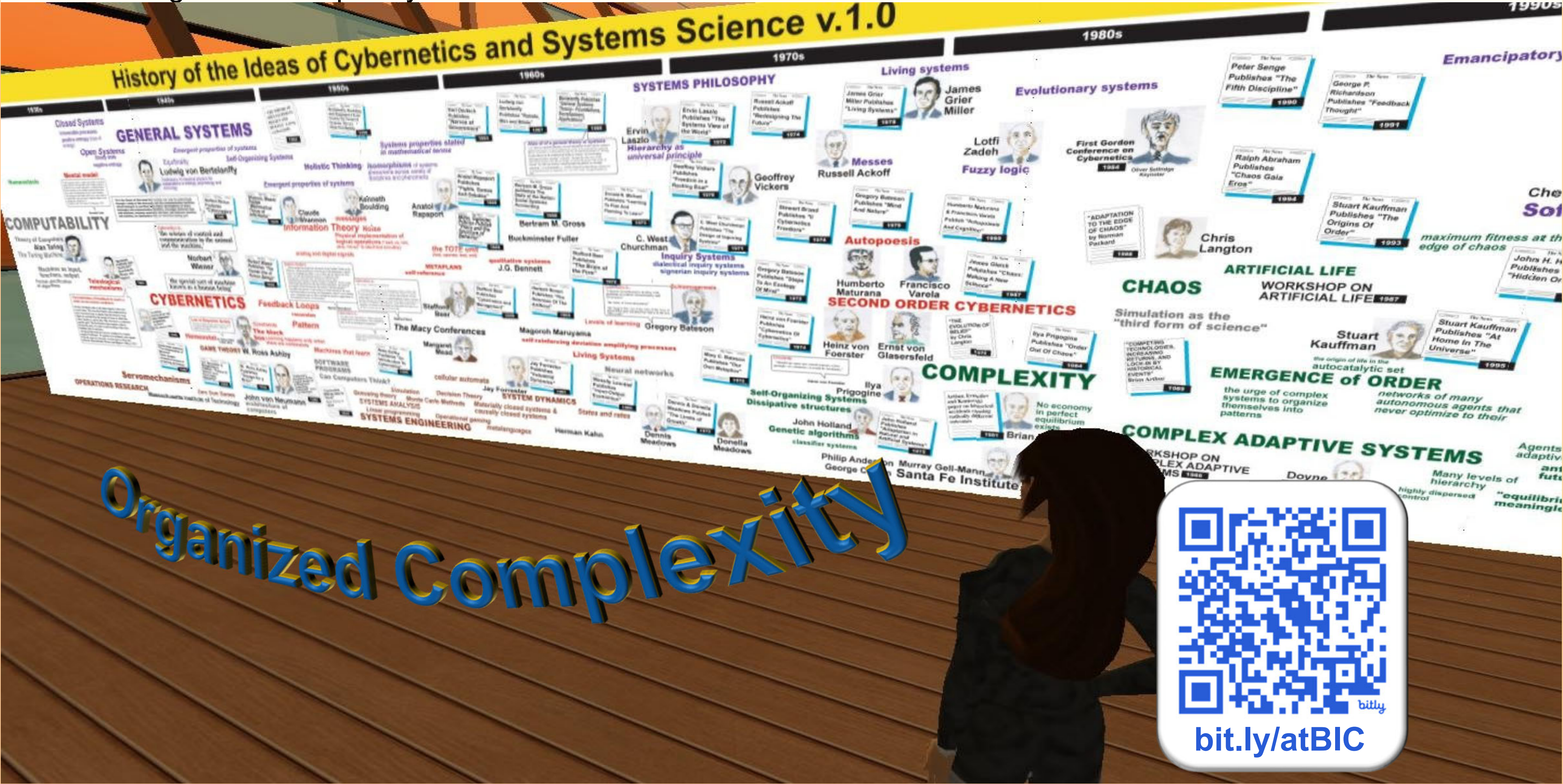
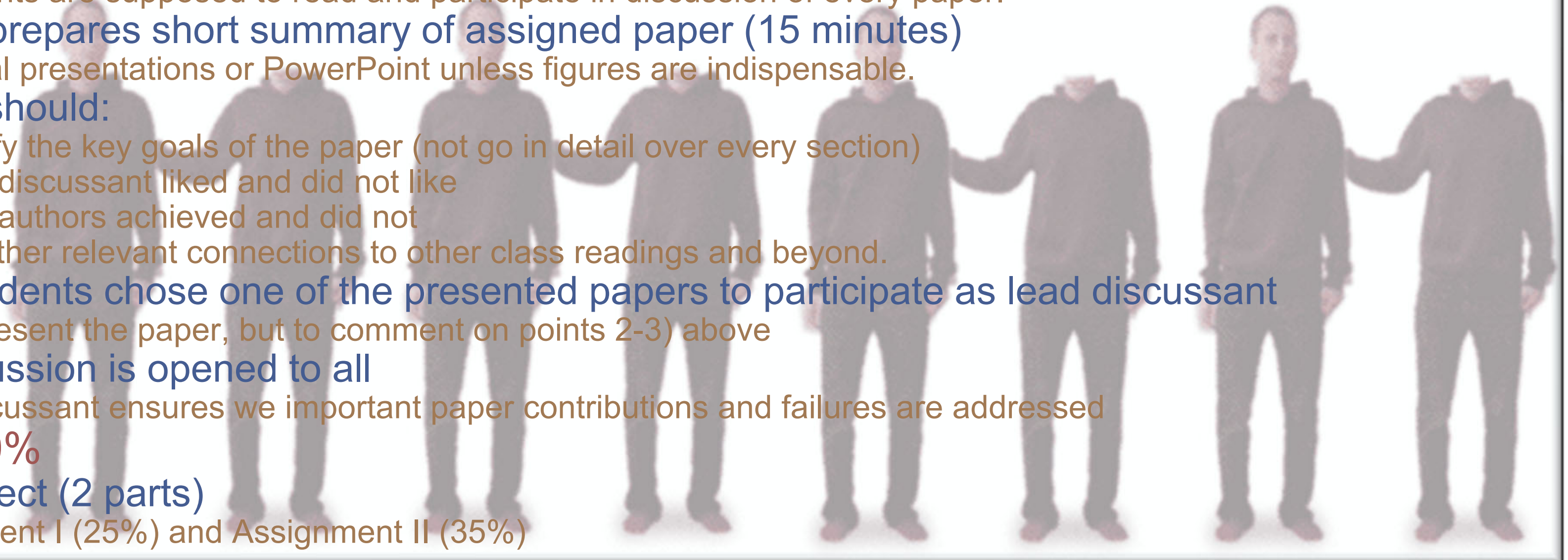
lecture 9: organized complexity



bit.ly/atBIC

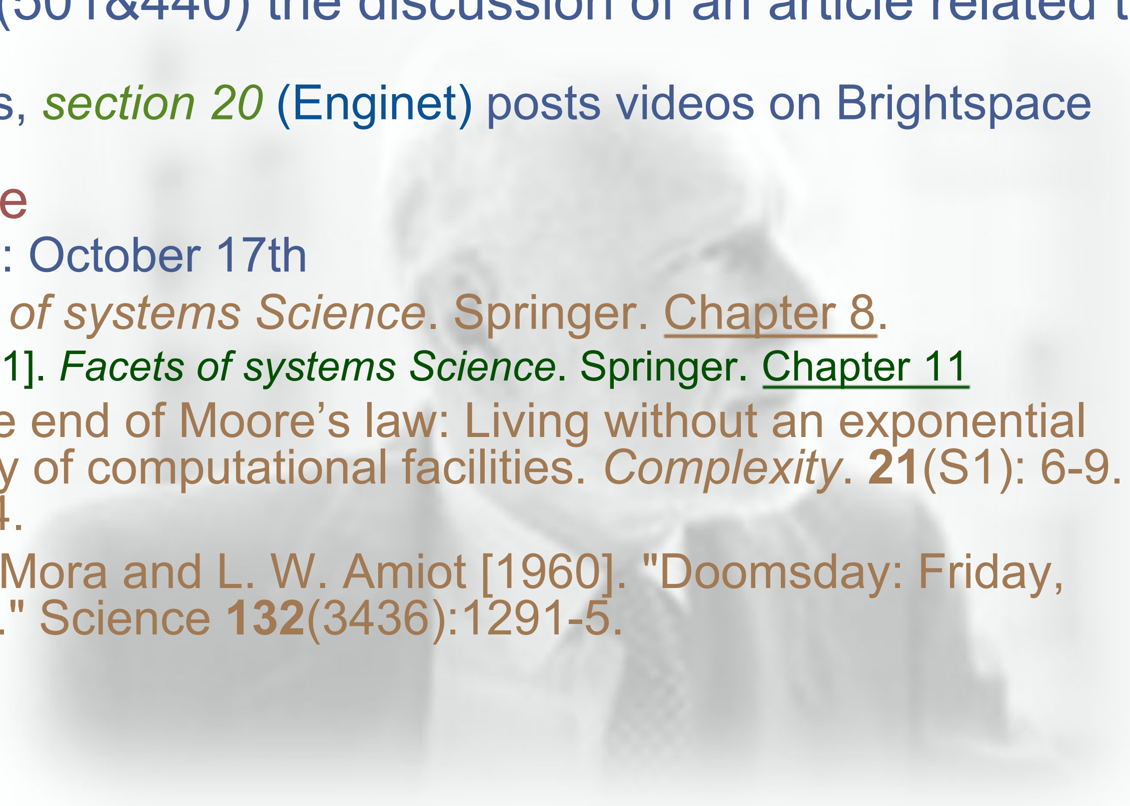
evaluation



- 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%)

rocha@binghamton.edu
casci.binghamton.edu/academics/ssie501

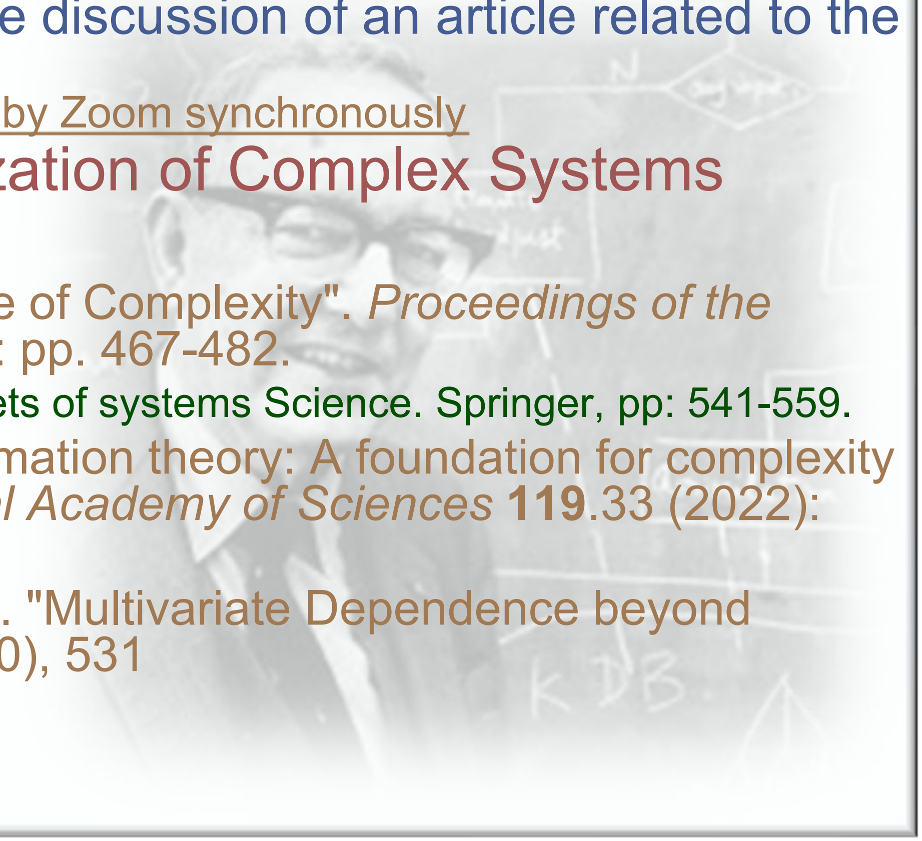
next readings (check brightspace)



- 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)
- Module 2: Systems Science
    - Discussion Set 4 (Group 4): October 17th
        - Klir, G.J. [2001]. *Facets of systems Science*. Springer. Chapter 8.
            - Optional: Klir, G.J. [2001]. *Facets of systems Science*. Springer. Chapter 11
        - Schuster, P. (2016). The end of Moore's law: Living without an exponential increase in the efficiency of computational facilities. *Complexity*. **21**(S1): 6-9. DOI 10.1002/cplx.21824.
        - Von Foerster, H., P. M. Mora and L. W. Amiot [1960]. "Doomsday: Friday, November 13, AD 2026." Science **132**(3436):1291-5.
- Future Modules
    - See brightspace

course outlook

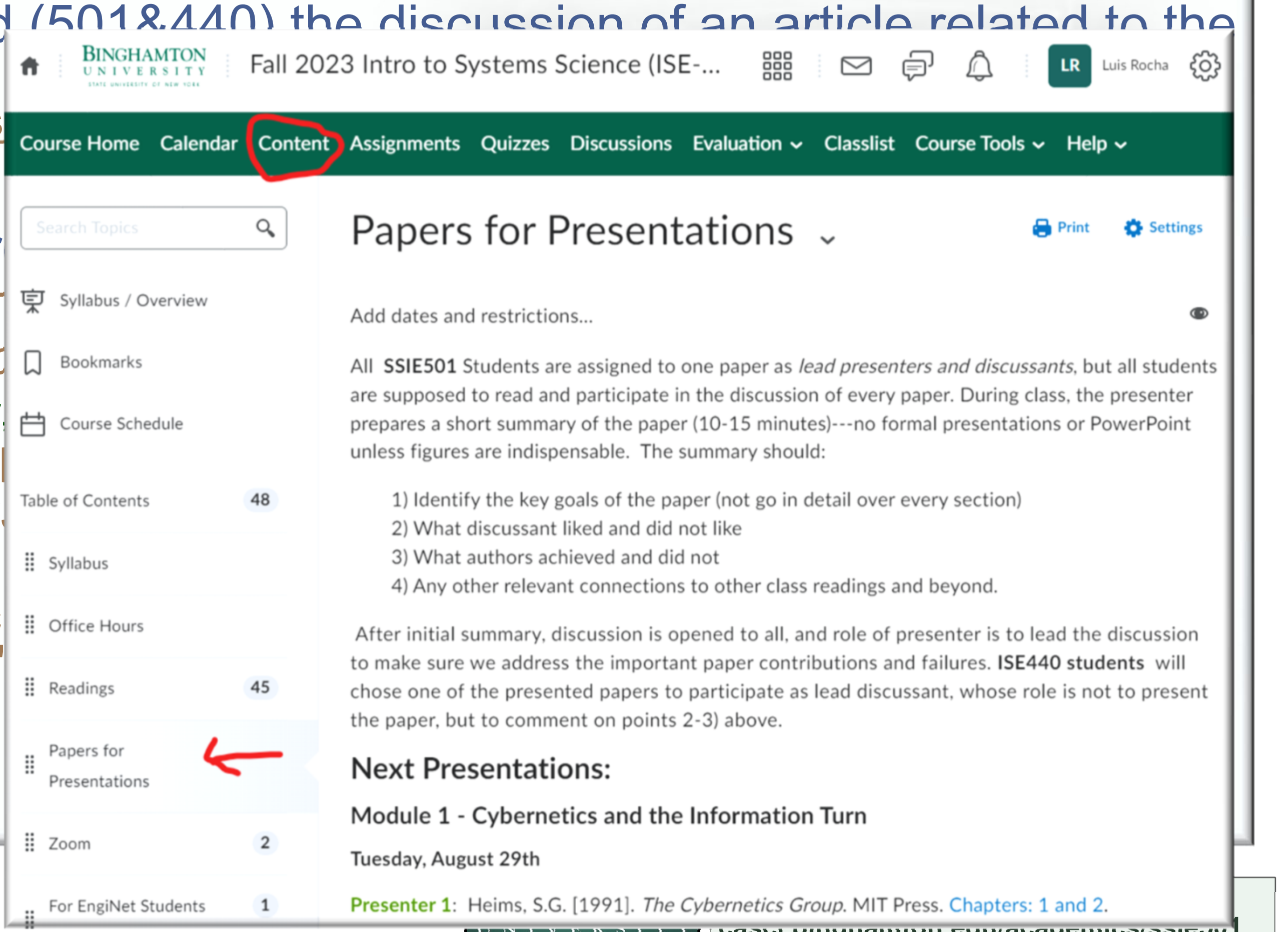
more upcoming readings (check brightspace)



- Paper Presentation: 20%
  - Present (501) and lead (501&440) the discussion of an article related to the class materials
    - Enginet students post/send video or join by Zoom synchronously
- Module 3: Module 3 - The Organization of Complex Systems
  - Discussion Set 5 (Group 5)
    - Simon, H.A. [1962]. "The Architecture of Complexity". *Proceedings of the American Philosophical Society*, **106**: pp. 467-482.
      - Also available in Klir, G.J. [2001]. Facets of systems Science. Springer, pp: 541-559.
    - Golan, Amos, and John Harte. "Information theory: A foundation for complexity science." *Proceedings of the National Academy of Sciences* **119**.33 (2022): e2119089119.
    - James, R., and Crutchfield, J. (2017). "Multivariate Dependence beyond Shannon Information". *Entropy*, **19**(10), 531
  - 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
    - Enginet students post/s
- Module 3: Module 3 -
  - Discussion Set 5 (Gr
    - Simon, H.A. [1962]. "
      American Philosophic
      - Also available in Klir
    - Golan, Amos, and Jo
      science." *Proceeding*
      e2119089119.
    - James, R., and Crutc
      Shannon Information'
  - See brightspace



Papers for Presentations

Add dates and restrictions...

All **SSIE501** Students are assigned to one paper as *lead presenters and discussants*, but all students are supposed to read and participate in the discussion of every paper. During class, the presenter prepares a short summary of the paper (10-15 minutes)---no formal presentations or PowerPoint unless figures are indispensable. The 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.

After initial summary, discussion is opened to all, and role of presenter is to lead the discussion to make sure we address the important paper contributions and failures. **ISE440 students** will chose one of the presented papers to participate as lead discussant, whose role is not to present the paper, but to comment on points 2-3) above.

Next Presentations:

Module 1 - Cybernetics and the Information Turn

Tuesday, August 29th

Presenter 1: Heims, S.G. [1991]. *The Cybernetics Group*. MIT Press. Chapters: 1 and 2.

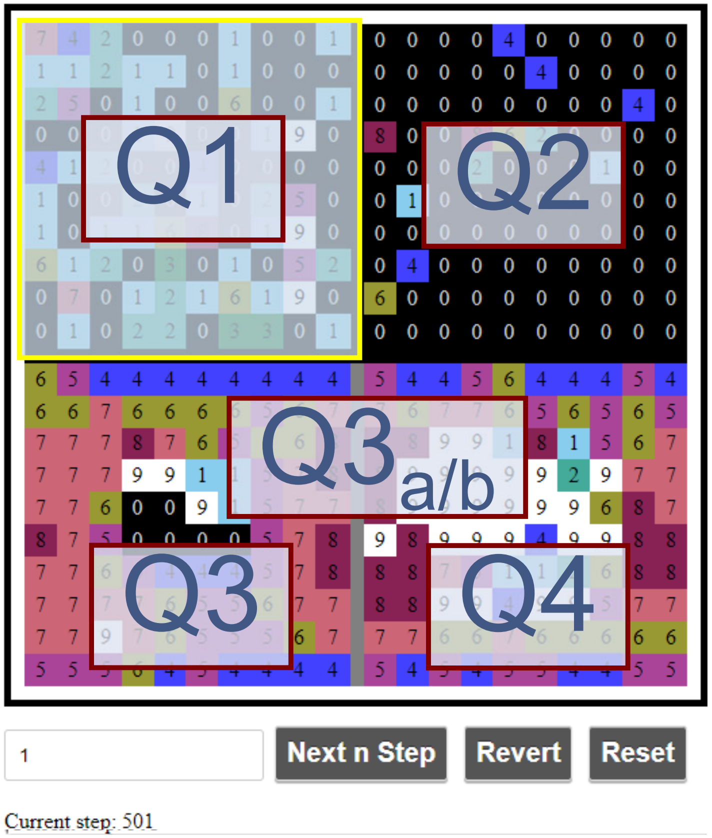
Second assignment

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.

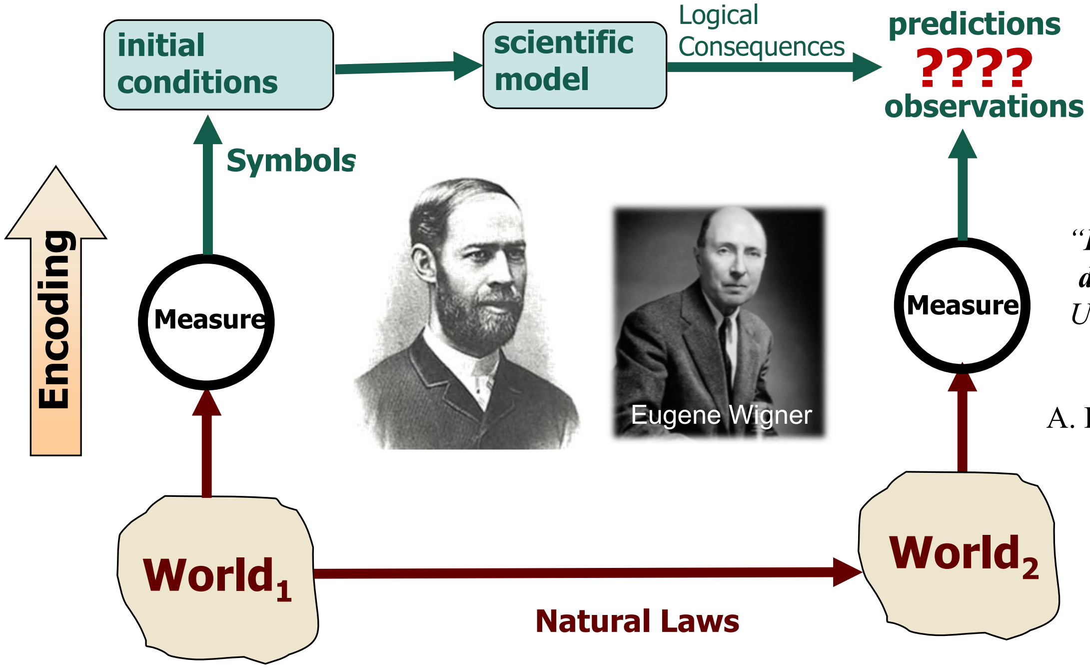
- Focus on uncovering quadrants
  - using data collection, descriptive patterns & statistics, and induction.
- Propose a formal model or algorithm of what each quadrant is doing.
  - Analyze, using deduction, the behavior of this algorithm.

What is it!!??



Current step: 501

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."

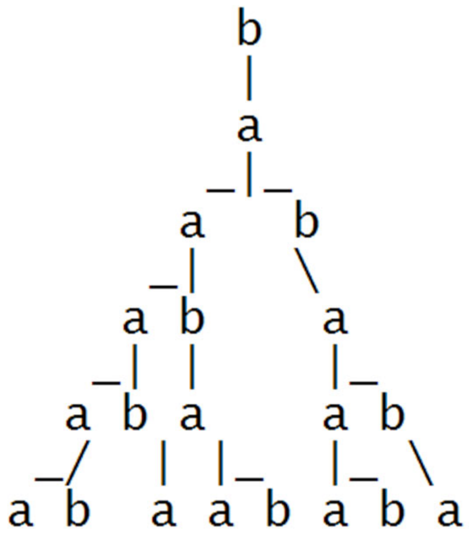
C. Shalizi [2024] "Opening a closed box." In: *Foundational Papers in Complexity Science, D.C.* Krakauer (Ed). pp. 149–169

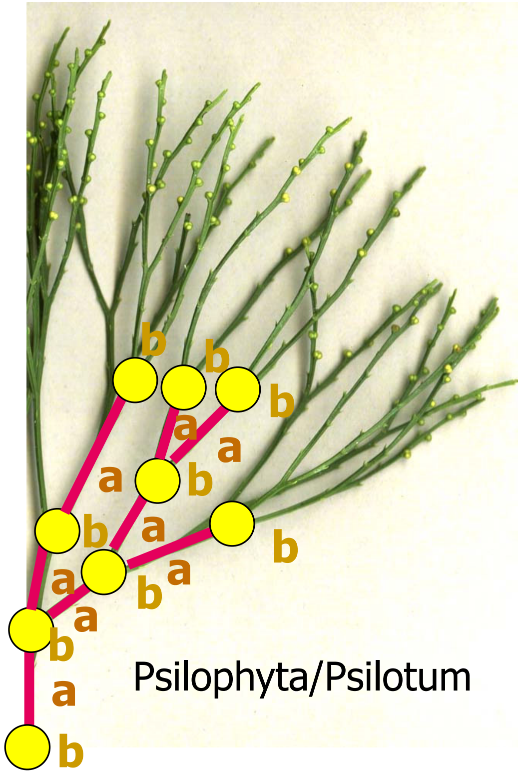
"The most direct and in a sense the most important problem which our conscious knowledge of nature should enable us to solve is the ***anticipation of future events***, so that we may arrange our present affairs in accordance with such anticipation". (Hertz, 1894)

What about our plant?

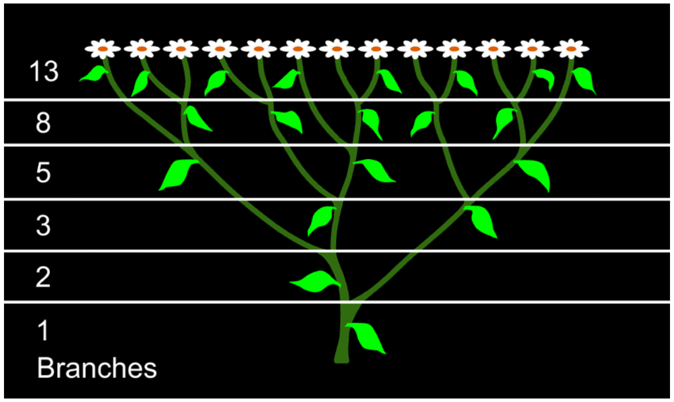
branching as a model (a general system?)

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





Psilophyta/Psilotum



Aristid Lindenmeyer

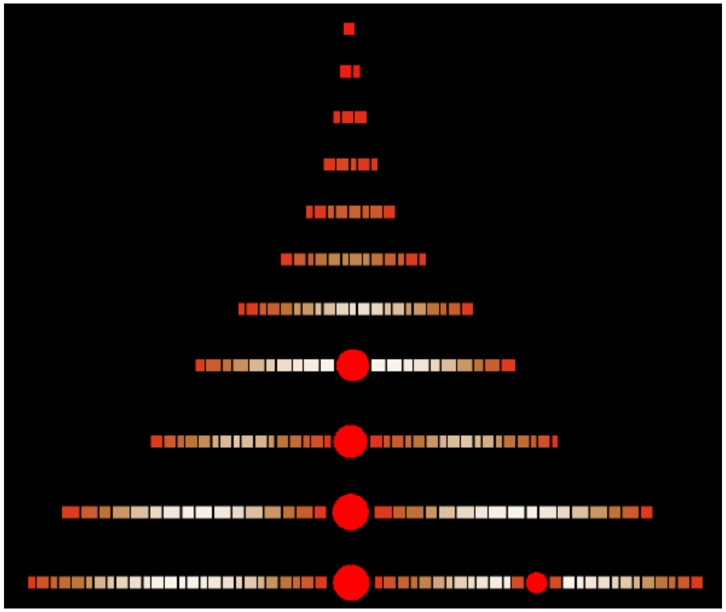
- Mathematical formalism proposed by the biologist Aristid Lindenmayer in 1968 as a foundation for an axiomatic theory of biological development.
  - applications in computer graphics
    - Generation of fractals and realistic modeling of plants
  - Grammar for rewriting Symbols
    - Production Grammar
    - Defines complex objects by successively replacing parts of a simple object using a set of recursive, rewriting rules or productions.
      - Beyond one-dimensional production (Chomsky) grammars
      - Parallel ***recursion***
      - Access to computers

parametric 2L-system

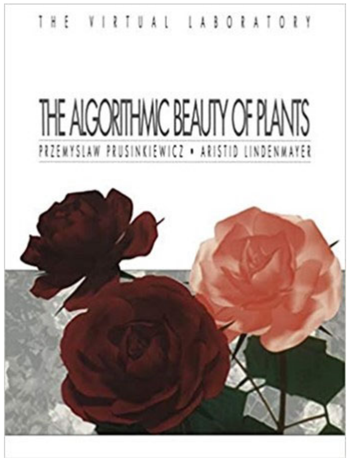
example

```
#define CH 900   /* high concentration */
#define CT 0.4   /* concentration threshold */
#define ST 3.9   /* segment size threshold */
#include H       /* heterocyst shape specification */
#ignore f ~ H

ω  :  -(90)F(0,0,CH)F(4,1,CH)F(0,0,CH)
p1 :  F(s,t,c)  :  t=1 & s>=6 →
                   F(s/3*2,2,c)f(1)F(s/3,1,c)
p2 :  F(s,t,c)  :  t=2 & s>=6 →
                   F(s/3,2,c)f(1)F(s/3*2,1,c)
p3 :  F(h,i,k) < F(s,t,c) > F(o,p,r)  :  s>ST|c>CT →
                   F(s+.1,t,c+0.25*(k+r-3*c))
p4 :  F(h,i,k) < F(s,t,c) > F(o,p,r)  :  !(s>ST|c>CT) →
                   F(0,0,CH) ~ H(1)
p5 :  H(s)  :  s<3 → H(s*1.1)
```



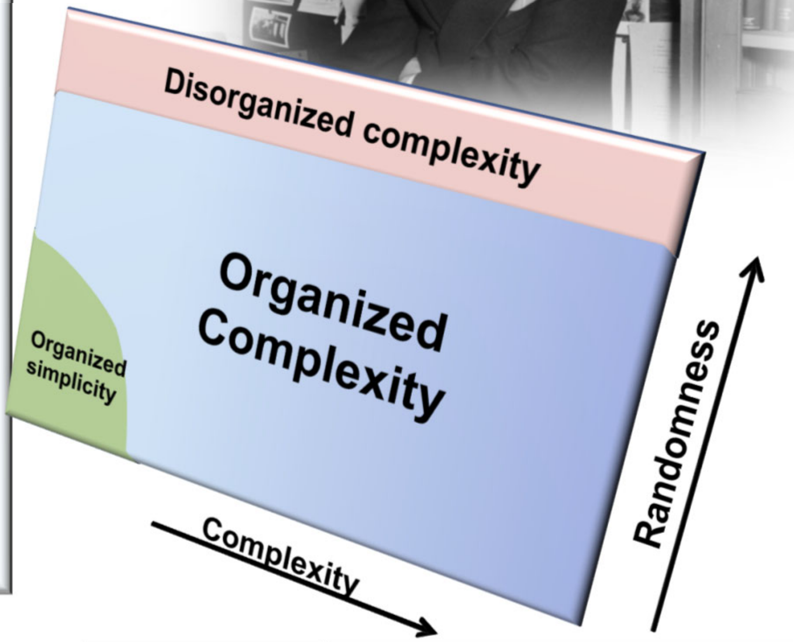
convenient tool for expressing developmental models with ***diffusion of substances***.
pattern of cells in *Anabaena catenula* and other blue-green bacteria



From: P. Prusinkiewicz and A. Lindenmayer [1991].
The Algorithmic Beauty of Plants.

Warren Weaver' classes of systems and problems

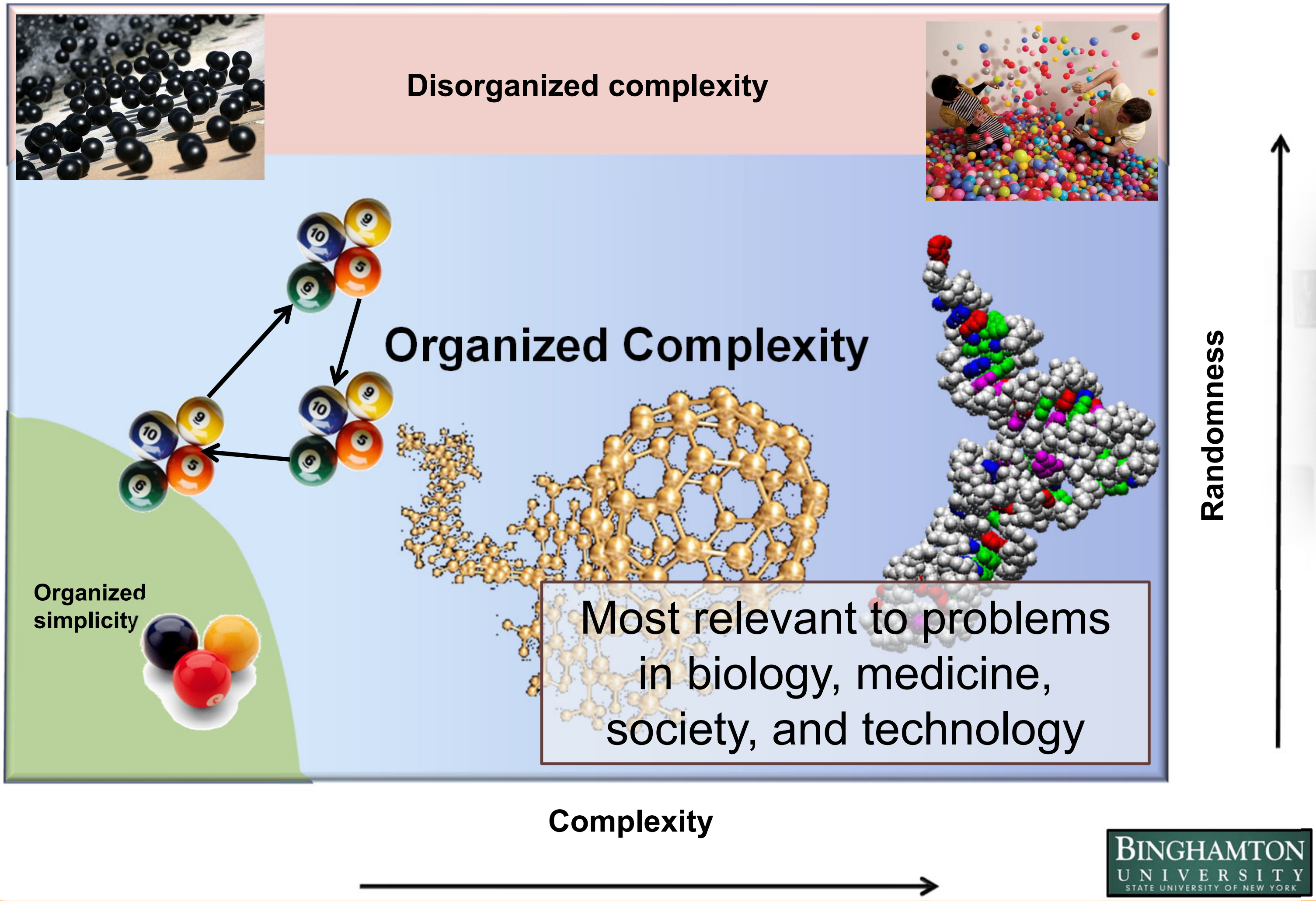
- organized simplicity
    - very small number of variables
        - Deterministic
    - classical mathematical tools
        - Calculus
- disorganized complexity
    - very large number of variables
        - Randomness, homogenous
    - statistical tools
- organized complexity
    - sizable number 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.

organized complexity

examples



Disorganized complexity

Organized Complexity

Most relevant to problems in biology, medicine, society, and technology

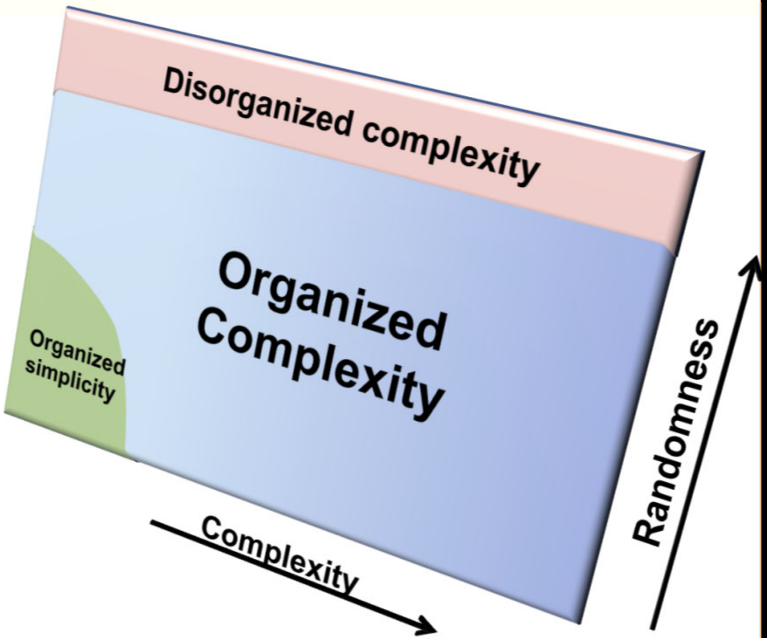
Organized simplicity

Complexity

Randomness

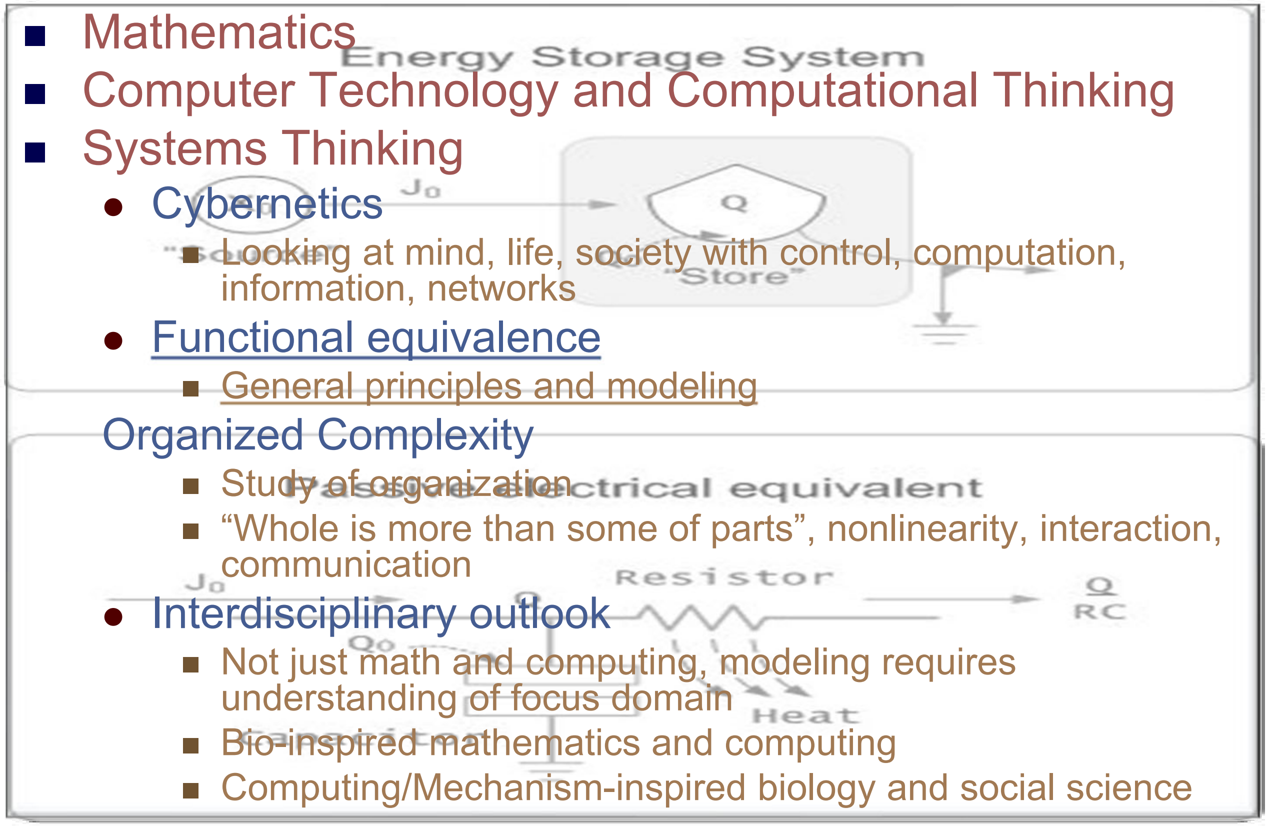
from computational to systems thinking

- 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**



systems movement

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

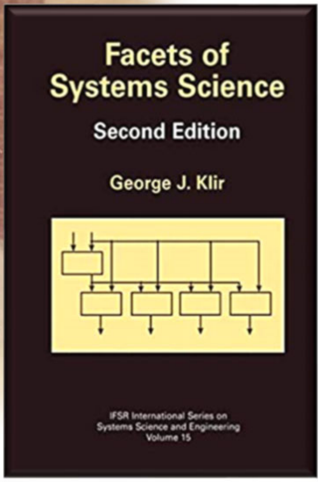

Ludwig
von Bertalanffy


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.)



Facets of Systems Science

Second Edition

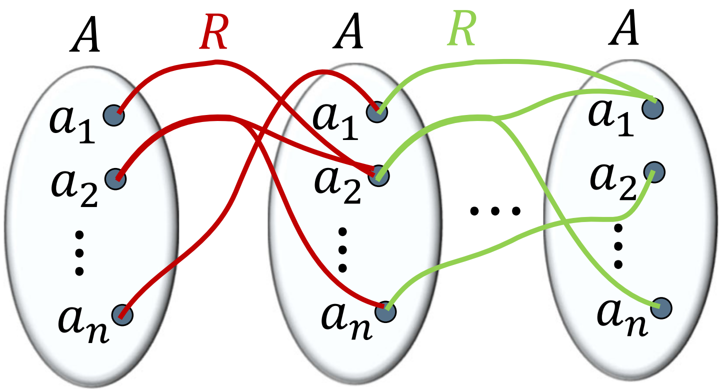
George J. Klir

IFSR International Series on Systems Science and Engineering Volume 15

what is a system?

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



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

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

……………………

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

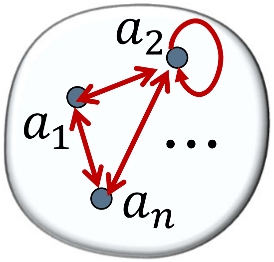
$$R \subseteq (A \times A) \times A,$$

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

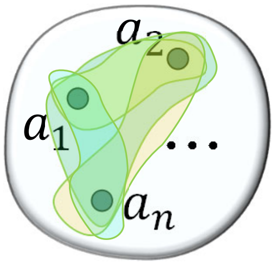
$$R \subseteq (A \times A) \times (A \times A).$$


George Klir

graph A



hypergraph A



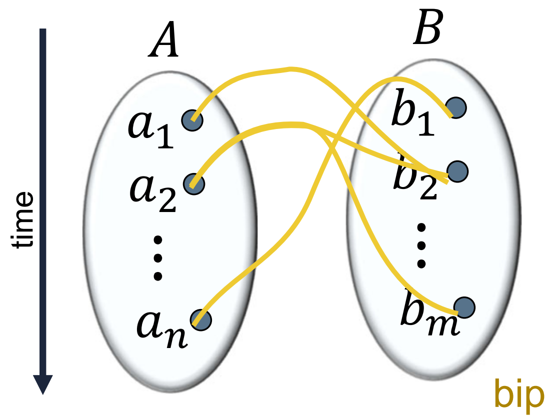
BINGHAMTON UNIVERSITY
STATE UNIVERSITY OF NEW YORK

rocha@binghamton.edu
casci.binghamton.edu/academics/ssie501

what is a system?

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



bipartite graph

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

$R \subseteq A \times B$,

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

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

....

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

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

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

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

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

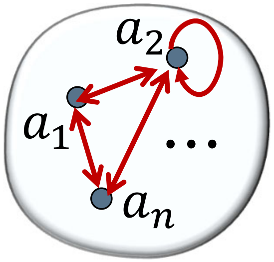
$R \subseteq A \times (A \times A)$,

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

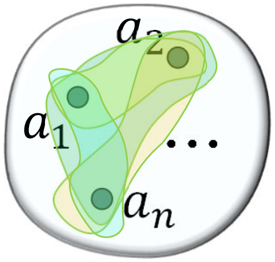
$R \subseteq (A \times A) \times (A \times A)$.


George Klir

graph A

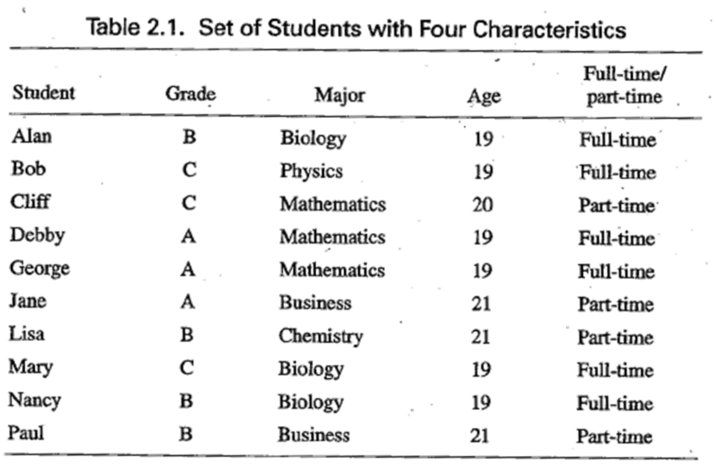


hypergraph A



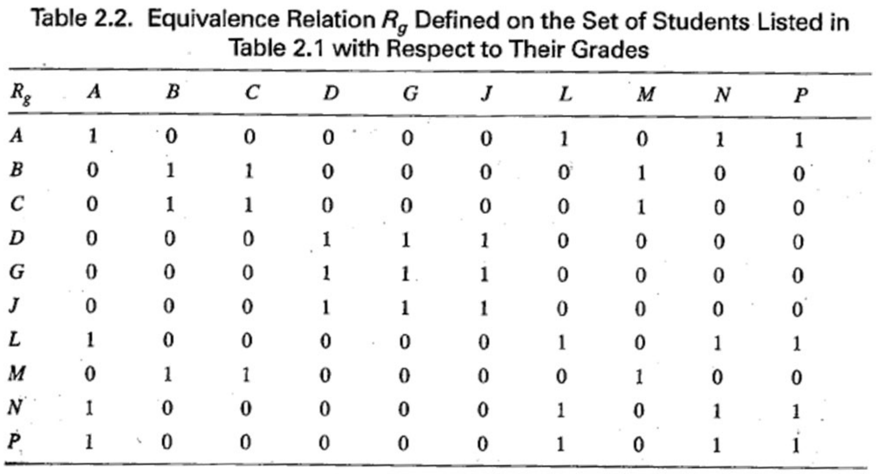
equivalence classes or multilayer network?

Table 2.1. Set of Students with Four Characteristics

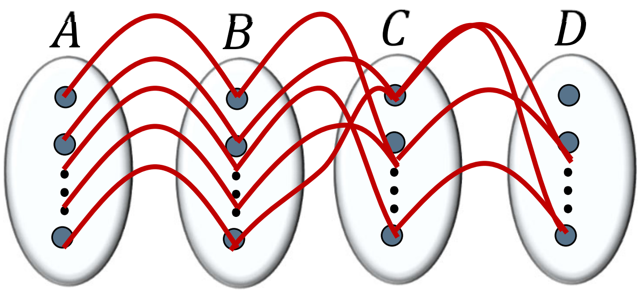


Student	Grade	Major	Age	Full-time/ part-time
Alan	B	Biology	19	Full-time
Bob	C	Physics	19	Full-time
Cliff	C	Mathematics	20	Part-time
Debby	A	Mathematics	19	Full-time
George	A	Mathematics	19	Full-time
Jane	A	Business	21	Part-time
Lisa	B	Chemistry	21	Part-time
Mary	C	Biology	19	Full-time
Nancy	B	Biology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

equivalence classes or multilayer network?

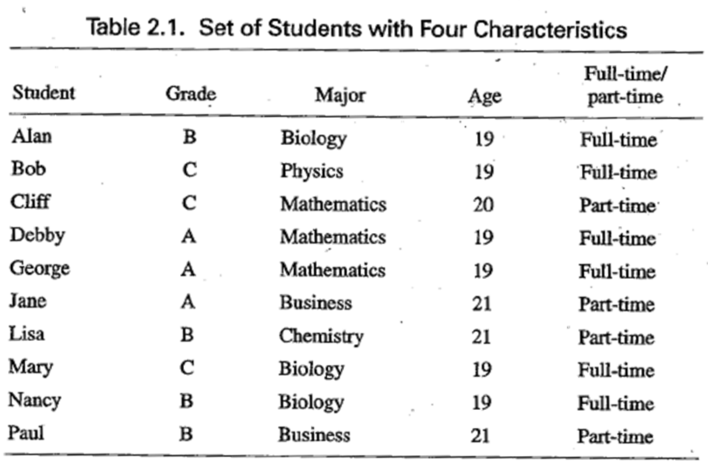


Table 2.1. Set of Students with Four Characteristics

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

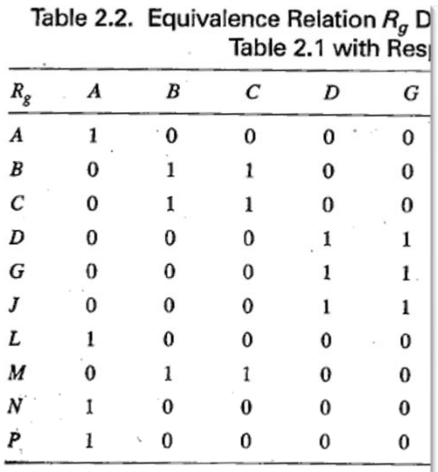
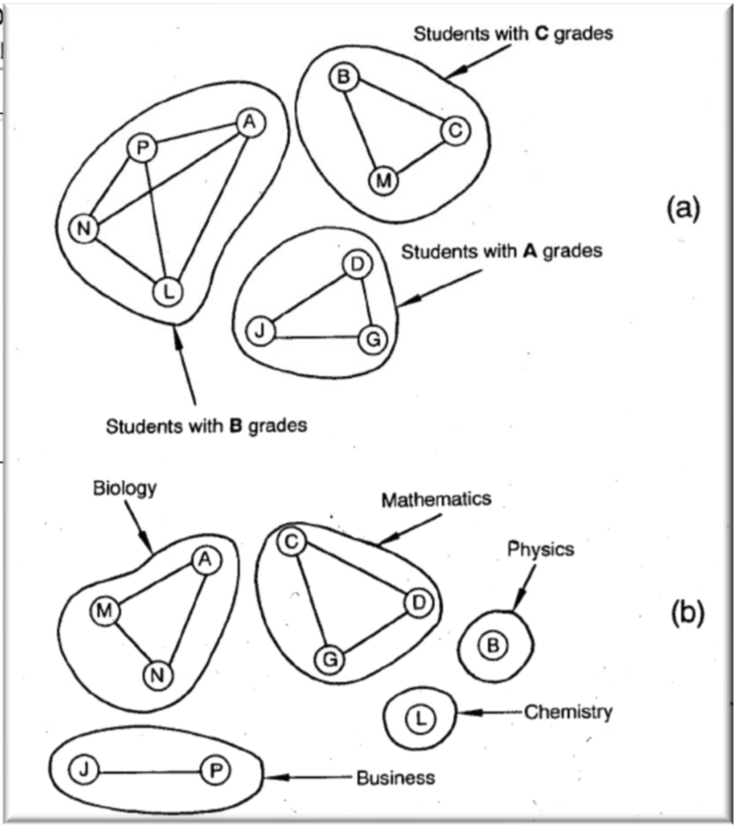
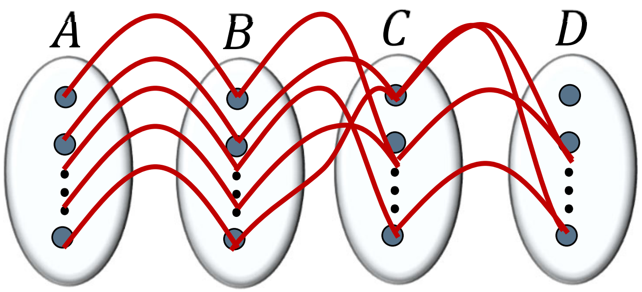


Table 2.2. Equivalence Relation R_g D
Table 2.1 with Res

R_g	A	B	C	D	G
A	1	0	0	0	0
B	0	1	1	0	0
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





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

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

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

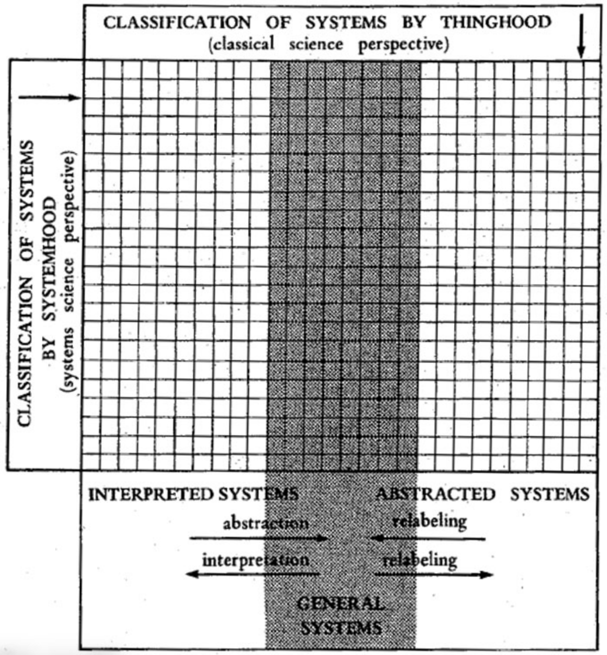


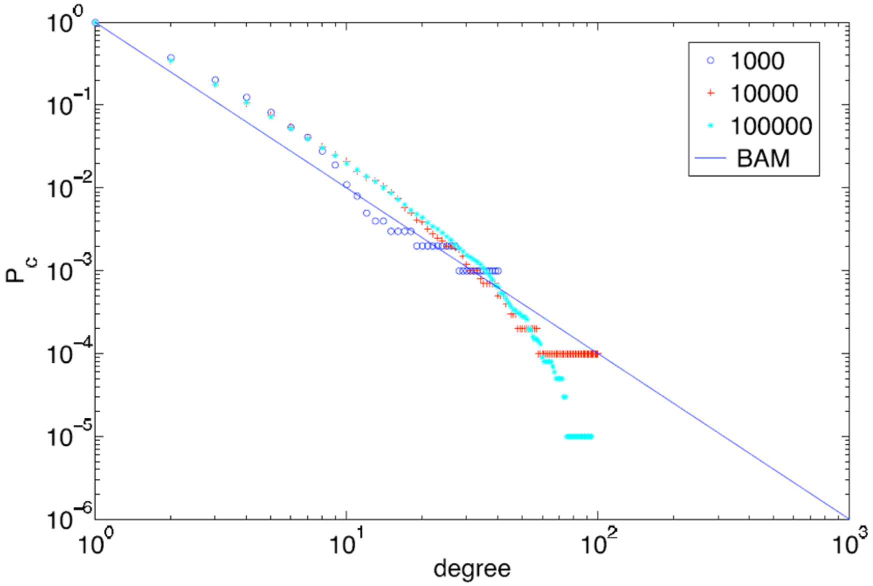
Figure 2.6. Two ways of classifying systems and the role of general systems.

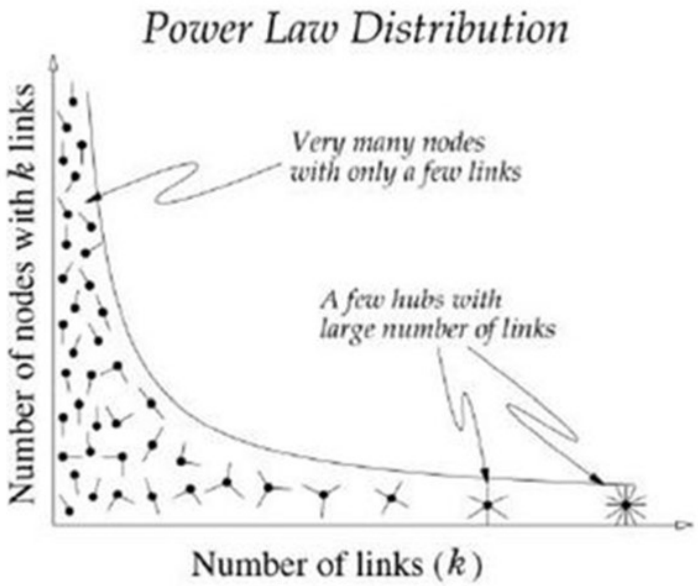
From Klir [2001]

example of general principle of organization

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

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



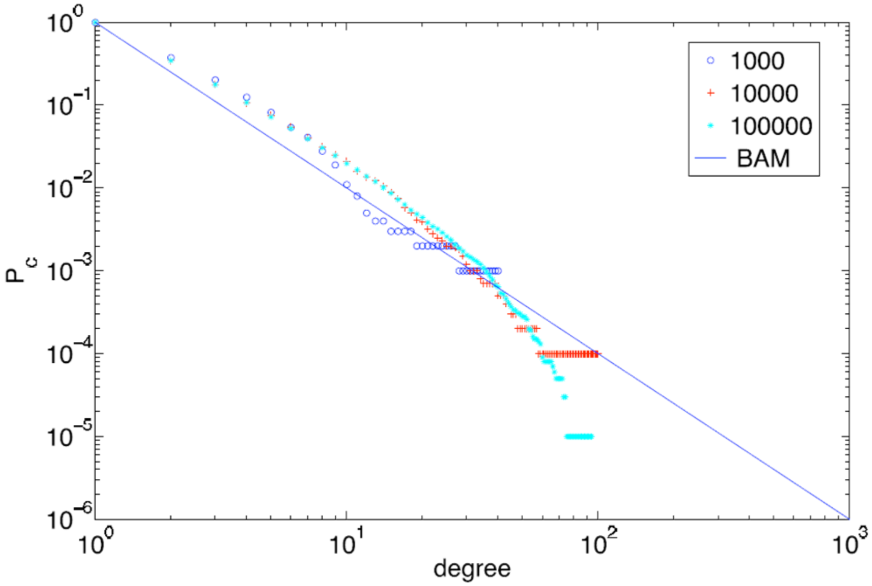


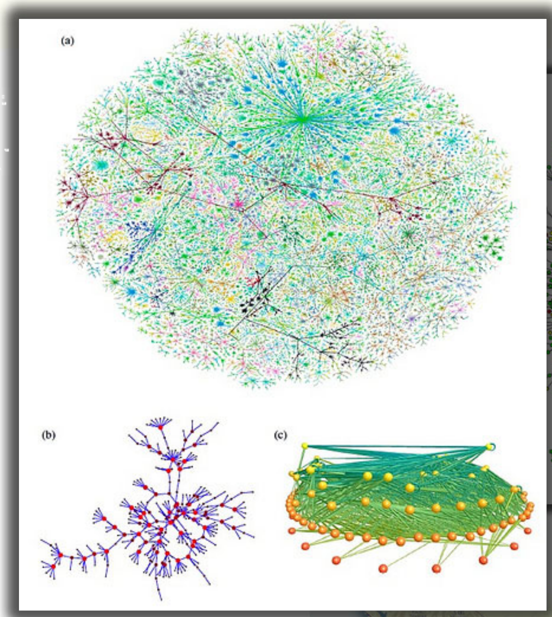
example of general principle of organization

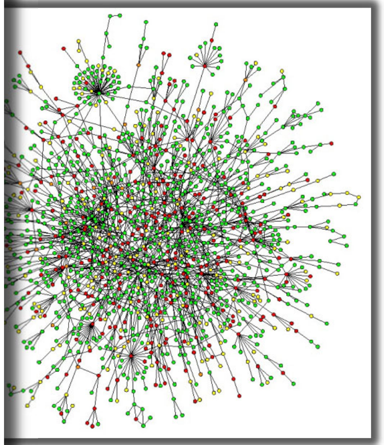
Barabasi-Albert Model: leads to power-law node degree distributions in networks

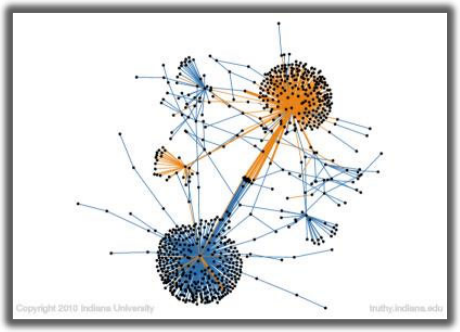
Amaral et al: Most real networks have a cut-off distribution for high degree nodes which can be computationally modeled with vertex aging.

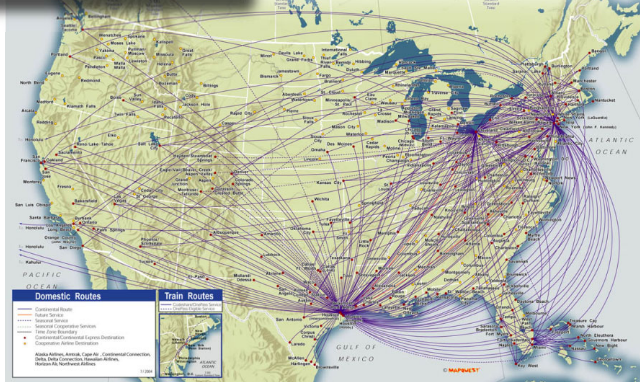
$$R \subseteq A^2 (= A \times A),$$



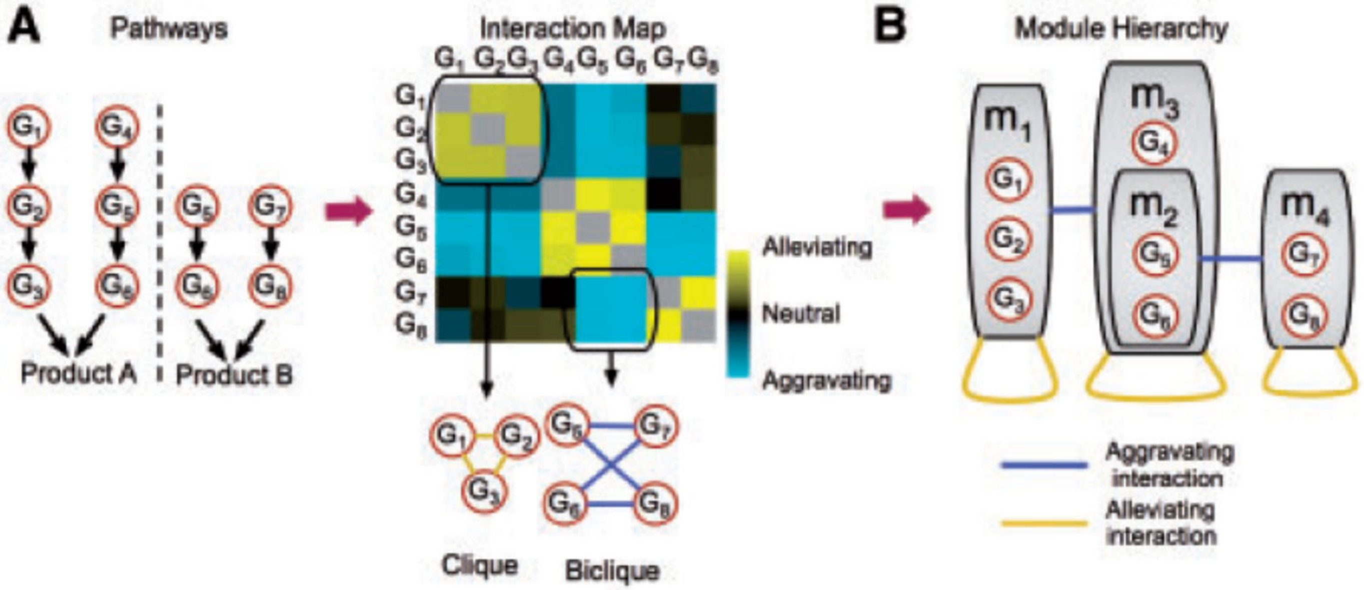






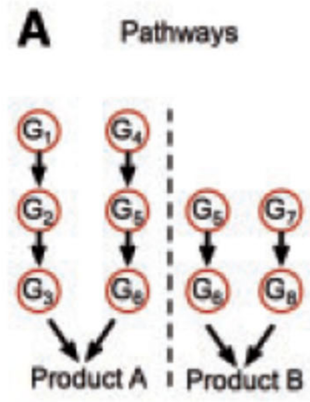


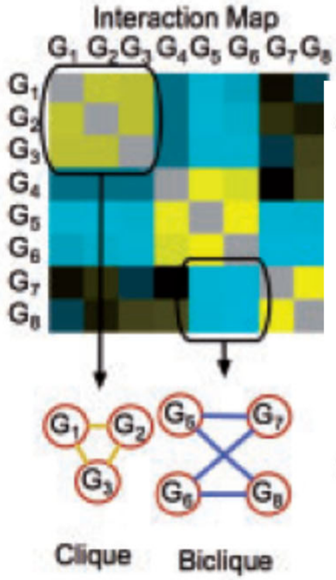
From genetic interaction maps (in yeast)

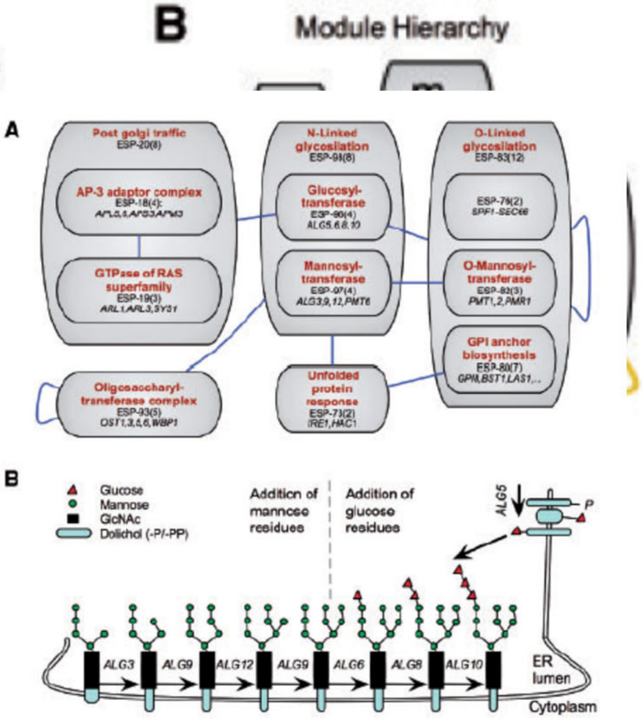


Jaimovich, Aet al. 2010. Modularity and directionality in genetic interaction maps. *Bioinformatics* **26**, no. 12 (June): i228-i236.

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.

Next lectures

readings

- Class Book
  - Klir, G.J. [2001]. *Facets of systems science*. Springer.
- Papers and other materials
  - Module 2: Systems Science
    - Discussion Set 4 (Group 4): October 17th
      - Klir, G.J. [2001]. *Facets of systems Science*. Springer. Chapter 8.
        - Optional: Klir, G.J. [2001]. *Facets of systems Science*. Springer. Chapter 11
      - Schuster, P. (2016). The end of Moore’s law: Living without an exponential increase in the efficiency of computational facilities. *Complexity*. **21**(S1): 6-9. DOI 10.1002/cplx.21824.
      - Von Foerster, H., P. M. Mora and L. W. Amiot [1960]. "Doomsday: Friday, November 13, AD 2026." Science **132**(3436):1291-5.