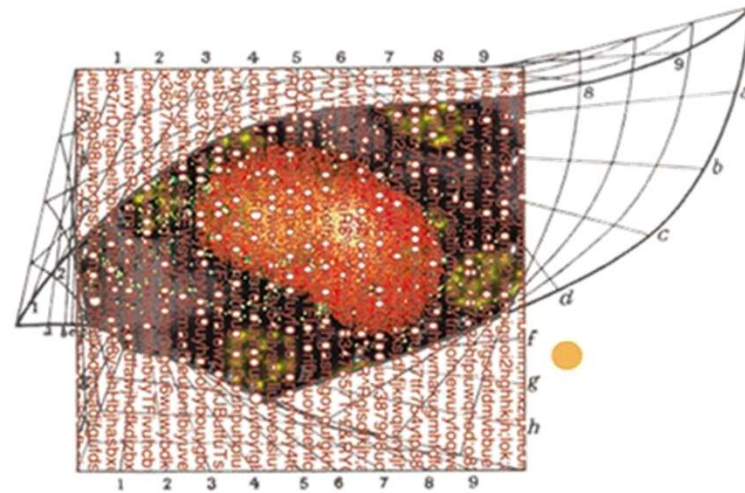
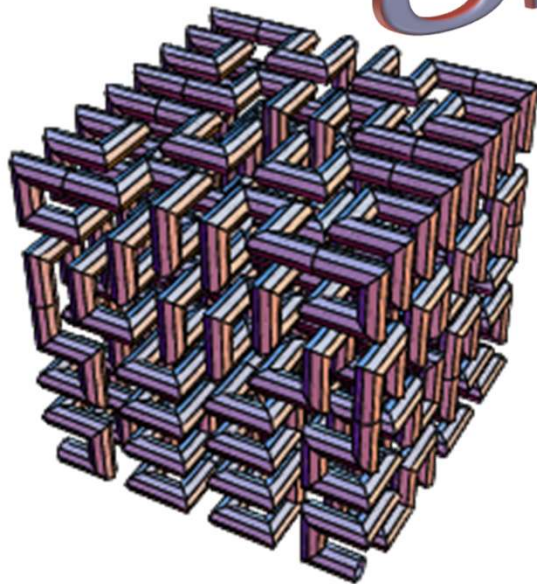
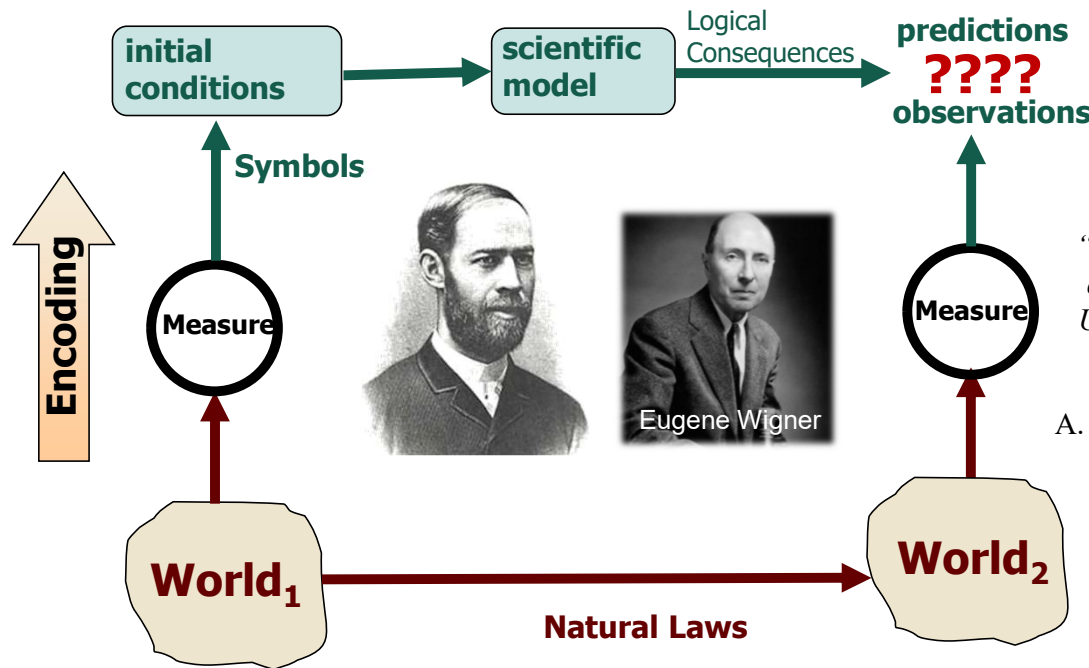


# Modeling Principles of Organization



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)

Building models



Lebombo bone

■ What do you see?

- Plants typically branch out
- How can we model that?

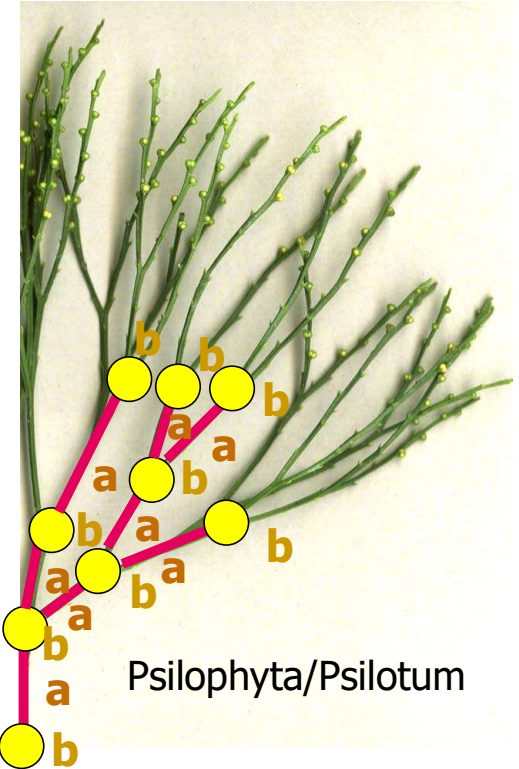
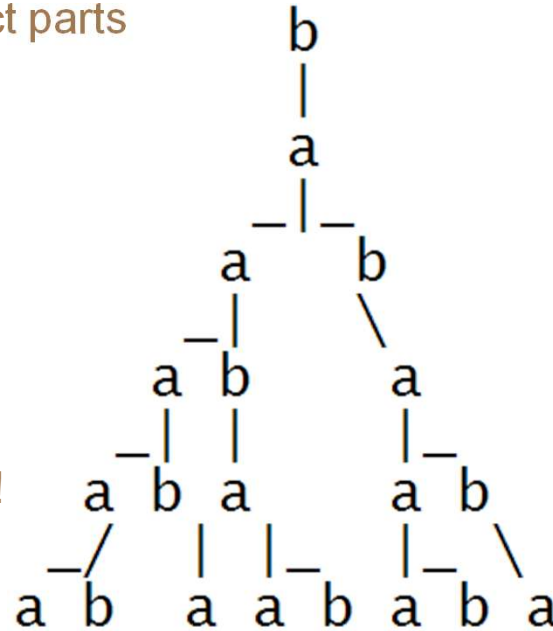
■ Observe the distinct parts

- Color them
- Assign symbols

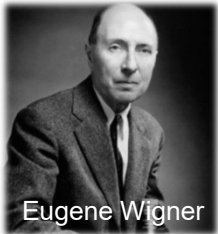
■ Build Model

- Initial State: b
- b -> a
- a -> b
- a -> ba

■ Does not model all!



Psilophyta/Psilotum



Eugene Wigner

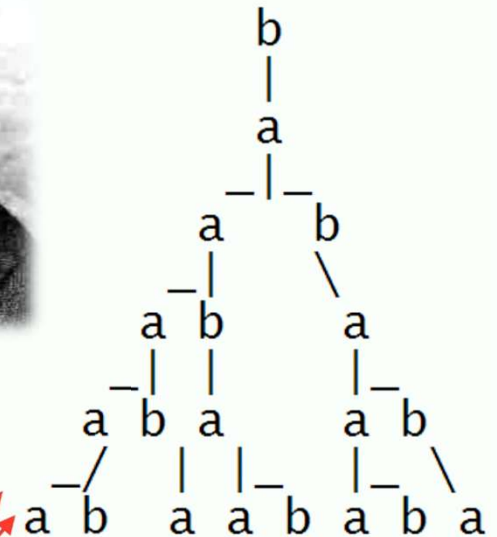
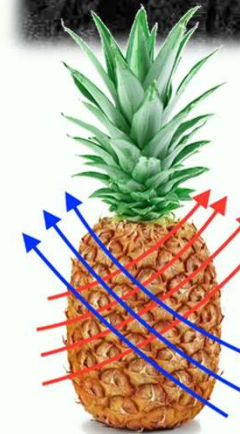


Heinrich Hertz

investigating our first model

■ **Rewriting** production rules

- Initial State: b
- $b \rightarrow a$
- $a \rightarrow ba$ 
  - $n=0$  : b
  - $n=1$  : a
  - $n=2$  : ba
  - $n=3$  : aba
  - $n=4$  : baaba
  - $n=5$  : aababaab
  - $n=6$  : babaabaababaa
  - $n=7$  : abaababaababaabaababa
- 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>

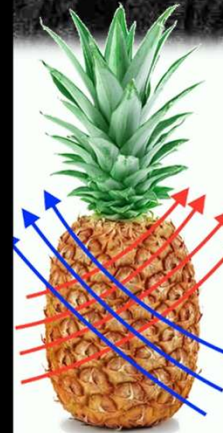
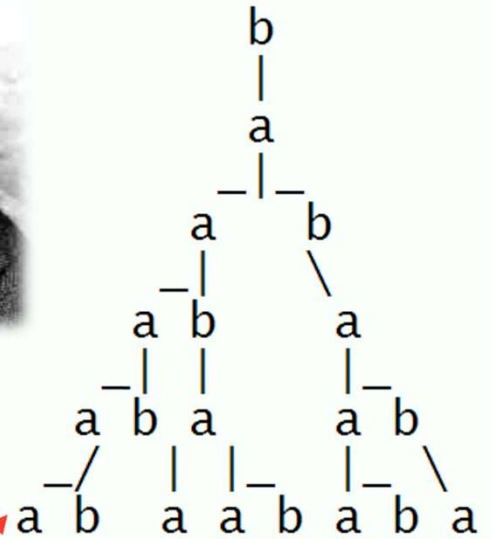


investigating our first model

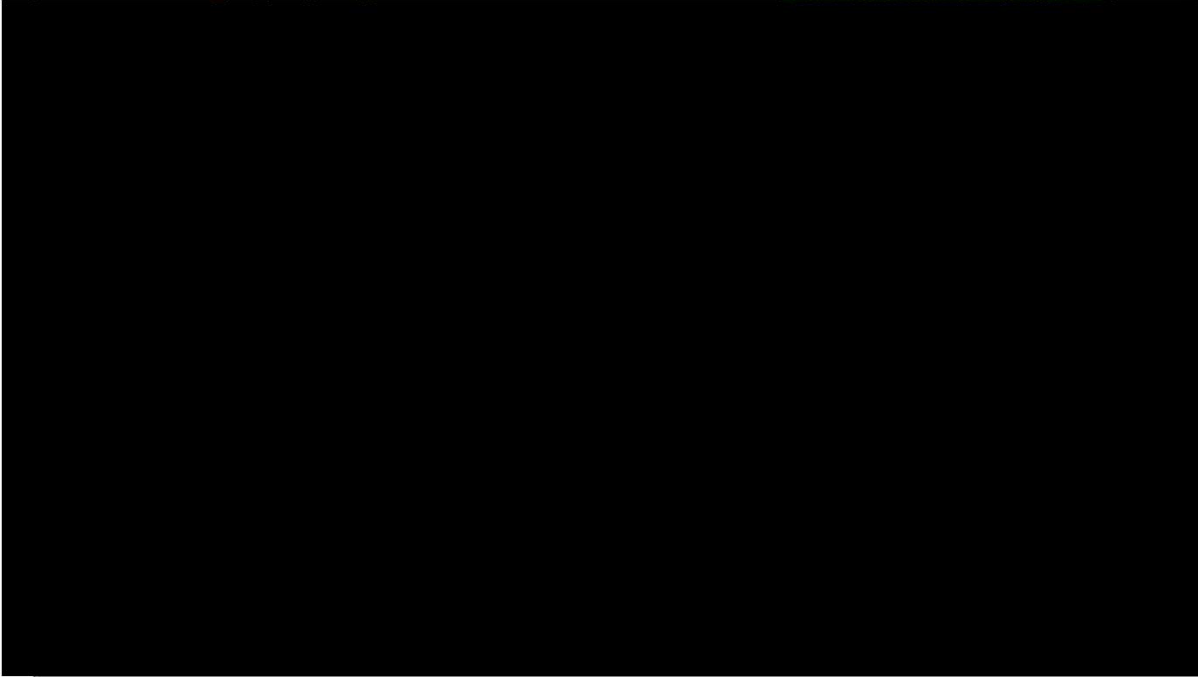
■ **Rewriting** production rules

- Initial State: b
- $b \rightarrow a$
- $a \rightarrow ba$

■  $n=0 : b$



[ms.html](#)  
[esco.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

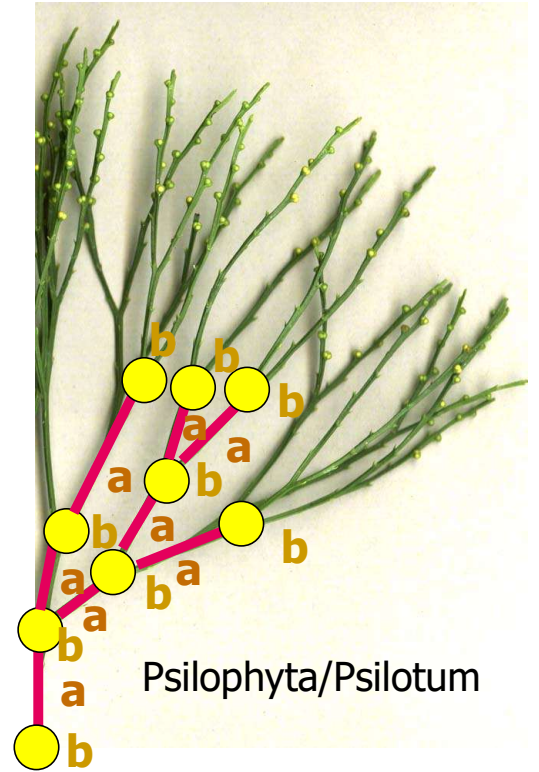
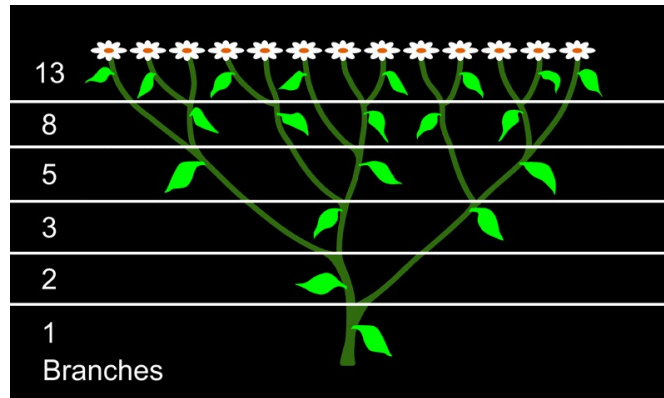
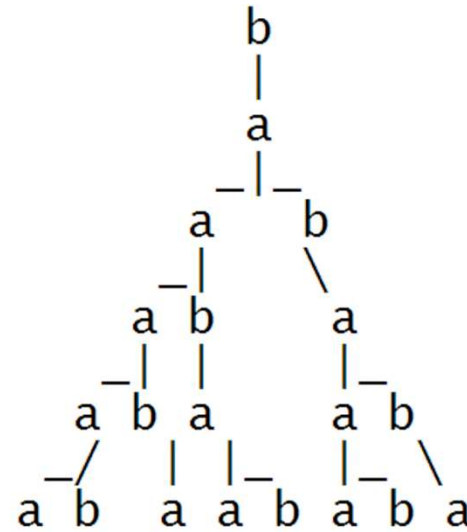


What about our plant?

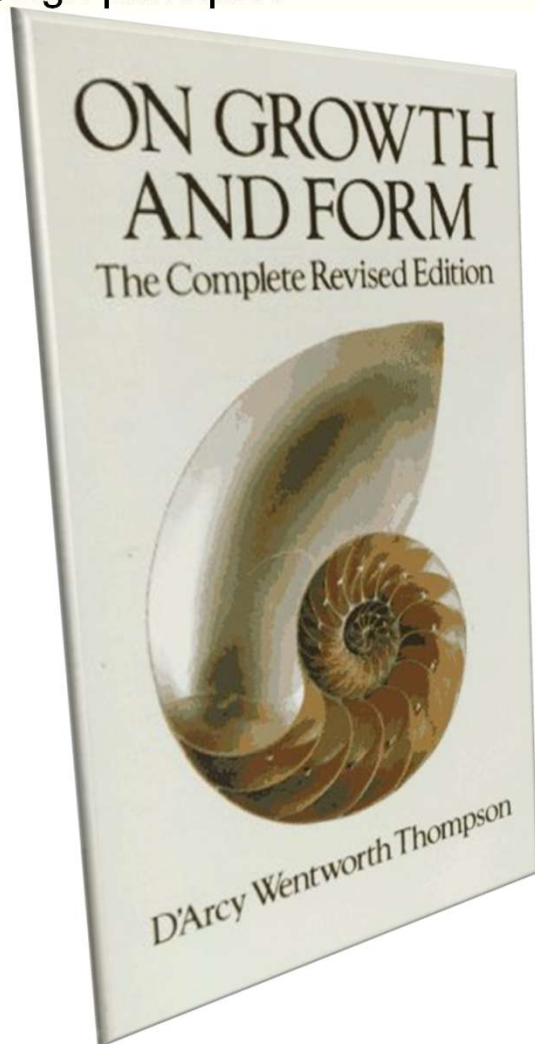
## branching model: a general system?

### ■ An Accurate Model

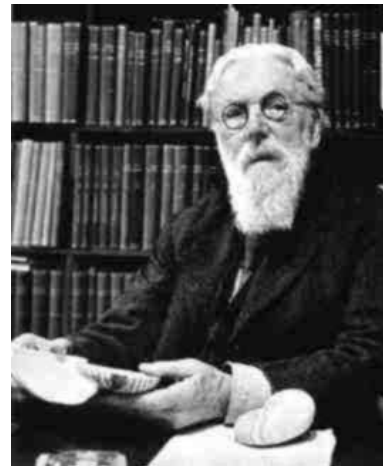
- Requires
  - Varying angles
  - Varying stem lengths
  - randomness
- The Fibonacci Model is similar
  - Initial State: b
  - b -> a
  - a -> ab
- *sneezewort*



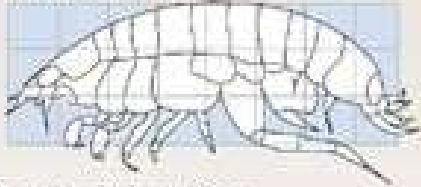
Psilophyta/Psilotum



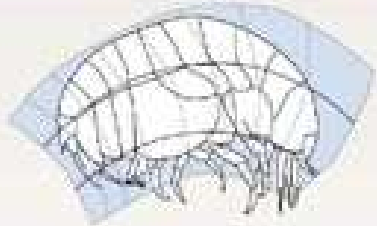
- D'Arcy Wentworth Thompson (1860 - 1948)
  - *On Growth and Form* (1917), laid the foundations of bio-mathematics
    - Equations to describe static patterns of living organisms
      - Shells, cauliflower head, etc.
    - Transformations of form changing a few parameters



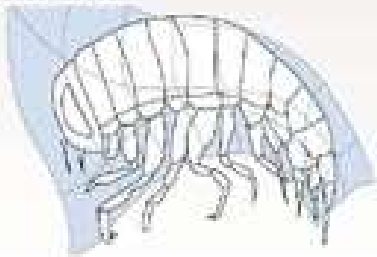
*Harpinia plumosa*



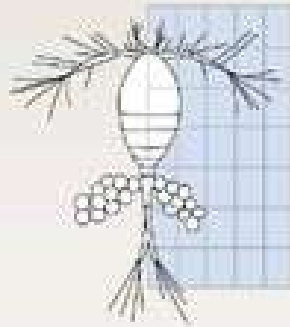
*Stegocephalus inflatus*



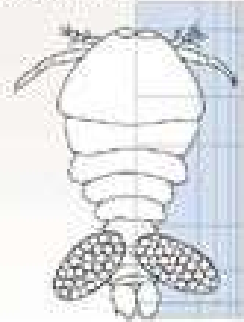
*Hyperia galba*



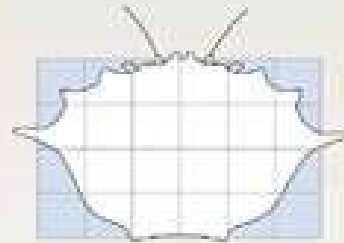
*Oithona nana*



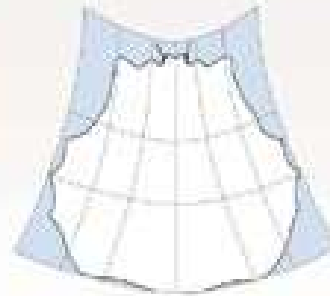
*Sapphirina*



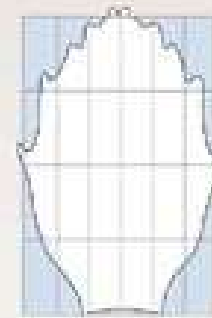
*Geryon*



*Paralomis*



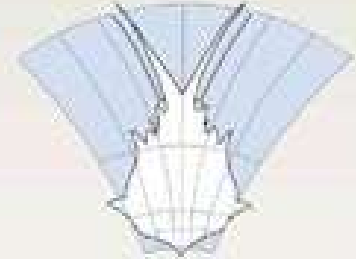
*Corystes*



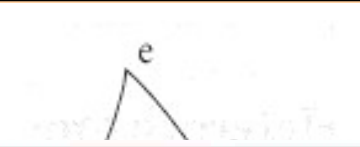
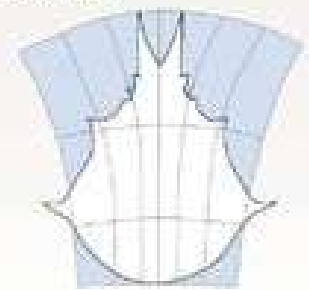
*Lupa*



*Scyramathia*



*Chorinus*

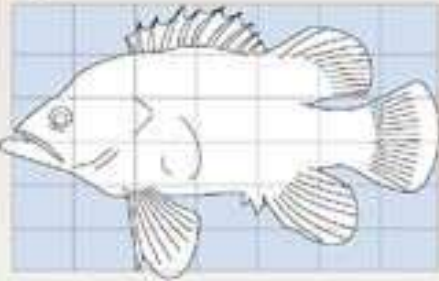


Arthur, Wallace. "D'Arcy Thompson and the theory of transformations." *Nature Reviews Genetics* 7.5 (2006): 401-406.

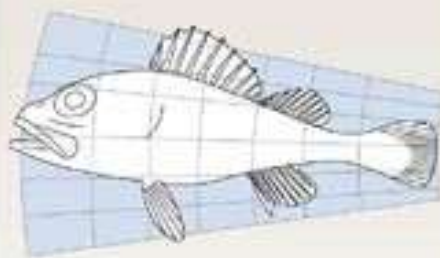
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D'Arcy Thompson

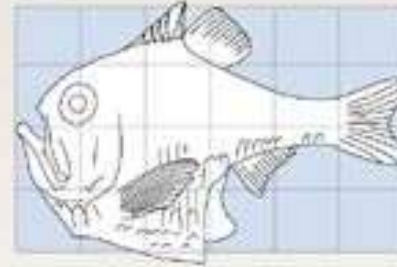
Polyprion



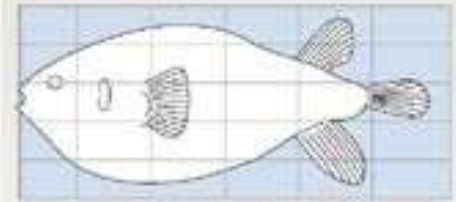
Scorpaena



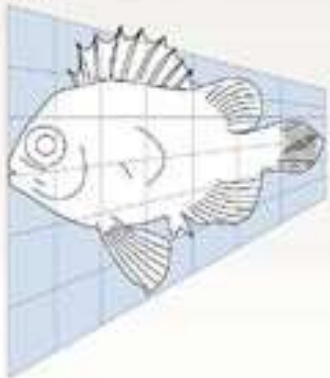
Argyrolepecus olfersi



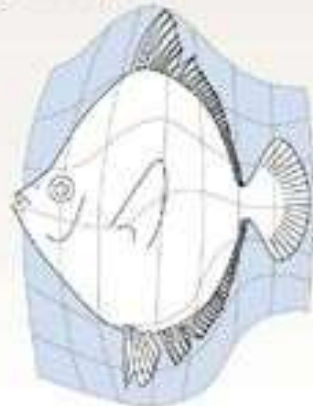
Diodon



Pseudopriacanthus altus



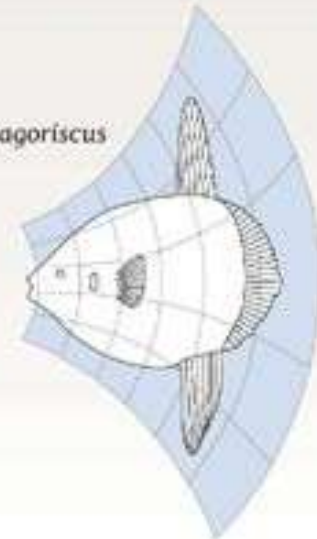
Antigonia capros



Sternoptyx diaphana



Orthogoriscus



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

Fig. 517. *Argyrolepecus Olfersi*.

Fig. 518. *Sternoptyx diaphana*.

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D'Arcy Thompson

Polyprion      Scorpaena

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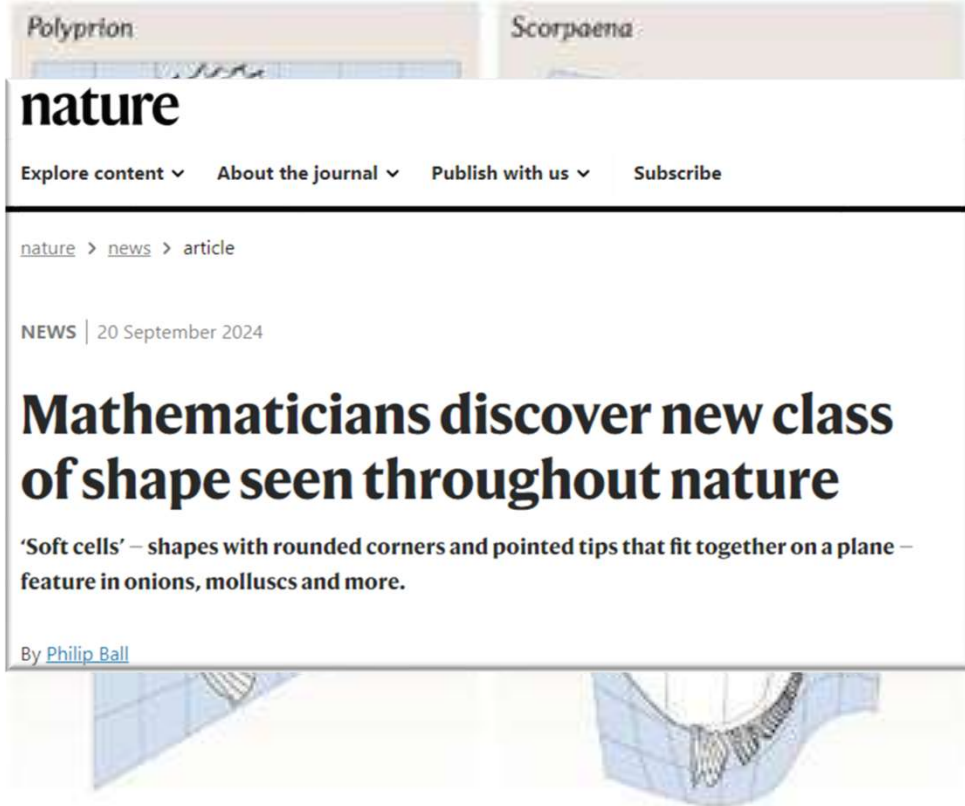
nature > news > article

NEWS | 20 September 2024

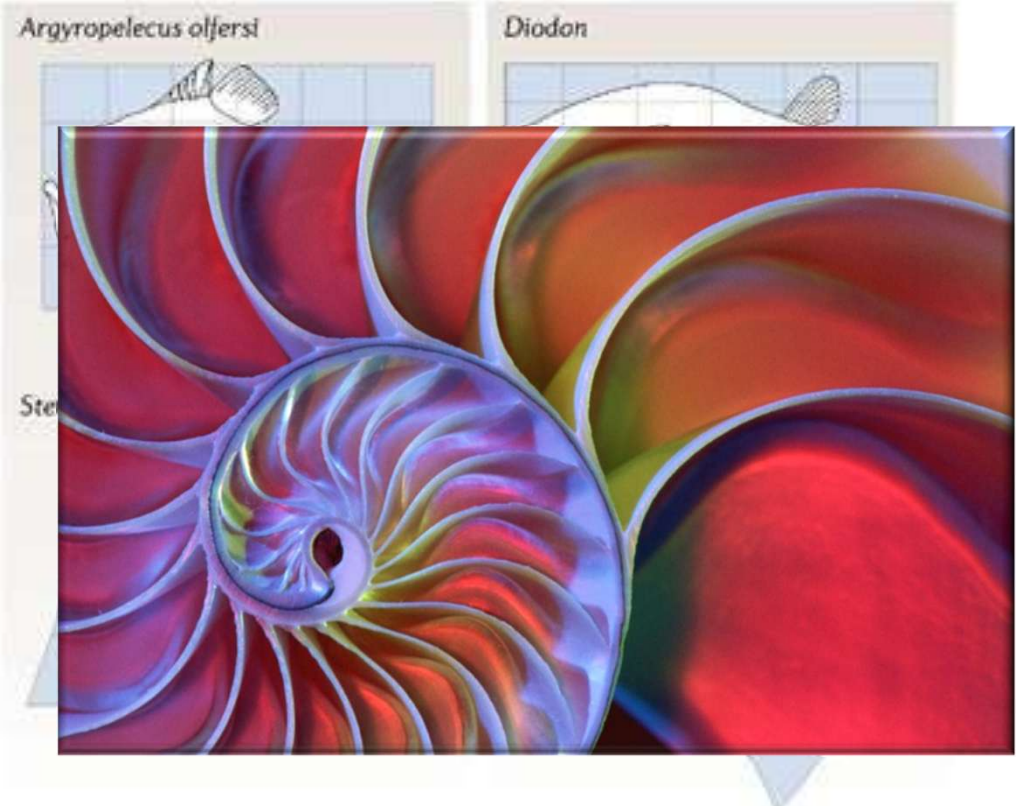
# Mathematicians discover new class of shape seen throughout nature

'Soft cells' – shapes with rounded corners and pointed tips that fit together on a plane – feature in onions, molluscs and more.

By [Philip Ball](#)



Argyropelecus olfersi      Diodon



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

Fig. 517. *Argyropelecus Olfersi*.

Fig. 518. *Sternoptyx diaphana*.

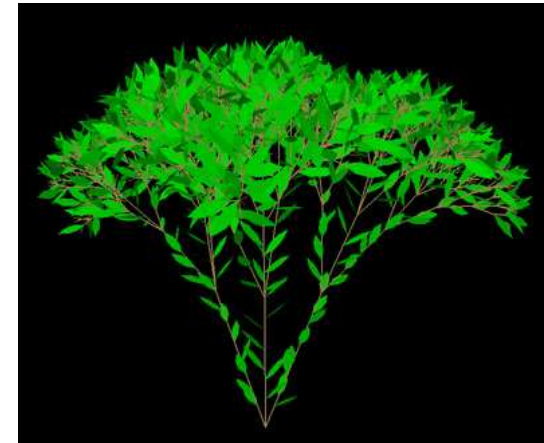
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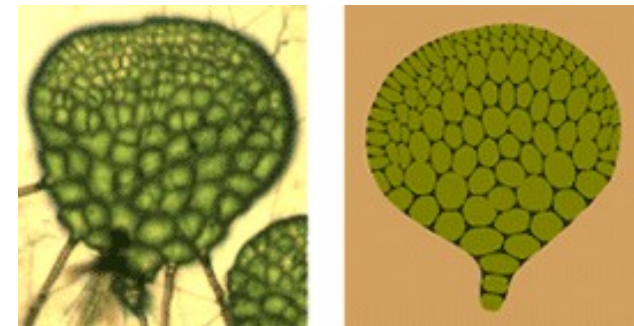
## Aristid Lindenmeyer

- 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



## models or realistic imitations?

- **Common features (design principle) between artificial and real plants**
  - Development of (macro-level) morphology from local (micro-level) logic
  - Parallel application of simple rules
  - Recursion
- **But are the algorithms the same as the biological *mechanism*?**
  - Real organisms need to economize information for coding complex phenotypes
    - The genome cannot encode every ripple of the brain or lungs
    - Organisms need to encode **compact procedures** for producing the same pattern (with randomness) again and again
- **But recursion alone does not explain form and morphogenesis**
  - One of the design principles involved
  - There are others
    - Selection, genetic variation, self-organization, epigenetics

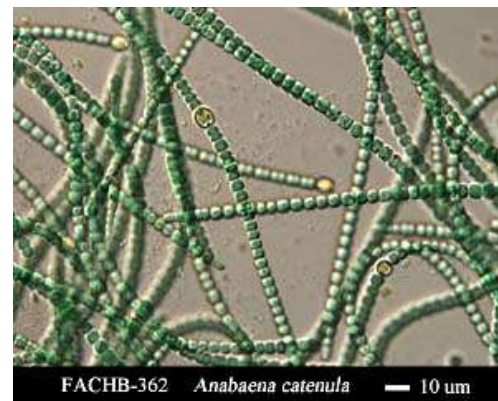
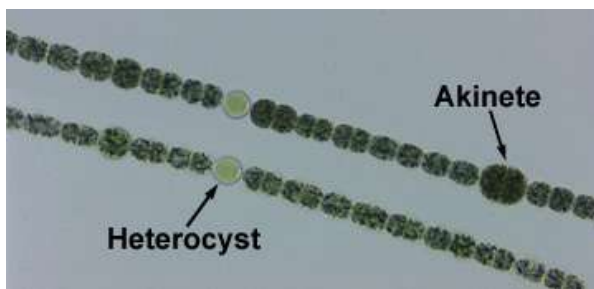
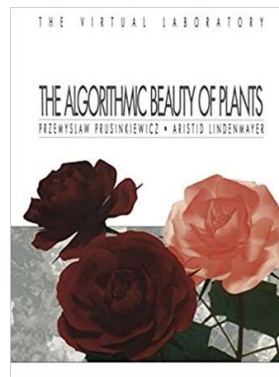


fern gametophyte *Microsorium linguaeforme* (left) and a simulated model using map L systems (right).

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
```

```
 $\omega$  : -(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*.

are all “models” equally acceptable/useful?

- No!
- William Ockham (c. 1285–1349):
  - “*entia non sunt multiplicanda praeter necessitatem*”
    - Loosely paraphrased as “make no unnecessary assumptions”, or “of two competing theories: simplest is often best”
- Explanatory “power” (cf. discussion on “beauty”)
- Generality
  - Example: model of lightning? “Thor gets mad.”
- Karl Popper (1902-1994): notion of Falsifiability
  - model/theories/assertions can not be confirmed by any number of empirical tests (Blackbox modeling)
    - but information gained when falsified
      - logical asymmetry between verification and falsification: many observations do not derive (universal) theories, a single observation can falsify it: scientific theories (deduced) from induction are testable.
  - falsifiability hard requirement for scientific models
    - tremendously important in science
- All of these matter in complex systems modeling
  - existing intuitive notions fail in complex systems
  - falsifiability: praxis/logistic problems



Popper (1972) Objective Knowledge