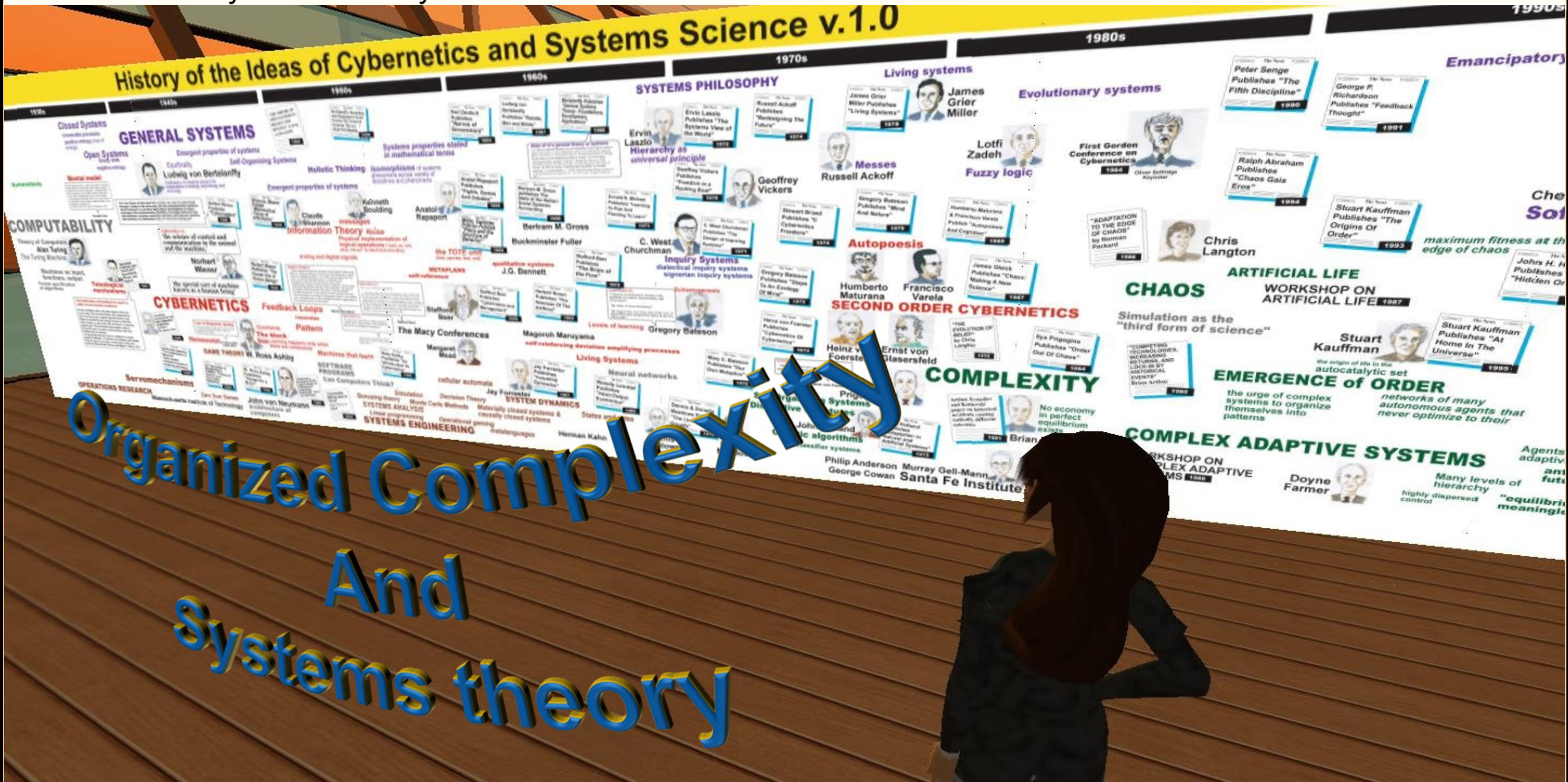
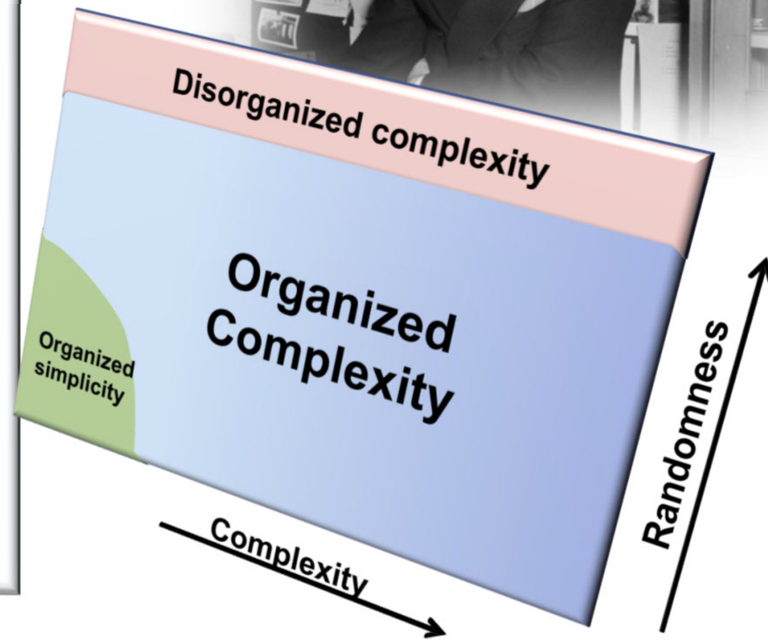
lecture 5: from cybernetics to systems science



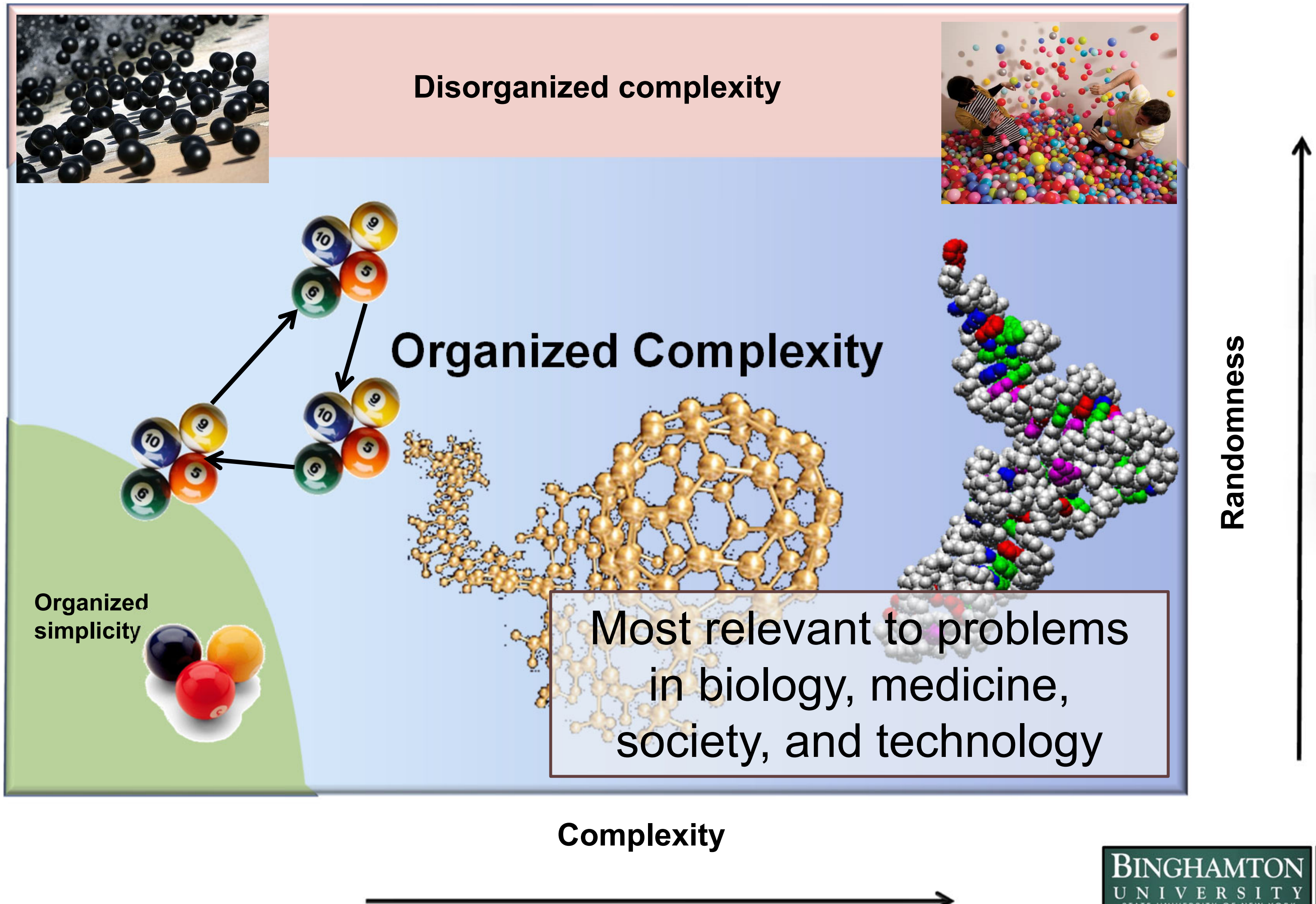
Warren Weaver’ classes of systems and problems

- 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



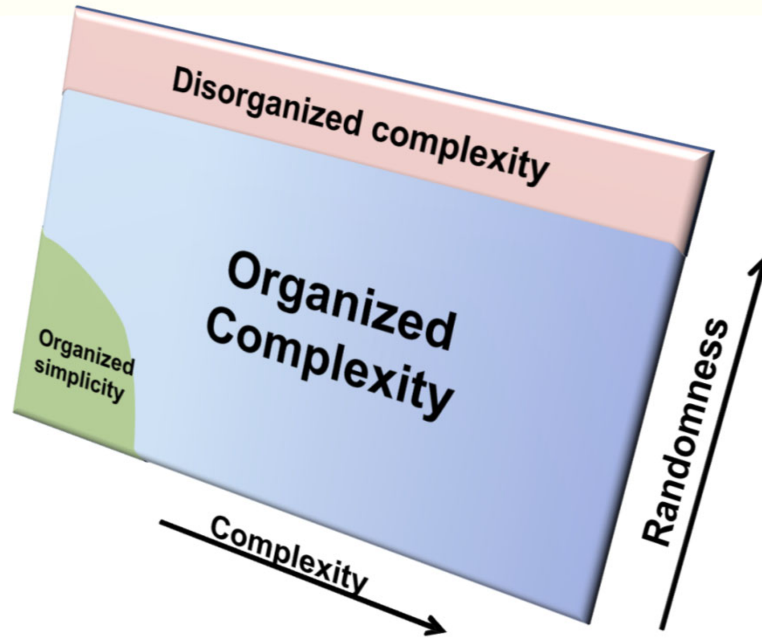
Weaver, W. [1948]. "Science and Complexity". *American Scientist*, **36**(4): 536-44.

examples


Disorganized complexity
Organized Complexity
Organized simplicity
Most relevant to problems in biology, medicine, society, and technology
Complexity
Randomness

from computational to systems thinking

- organized complexity
  - study of organization
    - whole is more than sum of parts
    - Organizational properties ("systemhood")
  - 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**
  - developing general-purpose computing further
    - Computational thinking and cybernetics
      - Some (all?) mechanisms and organizational principles are implementation-independent
      - Hardware vs software
  - **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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key roots

- Mathematics
- Computer Technology and Computational Thinking
- 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 just math and computing, modeling requires understanding of focus domain
    - Bio-inspired mathematics and computing
    - Computing/Mechanism-inspired biology and social science

1965: Society for the Advancement of General Systems Theory

Kenneth Boulding

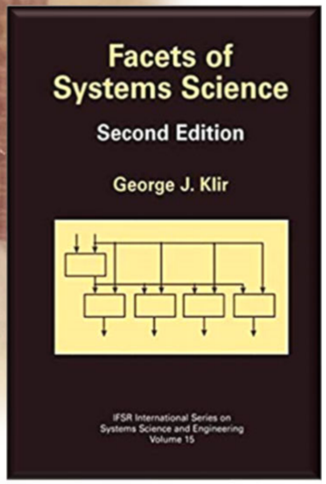
Ludwig von Bertalanffy

Ralph Gerard

Anatol Rapoport

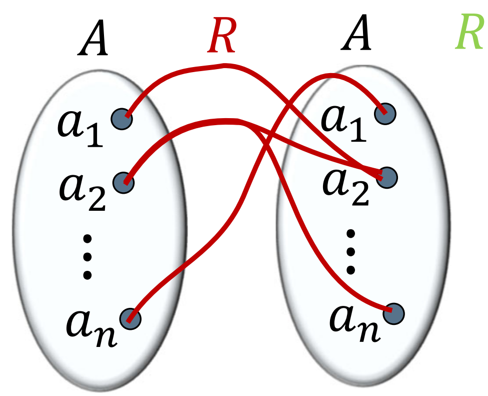
a science of organization across disciplines

- 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)
      - Same relation can be applied to different sets of objects
      - Systems science deals with **organizational properties** of systems independently of the items
    - Examples
      - Collections of books or music files are sets of things
      - But organization of such sets are systems (alphabetically, chronologically, typologically, etc.)

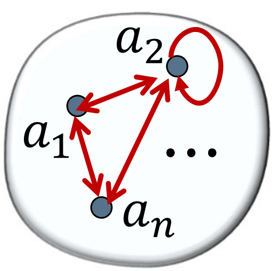


more formally: representation of multivariate of associations/interactions

- $S = (T, R)$
  - a (multivariate) 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



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



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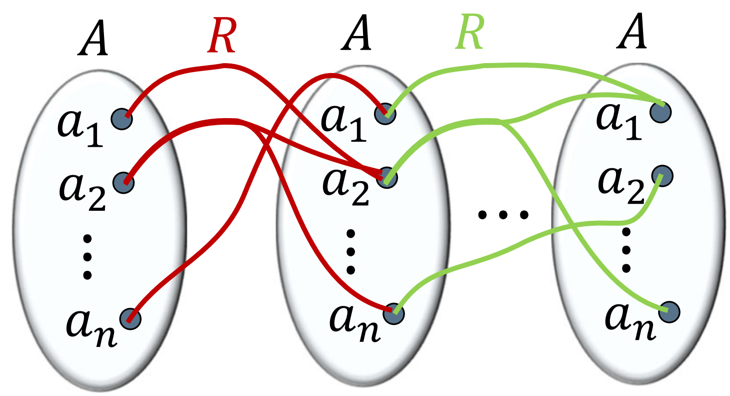

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....

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

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

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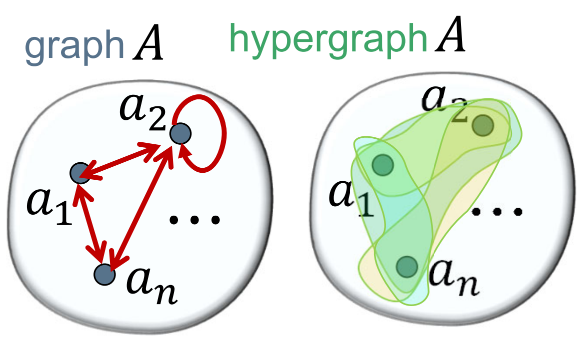

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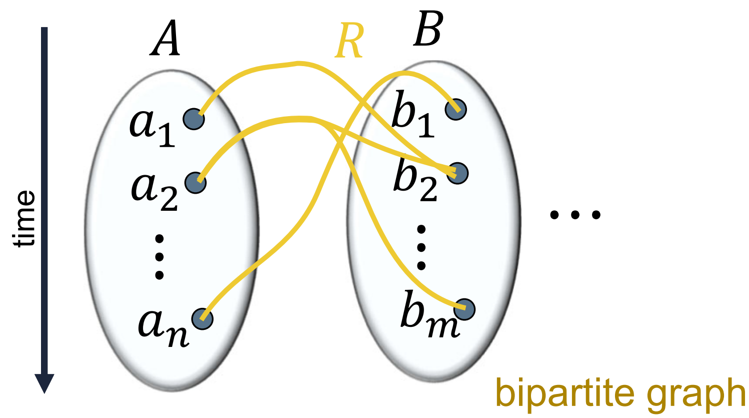

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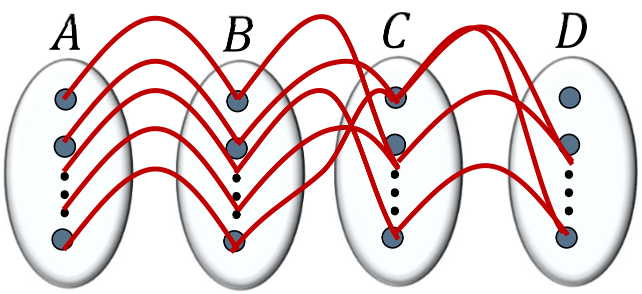
equivalence classes or multilayer network?

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

Table 2.2. Equivalence Relation R_g Defined on the Set of Students Listed in Table 2.1 with Respect to Their Grades

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



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

Note: same thinghood (set of students), but distinct systemhood or organization projected to a specific set (layer) as equivalence classes.

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Table 2.2. Equivalence Relation R_g D
Table 2.1 with Res

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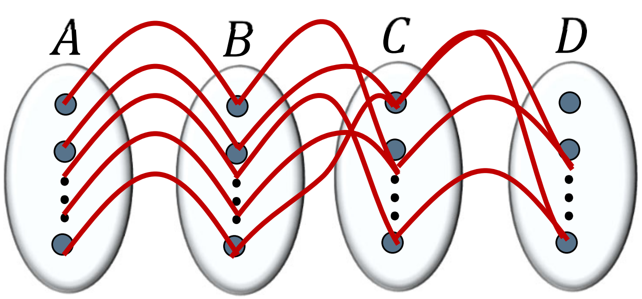
C	0	1	1	0	0
D	0	0	0	1	1
G	0	0	0	1	1
J	0	0	0	1	1
L	1	0	0	0	0
M	0	1	1	0	0
N	1	0	0	0	0
P	1	0	0	0	0



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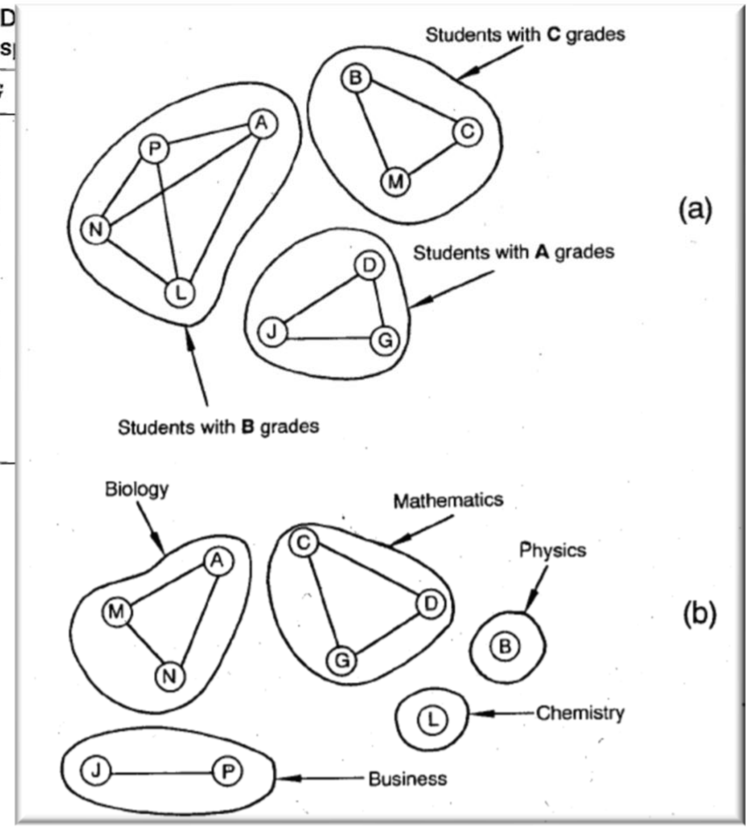

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study of "systemhood" separated from "thinghood"

- 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

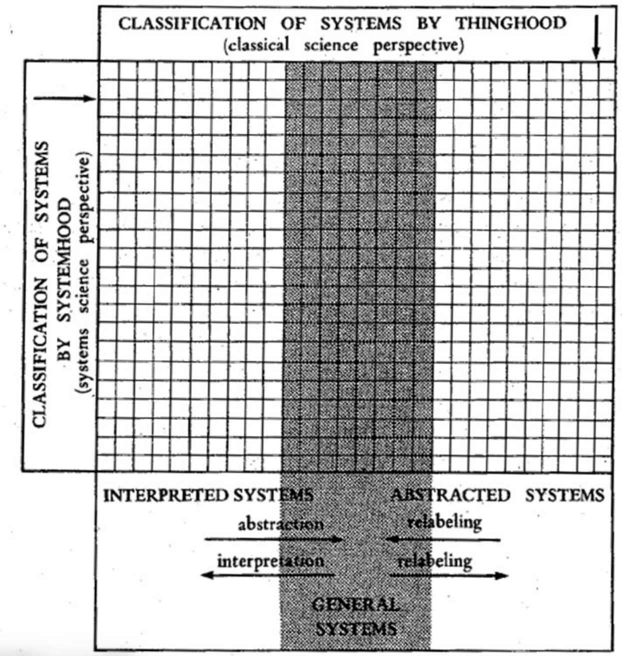


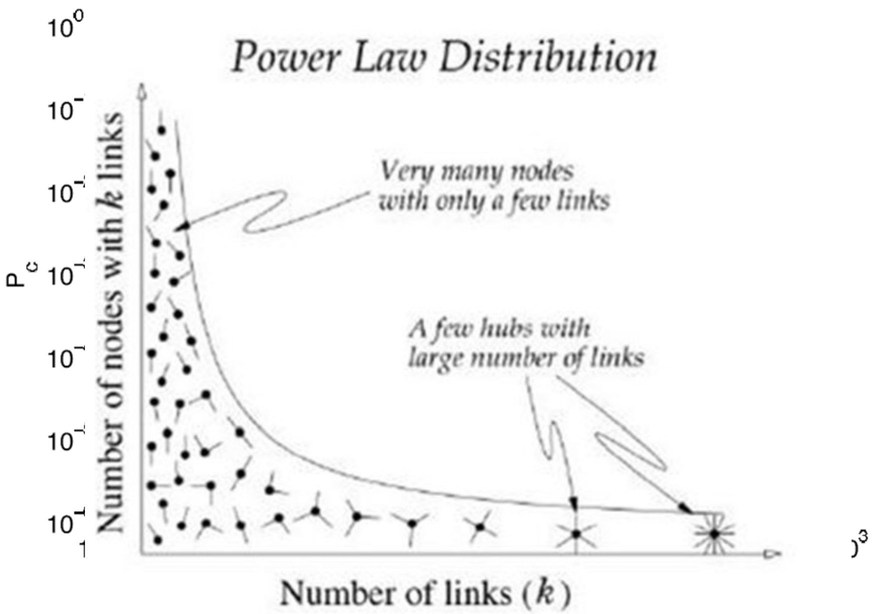
Figure 2.6. Two ways of classifying systems and the role of general systems.

From Klir [2001]

example of general principle of organization

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

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



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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.

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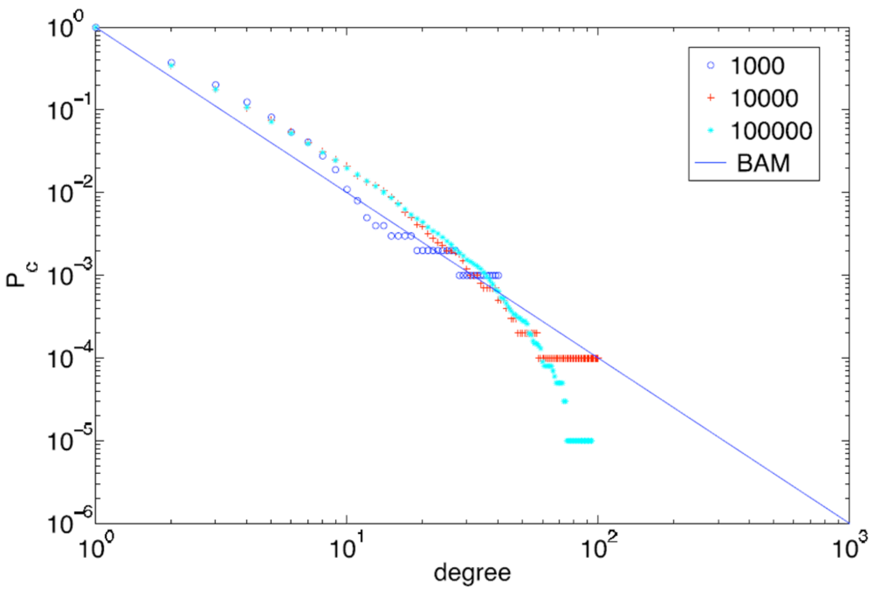

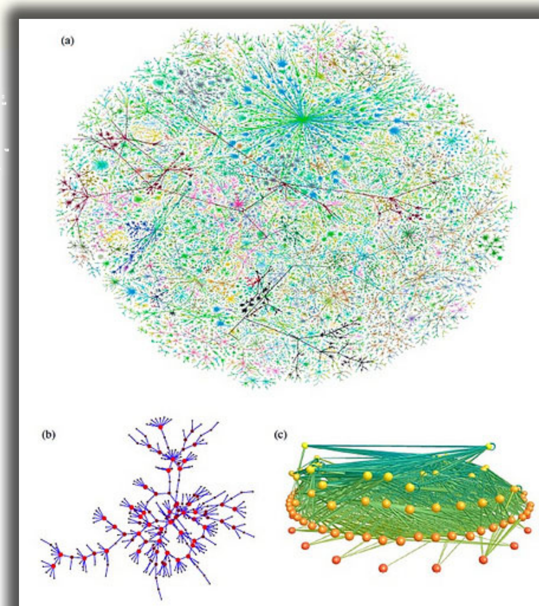

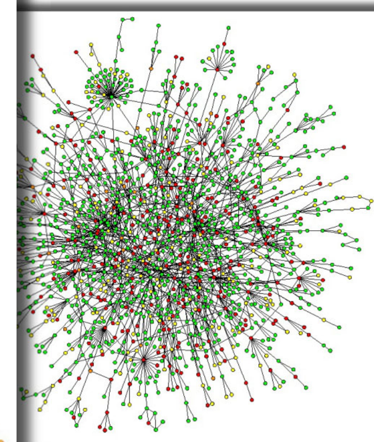

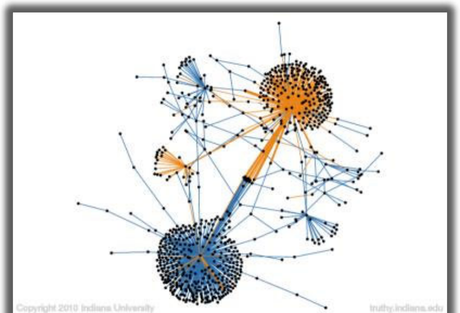

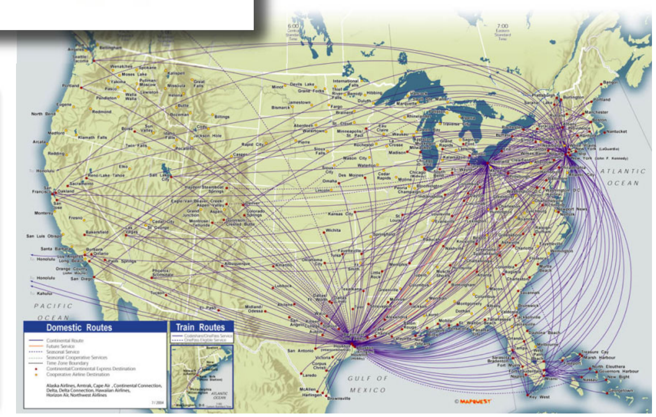

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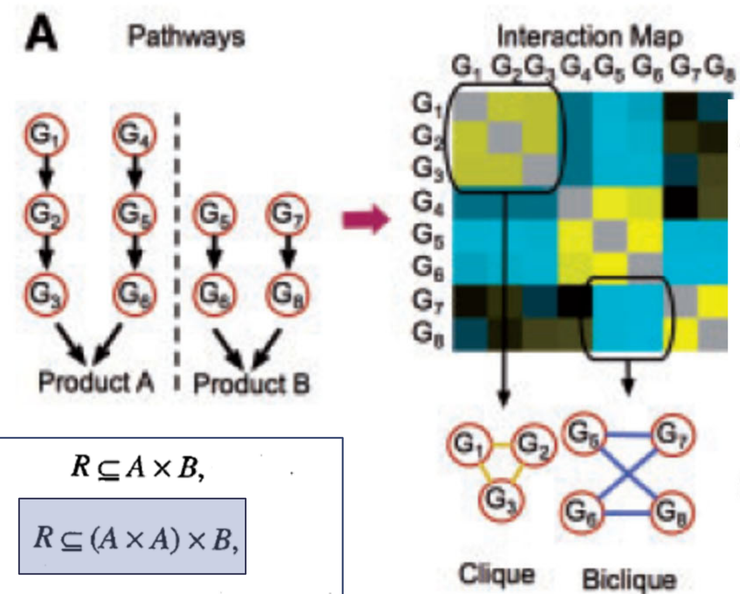
From genetic interaction maps (in yeast)



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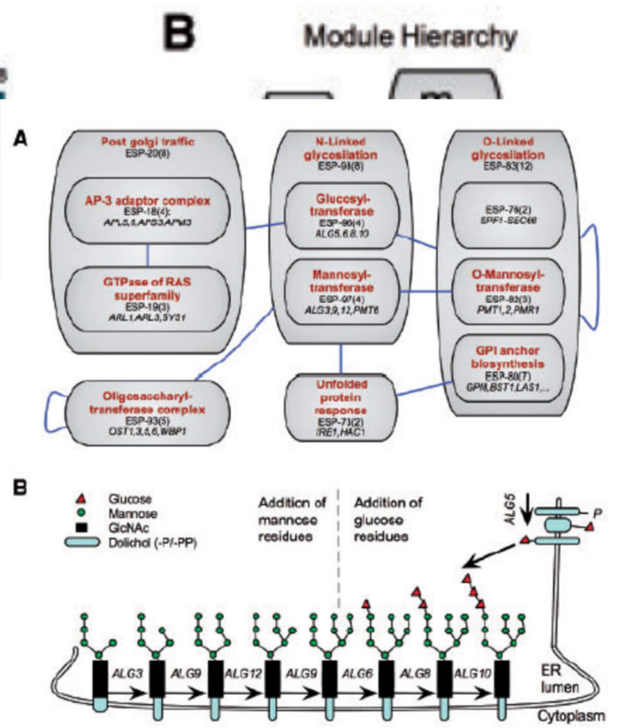
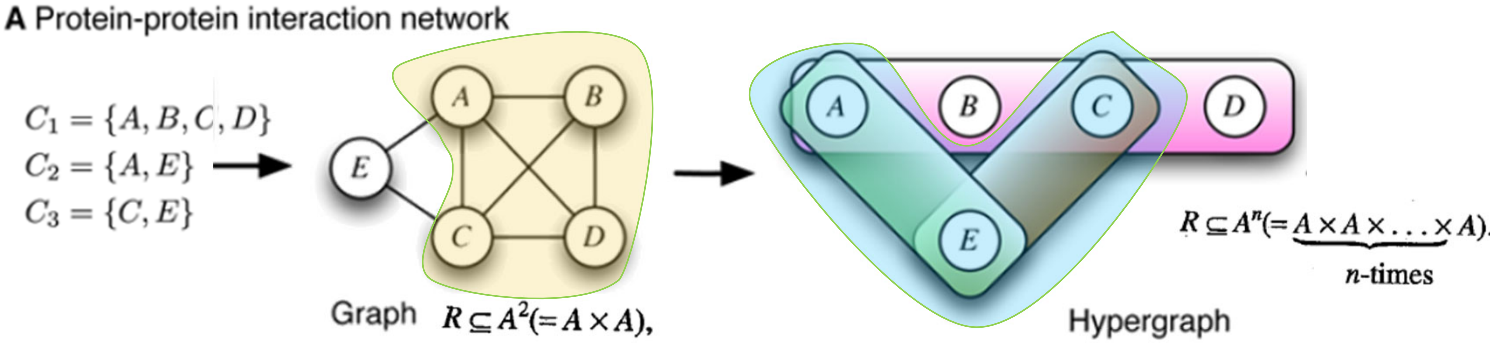


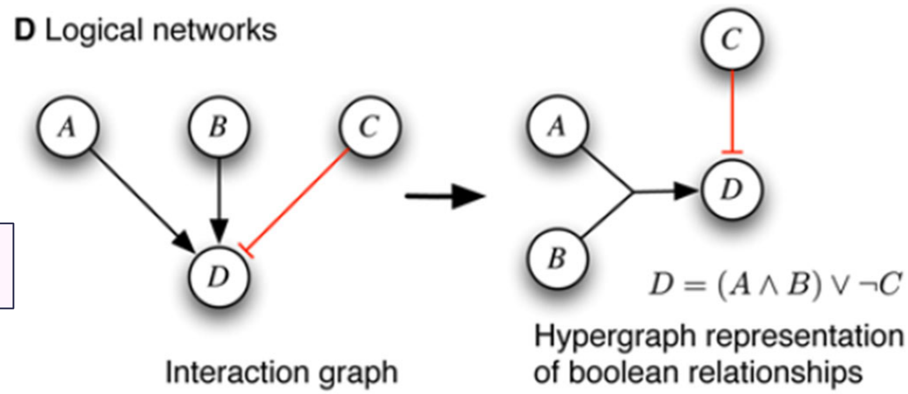
Jaimovich, Aet al. 2010. Modularity and directionality in genetic interaction maps. *Bioinformatics* **26**, no. 12 (June): i228-i236.

lead to different conclusions about underlying multivariate system



Max k-core:
$\{A,B,C,D\}, k = 3$

Max k-core:
$\{A,C,E\}, k = 2$



Separates (linearizes) contributions

Klamt S, Haus U-U, Theis F. [2010]. "Hypergraphs and cellular networks."*PLoS computational biology 5*(5): e1000385.

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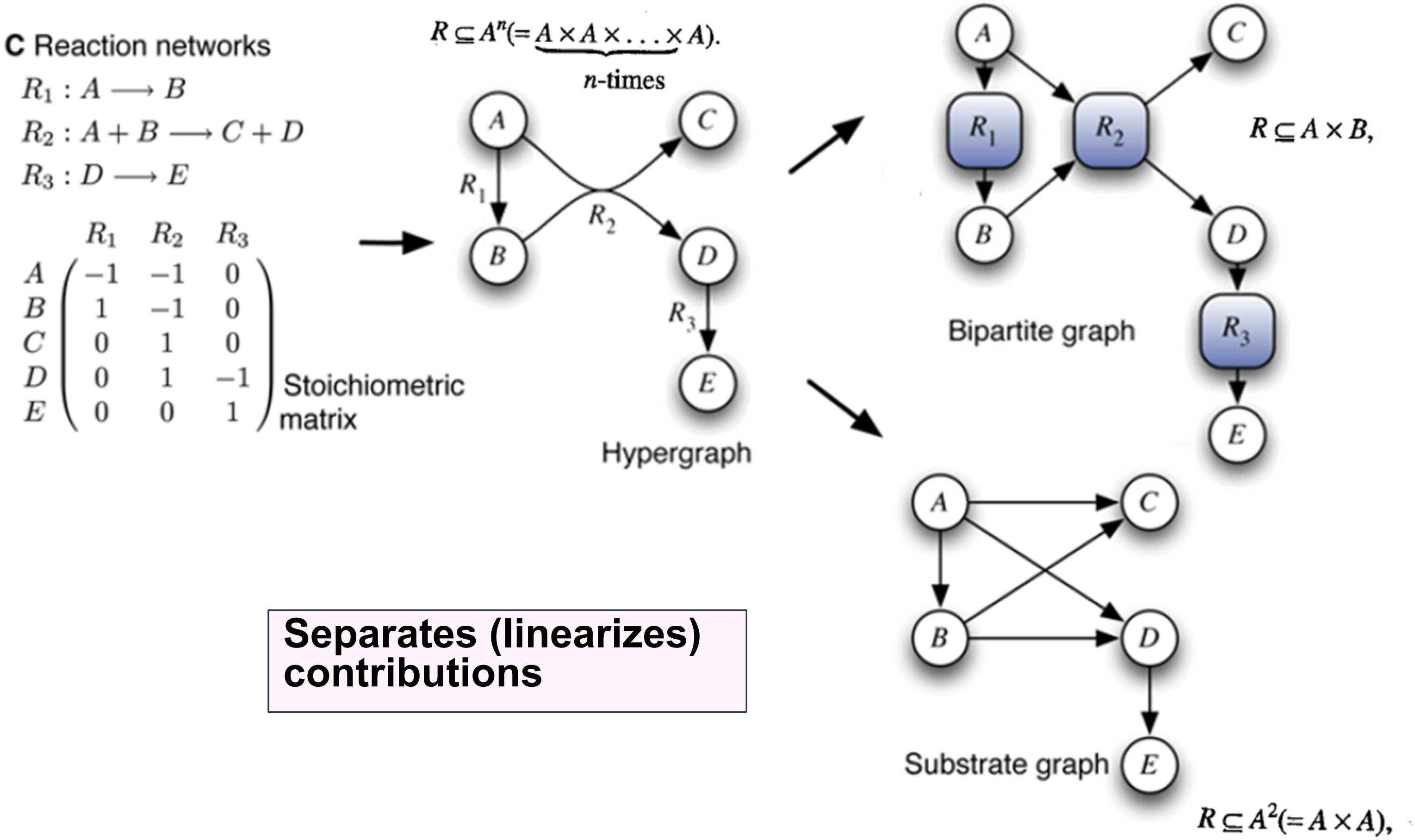

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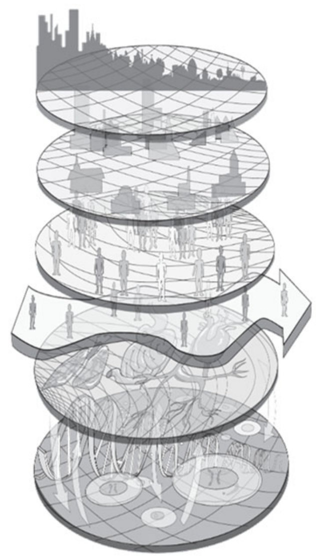
  - defined by specific discernable levels of human experience in nature and society
    - Psychology, Sociology, Political Science, Economics, Physics, Chemistry, Biology, etc
- CNS, systems/computational thinking
  - General-purpose tools and universal laws
    - Search for **general principles** of **organization**
    - Produce machines and tools for all sciences
  - Disciplines are orthogonal to traditional disciplines
    - machine learning, network science, data science & analytics, dynamical systems theory, operations research, etc.
- 2-dimensional science
  - traditional disciplines focus on experimental and observational methods for specific subject matter
  - disciplines of CNS focus on generality of their own methods to any type of data
  - Neither parallel disciplines nor general-purpose methods are sufficient to achieve ***interdisciplinarity***
    - Team culture is necessary
    - E.g. Systems biology, computational biology, computational social science, etc.



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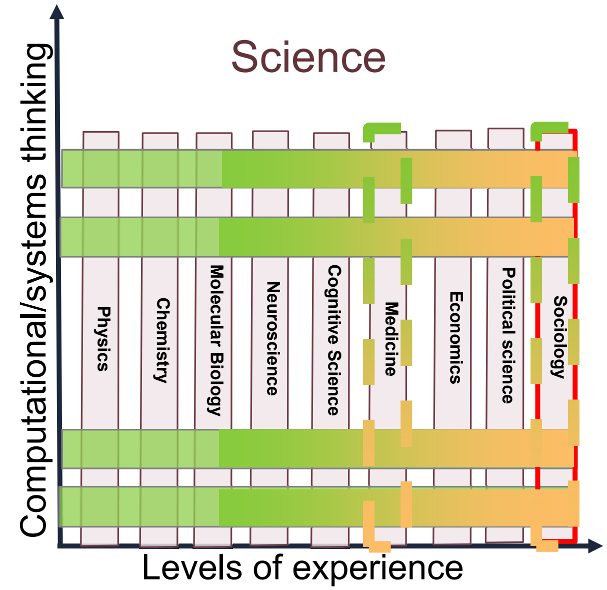

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complex networks & systems thinking

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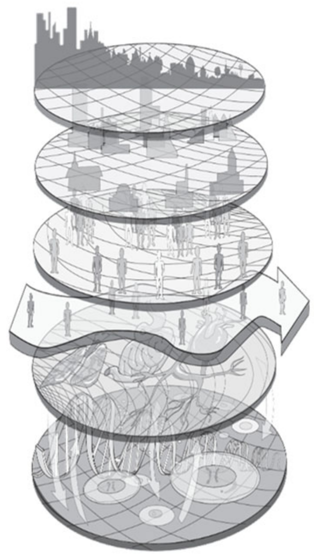

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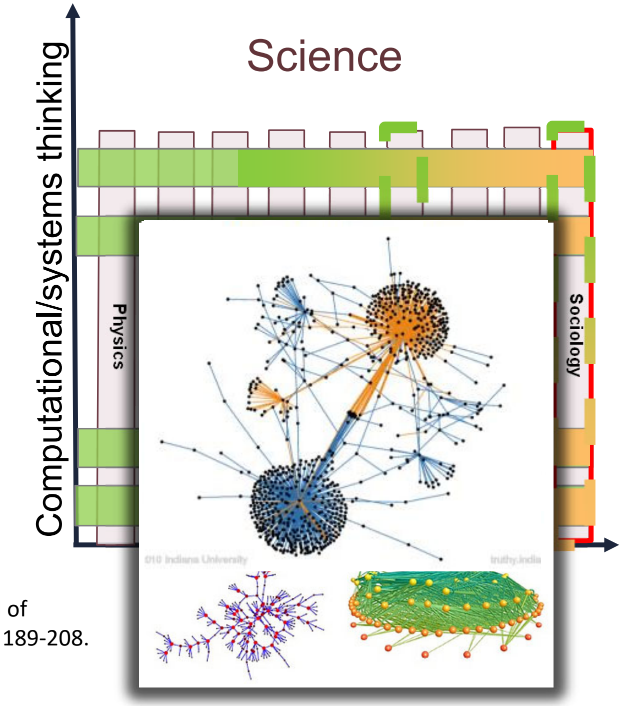

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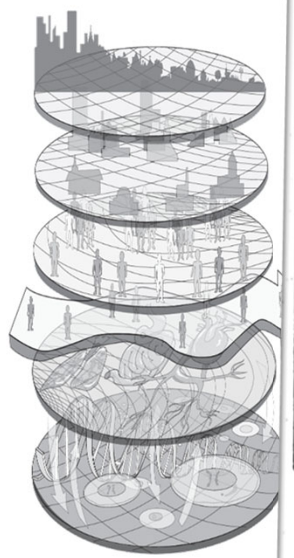

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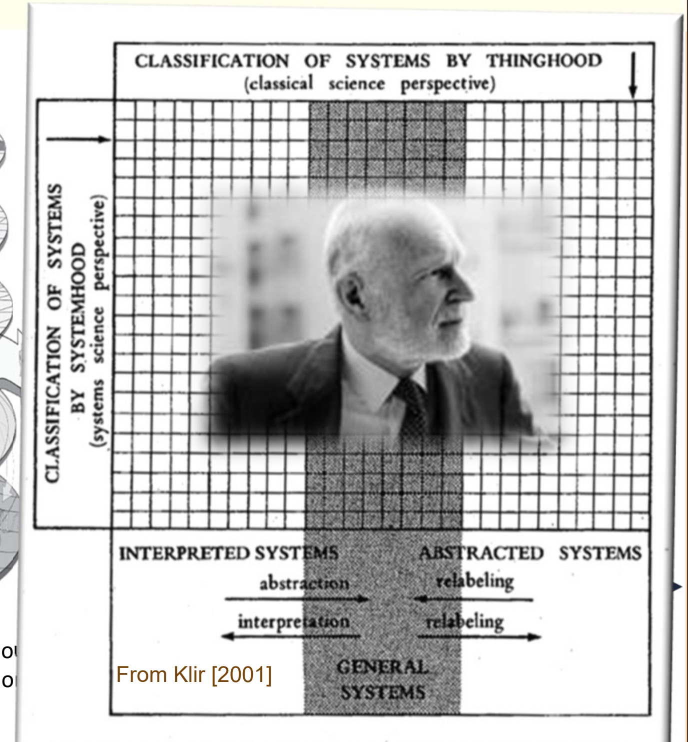


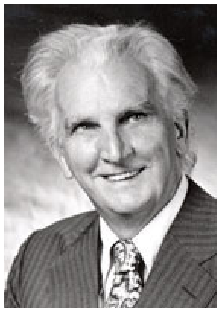
Figure 2.6. Two ways of classifying systems and the role of general systems.

CNS NRT

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
  - Information theory
  - Optimal scheduling and resource allocation (operations research, ISE)
  - dynamical systems, chaos, AI, Alife, machine learning, network science, etc.

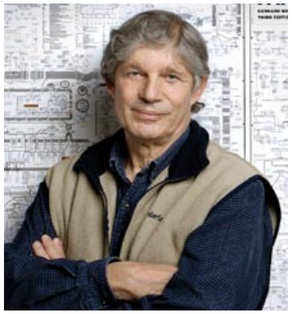
Ludwig von Bertalanffy



Kenneth Boulding

the theoretical biology component

- Systemhood properties of life
  - Search for a language of *generalized circuits*
  - Isomorphy of concepts, laws and models
  - Minimize duplication of efforts across fields
  - Unity of science
- Self-maintaining organization
  - **Dynamics** of regulation and development
    - **Networks** of simple interacting components
  - Dynamics of self-maintenance
    - Autopoiesis, auto-catalytic behavior, autonomy
- Evolutionary systems
  - Encoded production
  - Open-ended evolution
  - “leaky” systems


Stuart Kauffman


Ludwig von Bertalanffy


Howard Pattee

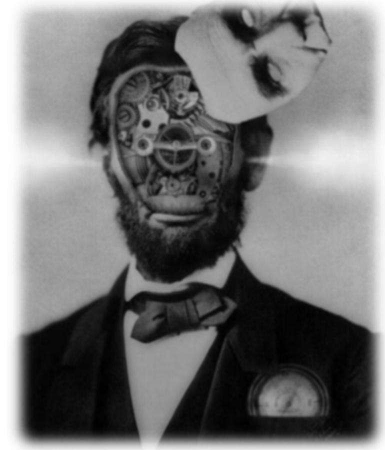

Francisco Varela

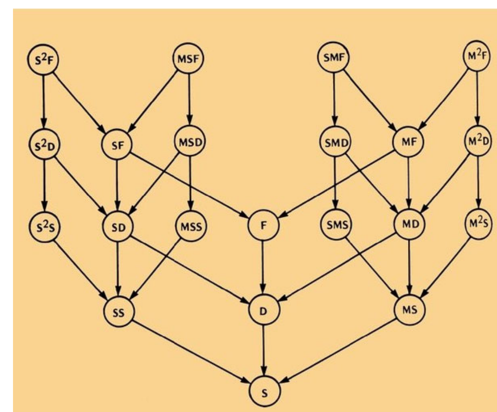
the theoretical biology component

Villa Serbelloni in 1966. Seated, from left to right: Christopher Longuet-Higgins, Ernst Mayr, ‘Wad’ Waddington, Ruth Sager, Brian Goodwin, Doris Manning and John Maynard Smith. Standing: A. G. Cairns-Smith, Rene’ Thom, Sam Devons, John Platt, Howard Pattee, Christopher Zeeman, Dick Lewontin, Karl Kornacker, Paul Lieber, Jack Cowan, Heinrich Kroeger, Lewis Wolpert and Donald Michie. *Towards a Theoretical Biology*, Edited by C.H. Waddington, Edinburgh University Press (1968).

The language lives on

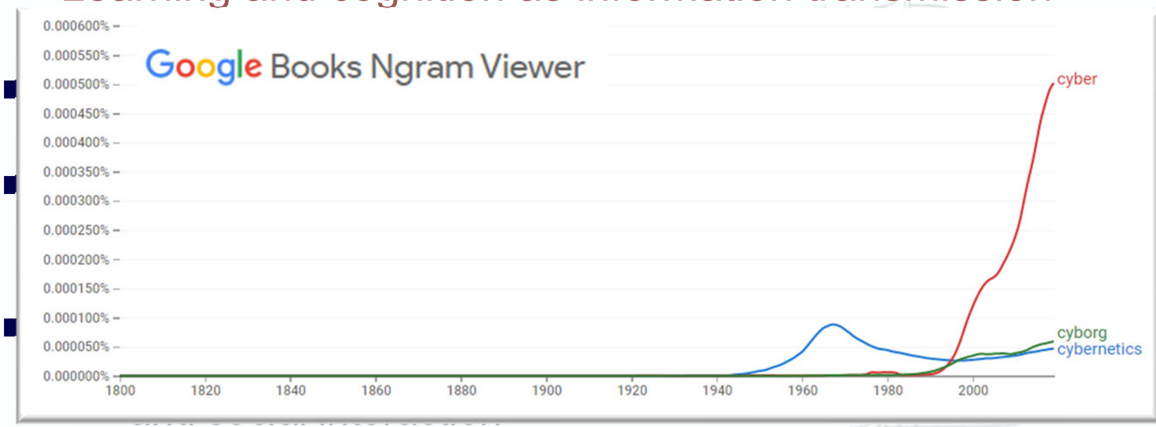
- Learning and cognition as information transmission
  - F … sm
- Con … ogy/model for understanding life and cognition
- Feedback has come to mean information about the outcome of any process or activity
  - No word existed previously in English to convey that concept
- Interaction and organization everywhere
  - Attention shifted from individualism and cause & effect, to circular causation and social interaction
- “Programmed” behavior
- Society and organisms as (general) systems
- Wiener’s prediction of a second industrial revolution centered on communication, control, computation, information, and organization was correct
  - Abundance of technology and mass production of communication devices
    - Grew out of the ideas first reported by the cyberneticians
  - Many disciplines are an offspring of cybernetics





The language lives on

- Learning and cognition as information transmission



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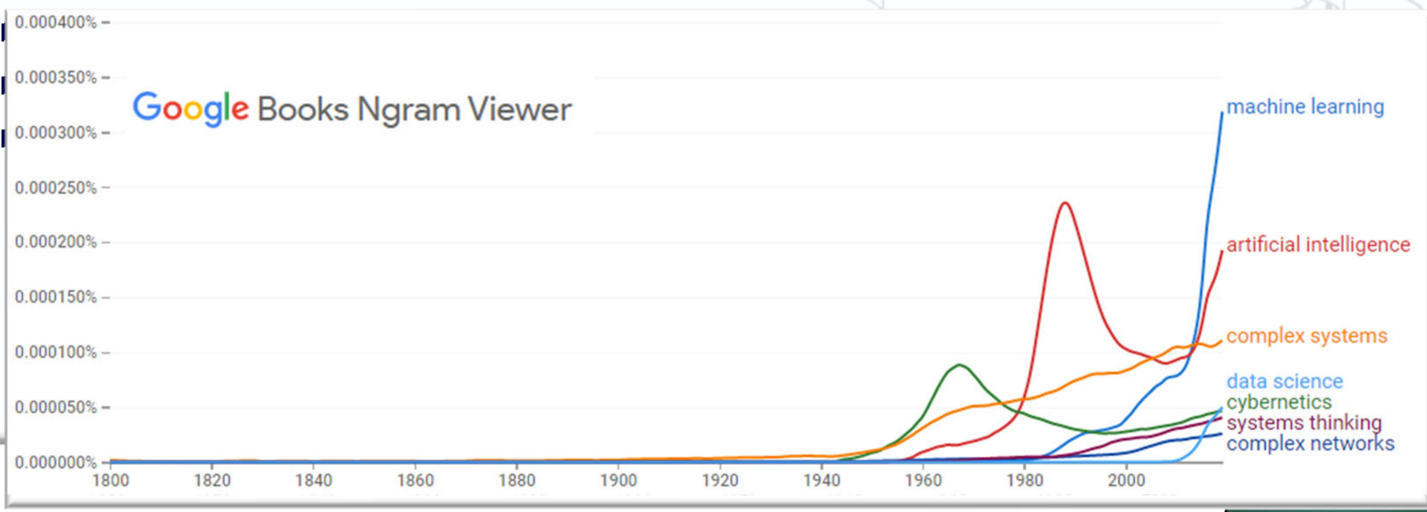

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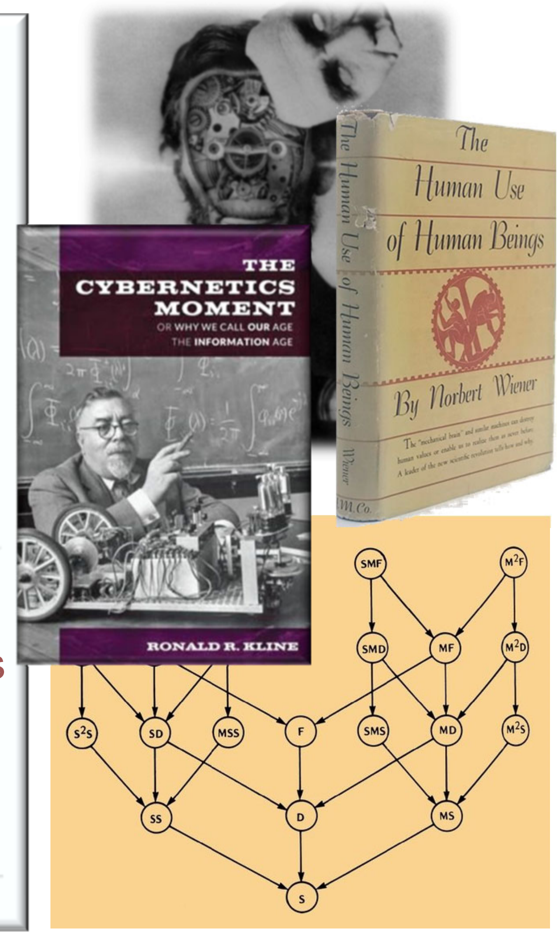

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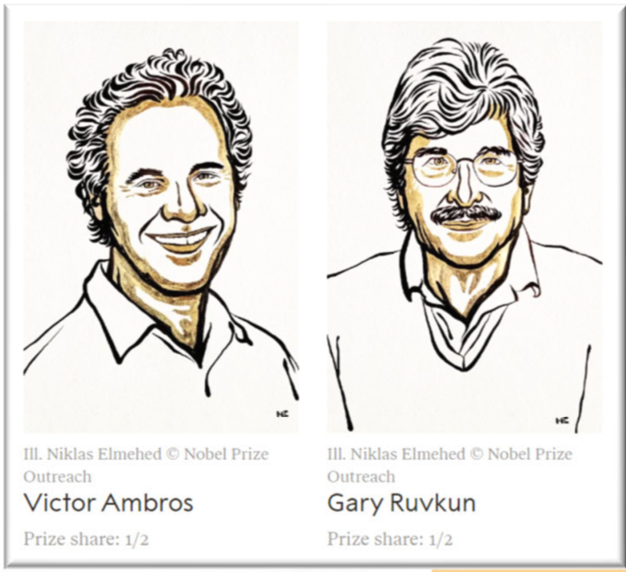
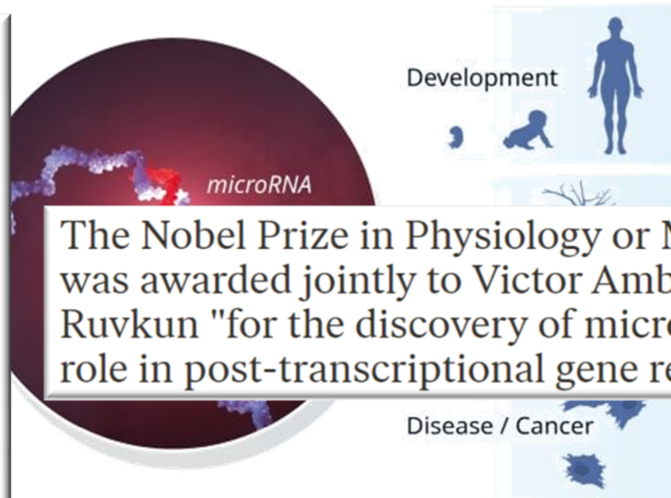
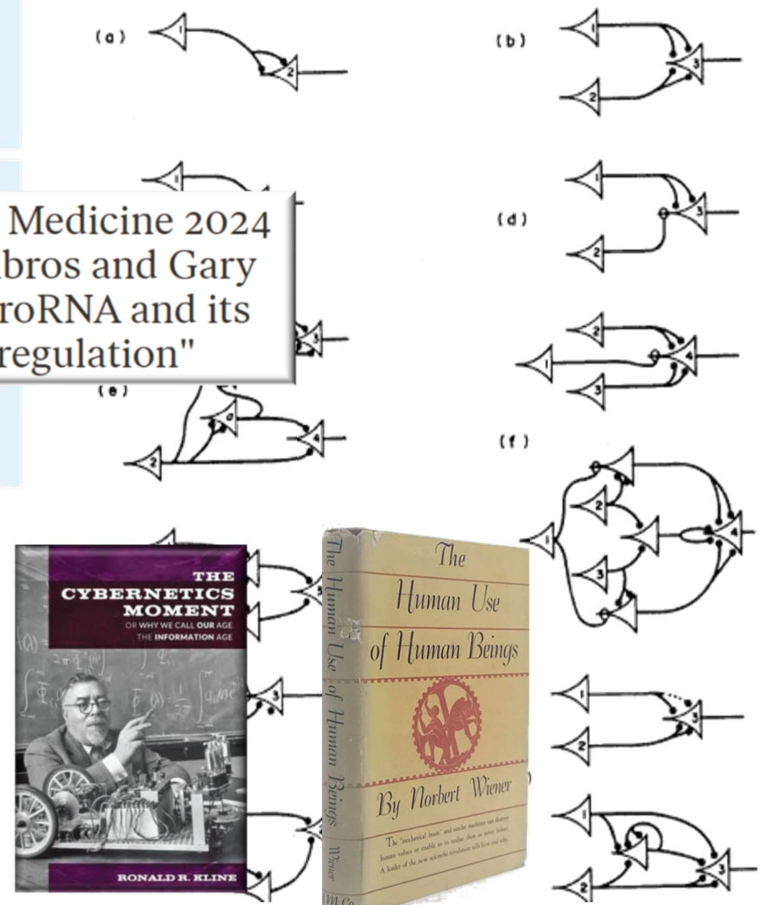
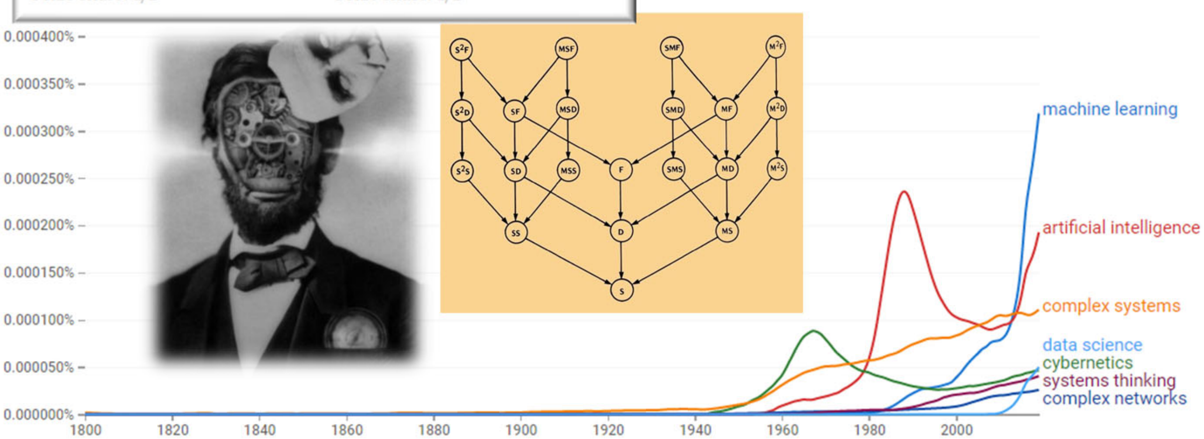




The Nobel Prize in Physiology or Medicine 2024 was awarded jointly to Victor Ambros and Gary Ruvkun "for the discovery of microRNA and its role in post-transcriptional gene regulation"





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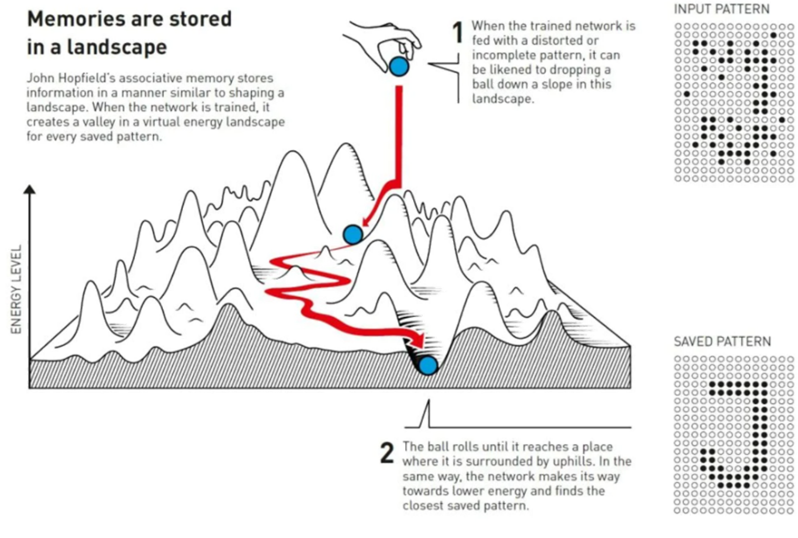
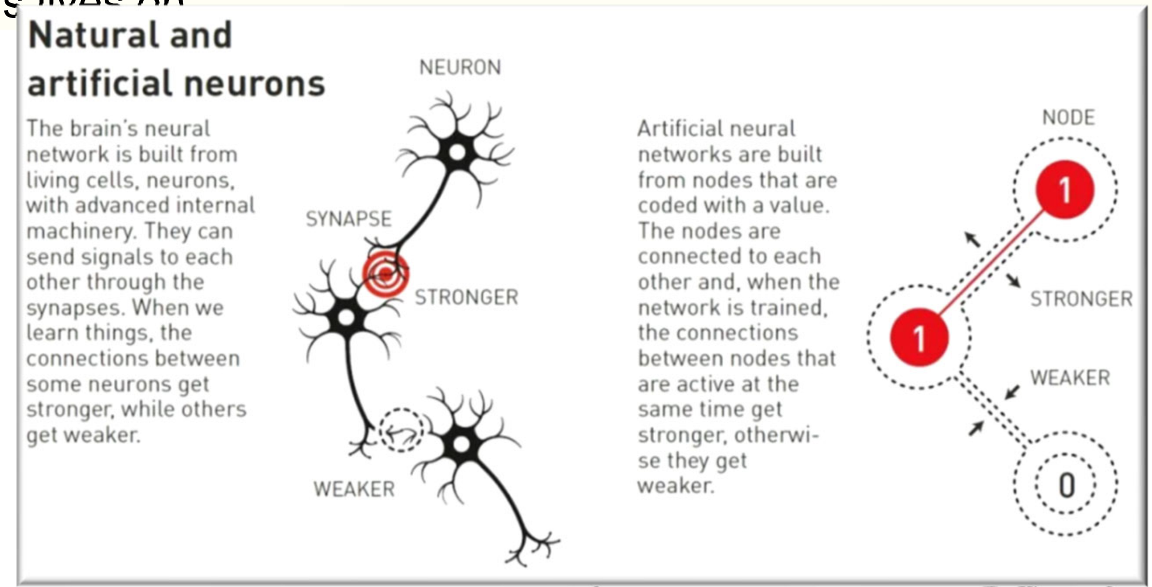
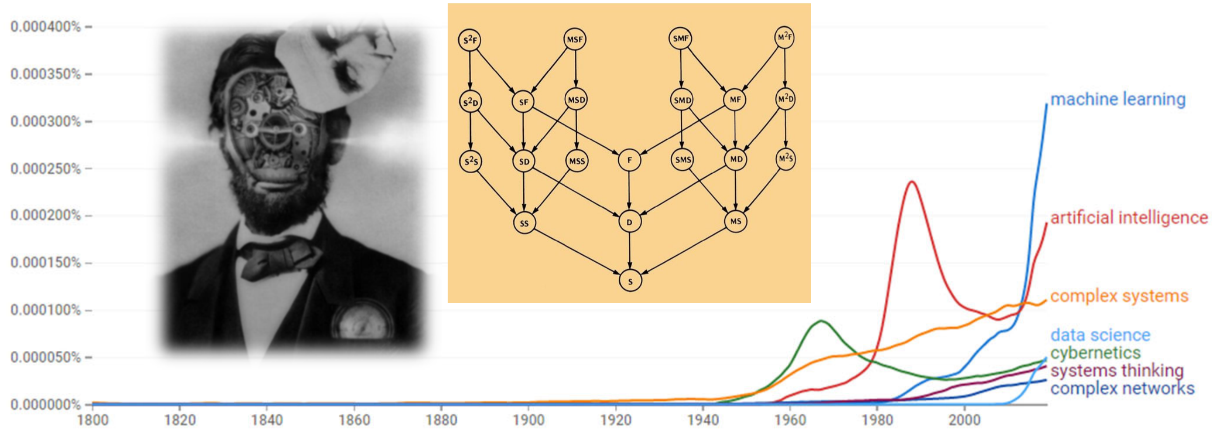
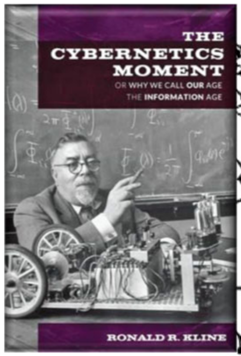
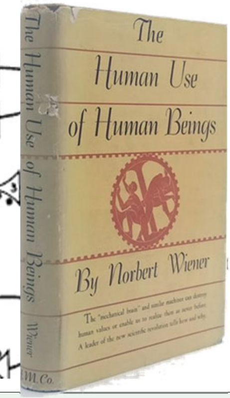


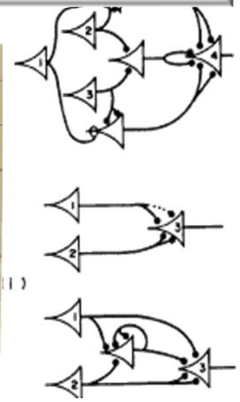
© Johan Jarnestad/The Royal Swedish Academy of Sciences











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The Nobel Prize in Physics 2024

John Hopfield

"for foundational discoveries and inventions that enable machine learning with artificial neural networks"

John Hopfield. Ill. Niklas Elmehed © Nobel Prize Outreach

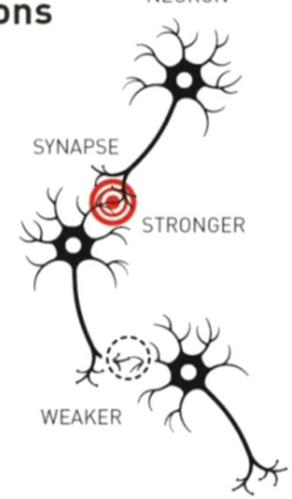
Geoffrey Hinton

"for foundational discoveries and inventions that enable machine learning with artificial neural networks"

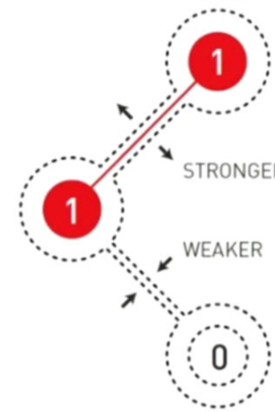
Geoffrey Hinton. Ill. Niklas Elmehed © Nobel Prize Outreach

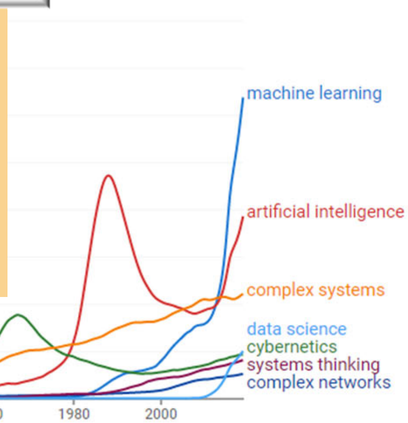
Natural and artificial neurons

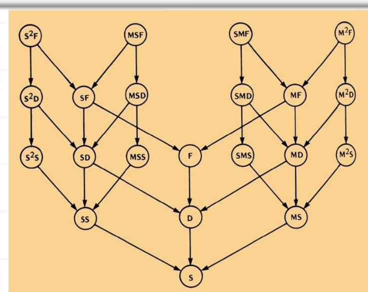
The brain's neural network is built from living cells, neurons, with advanced internal machinery. They can send signals to each other through the synapses. When we learn things, the connections between some neurons get stronger, while others get weaker.

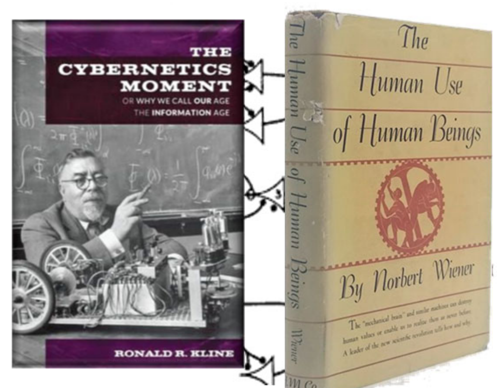


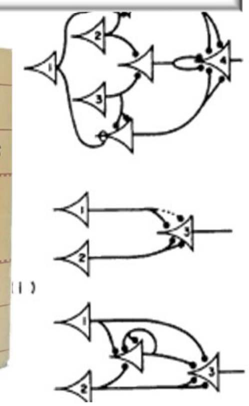
Artificial neural networks are built from nodes that are coded with a value. The nodes are connected to each other and, when the network is trained, the connections between nodes that are active at the same time get stronger, otherwise they get weaker.











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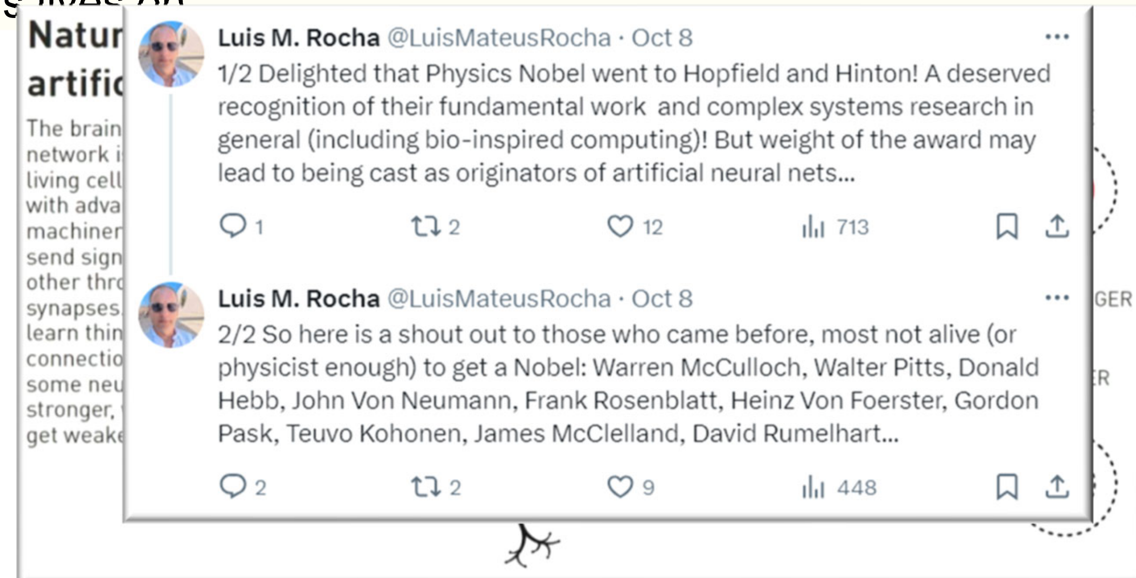

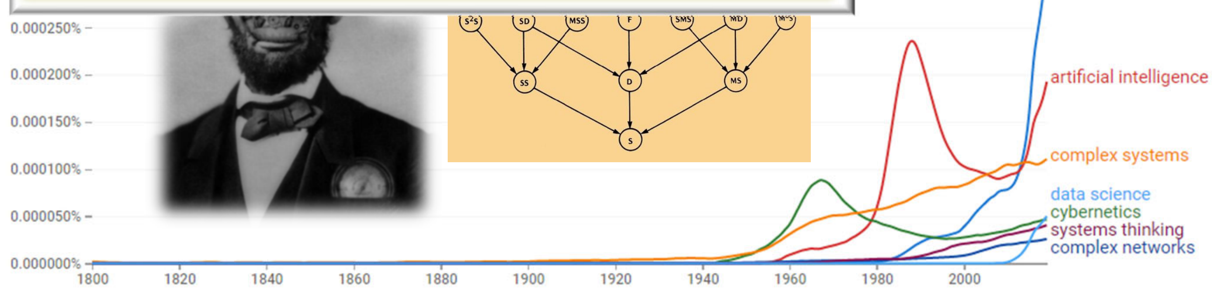

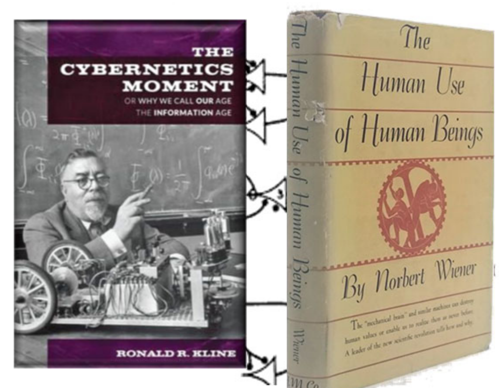

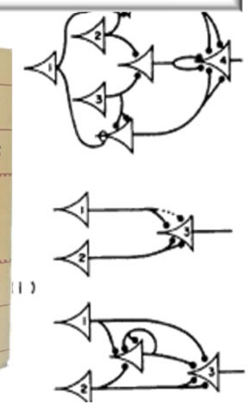

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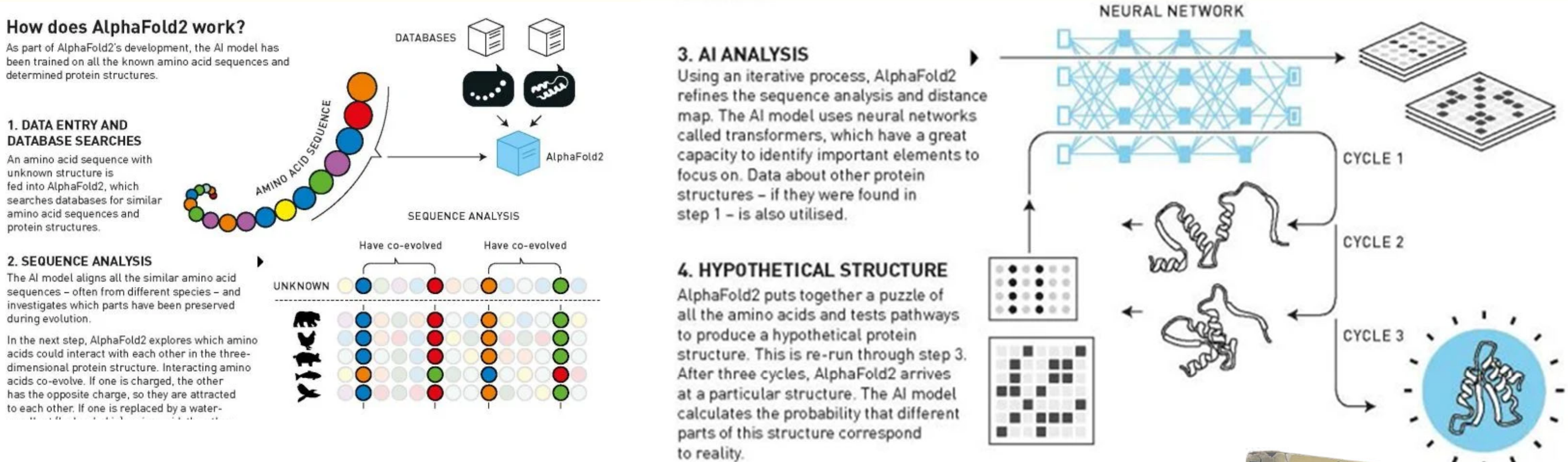

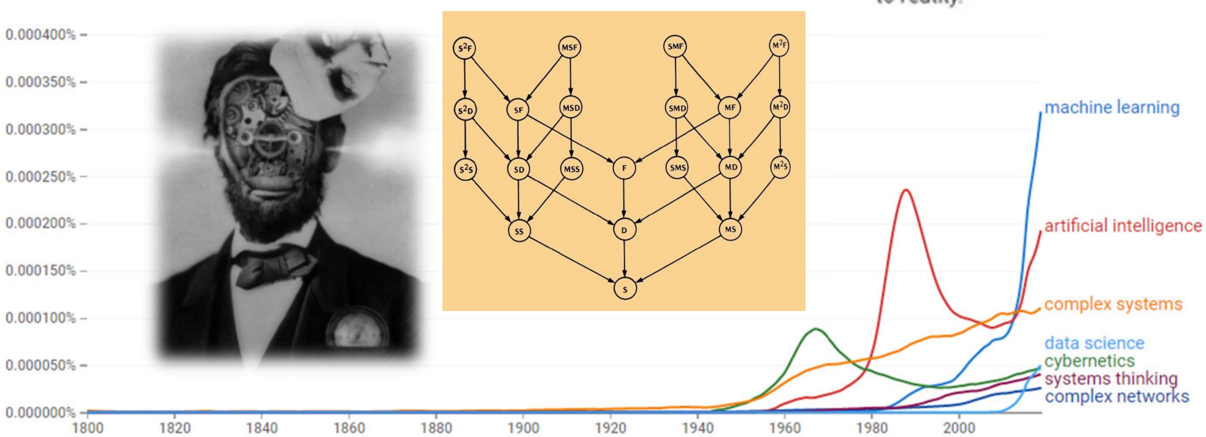

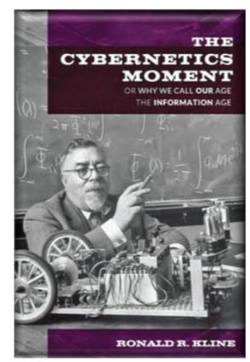

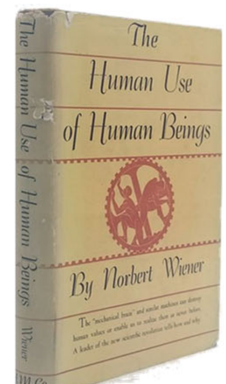

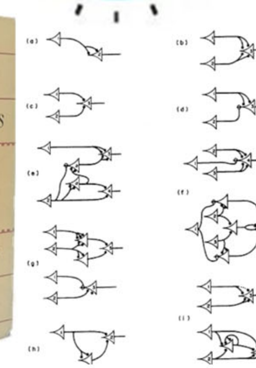

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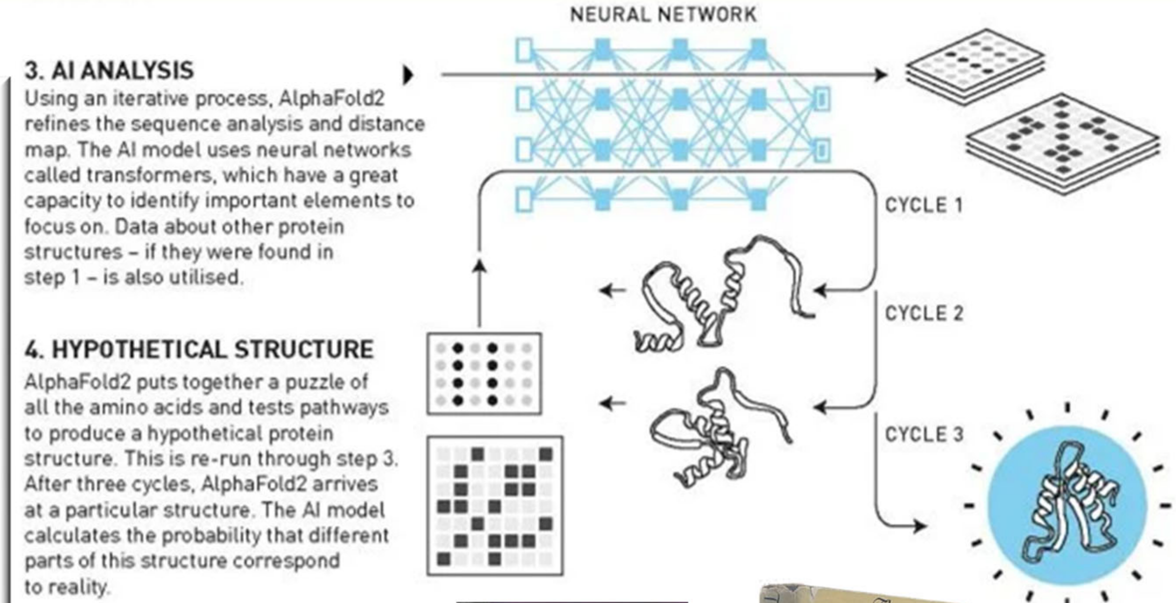

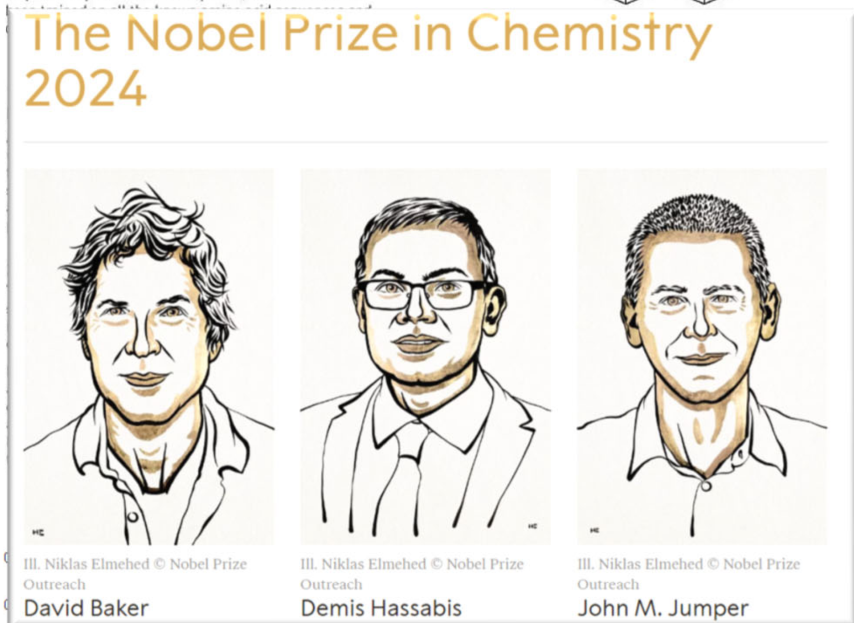

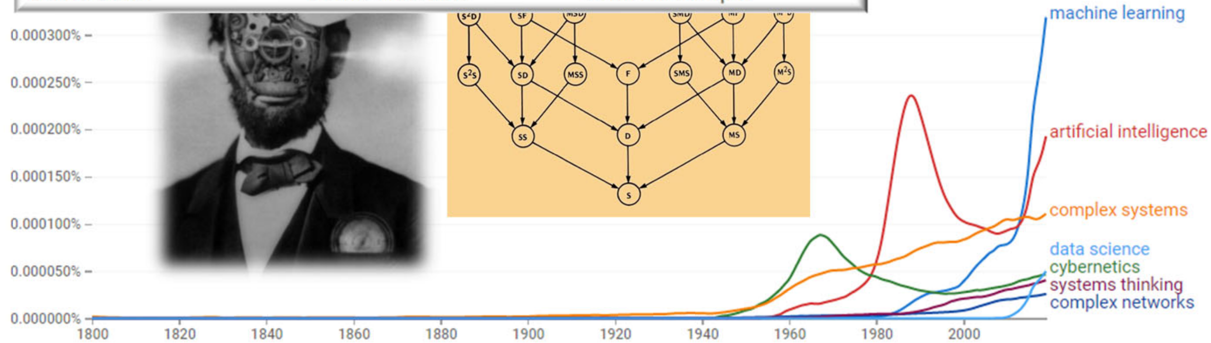

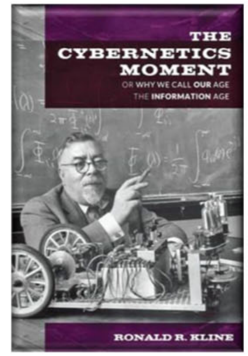

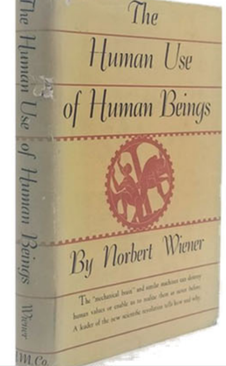

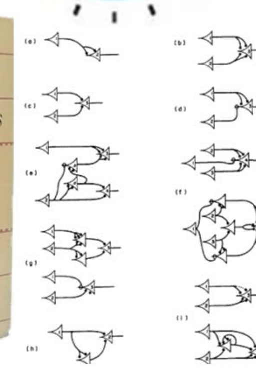

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