(COMPLEX) SYSTEMS SCIENCE

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MODELLING

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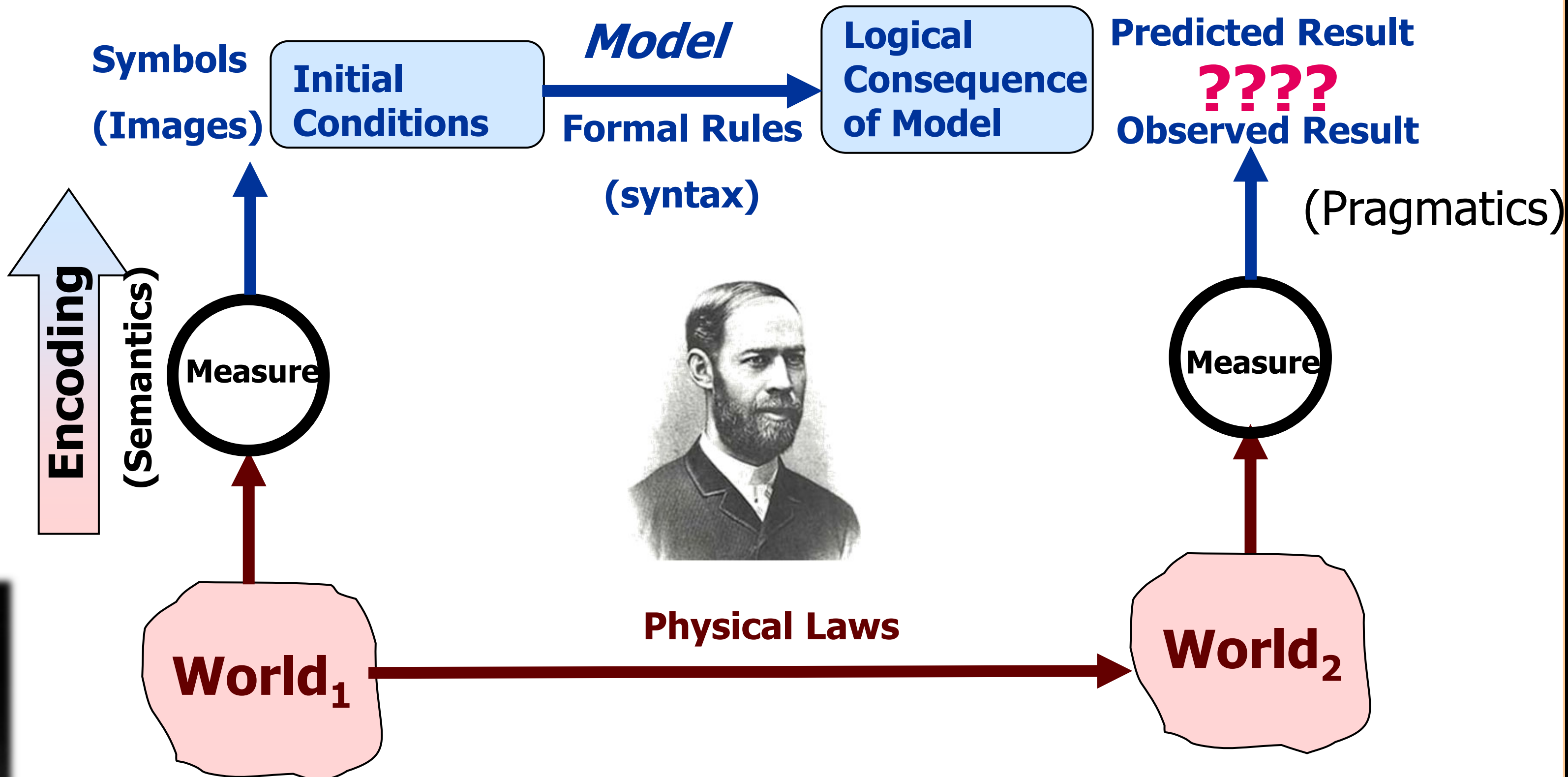
- ***Aristotle*** (384-322 BC)
  - First to relate symbols more explicitly to the external world and to successively clarify the nature of the symbol-world relation.
    - Student of Plato, educated Alexander the Great
    - first to consider specific ***observable*** factors which determine *motion*.
  - In ***Physics***
    - he recognized (mathematical) ***rules*** which could describe the ***relation*** between an object's weight, the medium's density and the consequent rate of motion (fall):
      - (1) for freely falling or freely rising bodies, speed is proportional to the density of the medium.
      - (2) in forced motion, speed is proportional to the force applied and inversely proportional to the mass of the body moved
    - first time that ***observable*** quantities had been expressed in symbolic (numerical) form allowing the results of observations to be used in calculations
      - The nature of ***causation***
      - http://classics.mit.edu/Aristotle/physics.html

Raphael's "*Plato and Aristotle*"

Modeling!

Hertzian modeling paradigm

"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)



Eugene Wigner

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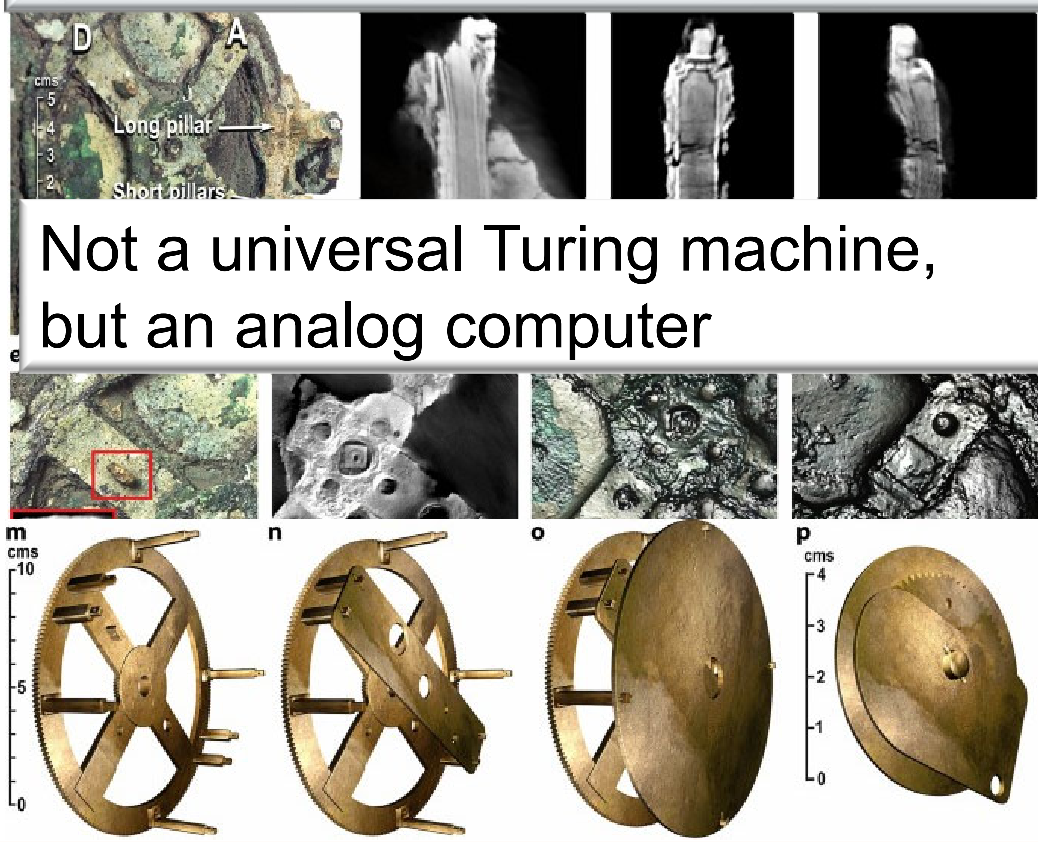
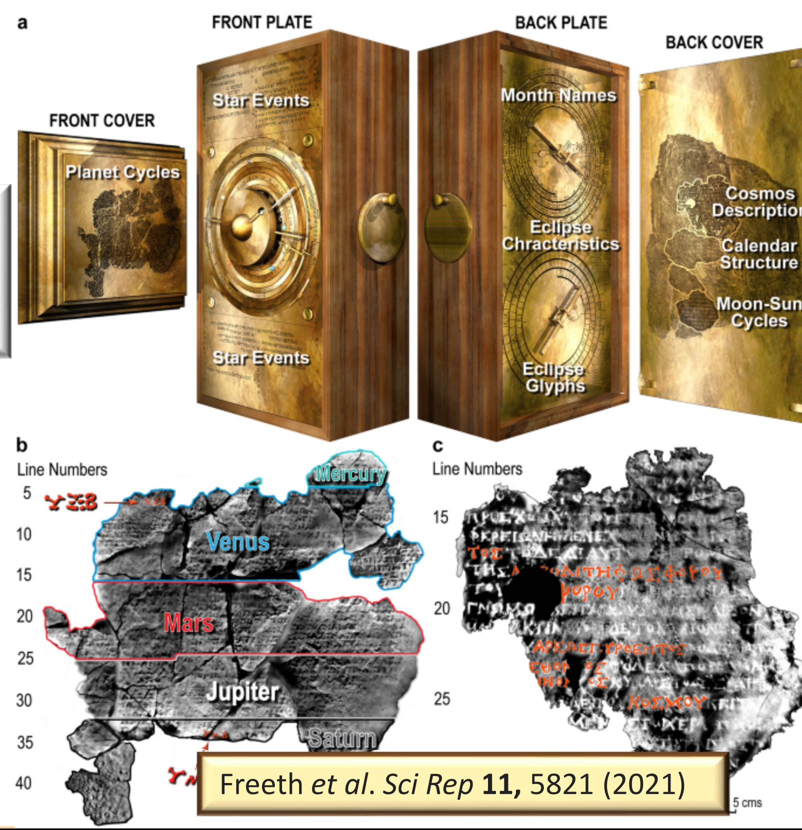
- 2,000-year-old astronomical calculator
  - bronze mechanical **analog** computer
    - discovered more than 100 years ago in a Roman shipwreck, was used by ancient Greeks to display astronomical cycles.
  - built around the end of the second century BC to calculate astronomical positions
  - With imaging and high-resolution X-ray tomography to study how it worked.
    - complicated arrangement of at least 30 precision, hand-cut bronze gears housed inside a wooden case covered in inscriptions.
    - technically more complex than any known device for at least a millennium afterwards.

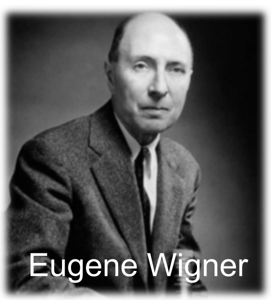


Not a universal Turing machine, but an analog computer



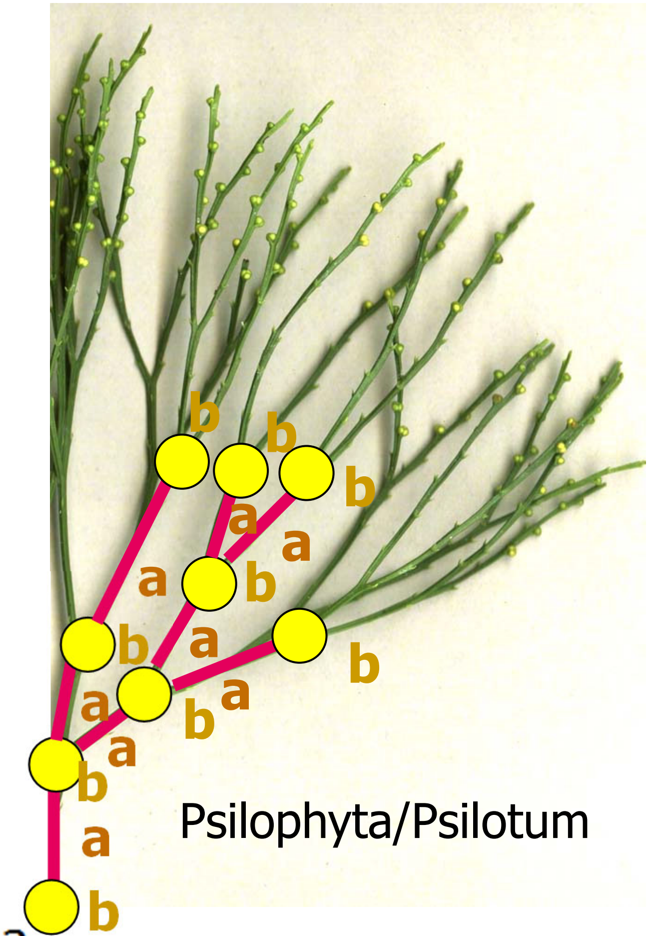
Freeth *et al*. *Sci Rep* **11,** 5821 (2021)

- What do you see?
  - Plants typically ***branch*** out
  - How can we ***model*** that?
    - Observe the distinct parts
      - Color them
      - Assign *symbols*
    - Build Model
      - Initial State: b
      - b -> a
      - ~~a -> b~~
      - a -> ab
    - Doesn't quite Work!


Eugene Wigner


Heinrich Hertz

```
            b
            |
            a
           _|_
          a    b
        _|      \
       a  b      a
      _|  |      |_
     a b  a      a b
   _/   | |_     |_ \
   a b  a a b    a b a
```



Psilophyta/Psilotum

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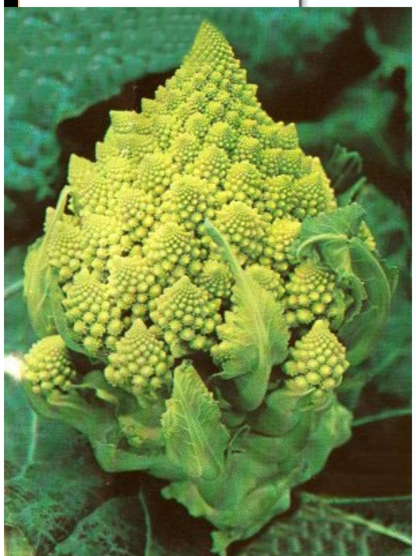
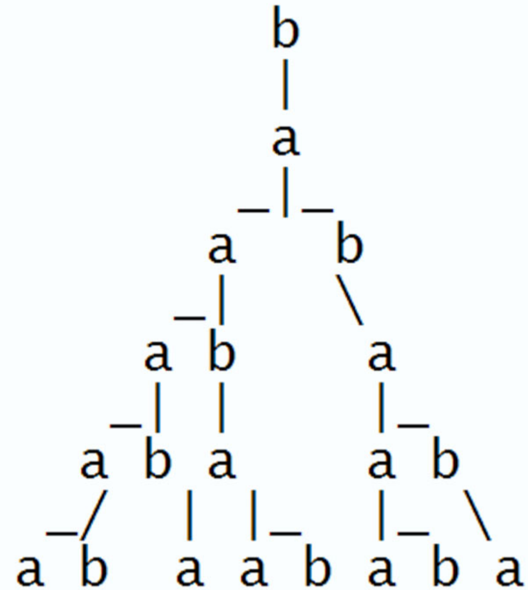
Our First Model



- ***Rewriting*** production rules
  - Initial State: b
  - b -> a
  - a -> ab
    - n=0 : b
    - n=1 : a
    - n=2 : ab
    - n=3 : aba
    - n=4 : abaab
    - n=5 : abaababa
    - n=6 : abaababaabaab
    - n=7 : abaababaabaababaababa
  - The length of the string is the Fibonacci Sequence
    - 1 1 2 3 5 8 13 21 34 55 89 ...
  - Fibonacci numbers in Nature
    - http://life-inspired.blogspot.pt/2015/02/links-for-modeling-principles-of.html
    - Romanesco: http://alt.venus.co.uk/weed/fractals/romanesco.htm



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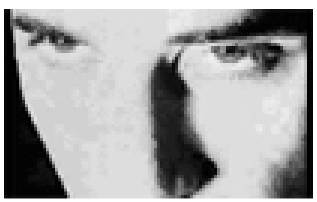
Mathematics

Language

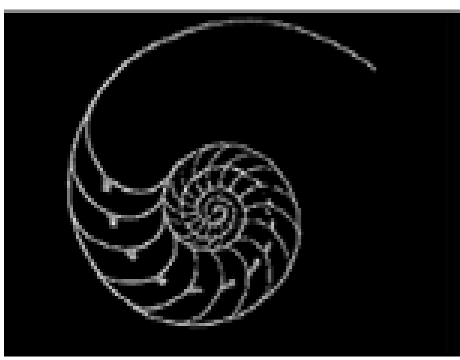


3.

1415926535 8979323846 2643383279
5028841971 6939937510 5820974944
5923078164 0628620899 8628034825
3421170679 8214808651 3282306647
0938446095 5058223172 5359408128
4811174502 8410270193 8521105559
6446229489 5493038196 4428810975
6659334461 2847564823 3786783165
2712019091 4564856692 3460348610
4543266482 1339360726 0249141273
7245870066 0631558817 4881520920
9628292540 9171536436 7892590360
0113305305 4882046652 1384146951
9415116094 3305727036 5759591953
0921861173 8193261179 3105118548
0744623799 6274956735 1885752724
8912279381

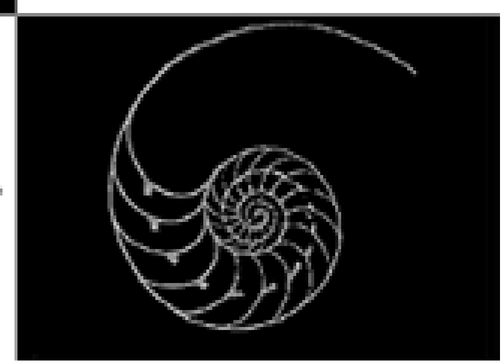
Is The

Of Nature



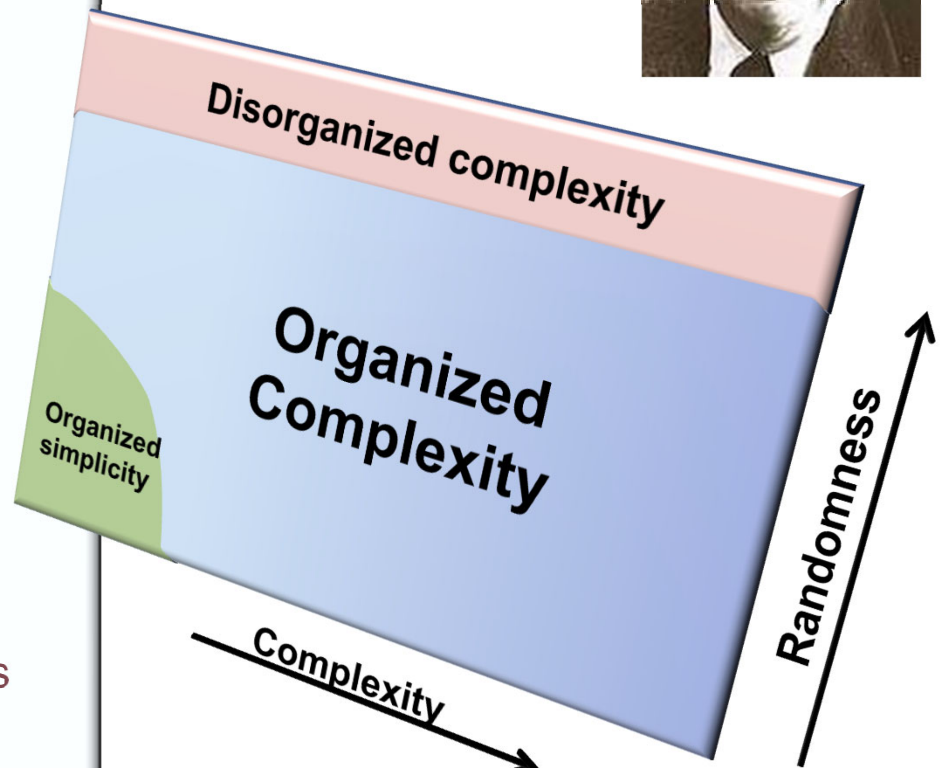
http://pithemovie.com

When I was a kid my mother told me
never to stare into the centre of the sun.
So once, when I was 6,
I did



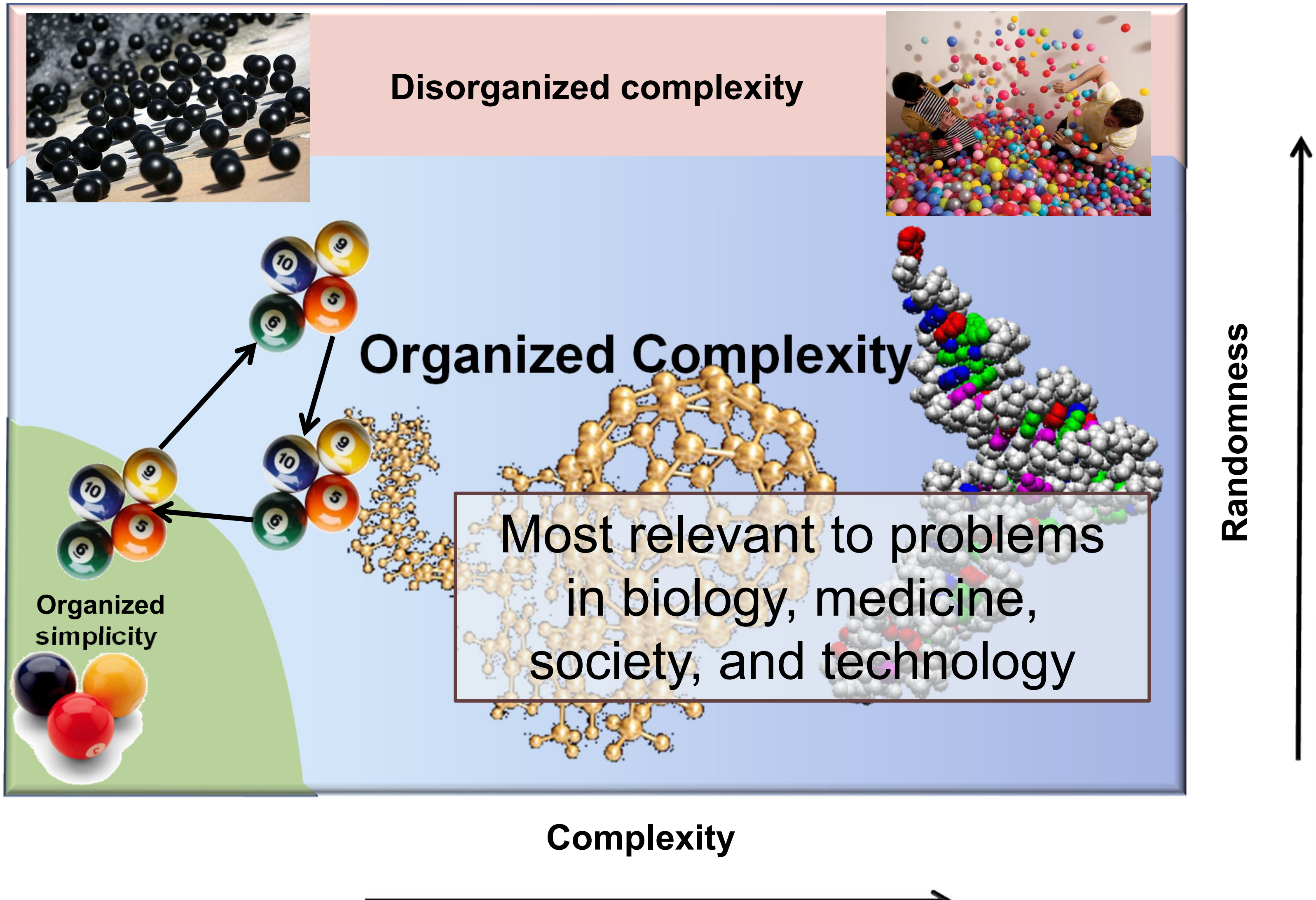
Warren Weaver' classes of systems and problems

- organized simplicity
  - very small number of variables
    - Deterministic
  - classical mathematical tools
    - Calculus
- disorganized complexity
  - very large number of variables
    - Randomness, homogenous
  - statistical tools
- organized complexity
  - sizable number of variables which are interrelated into an organic whole
  - study of organization
    - whole more than sum of parts
    - Massive combinatorial searches need for new mathematical and computational tools



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

examples



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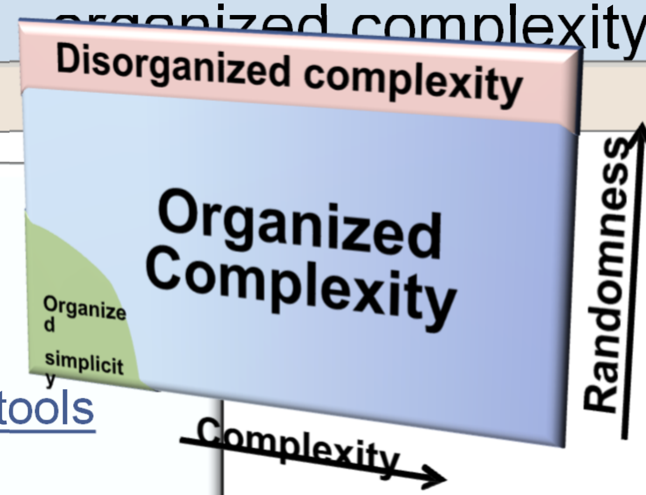
organized complexity

From systems science to informatics



- organized complexity
  - study of organization
    - whole is more than sum of parts
    - Systemhood properties
  - Need for new mathematical and computational tools
    - Massive combinatorial searches
    - Problems that can only be tackled with computers
      - Computer as lab
  - Interdisciplinary and collaborative science
    - Thrives in problem-driven environments
      - Los Alamos, Santa Fe, all new computing centers.
- **thinghood and systemhood**
  - **Integration** of empirical science with general systems
    - Interdisciplinarity coupled with computational modeling
  - Understanding structure and *function*
    - Of multi-level wholes
      - Systems biology, Evolutionary thinking, Systems thinking
    - **Emergence** (or collective behavior)
      - How do elements combine to form new unities?
      - **Micro- to macro-level behavior**

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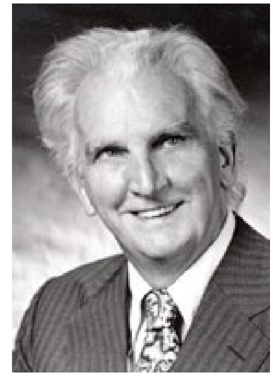
systems movement

key roots

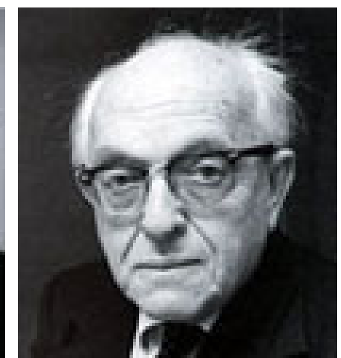
- Mathematics
- Computer Technology
- Systems Thinking
  - Cybernetics
    - Looking at mind, life, society with control, computation, information, networks
  - Functional equivalence
    - General principles and modeling
  - Organized Complexity
    - Study of organization
    - "Whole is more than some of parts", nonlinearity, interaction, communication
  - Interdisciplinary outlook
    - Not juts math and computing, modeling requires understanding of focus domain
    - Bio-inspired mathematics and computing
    - Computing/Mechanism-inspired biology and social science



Kenneth Boulding

Ludwig von Bertalanffy

Ralph Gerard



Anatol Rapoport

1965: Society for the Advancement of General Systems Theory

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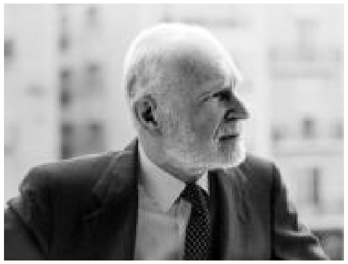
- Systemhood properties of nature
  - Robert Rosen
    - Systems depends on a specific adjective: **thinghood**
    - **Systemhood**: properties of arrangements of items, independent of the items
      - Similar to "setness" or cardinality
  - George Klir
    - **Organization** can be studied with the mathematics of **relations**
    - $S = (T, R)$
      - S: a System, T: a set of things(thinghood), R: a (or set of) relation(s) (Systemhood)
    - Examples
      - Collections of books or music files are sets of things
      - But organization of such sets are systems (alphabetically, chronologically, typologically, etc.)



more formally

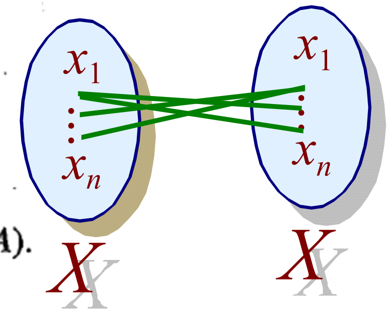
- $S = (T, R)$
  - a System
- $T = \{A_1, A_2, \ldots, A_n\}$
  - A set (of sets) of things: *thinghood*
- Cartesian Product
  - Set of all possible associations of elements from each set
    - All *n*-tuples
  - $\{A_1 \times A_2 \times \ldots \times A_n\}$
- R: a relation (systemhood)
  - Subset of cartesian product on T.
    - Many relations R can be defined on the same T

$$\boxed{R \subseteq A^2 (= A \times A),}$$

$$R \subseteq A^2 (= A \times A \times A),$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$R \subseteq A^n (= \underbrace{A \times A \times \ldots \times A}_{n\text{-times}}).$$



$$R \subseteq (A \times A) \times A,$$

$$R \subseteq A \times (A \times A),$$

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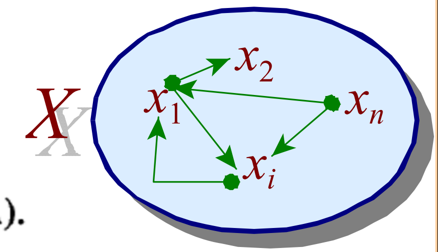


$$\boxed{R \subseteq A \times B,}$$

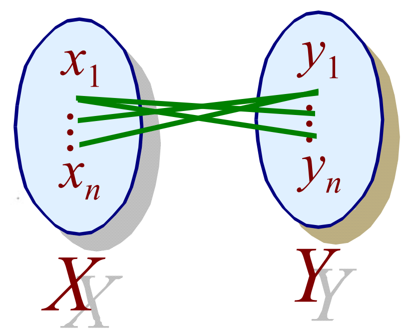
$$R \subseteq (A \times A) \times B,$$

$$R \subseteq (A \times B) \times (A \times B),$$

$$R \subseteq (A \times A \times A) \times B,$$

$$R \subseteq (A \times A \times A) \times (B \times B),$$

$$R \subseteq (A \times B) \times (A \times B) \times (A \times B).$$



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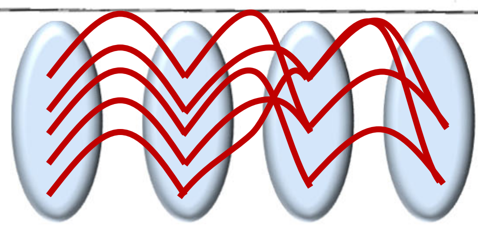
example

Table 2.1. Set of Students with Four Characteristics

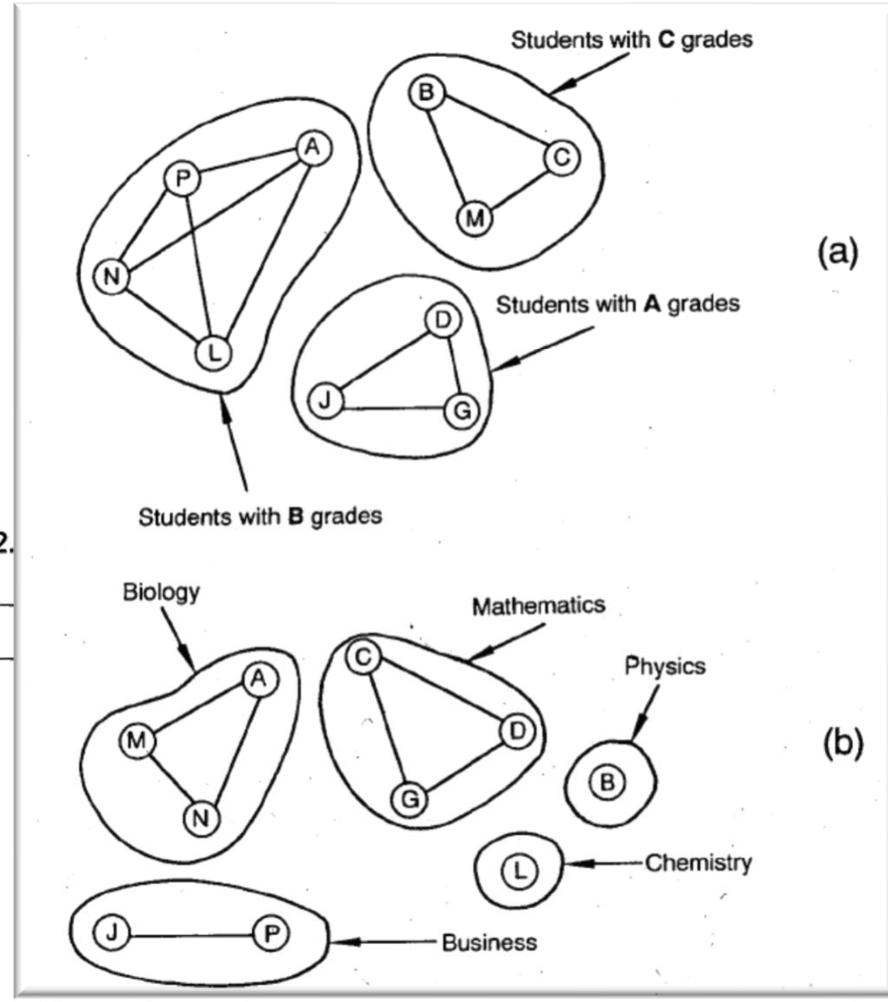
Student	Grade	Major	Age	Full-time/ part-time
Alan	B	Biology	19	Full-time
Bob	C	Physics	19	Full-time
Cliff	C	Mathematics	20	Part-time
Debby	A	Mathematics	19	Full-time
George	A	Mathematics	19	Full-time
Jane	A	Business	21	Part-time
Lisa	B	Chemistry	21	Part-time
Mary	C	Biology	19	Full-time
Nancy	B	Biology	19	Full-time
Paul	B	Business	21	Part-time



$$R \subseteq A \times B \times C \times D$$

Table 2.2.

R_g	A									
A	1									
B	0									
C	0									
D	0									
G	0									
J	0									
L	1									
M	0									
N	1	0	0	0	0	0	1	0	1	1
P	1	0	0	0	0	0	1	0	1	1



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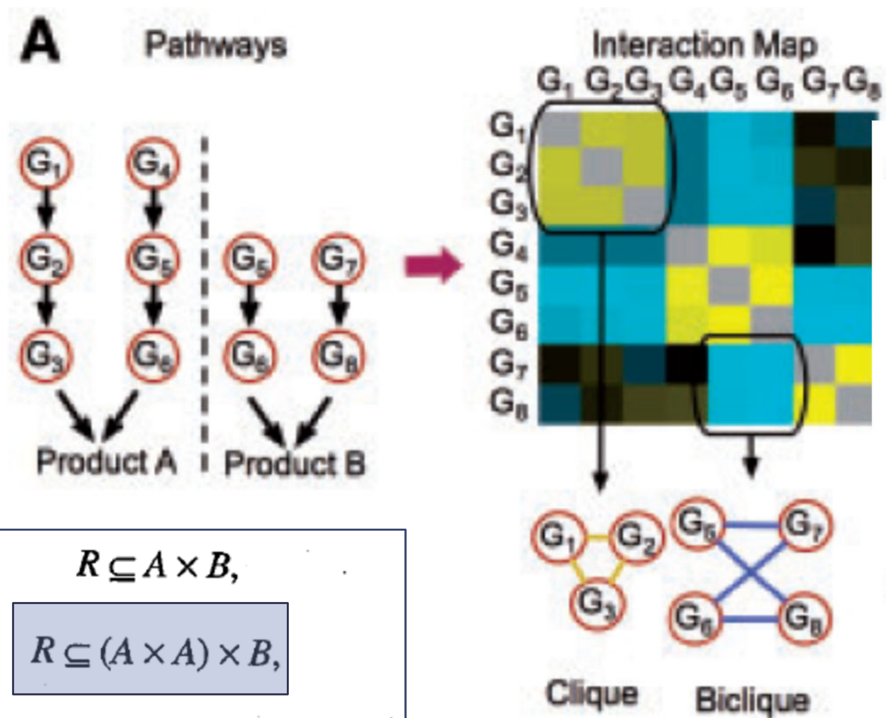
From genetic interaction maps (in yeast)



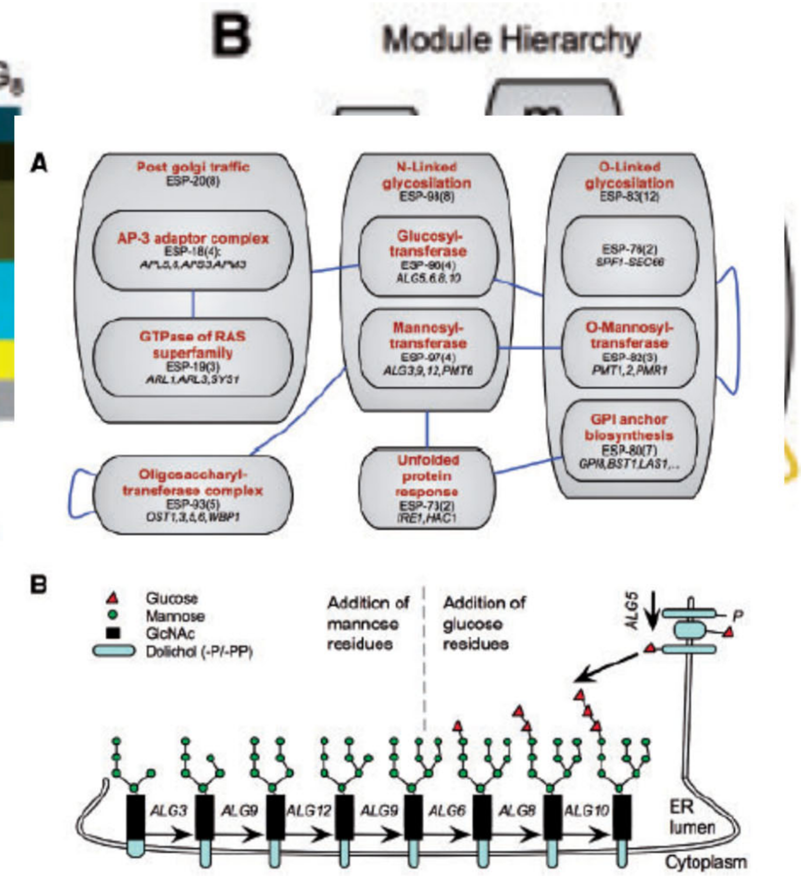
$$R \subseteq A \times B,$$

$$\boxed{R \subseteq (A \times A) \times B,}$$

$$R \subseteq (A \times B) \times (A \times B),$$

$$R \subseteq (A \times A \times A) \times B,$$

$$R \subseteq (A \times A \times A) \times (B \times B),$$



Jaimovich, Aet al. 2010. Modularity and directionality in genetic interaction maps. Bioinformatics 26, no. 12 (June): i228-i236.

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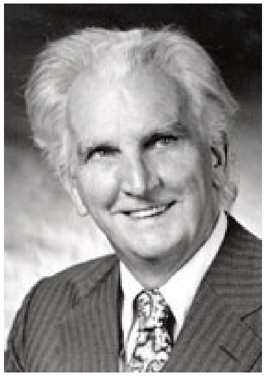
Models of organized complexity

- Systemhood properties
  - Search for a language of *generalized circuits*
  - Isomorphisms of concepts, laws and models across fields
  - Minimize duplication of efforts across fields
  - Unity of science
- Not mathematics
  - Kenneth Boulding
    - "in a sense, because mathematics contains all theories it contains none; it is the language of theory, but it does not give us the content"
    - "body of systematic theoretical construction which will discuss general relationships of the empirical World".
    - "somewhere between the specific that has no meaning and the general that has no content there must be, for each purpose an at each level of abstraction, an optimum degree of generality".
  - Empirical and problem-driven
- Other relevant areas
  - Mathematical theories of control and generalized circuits
  - Optimal scheduling and resource allocation (operations research)
  - dynamical systems, chaos, AI, Alife, machine learning, network science, etc.

Ludwig von Bertalanffy



Kenneth Boulding

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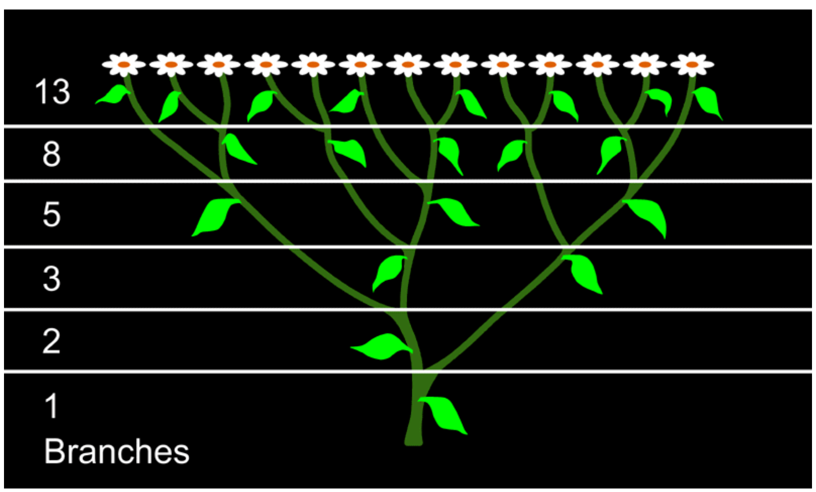
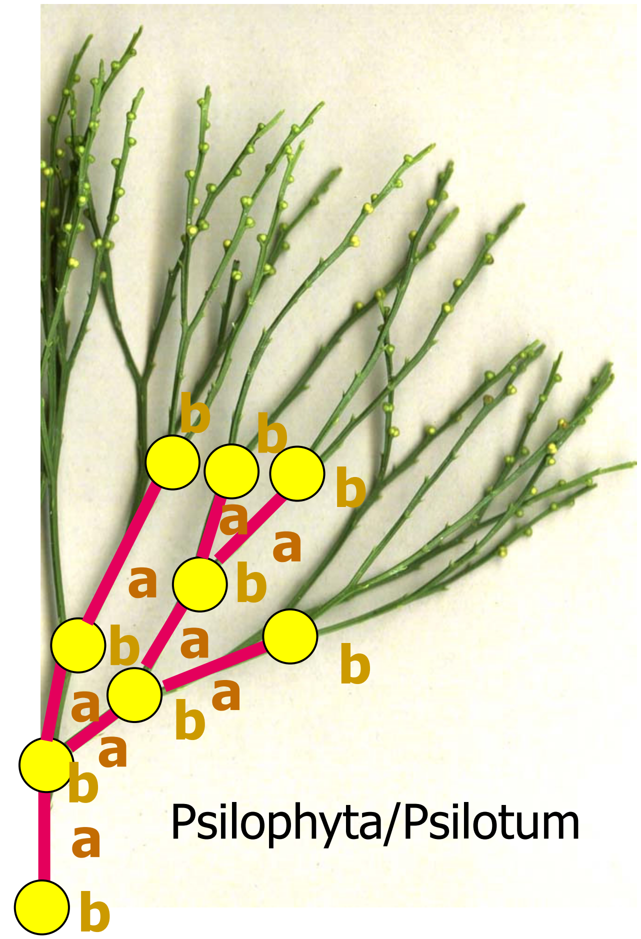
Branching as a general system

- An Accurate Model
  - Requires
    - Varying angles
    - Varying stem lengths
    - randomness
  - The Fibonacci Model is similar
    - Initial State: b
    - b -> a
    - a -> ab
  - *sneezewort*

```
                b
                |
                a
               _|_
             a     b
            _|      \
          a  b       a
         _|  |       |_
        a  b  a      a  b
      _/   |  |_     |_  \
     a  b  a  a  b  a  b  a
```





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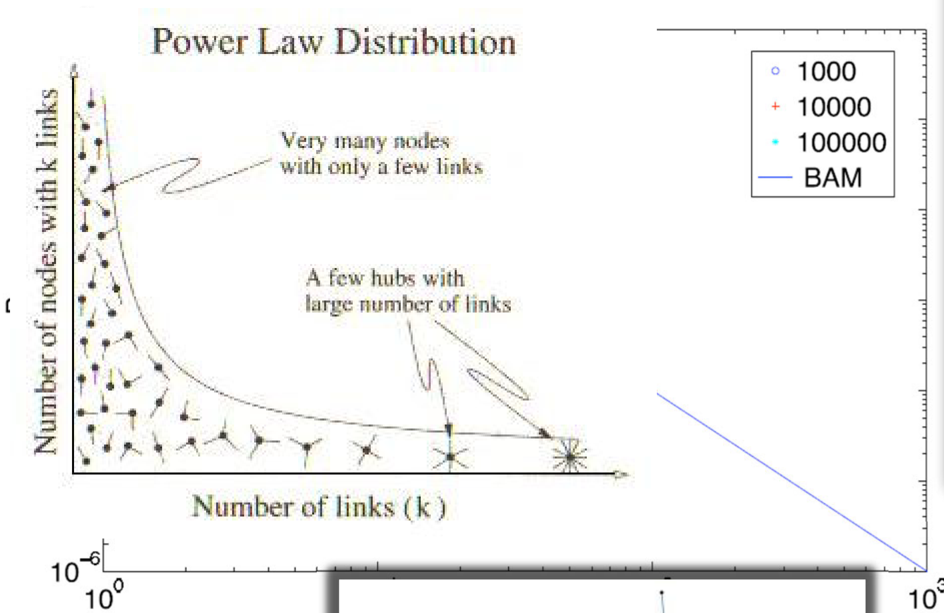
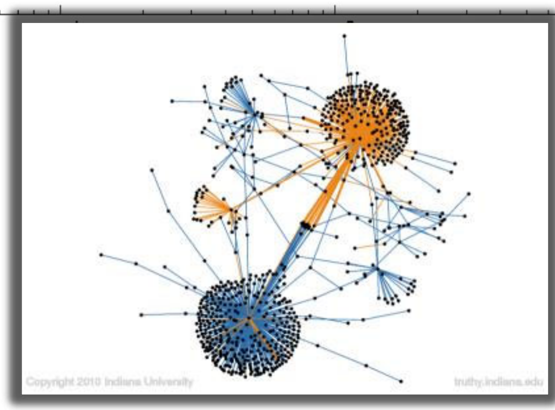
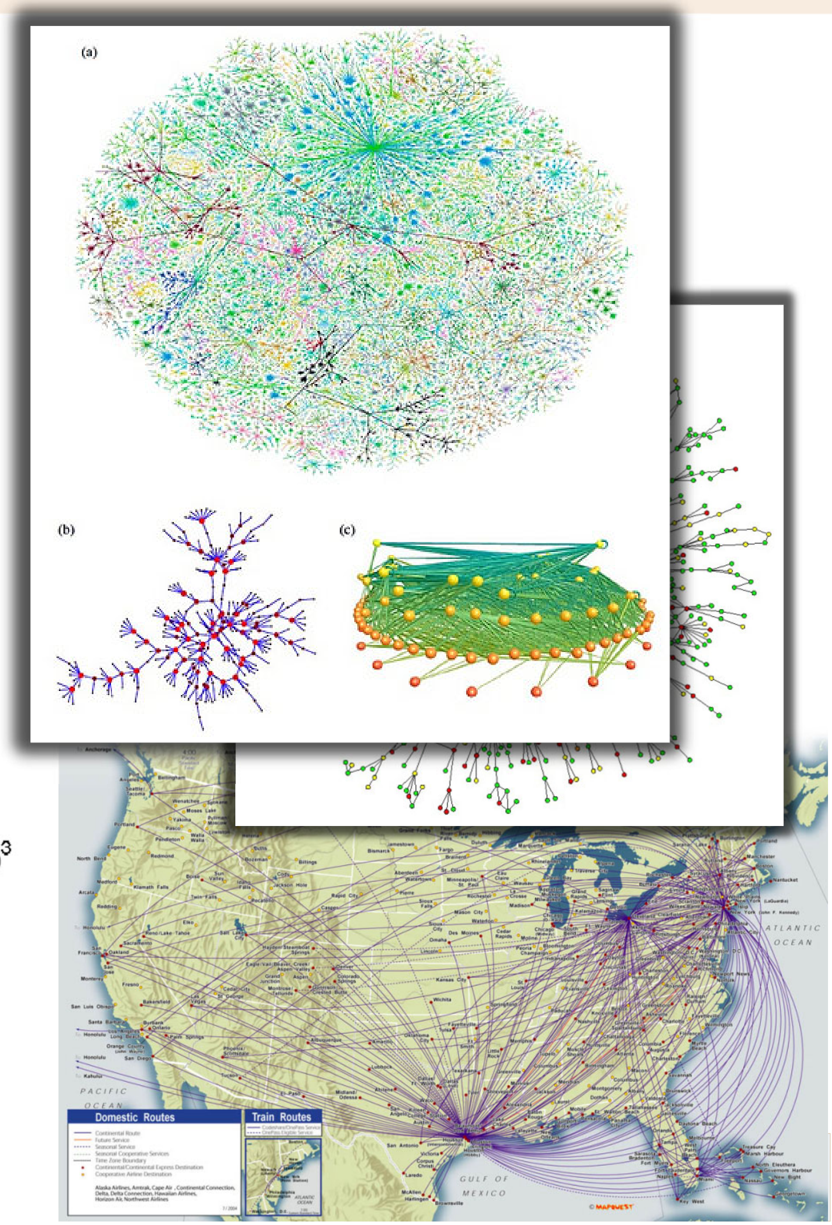
example of general principle of organization

Barabasi-Albert Model: leads to power-law node degree distributions in networks

Amaral et al: Most real networks have a cut-off distribution for high degree nodes which can be computationally modeled with vertex aging.







study of "systemhood" separated from "thinghood"

- Study of "systemhood" properties
  - Classes of isomorphic abstracted systems
  - Search of **general principles** of **organization**
    - Weaver's organized complexity (1948)
- Systemhood properties
  - preserved under suitable transformation from the set of things of one system into the set of things from the other system
    - Divides the space of possible systems (relations) into equivalent classes
- Devoid of any interpretation!
  - General systems
    - Canonical examples of equivalence classes

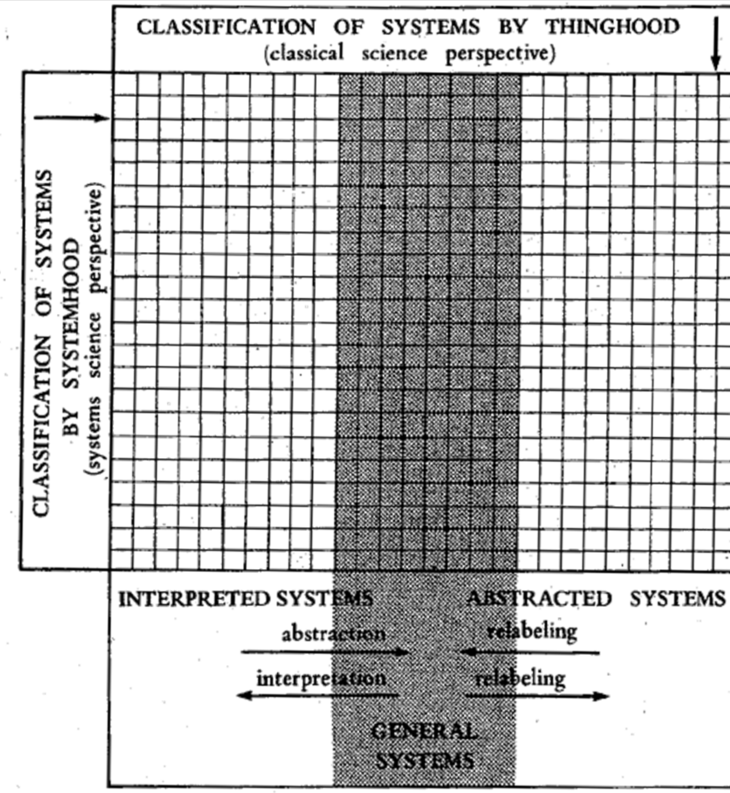
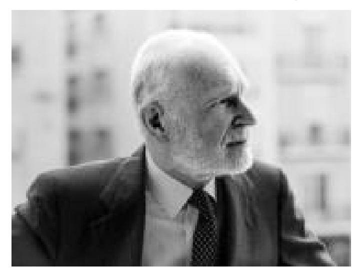


Figure 2.6. Two ways of classifying systems and the role of general systems.



From Klir [2001]

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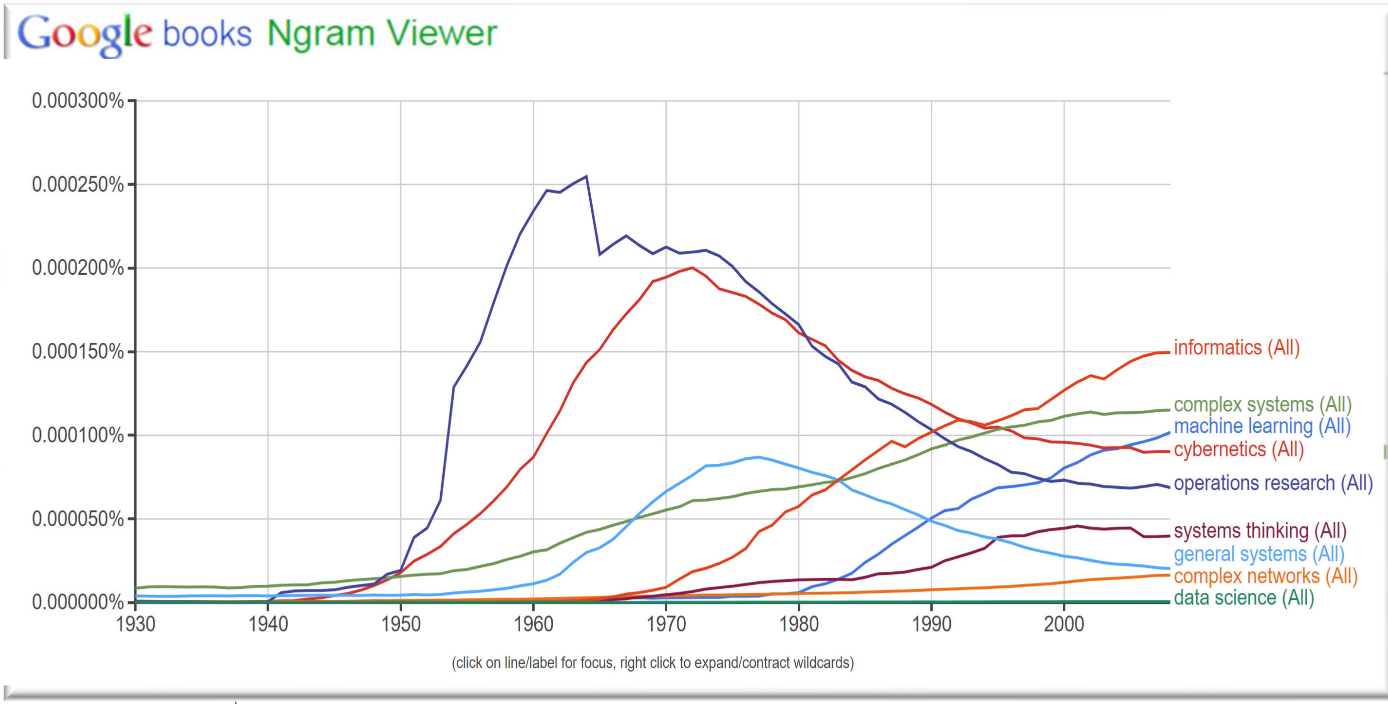
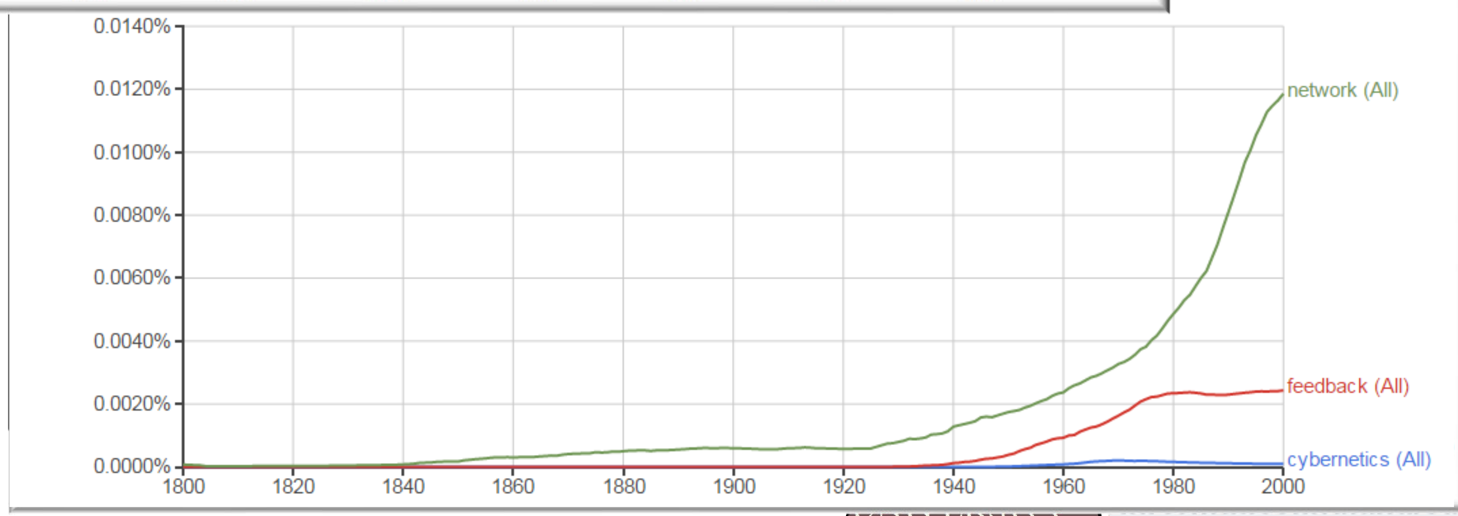
Cybernetics and systems science

The language lives on



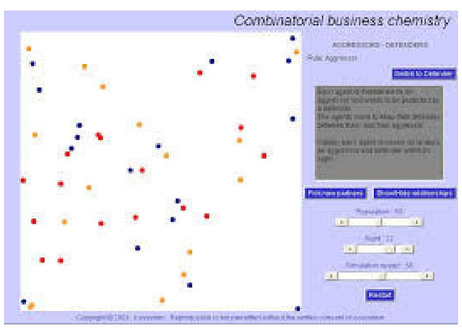


systems/computational thinking

Training to see the world differently

- The complexity worldview
  - Interdisciplinary and collaborative
    - Integration of empirical sciences with general-purpose modeling
    - Thrives in problem-driven environments
      - Los Alamos, Santa Fe, new computing centers
  - Data-driven, computational and mathematical modeling
    - Massive combinatorial searches
    - Networks, feedback, statistics, machine learning, dynamical systems
  - study of organization
    - whole is more than sum of parts
  - Nonlinear thinking
    - **Counterintuitive system-level properties**

Small changes in micro-level rules can change macro-level behavior dramatically



ICOSYSTEM

- Intuition can be a poor guide to predicting the behavior of a complex system.
- Simulation is a powerful tool for harnessing the dynamics of complex systems.

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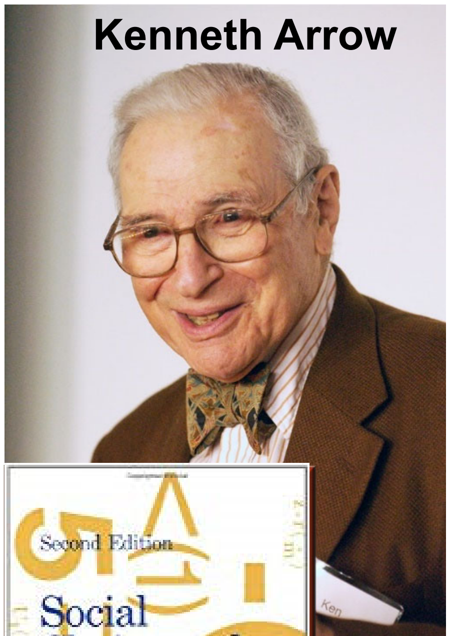
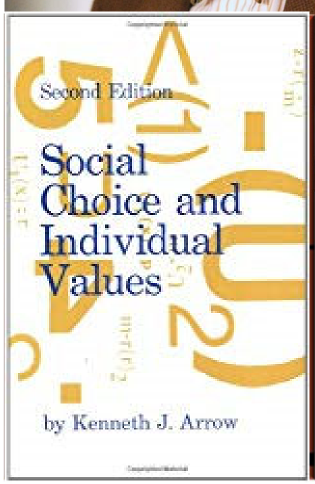
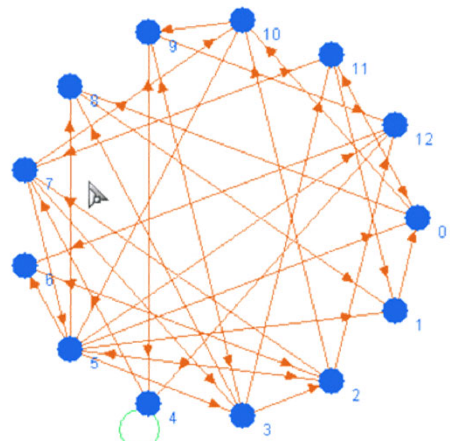
Training to see the world differently

- The complexity worldview
  - Nonlinear thinking
    - **Counterintuitive system-level properties**

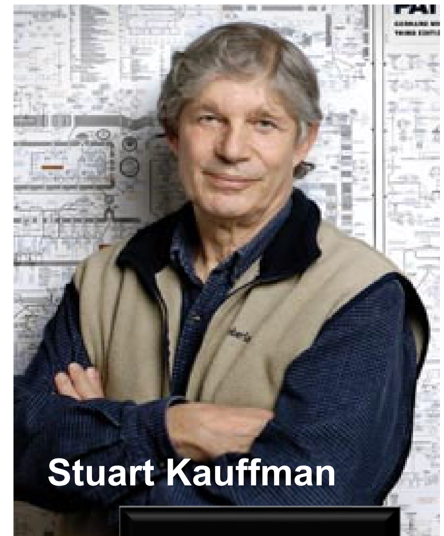
How can world function when "everything is connected"?

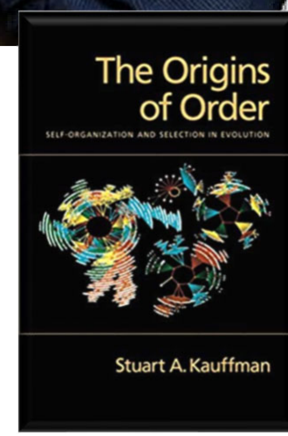






NK Boolean Network (N=13, K=3)





- When mean number of links greater than 2, dynamics is chaotic (with lower probability of "on", better)

- 3 or more choices lead to unstable collective political choices

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