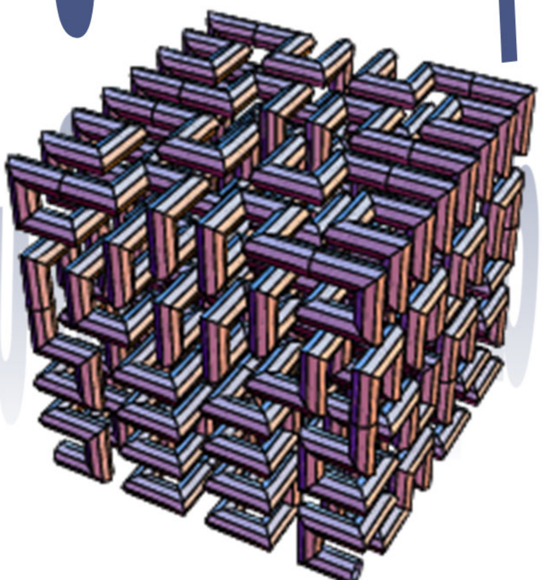
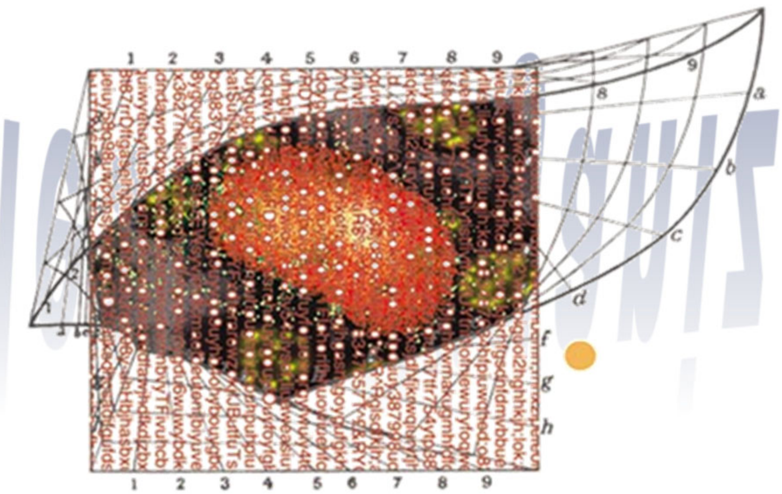
Modeling Principles of Organization





rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

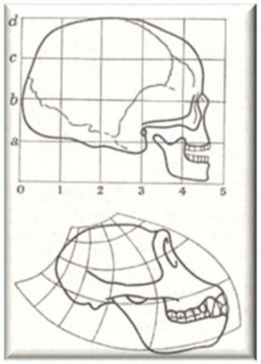
key events coming up

- Labs: 35% (ISE-483)
  - Complete 5 (best 4 graded) assignments based on algorithms presented in class
    - Lab 1 : February 5th
      - *Measuring Information* (Assignment 1)
        - Delivered by SSIE583 Group 3
        - Due: February 12th
    - Lab 2 : February 19th
      - *L-Systems* (Assignment 2)
        - Delivered by SSIE583 Group 1
        - Due: February 26th
- SSIE – 583 -Presentation and Discussion: 25%
  - Present and lead the discussion of an article related to the class materials
    - Enginet students post/send video or join by Zoom
  - Dates TBA
    - Kauffman, S.A. [1969]. "Metabolic stability and epigenesis in randomly constructed genetic nets". *Journal of Theoretical Biology* **22**(3):437-467.
      - Yoshiaki Fujita
    - Conrad, M. [1990]. "The geometry of evolution.“ *Biosystems* **24**: 61-81.
      - Mario Franco
    - Stanley, Kenneth O., Jeff Clune, Joel Lehman, and Risto Miikkulainen. “Designing Neural Networks through Neuroevolution.” *Nature Machine Intelligence* **1**, no. 1 (January 2019): 24–35.
      - Jessica Lasebikan
    - Discussion by all

bit.ly/atBIC

learn more

- Class Book
  - Floreano, D. and C. Mattiussi [2008]. *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. MIT Press. **Preface, Sections 4.1, 4.2**.
    - Nunes de Castro, Leandro [2006]. *Fundamentals of Natural Computing: Basic Concepts, Algorithms, and Applications*. Chapman & Hall. **Chapter 1,** pp. 1-23. Chapter 7, sections **7.1, 7.2** and **7.4** – Fractals and L-Systems, **Appendix B.3.1** – Production Grammars
- Lecture notes
  - Chapter 1: What is Life?
  - Chapter 2: The logical Mechanisms of Life
  - Chapter 3: Formalizing and Modeling the World
    - posted online @ casci.binghamton.edu/academics/i-bic



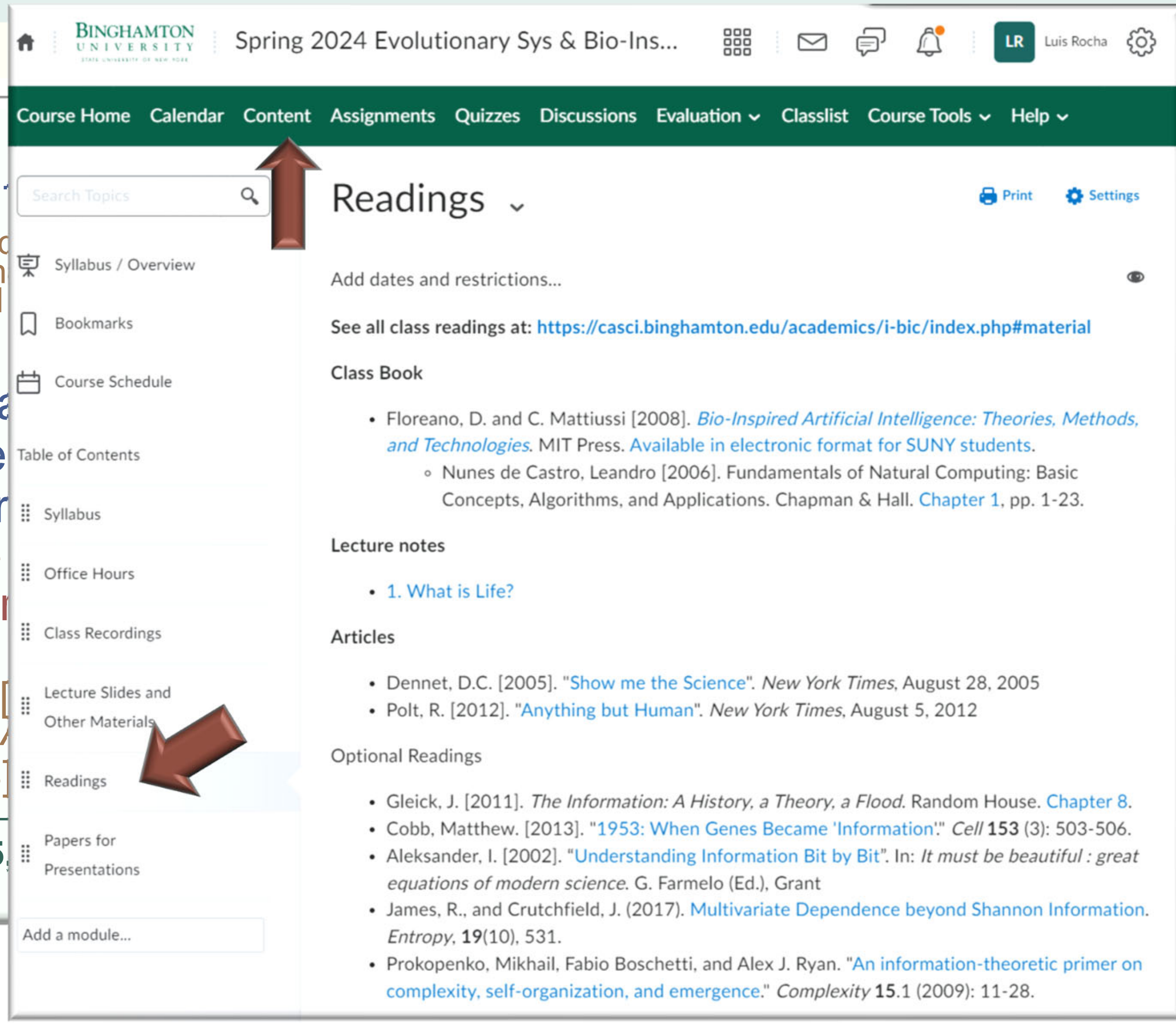
- Papers and other materials
  - Optional
    - Wigner, E.P. [1960], "The unreasonable effectiveness of mathematics in the natural sciences". *Comm. Pure Appl. Math.*, **13**: 1-14.
    - Flake's [1998], *The Computational Beauty of Life*. MIT Press.
      - Chapter **1** – Introduction
      - Chapters **5, 6** (7-9) – Self-similarity, fractals, L-Systems

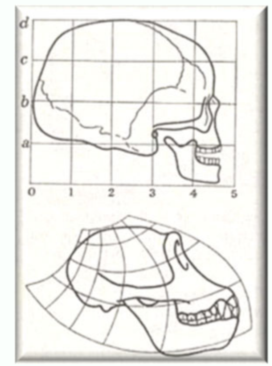
BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@indiana.edu
casci.binghamton.edu/academics/i-bic

readings until now

learn more

- Class Book
  - Floreano, D. and ... *Methods, and Technologies*. MI...
    - Nunes de Castro ... *Applications*. Ch... **Appendix B.3.1** ...orithms, and ...actals and L-Systems,
- Lecture notes
  - Chapter 1: Wha...
  - Chapter 2: The...
  - Chapter 3: For...
    - posted online
- Papers and other r...
  - Optional
    - Wigner, E.P. [... *Comm. Pure* ...atural sciences".
    - Flake's [1998]...
      - Chapter **1** –...
      - Chapters **5**,...





bit.ly/atBIC

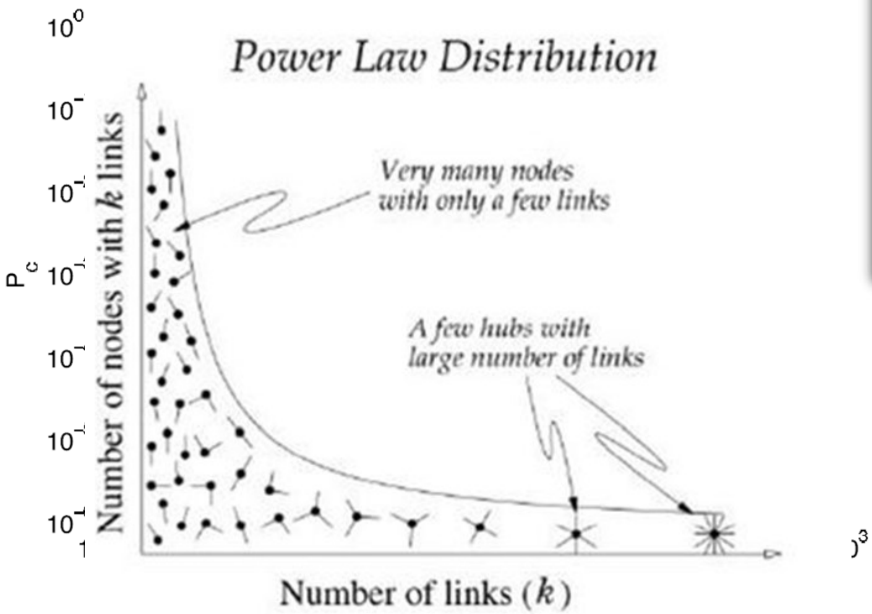
BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK

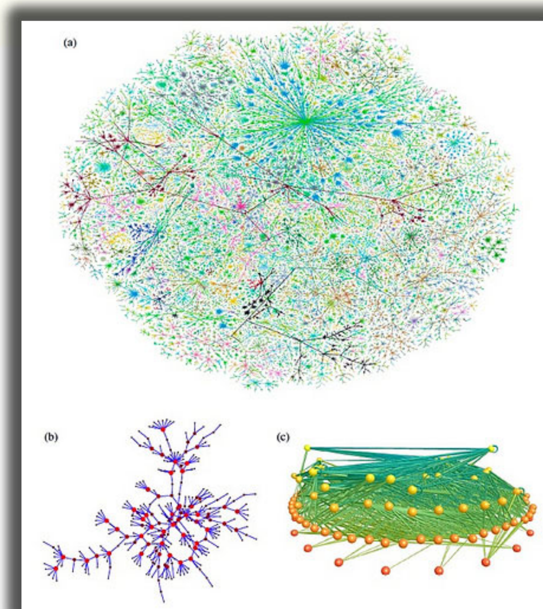
rocha@indiana.edu
casci.binghamton.edu/academics/i-bic

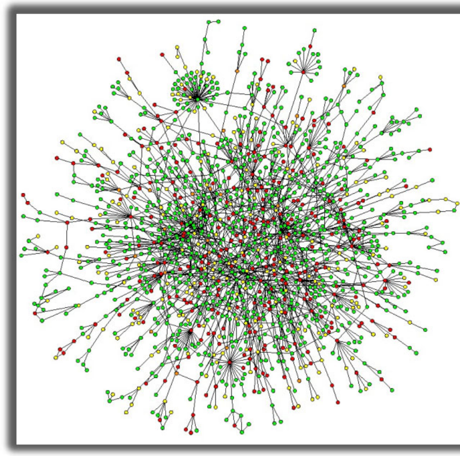
example of general principle of organization

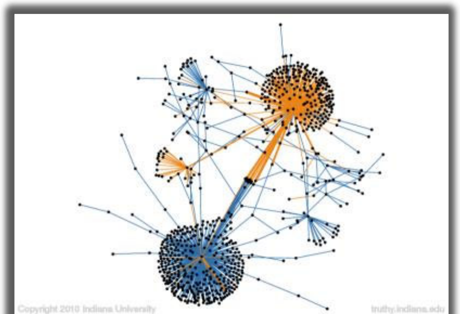
Barabasi-Albert Model: leads to power-law node degree distributions in networks

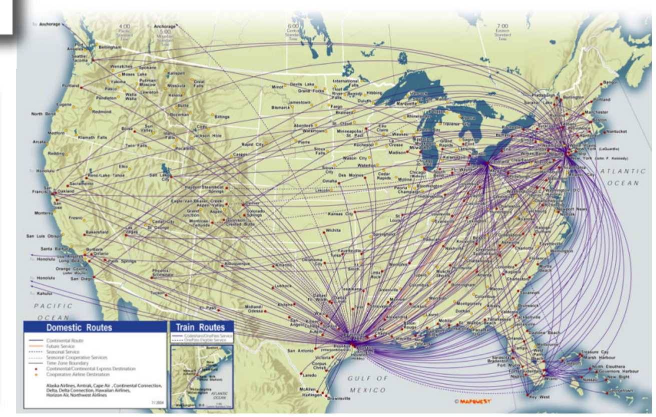
Amaral et al: Most real networks have a cut-off distribution for high degree nodes which can be computationally modeled with vertex aging.







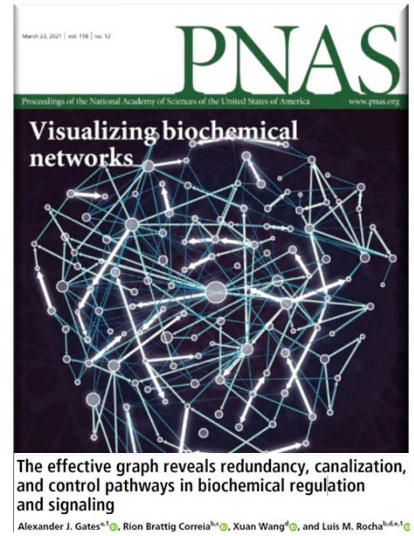


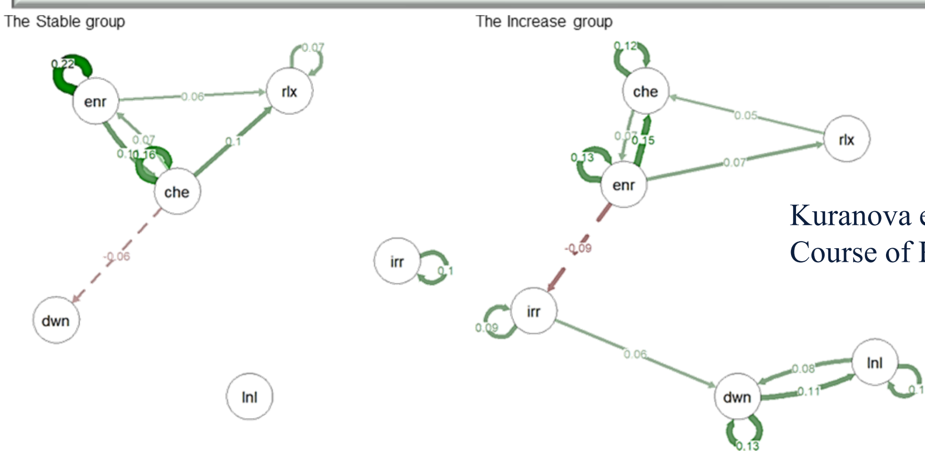


BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

“life-as-it-could-be” is the *systemhood* of life

- A system possesses ***systemhood*** and ***thinghood*** properties
  - *Thinghood* refers to the specific material that makes up the system
  - *Systemhood* are the abstracted, organizational properties
    - E.g. a clock can be made of different things, but there are implementation-independent properties of “clockness”
    - E.g. Evolutionary systems are organized according to a genotype/phenotype map, but such maps do not need to be made of DNA and Protein
      - Langton’s extended Gtype/Ptype
  - Systems science deals with the implementation-independent aspects of systems
    - Allows the conceptualization of unobserved organizations, e.g. “life-as-it-could-be”
      - E.g. networks of logical units to represent biochemical (or psychopathology) regulation and dynamics
    - But systems science is supposed to be validated empirically on thinghood
      - Otherwise it is mathematics or sophisticated thought experiments (computational philosophy)





Gates, Correia, Wang & Rocha [2021]. *PNAS*. **118** (12): e2022598118.

Kuranova et al. [2021] “Network Dynamics of Momentary Affect States and Future Course of Psychopathology in Adolescents.” *PLOS ONE* 16(3): e0247458.

Bringmann et al. [2022] "Psychopathological Networks: Theory, Methods and Practice." *Behaviour Research and Therapy* **149**: 104011.

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@indiana.edu
casci.binghamton.edu/academics/i-bic

"life-as-it-could-be" is the *systemhood* of life

- A system possesses ***systemhood*** and ***thinghood*** properties
  - *Thinghood* refers to the specific material that makes up the system
  - *Systemhood* are the abstracted, organizational properties
    - E.g. a clock can be made of different things, but there are implementation-independent properties of "clockness"
    - E.g. Evolutionary systems are organized according to a genotype/phenotype map, but such maps do not need to be made of DNA and Protein
      - Langton's extended Gtype/Ptype
  - Systems science deals with the implementation-independent aspects of systems
    - Allows the conceptualization of unobserved organizations, such as "life-as-it-could-be"
      - E.g. networks of logical units to represent biochemical (or psychopathology) regulation and dynamics
    - But systems science is supposed to be validated empirically on thinghood
      - Otherwise it is mathematics or sophisticated thought experiments (computational philosophy)
  - Criticisms
    - Circumscribed to theories of life (reality is stranger than fiction)
    - Alife rarely goes beyond showing artificial behavior that resembles real life
    - The role of materiality: embodiment in life as major feature of evolutionary system
      - evolutionary robotics, embodied cognition

post-reductionism synthetic approaches

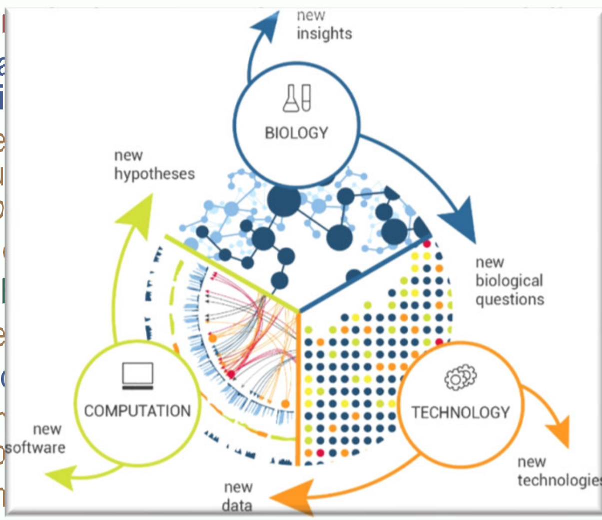
- Reductionism in Biology (analysis)
  - search and characterization of the *function* of building blocks (genes and molecules)
- Post-genome informatics
  - Minoro Kanehisa: biology is moving onto synthesis from structural and functional genomics
- Computational and systems biology
  - Non-reductionist modeling of life from analysis of large-scale biochemical information
    - Synthesis of biological knowledge from genomic **information**
      - The genome contains information about building blocks but it is naive to assume that it also contains the information on how the building blocks relate, develop, and evolve.
- Biomedical complexity pursued as systems modeling but tested in "life as we know it"
  - Towards an interdisciplinary understanding of basic ***principles*** of life via the search and characterization of networks of building blocks (genes and molecules)
    - Systems biology embraces the view that most interesting human organism traits such as immunity, development and even diseases such as cancer arise from the *operation of complex biological systems or networks*.
    - Multilevel regulation and signaling networks in health and disease
      - E.g. social determinants of health, epidemiology
    - Systems concepts such as control, modularity, networks, information and hierarchies
  - Grand (Modeling) Challenge
    - Given a complete genome sequence, reconstruct (synthesize) in a computer the functioning of a biological organism
    - Synthetic as artificial life, but grounded to "life-as-observed."

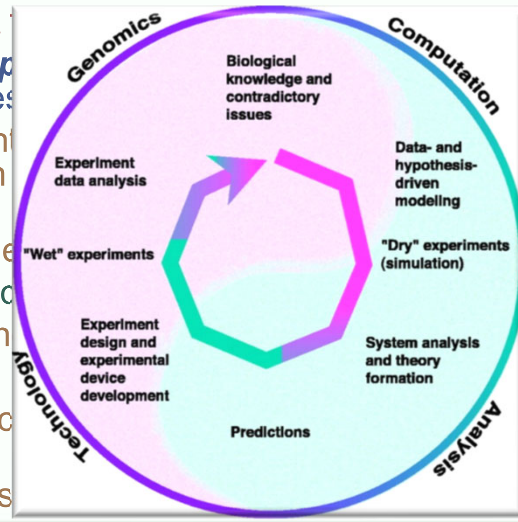
Kitano, Hiroaki. "Systems biology: a brief overview." *Science* 295.5560 (2002): 1662-1664
Villa, A. & S.T. Sonis. "System biology." In *Translational Systems Medicine and Oral Disease*, pp. 9-16. Academic Press, 2020.

rocha@indiana.edu
casci.binghamton.edu/academics/i-bic

post-reductionism synthetic approaches

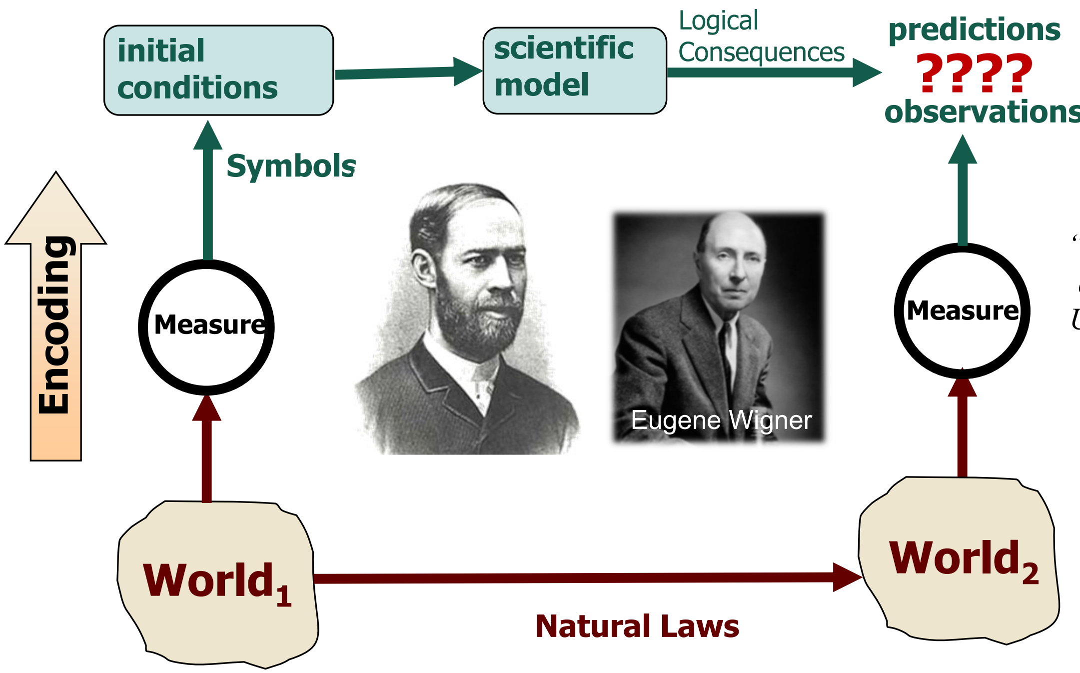
- Reductionism in Biology (analysis)
  - search and characterization of the *function* of building blocks (genes and molecules)
- Post-genome informatics
  - Minoro Kanehisa: biology is moving onto <u>synthesis</u> from structural and functional genomics
- Computational and systems biology
  - Non-reductionist modeling of life from analysis of large-scale biochemical information
    - Synthesis of biological knowledge from genomic **<u>information</u>**
      - The genome contains information about building blocks but it is naive to assume that it also contains the information on how the building blocks relate, develop, and evolve.
- Biomedical co … but
  - Towards a … sic *p* … nd characteri … enes
    - Syste … st in … such as immu … such … *on of comp*
    - Multil … in he
      - … emic
    - Syste … ty, n … ies
  - Grand (M
    - Given … struc … unctioning of a b
    - Synth … e-as





Kitano, Hiroaki. "Systems biology: a brief overview." *Science* 295.5560 (2002): 1662-1664
Villa, A. & S.T. Sonis. "System biology." In *Translational Systems Medicine and Oral Disease*, pp. 9-16. Academic Press, 2020.

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"*

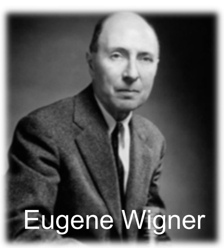
"The most direct and in a sense the most important problem which our conscious knowledge of nature should enable us to solve is the ***anticipation of future events***, so that we may arrange our present affairs in accordance with such anticipation". (Hertz, 1894)

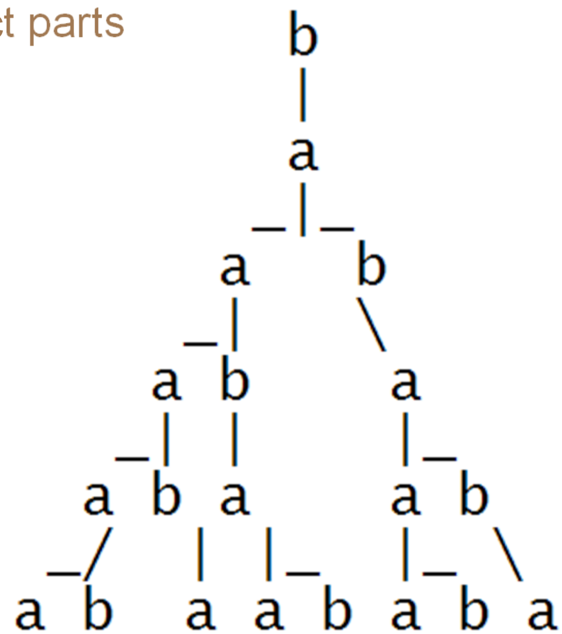
rocha@binghamton.edu
casci.binghamton.edu/academics/i-bic

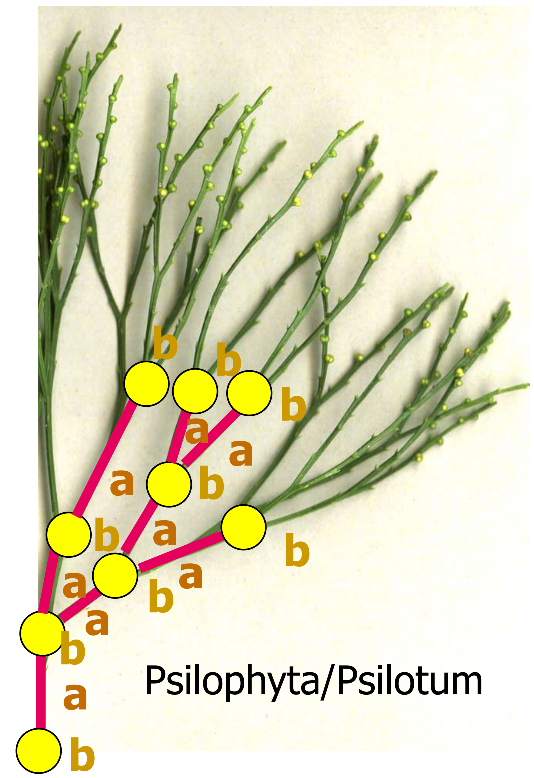
Building models

- 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 -> ba
    - Does not model all!


Heinrich Hertz


Eugene Wigner

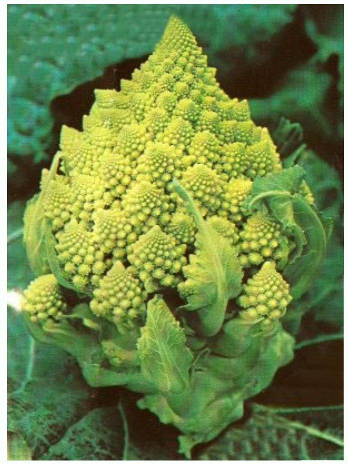


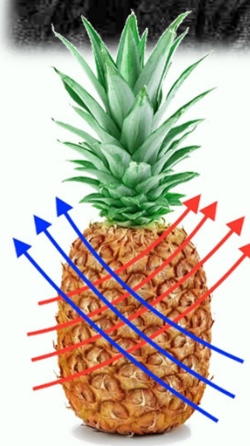


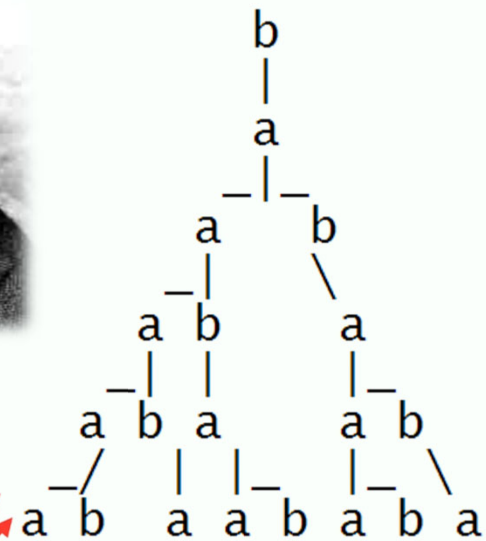
BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@indiana.edu
casci.binghamton.edu/academics/i-bic

our first model of life

- ***Rewriting*** production rules
  - Initial State: b
  - b -> a
  - a -> ba
    - n=0 : b
    - n=1 : a
    - n=2 : ba
    - n=3 : aba
    - n=4 : baaba
    - n=5 : aababaab
    - n=6 : babaabaababaa
    - 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
    - https://sciber.blogspot.com/2022/09/modeling-systems.html
    - Romanesco: https://www.wussu.com/fractals/romanesco.htm

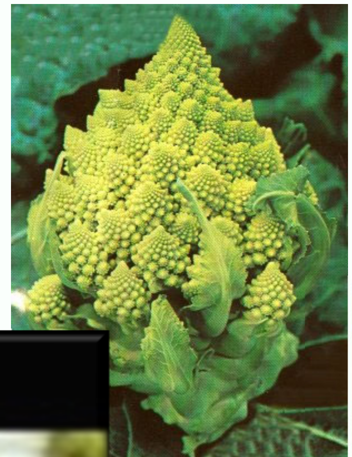


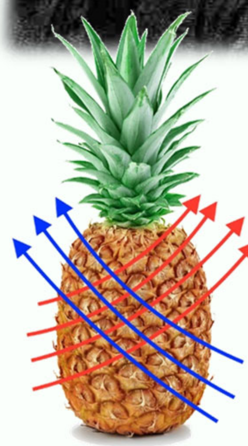


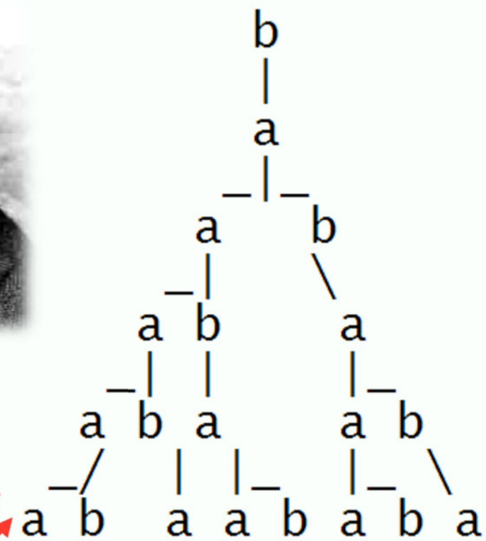


our first model of life

- ***Rewriting*** production rules
  - Initial State: b
  - b -> a
  - a -> ba
    - n=0 : b
    - n=1 : a
    - n=2 : ba







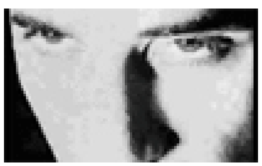
acci Sequence

09/modeling-systems.html

om/fractals/romanesco.htm

Mathematics

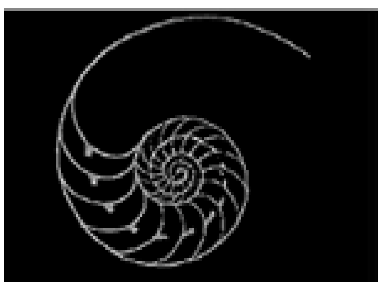
Language



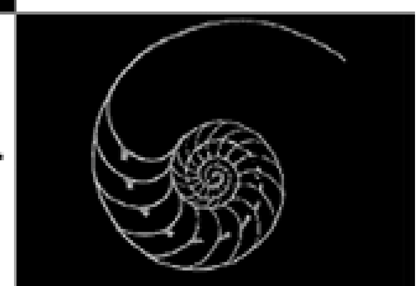
3.
1415926535 8979323846 2643383279
5028841971 6939937510 5820974944
5923078164 0628620899 8628034825
3421170679 8214808651 3282306647
0938446095 5058223172 5359408128
4811174502 8410270193 8521105559
6446229489 5493038196 4428810975
6659334461 2847564823 3786783165
2712019091 4564856692 3460348610
4543266482 1339360726 0249141273
7245870066 0631558817 4881520920
9628292540 9171536436 7892590360
0113305305 4882046652 1384146951
9415116094 3305727036 5759591953
0921861173 8193261179 3105118548
0744623799 6274956735 1885752724
8912279381

Is The

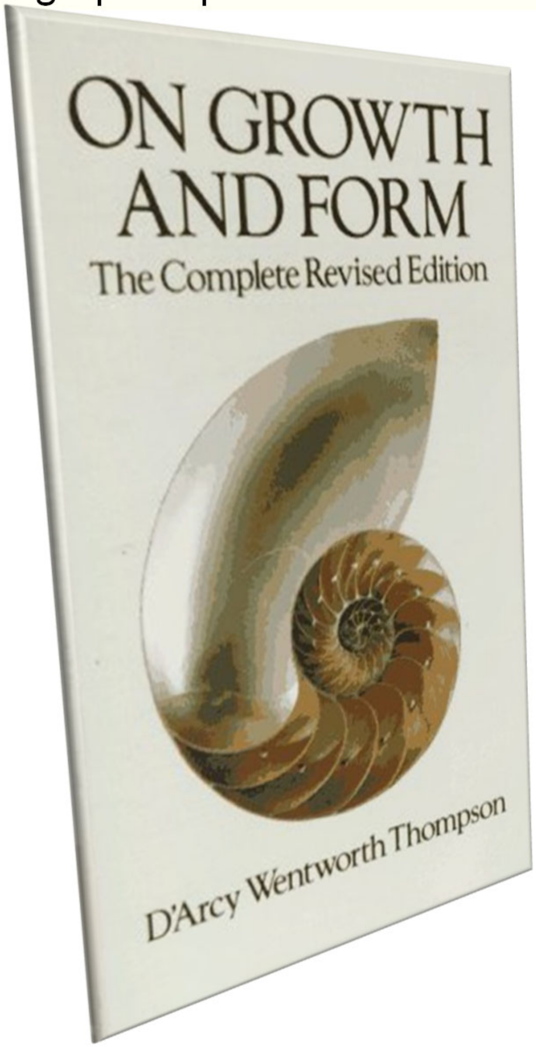
Of Nature



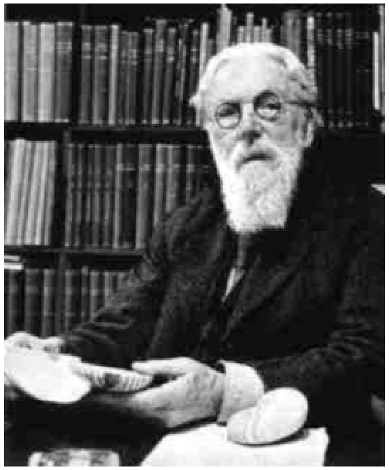
When I was a kid my mother told me
never to stare into the centre of the sun.
So once, when I was 6,
I did

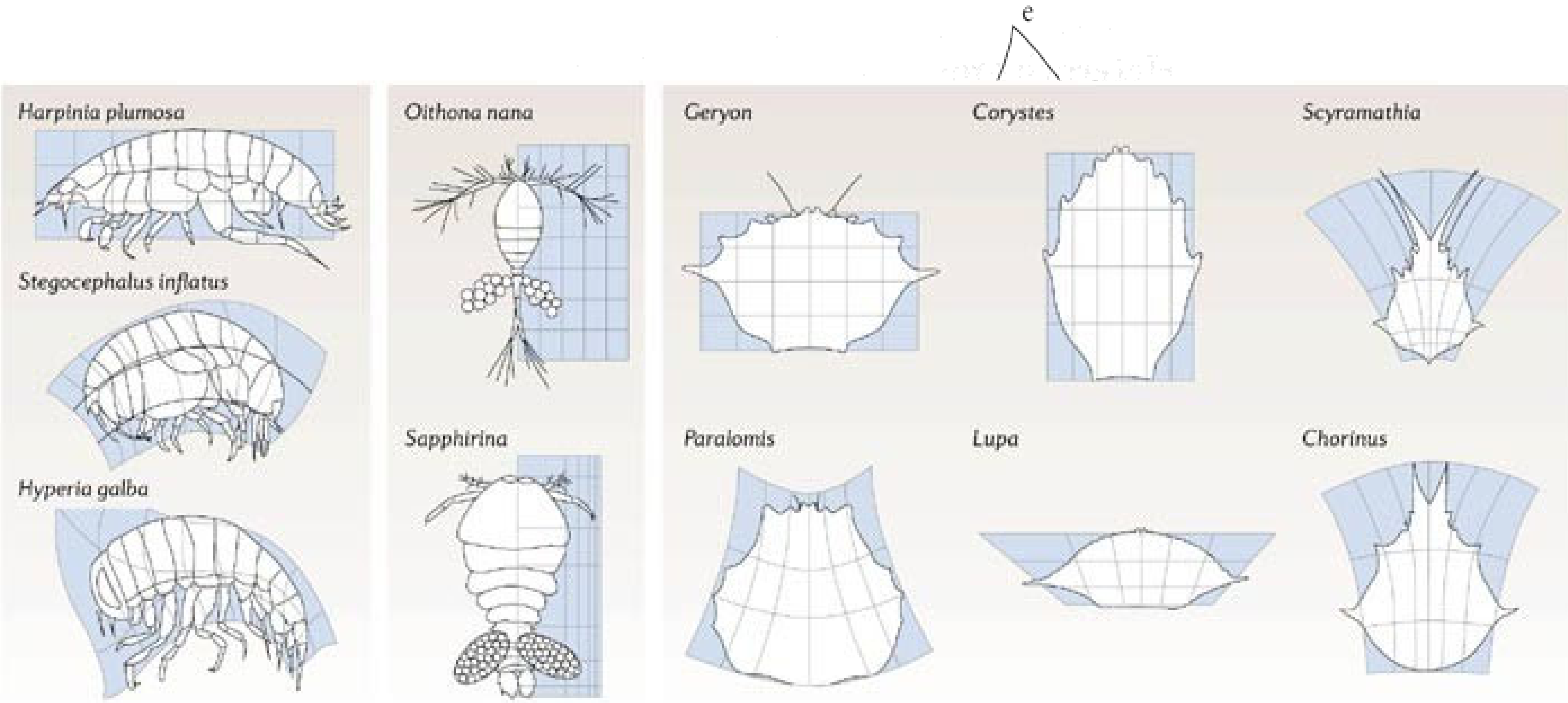


design principles



- D'Arcy Wentworth Thompson (1860 - 1948)
  - *On Growth and Form* (1917), laid the foundations of bio-mathematics
    - Equations to describe static patterns of living organisms
      - Shells, cauliflower head, etc.
    - Transformations of form changing a few parameters

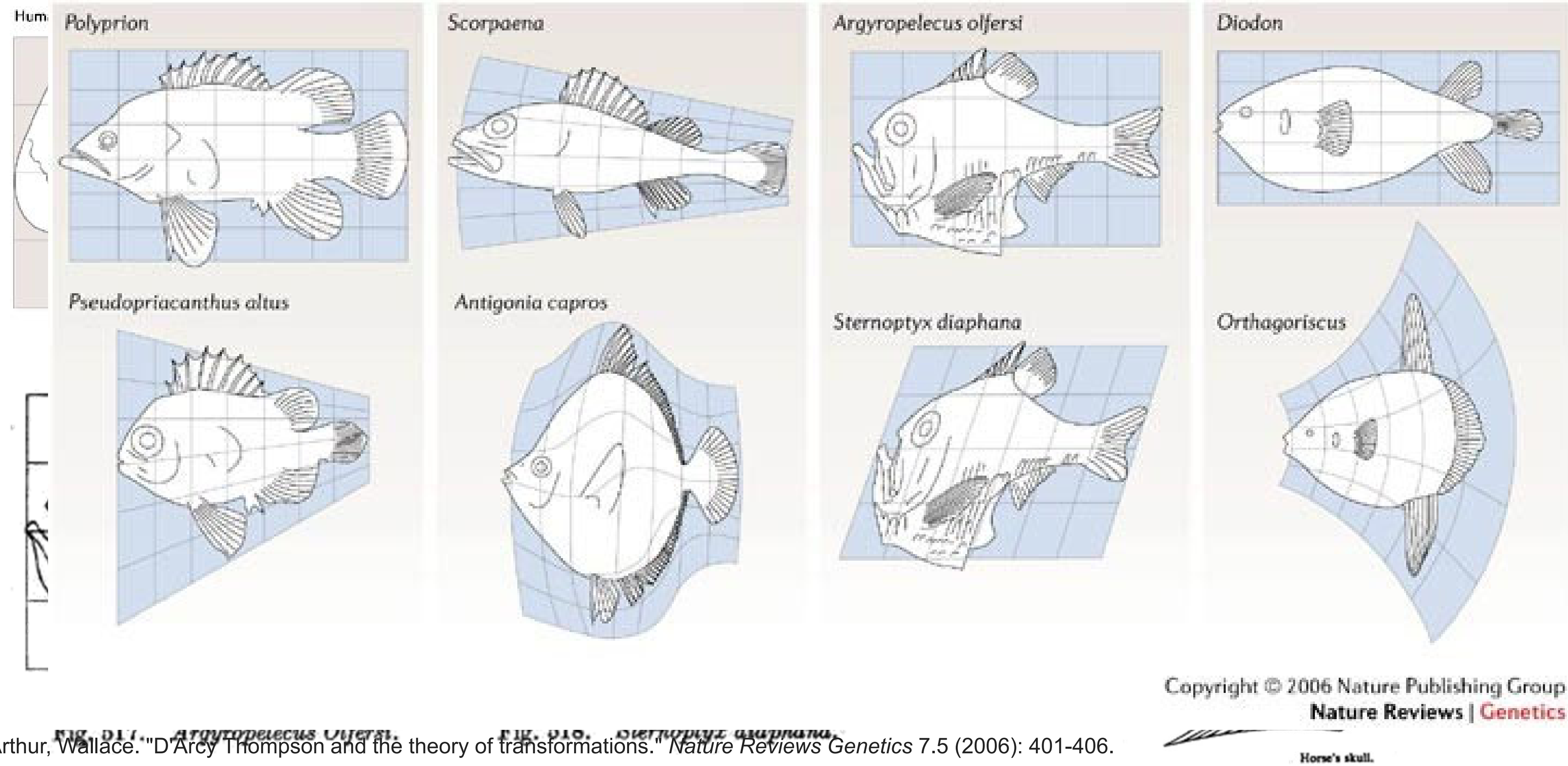




Nature Reviews | Genetics

Arthur, Wallace. "D'Arcy Thompson and the theory of transformations." *Nature Reviews Genetics* 7.5 (2006): 401-406.

D'Arcy Thompson

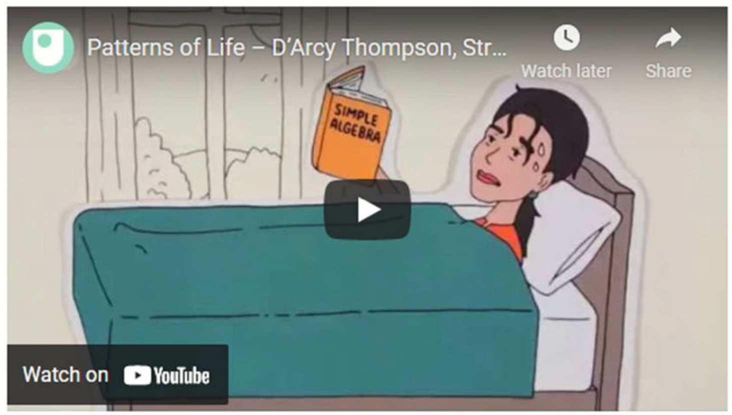


Arthur, Wallace. "D'Arcy Thompson and the theory of transformations." *Nature Reviews Genetics* 7.5 (2006): 401-406.

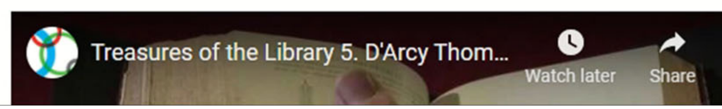
Peter Hilton (1923-2010) discusses intriguing number tricks that can be explained by analysing the properties of Fibonacci numbers and the related Lucas numbers. The explanations themselves benefit from further explanations which, in their turn, lead to further discoveries. Recorded at Imperial College London during the 1996 London Mathematical Society Popular Lecture series.

D'Arcy Thompson

- In retrospect: On Growth and Form by Phillip Ball.
- D'Arcy Thompson's Affine Fish Transformations @ Wolfram
- S.J. Gould. [1971] "D'Arcy Thompson and the Science of Form". *New Literary History*, 2 (2): 229-258
- W. Arthur [2006]. "D'Arcy Thompson and the theory of transformations".*Nature Reviews Genetics* **7**, 401-406.
- Geometry of Growth and Form: Commentary on D'Arcy Thompson
- Java applet for shell sketching



Patterns of Life - D'Arcy Thompson, Structuralism and the Shape of Life



exploring similarities across nature

- self-similar structures
  - Trees, plants, clouds, mountains
    - morphogenesis
  - Mechanism
    - Iteration, recursion, feedback
- dynamical systems and unpredictability
  - From limited knowledge or inherent in nature?
  - Mechanism
    - Chaos, measurement
- self-organization, collective behavior, emergence
  - Complex behavior from collectives of many simple units or agents
    - cellular automata, dynamical networks, morphogenesis, swarms, brains, social systems
  - Mechanism
    - Parallelism, multiplicity, multi-solutions, redundancy
- evolution
  - Adaptation, learning, social evolution
  - Mechanism
    - Reproduction, transmission, variation, selection, Turing's tape
- Network causality (heterogenous complexity)
  - Behavior derived from many inseparable sources
    - Immune system, anticipatory systems, brain-body-environment-culture, embodiment, epigenetics, culture
  - Mechanism
    - Modularity, control, hierarchy, connectivity, stigmergy, redundancy

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK
rocha@indiana.edu
casci.binghamton.edu/academics/i-bic