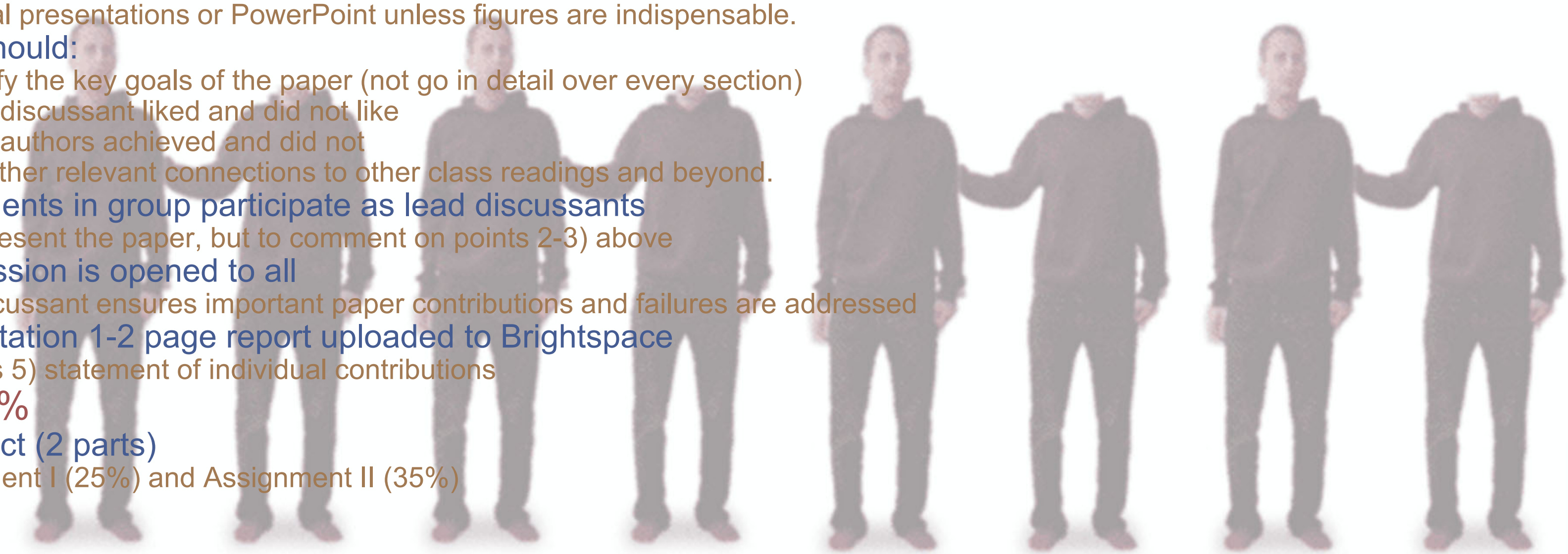
lecture 14:

Complexity and Computational limits

evaluation

- Participation: 20%.
  - class discussion, everybody reads and discusses every paper
  - engagement in class, including online
- Paper Presentation and Discussion: 20%
  - All students are assigned to a Reading and Discussion Group
  - **SSIE501** students in group present and discuss papers
    - all students are supposed to read and participate in discussion of every paper.
    - *section 01 groups* present in class, *section 20 groups* present via zoom or send a video
  - Presenter group 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 in group participate as lead discussants
    - not to present the paper, but to comment on points 2-3) above
  - Class discussion is opened to all
    - lead discussant ensures important paper contributions and failures are addressed
  - Post presentation 1-2 page report uploaded to Brightspace
    - 1-4) plus 5) statement of individual contributions
- Black Box: 60%
  - Group Project (2 parts)
    - Assignment I (25%) and Assignment II (35%)



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next readings (check brightspace)

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
  - *section 01* presents in class, *section 20* (Enginet) posts videos on Brightspace (exceptions possible)
- Tuesday November 7th
  - Module 3: The Organization of Complex Systems
    - Reading and Discussion Group 3 (Enginet)
      - Kolchinsky, Artemy, and David H. Wolpert. “Semantic Information, Autonomous Agency and Non-Equilibrium Statistical Physics.” *Interface Focus* **8**, no. 6 (December 6, 2018): 20180041.
      - Scheffer, Marten, et al. "Early-warning signals for critical transitions." *Nature* **461**.7260 (2009): 53. (Left from April 2)
        - Optional: Leemput, Ingrid A van de, Marieke Wichers, Angélique O J Cramer, Denny Borsboom, Francis Tuerlinckx, Peter Kuppens, Egbert H van Nes, et al. "Critical Slowing down as Early Warning for the Onset and Termination of Depression." *Proceedings of the National Academy of Sciences* **111**, no. 1 (January 2014): 87–92.
        - Optional: Xu, Li, Denis Patterson, Simon Asher Levin, and Jin Wang. “Non-Equilibrium Early-Warning Signals for Critical Transitions in Ecological Systems.” *Proceedings of the National Academy of Sciences* **120**, no. 5 (January 31, 2023): e2218663120.
- Future Modules
  - See brightspace

more upcoming readings (check brightspace)

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
  - *section 01* presents in class, *section 20* (Enginet) posts videos on Brightspace (exceptions possible)
- Module 4 – Multi-level complexity
  - November 14th
    - Reading and Discussion Group 4
      - Pattee, Howard H. "The Physical Basis and Origin of Hierarchical Control." In *Hierarchy Theory: The Challenge of Complex Systems*, edited by Howard H. Pattee, 73–108. New York: Brazillier, 1973.
      - Rosen, Robert. "On Complex Systems." *European Journal of Operational Research* **30**, no. 2 (June 1987): 129–34.
      - Lazebnik, Y [2002]. "Can a biologist fix a radio?--Or, what I learned while studying apoptosis". *Cancer Cell*, **2**(3):179-182.
        - Optional: Gates, Alexander J., Rion Brattig Correia, Xuan Wang, and Luis M. Rocha. "The Effective Graph Reveals Redundancy, Canalization, and Control Pathways in Biochemical Regulation and Signaling." *Proceedings of the National Academy of Sciences* **118**, no. 12 (March 23, 2021): e2022598118.
  - November 16th / 28th ?
    - Reading and Discussion Group 5 (Enginet)
      - Theise, N.D., and M.C. Kafatos. [2013]. "Complementarity in Biological Systems: A Complexity View." *Complexity* **18** (6): 11-20.
      - Gallotti, Riccardo, Giulia Bertagnolli, and Manlio De Domenico (2021). "Unraveling the Hidden Organisation of Urban Systems and Their Mobility Flows." *EPJ Data Science* **10** (1).
      - Pescosolido, Bernice A., et al. "Linking genes-to-global cultures in public health using network science." *Handbook of applied system science* (2016): 25-48.
        - Optional: Mabry, Patricia L., and Robert M. Kaplan. "Systems Science: A Good Investment for the Public's Health." Health Education & Behavior 40, no. 1_suppl (October 2013):Future Modules
  - See brightspace

more upcoming readings (check brightspace)

- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
  - *section 01* presents in class, *section 20* (Enginet) posts videos on Brightspace (exceptions possible)
- Module 4 – Multi-level complexity
  - November 28th ?
    - Reading and Discussion Group 1
      - Prieto-Curiel, et al [2023]. “Reducing Cartel Recruitment Is the Only Way to Lower Violence in Mexico.” *Science* **381** (6664): 1312–16.
        - Optional: Caulkins, Jonathan P., Beau Kilmer, and Peter Reuter [2023]. “Modeling Cartel Size to Inform Violence Reduction in Mexico.” *Science* **381**, no. 6664: 1291–93.
    - Reading and Discussion Group 2
      - Gan, Xiao et al. [2023] “Network Medicine Framework Reveals Generic Herb-Symptom Effectiveness of Traditional Chinese Medicine.” *Science Advances* **9**, (43): eadh0215
- Module 5 – Interdisciplinarity
  - November 30th ?
    - Reading and Discussion Group 3
      - Wu, L., Wang, D., & Evans, J. A. [2019].”Large teams develop and small teams disrupt science and technology”. *Nature* **566**: 378–382
    - Reading and Discussion Group 4
      - Trochim, William M et al [2006]. “Practical Challenges of Systems Thinking and Modeling in Public Health.” *American Journal of Public Health* **96**(3): 538–46.
        - Optional: Rusoja, Evan, et al [2018]. “Thinking about Complexity in Health: A Systematic Review of the Key Systems Thinking and Complexity Ideas in Health.” *Journal of Evaluation in Clinical Practice* **24** (3): 600–6
    - Reading and Discussion Group 5
      - Editorial. (2015). Mind meld. *Nature*, **525**(7569), 289–90.
      - Van Noorden, R. (2015). Interdisciplinary research by the numbers. *Nature*, **525**(7569), 306–7.
      - Ledford, H. (2015). How to solve the world’s biggest problems. *Nature*, **525**(7569), 308–11.
        - Optional: Kaushal, A., & Altman, R. B. (2019). “Wiring minds”. *Nature*, **576**(7787), S62-S63.
        - Optional: Iwasaki, A. (2019) “Why we need to increase diversity in the immunology research community”. *Nat Immunol* **20**, 1085–1088.
    - See brightspace

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Questions and suggestions

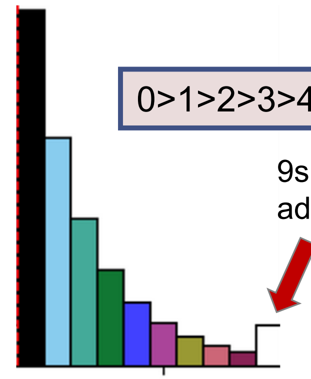
- Remember "published" facts
  - Odd/Even behavior in Q1
  - Statistical behavior in Q2
  - Different regions, transition sequence, complexity in Q4
- Collect or request data (cite)
- Are there quadrant dependencies?
- Focus on smaller grid (mask) subsets?
- Think of neighborhoods and boundary conditions
- **Move from descriptive to mechanistic models**
- Induction and deduction
  - Data and reasoning
  - Given a model, are things you have never seen possible?

$$state(cell(i,j))_{t+1} = ?_t \otimes ?.....$$

Q1

1. $0 \rightarrow 0$
2. $\{5\} \rightarrow \{0, 5\}$
3. $\{2, 4, 6, 8\} \rightarrow \{0, 2, 4, 6, 8\}$
4. $\{1, 3, 7, 9\} \rightarrow \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$

Q2



0>1>2>3>4>5>6>7>8 >? 9

9s seem to have a slight advantage in prevalence ?

Q3 **Q4**

Are inner regions the same?

$\rightarrow 0$
$\rightarrow 3$
$\rightarrow 6$
$\rightarrow 9$

Inner region model

$0 \rightarrow 3 \rightarrow 9 \rightarrow 6 \rightarrow 0$

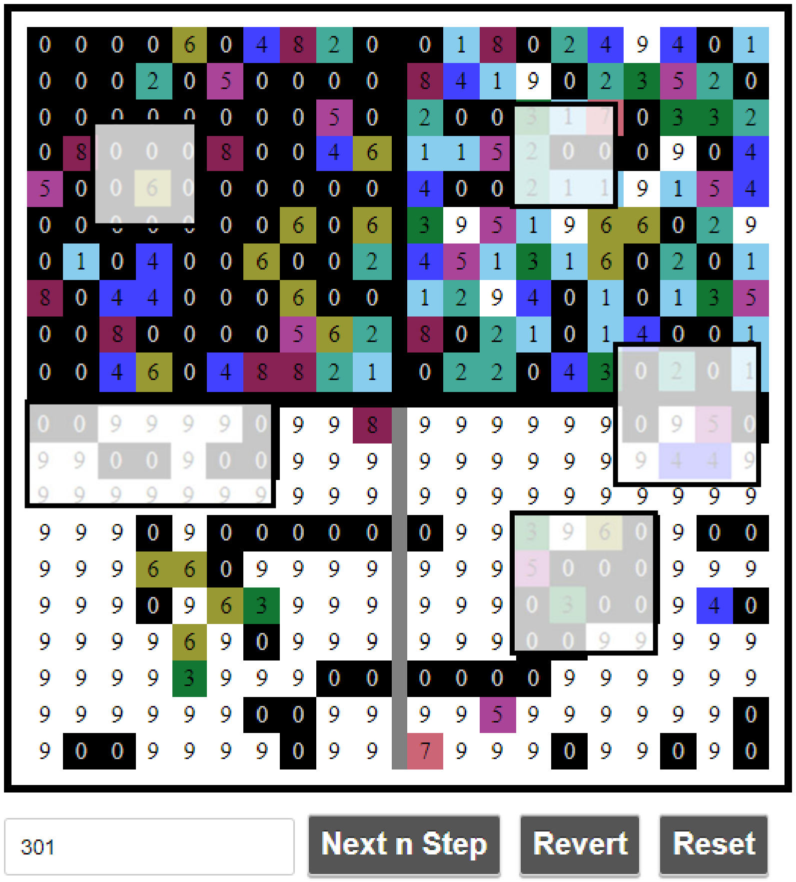
Outer region model

$\rightarrow 0$
$\rightarrow 9$

?

0 $\rightarrow$ **3,9**
1,2 $\rightarrow$ **0,3,9**
3,4,5 $\rightarrow$ **0,6,9**
6,7,8 $\rightarrow$ **0,3,9**
9 $\rightarrow$ **0,6**

Methods to employ



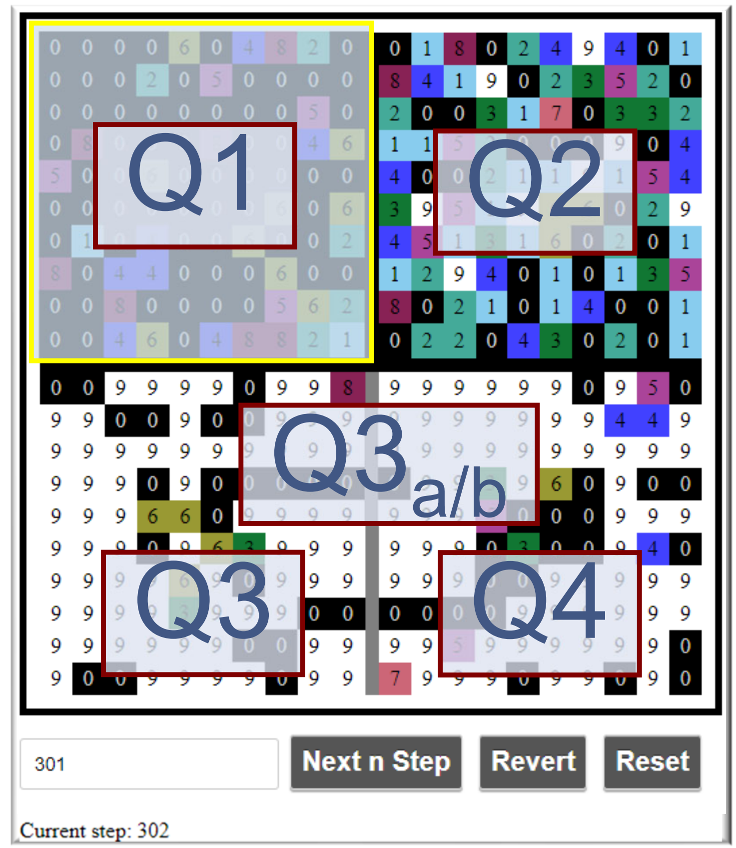
- Data-driven analysis
  - Klir's GSPS
    - Mask analysis of smaller grids
      - E.g. predict behavior of a given cell in Q1
    - Correlations
    - Information theory
- Description model
  - Statistical
- mechanistic model
  - Causal
- Validate
  - Check distributions observed against those predicted
- Make predictions given models
  - Validate
  - Consider the unobserved

$$state(cell(i,j))_{t+1} = ?_t \otimes ?.....$$

The Black Box: Due: December 1st, 2023

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, statistical tests, and induction.
- Propose a formal model or algorithm of what each quadrant is doing.
  - Analyze, using deduction, the behavior of this algorithm.



What is it!!??

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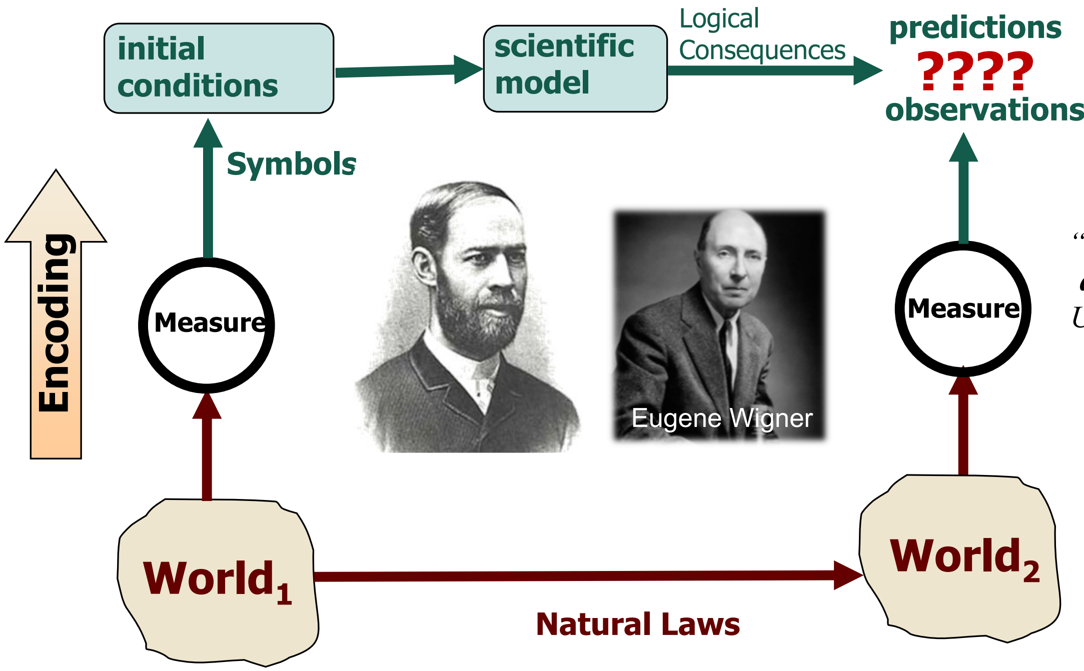
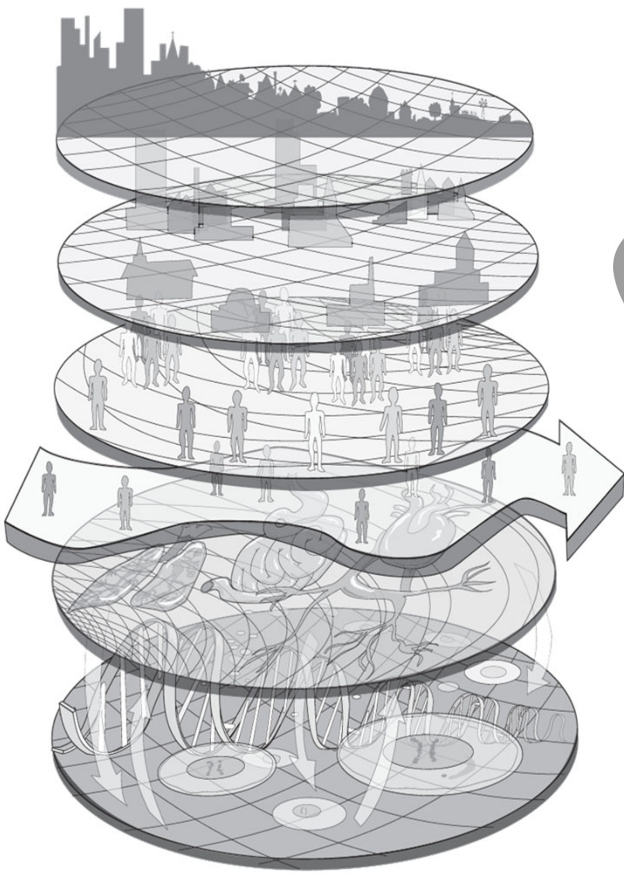
Hertzian scientific modeling paradigm



*"**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"*

"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)



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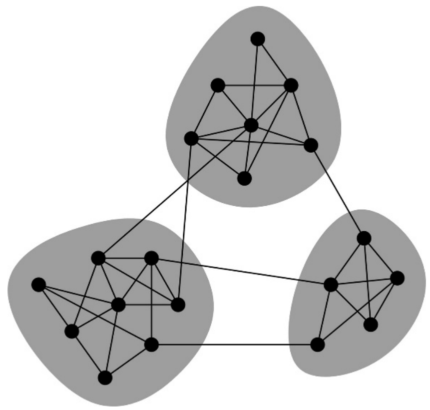
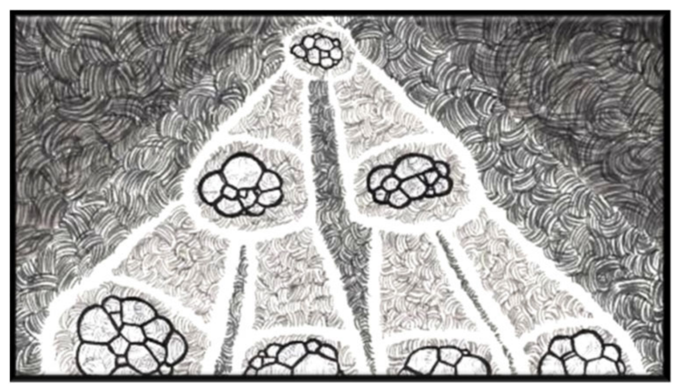


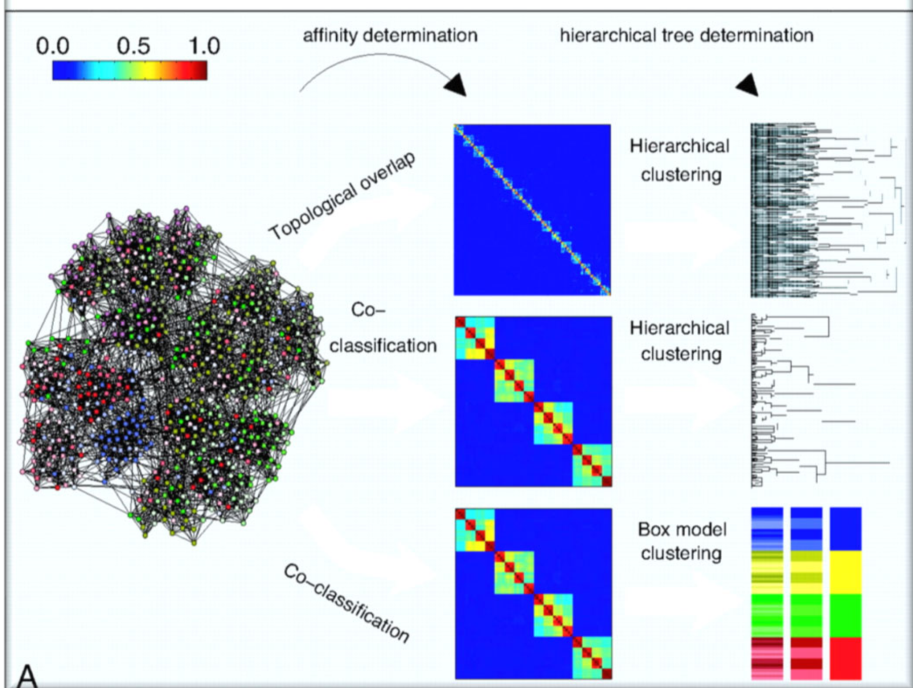
Newman, M.E.J. (2006). "Modularity and community structure in networks." *PNAS* **103** (23): 8577-8582.

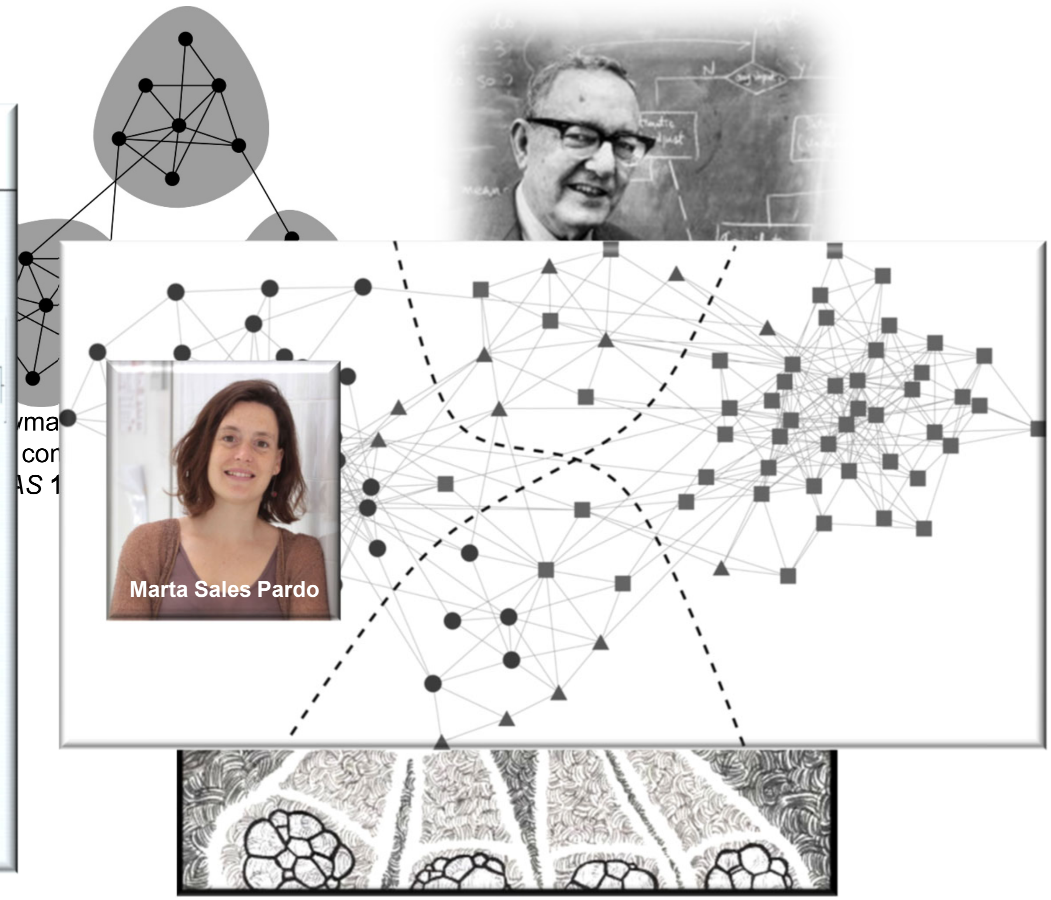
Simon, H.A. [1962]. "The Architecture of Complexity". *Proc. Am. Phil. Soc.*, **106**: pp. 467-482.



Good news I: Simon’s “architecture of complexity” (near-decomposability)

Sales-Pardo, et al (2007). Extracting the hierarchical organization of complex systems. *PNAS*, **104**(39), 15224-15229.





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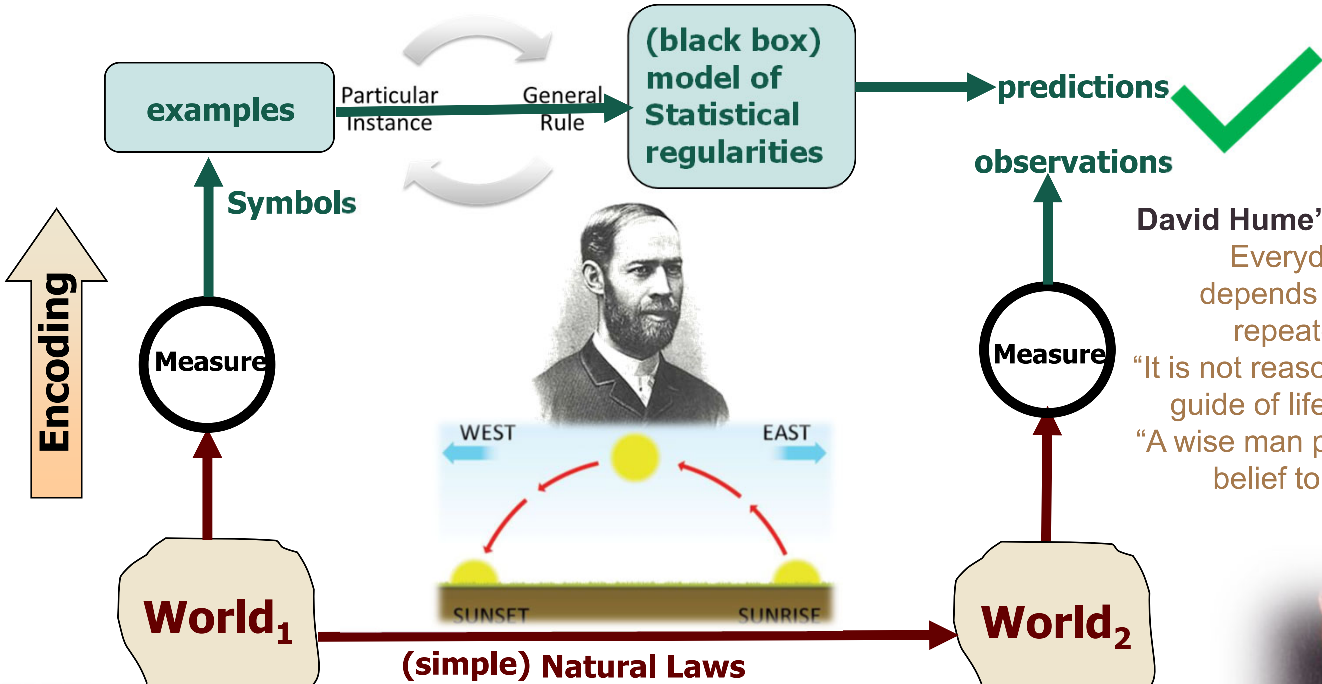
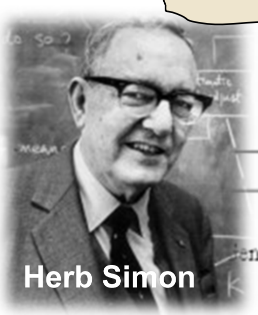
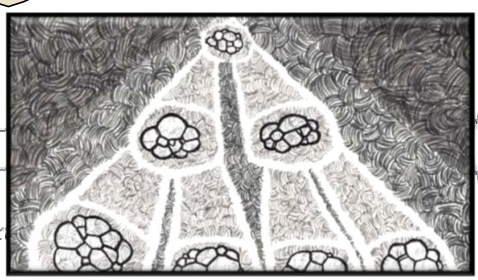
good news II: induction



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"





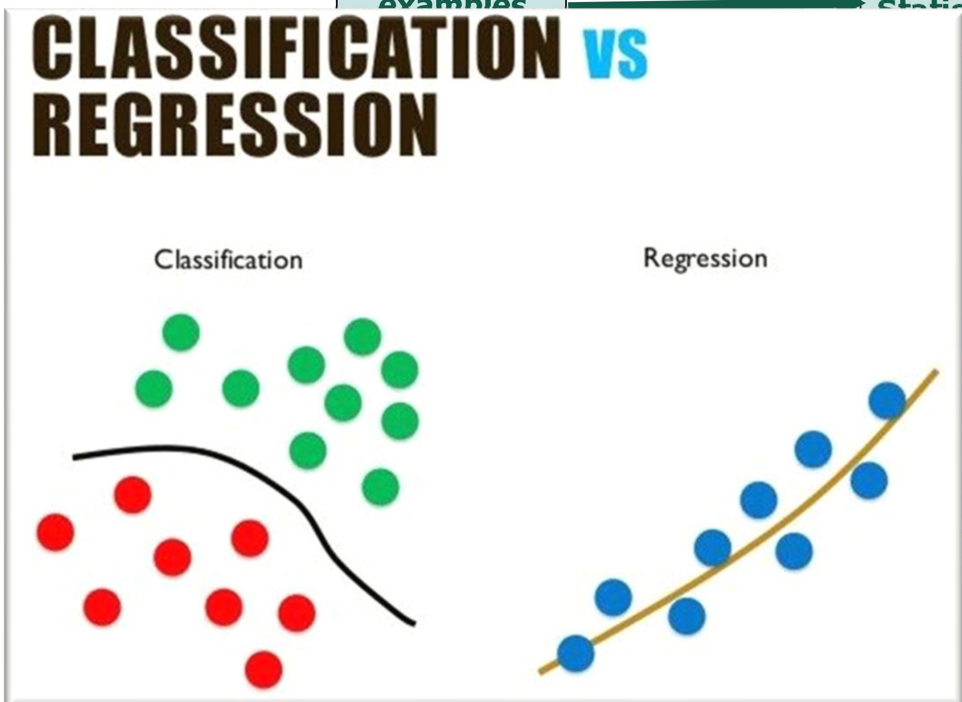
Studying (multilayered, contextual) complexity possible if world is near-decomposable and predictable from past examples

good news II: induction

Particular → General

(black box) model of Statistical ...arities → **predictions**

observations



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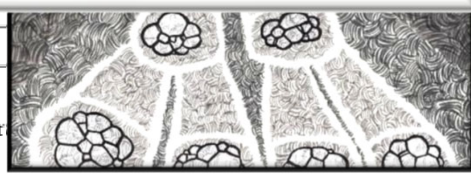
world$_2$



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

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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…)
    - 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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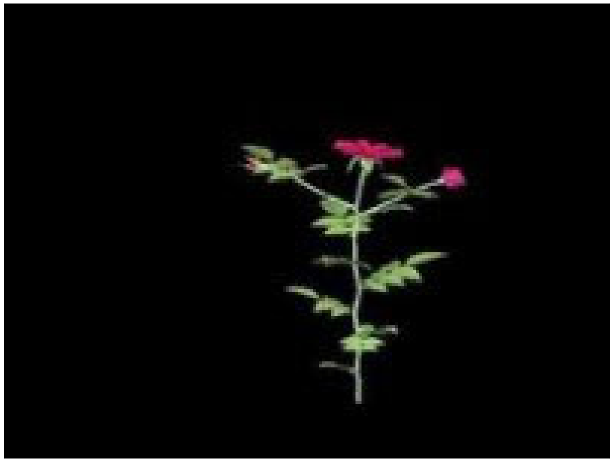
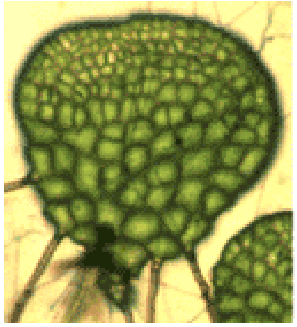
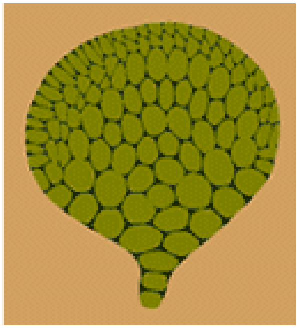
models or realistic imitations?

- 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



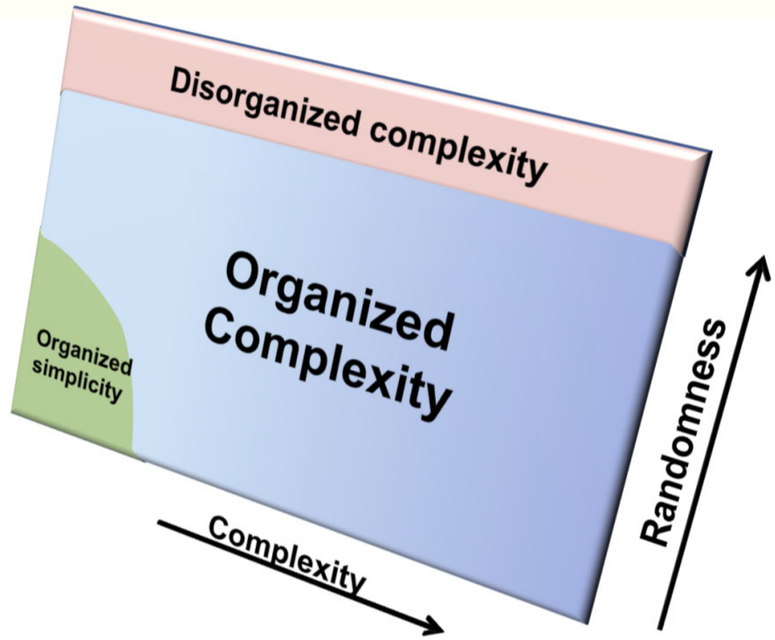




fern gametophyte Microsorium linguaeforme (left) and a simulated model using map L systems (right).

What is it?

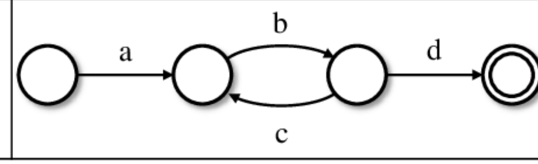
- dictionary
  - Having many varied or interrelated parts, patterns or elements
    - Quantity of parts and extent of interrelations
    - Organizational complexity
- Subjective or epistemic connotation
  - Ability to understand or cope
    - Complexity is in the eyes of the observer
      - Brain to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

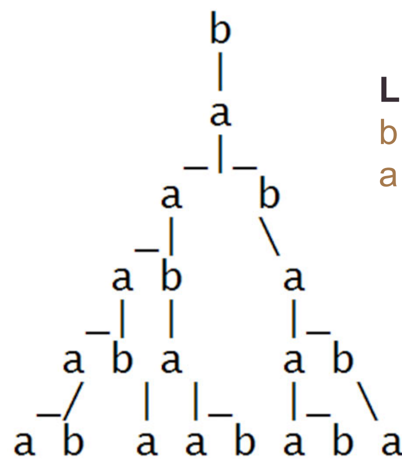


Weaver, W. [1948]. "Science and Complexity". *American Scientist*, **36**(4): 536-44.

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

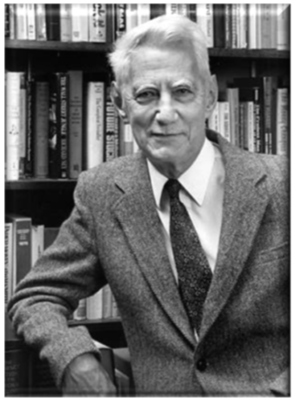
- Proportional to the amount of *information* needed to resolve any uncertainty with the system involved
  - In a syntactic way
    - Related to number of alternatives left undecided to characterize a particular element
  - Examples
    - Hartley Measure
    - Shannon Entropy

including more structure reduces surprise

information is surprise

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

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



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

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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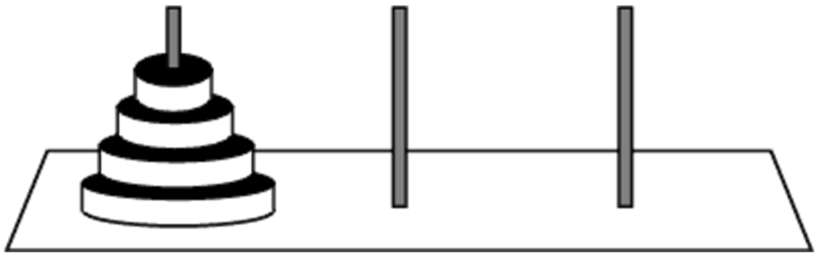
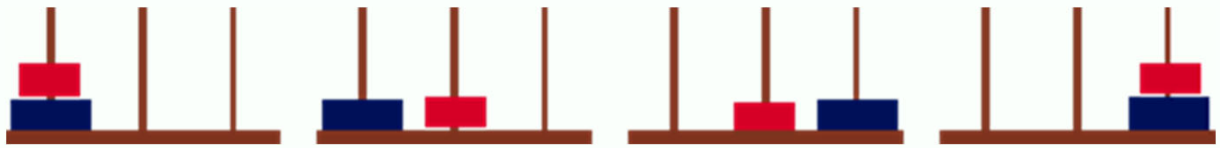
Facing limits

- 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?

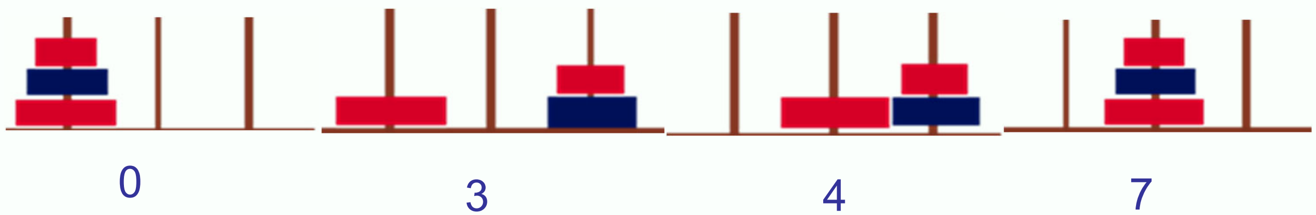


Recursive building blocks

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

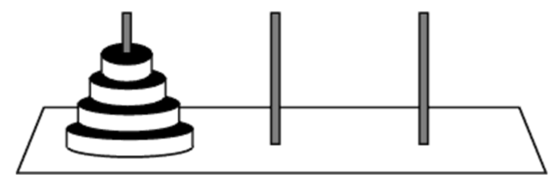


  - N=3



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

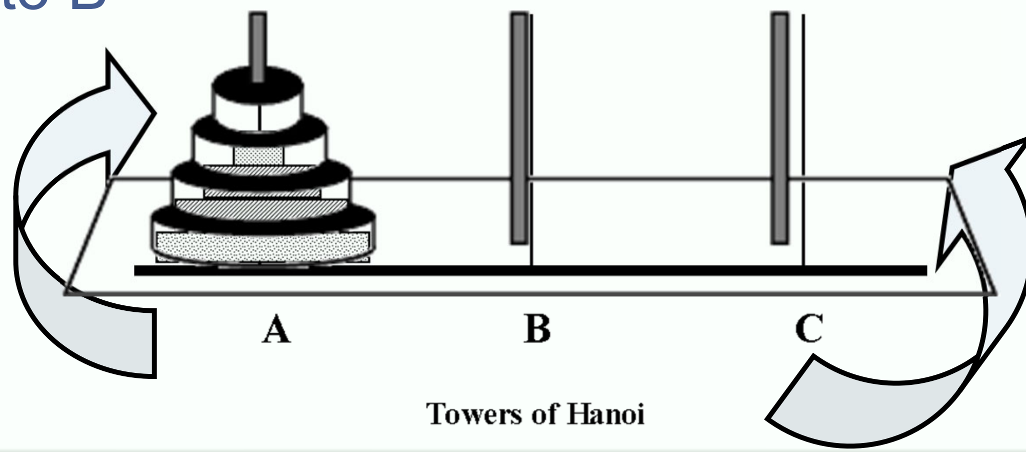
H3 uses H2 twice, plus 1 move of the largest disk



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

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

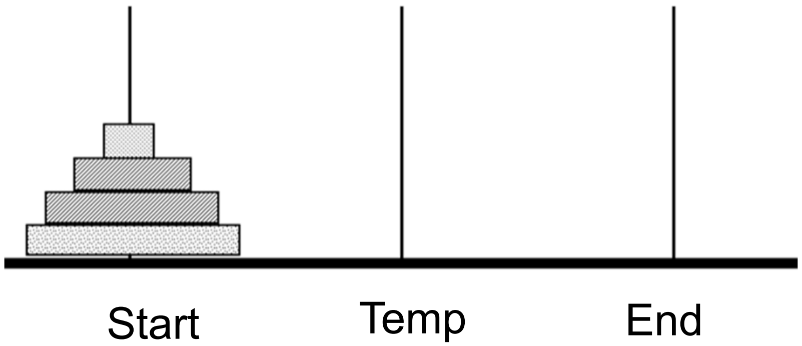
- Algorithm to move n disks from A to C
  - Move top n-1 disks from A to B
  - Move biggest disk to C
  - Move n-1 disks on B to C
- Recursion
  - Until H2

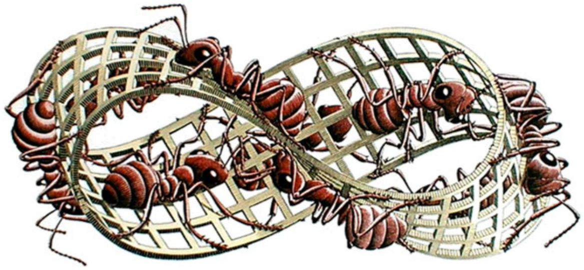


Towers of Hanoi

An Algorithm that uses itself to solve a problem recursion

- 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 10
Name	Symbol	
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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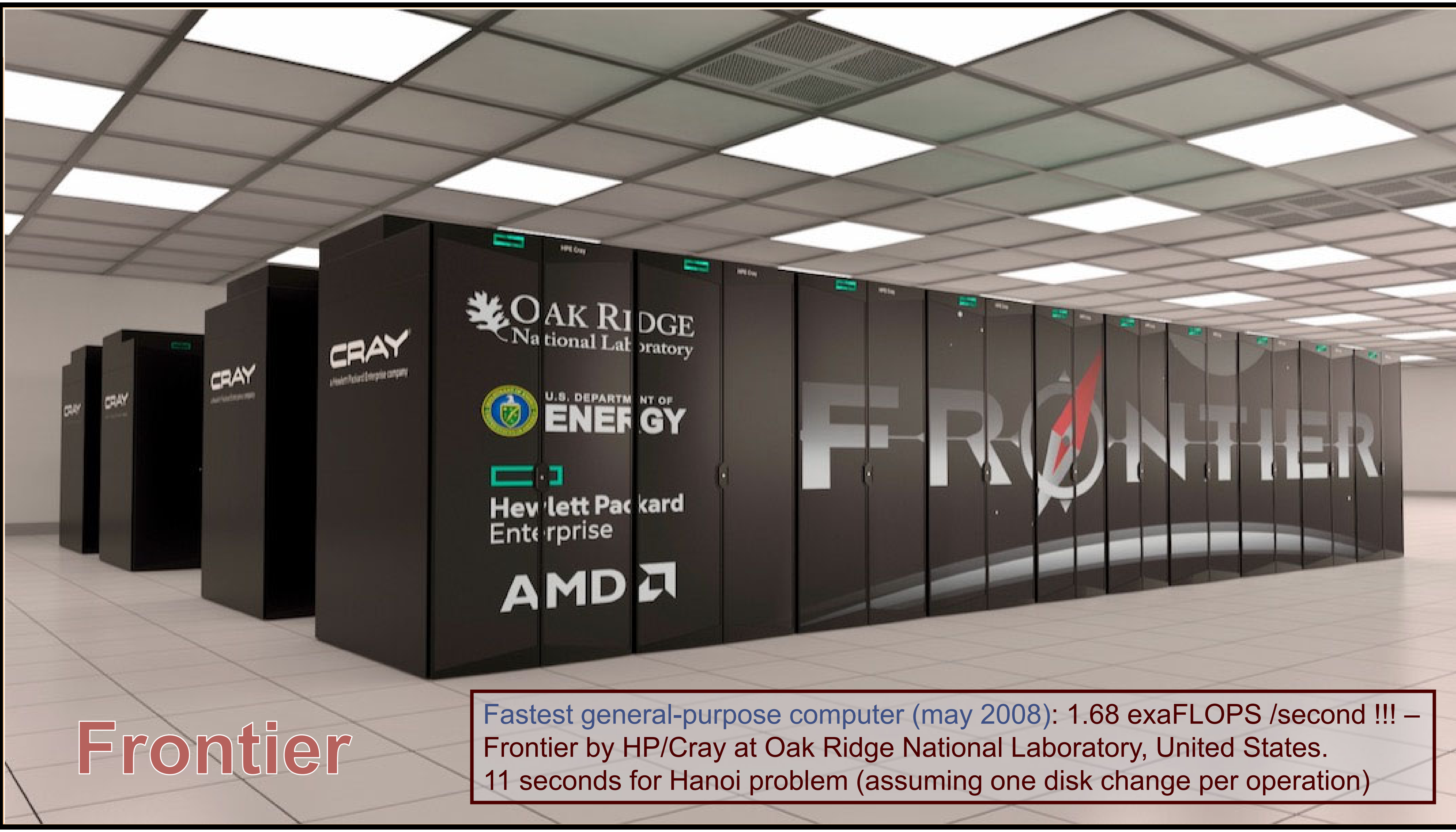

Frontier

Fastest general-purpose computer (may 2008): 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 10^{93} bits**
  - ***transcomputational problems***

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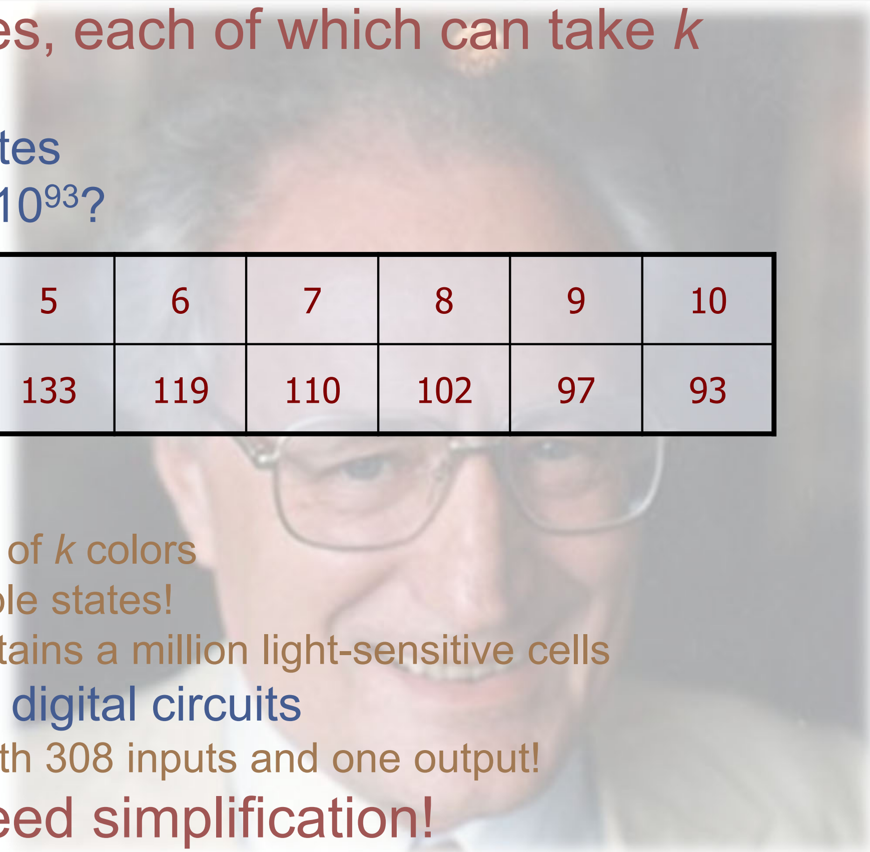
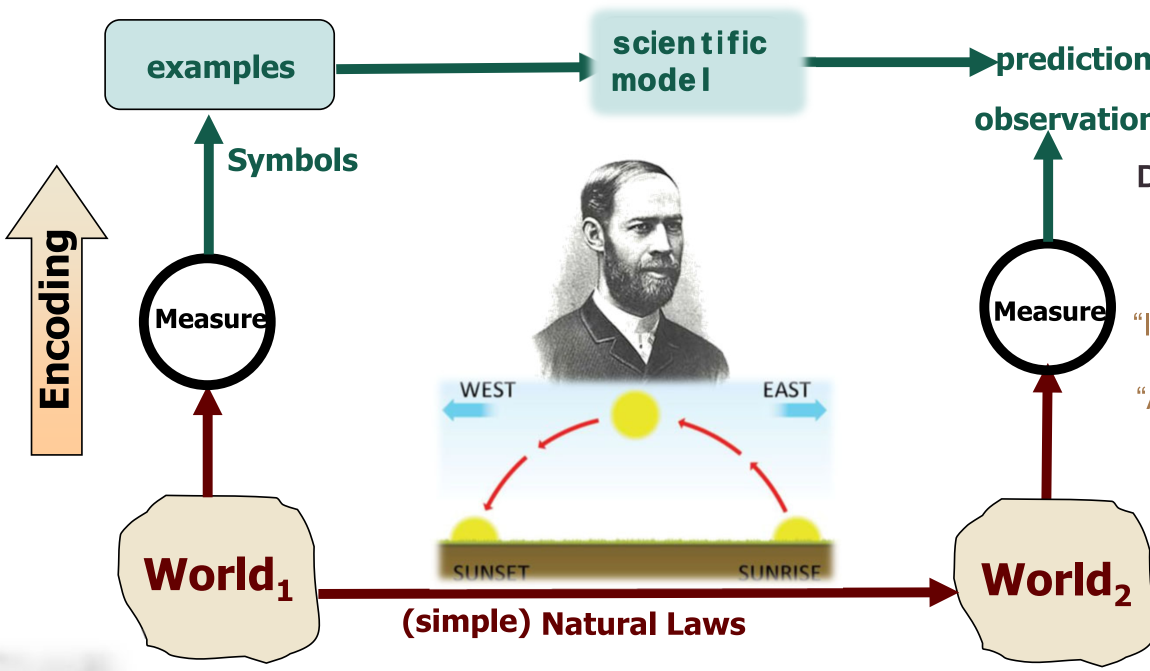


- A system of *n* variables, each of which can take *k* different states
  - k^n possible system states
  - When is it larger than 10^{93}?

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

readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 3 - The Organization of Complex Systems
    - Reading and Discussion Group 3 (Enginet)
      - Kolchinsky, Artemy, and David H. Wolpert. "Semantic Information, Autonomous Agency and Non-Equilibrium Statistical Physics." *Interface Focus* **8**, no. 6 (December 6, 2018): 20180041.
      - Scheffer, Marten, et al. "Early-warning signals for critical transitions." *Nature* **461**.7260 (2009): 53. (Left from April 2)
        - Optional: Leemput, Ingrid A van de, Marieke Wichers, Angélique O J Cramer, Denny Borsboom, Francis Tuerlinckx, Peter Kuppens, Egbert H van Nes, et al. "Critical Slowing down as Early Warning for the Onset and Termination of Depression." *Proceedings of the National Academy of Sciences* **111**, no. 1 (January 2014): 87–92.
        - Optional: Xu, Li, Denis Patterson, Simon Asher Levin, and Jin Wang. "Non-Equilibrium Early-Warning Signals for Critical Transitions in Ecological Systems." *Proceedings of the National Academy of Sciences* **120**, no. 5 (January 31, 2023): e2218663120.

readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 4 – Multi-level Complexity
    - Reading and Discussion Group 4
      - Pattee, Howard H. “The Physical Basis and Origin of Hierarchical Control.” In *Hierarchy Theory: The Challenge of Complex Systems*, edited by Howard H. Pattee, 73–108. New York: Brazillier, 1973.
      - Rosen, Robert. “On Complex Systems.” *European Journal of Operational Research* **30**, no. 2 (June 1987): 129–34.
      - Lazebnik, Y [2002]. "Can a biologist fix a radio?--Or, what I learned while studying apoptosis". *Cancer Cell*, **2**(3):179-182.
        - Optional: Gates, Alexander J., Rion Brattig Correia, Xuan Wang, and Luis M. Rocha. “The Effective Graph Reveals Redundancy, Canalization, and Control Pathways in Biochemical Regulation and Signaling.” *Proceedings of the National Academy of Sciences* **118**, no. 12 (March 23, 2021): e2022598118.