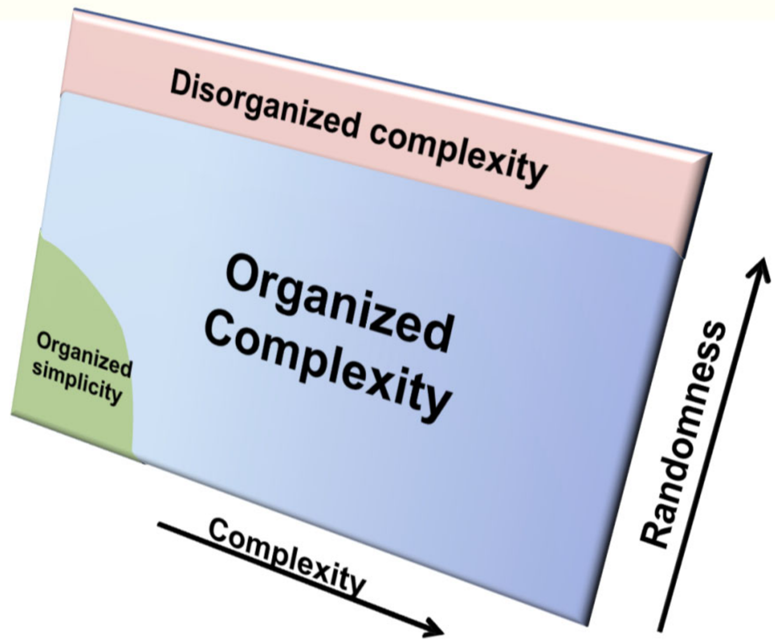




fern gametophyte Microsorium linguaeforme (left) and a simulated model using map L systems (right).

What is it?

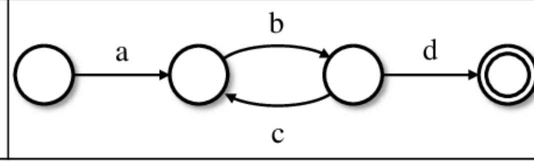
- dictionary
  - Having many varied or interrelated parts, patterns or elements
    - Quantity of parts and extent of interrelations
    - Organizational complexity
- Subjective or epistemic connotation
  - Ability to understand or cope
    - Complexity is in the eyes of the observer
      - Brain to a neuroscientist and to a butcher
  - *Quantity of information* required to describe a system

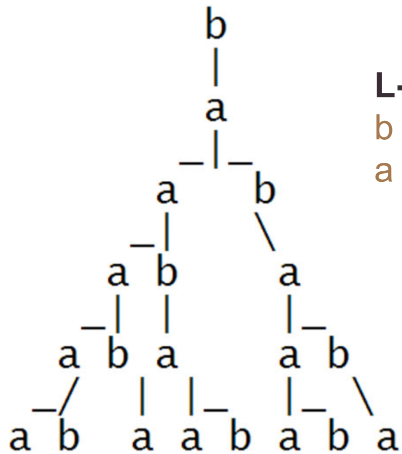


Weaver, W. [1948]. "Science and Complexity". *American Scientist*, **36**(4): 536-44.

descriptive complexity

- Proportional to the amount of *information* required to describe the system
  - In a syntactic way
    - Measure number of entities (variables, states, components) and variety and structure of relationships among them
  - General requirements
    - Nonnegative quantity
    - If system A is a homomorphic image of B, then the complexity of A should not be greater than B
    - If A and B are isomorphic, then their complexity should be the same
    - If system C consists of two non-interacting subsystems B and neither is a homomorphic image of the other, then the complexity of C should be equal to the sum of the complexities of A and B
  - Size of shortest description or program in a standard language or universal computer
    - generative
    - Applicable to any system
    - Difficult to determine shortest description
    - A.K.A. Kolmogorov complexity

Input strings	1. abcbcbcbcbcbd 2. abd 3. abcbcbcbd 4. abcbcbcbcbcbcbcbcbcbcbcbcbd
Regular expression	a(bc)$^{\{0,13\}}$bd more generalized: a(bc)*bd
Automaton	



L-System for Branching

b -> a

a -> ab

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Uncertainty-based complexity

- Proportional to the amount of *information* needed to resolve any uncertainty with the system involved
  - In a syntactic way
    - Related to number of alternatives left undecided to characterize a particular element
  - Examples
    - Hartley Measure
    - Shannon Entropy

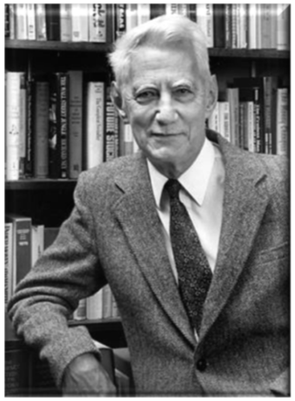
including more structure reduces surprise

information is surprise

$$H(A) = \log_2 |A|$$

Hartley, R.V.L., "Transmission of Information", *Bell System Technical Journal*, July 1928, p.535.

$$H_S(A) = -\sum_{i=1}^{n} p(x_i) \log_2\big(p(x_i)\big)$$



C. E. Shannon [1948], "A mathematical theory of communication". *Bell System Technical Journal*, **27**:379-423 and 623-656

Trade-off between descriptive and uncertainty-based complexity

- When one is reduced, the other is likely to increase
  - Trade certainty for acceptable descriptive complexity
    - Models of phenomena in the realm of organized complexity require large descriptive complexity
    - But to be manageable, we must simplify by accepting larger uncertainty (and smaller descriptive complexity)
- Descriptive and uncertainty-based complexity pertain to systems
  - Characterized by information
- Computational complexity pertains to systems problems
  - Characterization of the time or space (memory) requirements for solving a problem by a particular algorithm
- (epistemic) Complexity-relative-to-a-model (Rosen)
  - When and how a model fails

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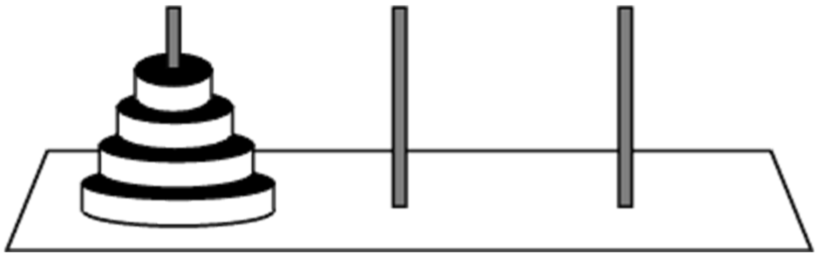
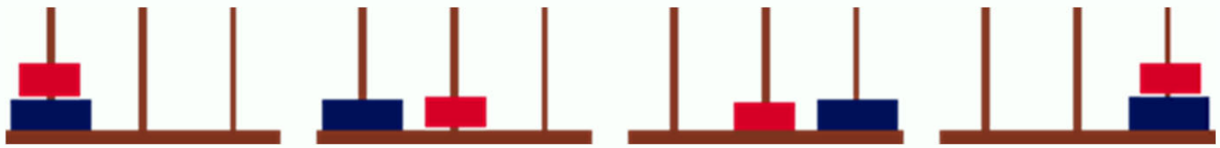
Facing limits

- Invented by French Mathematician Édouard Lucas in 1883
  - *At the Tower of Brahma in India, there are three diamond pegs and sixty-four gold disks. When the temple priests have moved all the disks, one at a time preserving size order, to another peg the world will come to an end.*
    - If the priests can move a disk from one peg to another in one second, how long does the World have to exist?

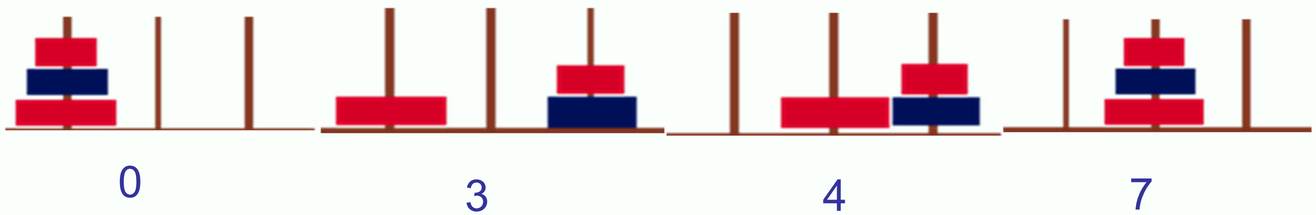


Recursive building blocks

- Solve for the smallest instances and then try to generalize
  - N=2

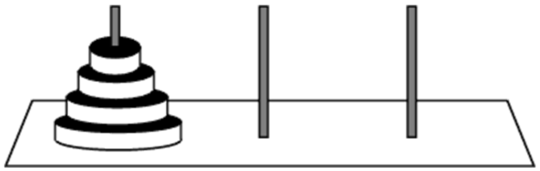


  - N=3



Use Hanoi_2 (H2) as building block (of 3 moves)

H3 uses H2 twice, plus 1 move of the largest disk



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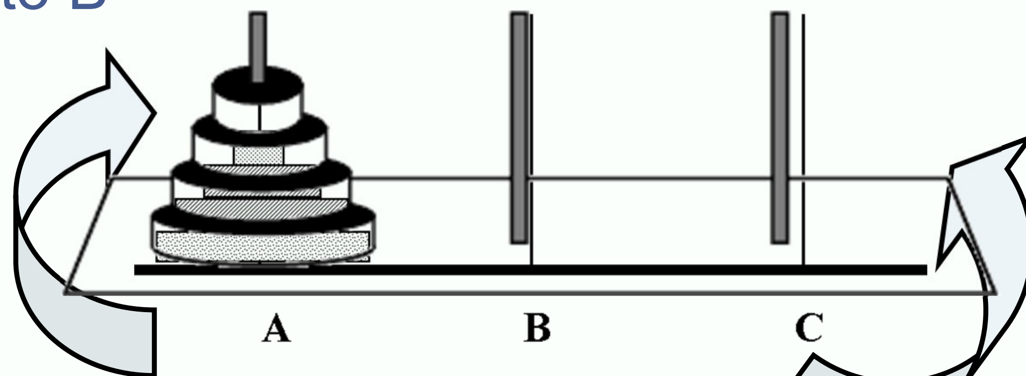
Use Hanoi_2 (H2) as building block (of 3 moves)

H3 uses H2 twice, plus 1 move of the largest disk

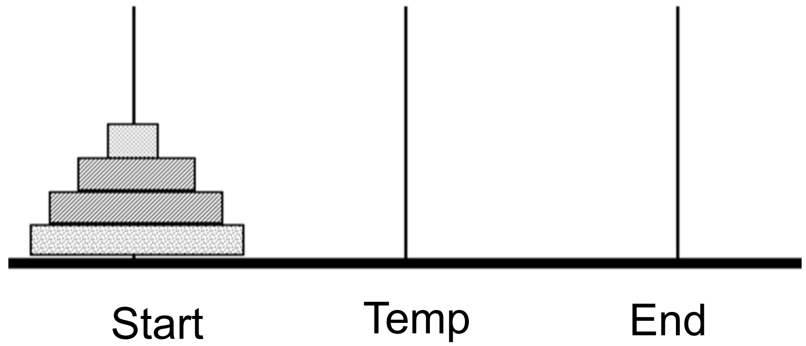
- Algorithm to move n disks from A to C
  - Move top n-1 disks from A to B
  - Move biggest disk to C
  - Move n-1 disks on B to C
- Recursion
  - Until H2

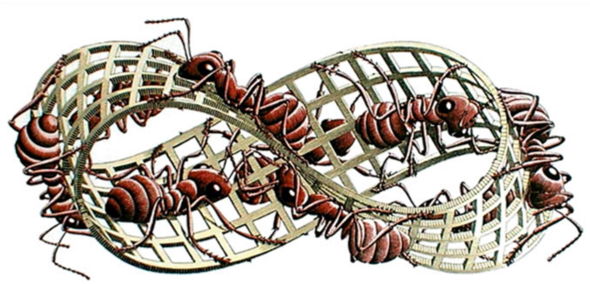


Towers of Hanoi

An Algorithm that uses itself to solve a problem

- Hanoi (*Start*, *Temp*, *End*, n)
  - If n = 1 then
    - Move *Start*'s top disk to *End*
  - Else
    - Hanoi (*Start*, *End*, *Temp*, n-1)
    - Move *Start*'s top disk to *End*
    - Hanoi (*Temp*, *Start*, *End*, n-1)





Prefix		Base
Name	Symbol	10
quetta	Q	10^{30}
ronna	R	10^{27}
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}

"FLOPS"

(FLoating Point Operations Per Second)

585 billion years in seconds!!!!!!!!

Earth: 5 billion years

Universe: 15 billion years

Fastest Computer: 1.68 exaFLOPS a second ($\approx 2^{60.54}$), $2^{64} / 2^{60.54}$,needs ≈ 11 seconds!

- Resources required during computation of an algorithm to solve a given problem
  - Time
    - how many steps does it take to solve a problem?
  - Space
    - how much memory does it take to solve a problem?
- The Hanoi Towers Problem
  - $f(n)$ is the number of times the HANOI algorithm moves a disk for a problem of n disks
    - $f(1)=1, f(2)=3, f(3)=7$
    - $f(n)= f(n\text{-}1) + 1 + f(n\text{-}1) = 2 \times f(n\text{-}1) + 1$
  - Every time we add a disk, the time to compute is at least double
    - $f(n) = 2^n - 1$

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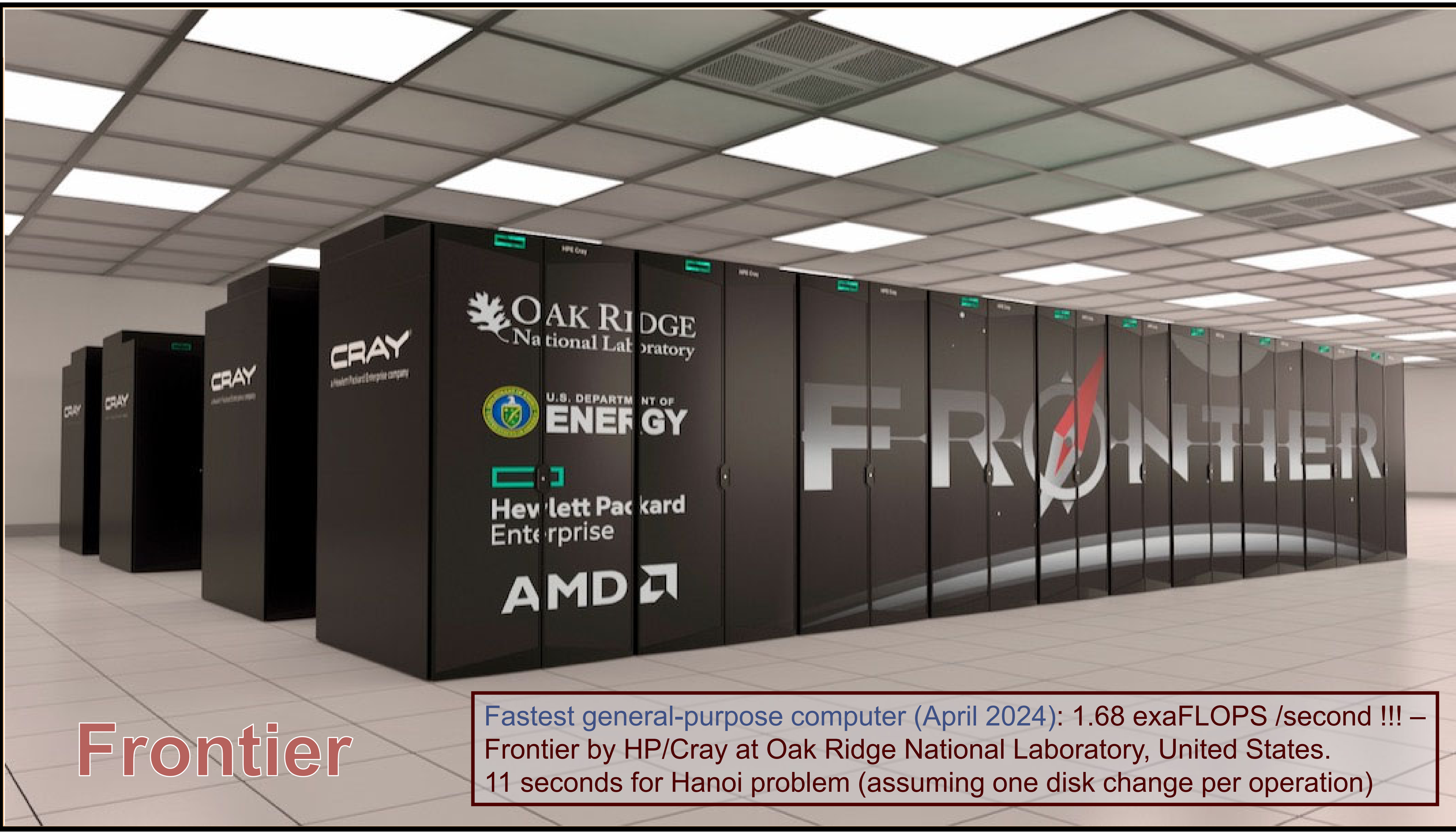
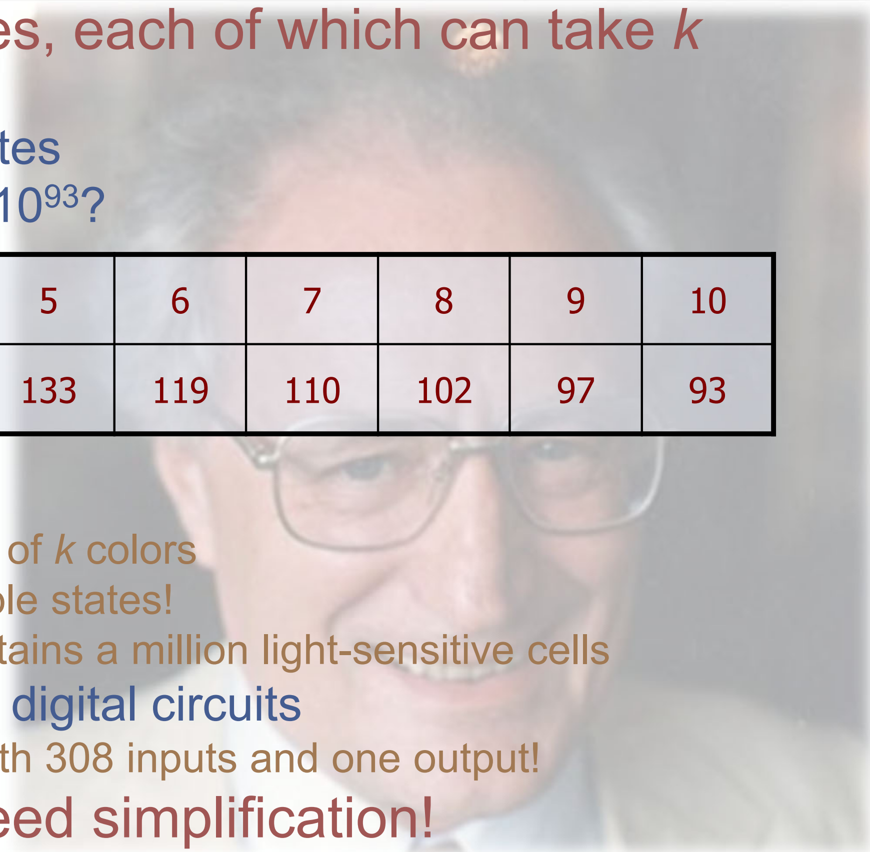


Frontier

Fastest general-purpose computer (April 2024): 1.68 exaFLOPS /second !!! –
Frontier by HP/Cray at Oak Ridge National Laboratory, United States.
11 seconds for Hanoi problem (assuming one disk change per operation)

- Physical Limit of Computation
  - Hans Bremmermann in 1962
  - "no data processing system, whether artificial or living, can process more than 2×10^{47} bits per second per gram of its mass."
    - Based on the idea that information could be stored in the energy levels of matter
    - Calculated using Heisenberg's uncertainty principle, the Hartley measure, Planck's constant, and Einstein's famous $E = mc^2$ formula
  - A computer with the mass of the entire Earth and a time period equal to the estimated age of the Earth
    - **would not be able to process more than about $\boxed{10^{93}\text{ bits}}$**
  - ***transcomputational problems***

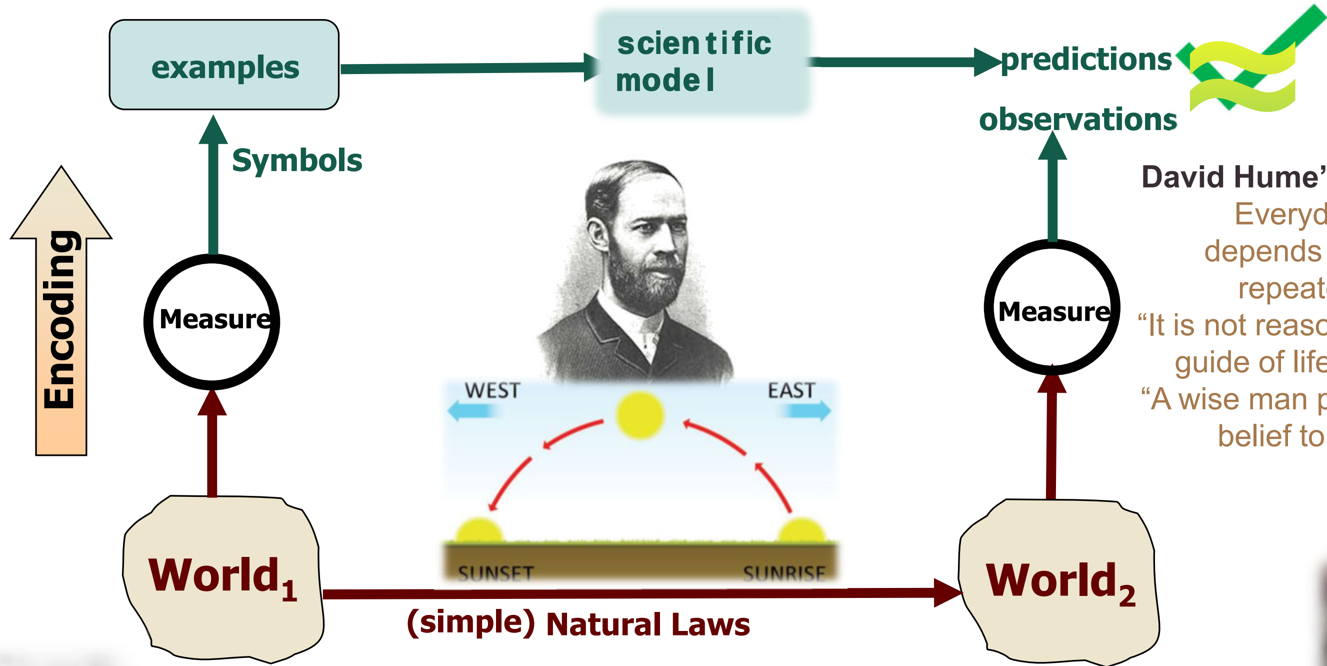


- A system of n variables, each of which can take k different states
  - k^n possible system states
  - When is it larger than 10^{93}?

k	2	3	4	5	6	7	8	9	10
n	308	194	154	133	119	110	102	97	93

  - Pattern Recognition
    - Grid of $n = q^2$ squares of k colors
    - *Blackbox*: 10^{100} possible states!
    - The human retina contains a million light-sensitive cells
  - Large scale integrated digital circuits
    - K= 2 (bits): a circuit with 308 inputs and one output!
- Complex Problems need simplification!

Bad news I: computational limits



David Hume's Empiricism

Everyday knowledge depends on patterns of repeated experience

"It is not reason which is the guide of life, but custom."

"A wise man proportions his belief to the evidence"

Hans Bremmermann

Model complexity

We must simplify computational models

Tradeoff descriptive and uncertainty-based complexity

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readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 3 - The Organization of Complex Systems
    - Discussion set 6 (Group 6): November 5th
      - Barabasi, A.-L. (2015). *Network Science*, Chapter 1.
      - Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world'networks. *Nature*, **393**(6684), 440-442.
      - Torres, Leo, Ann S. Blevins, Danielle Bassett, and Tina Eliassi-Rad. "The Why, How, and When of Representations for Complex Systems." *SIAM Review* **63**, no. 3 (January 2021): 435–85.