Life & Complexity

Organisation, information and optimisation in real and simulated biological systems

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9 August, Camp 2007


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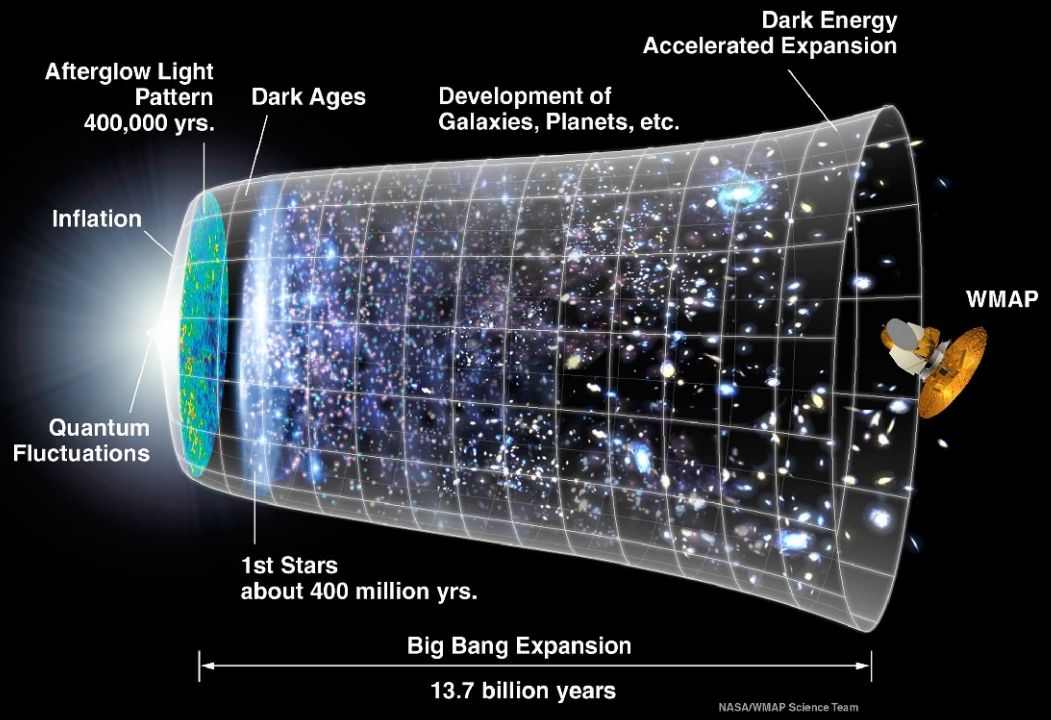
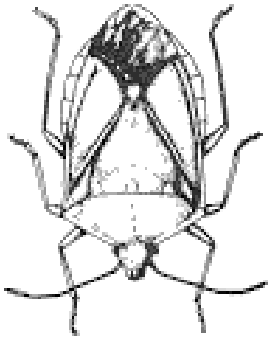
50 µm
29.05.2003, 200x

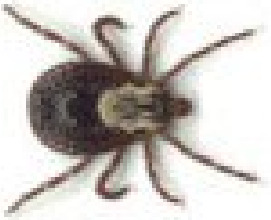
Big Bang

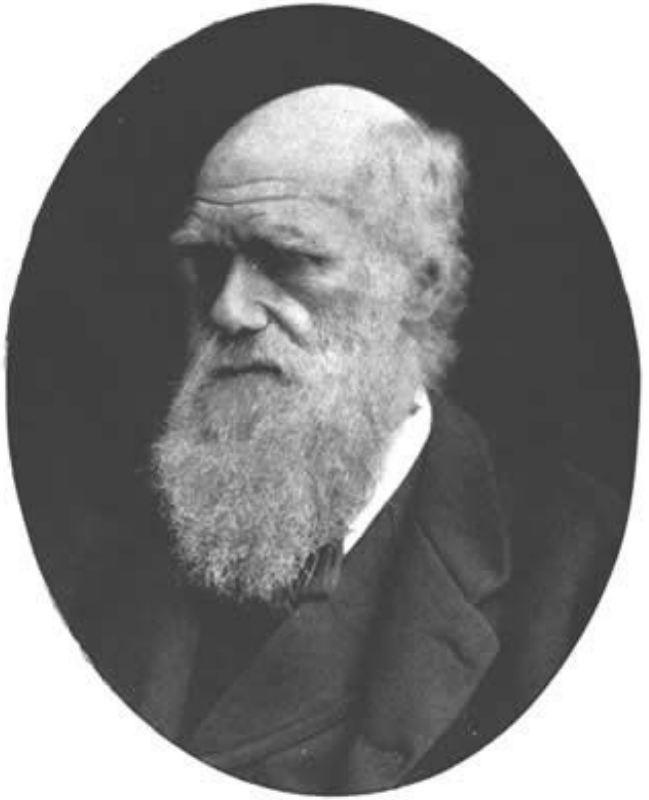


Slime Mold

The world is full of bugs!





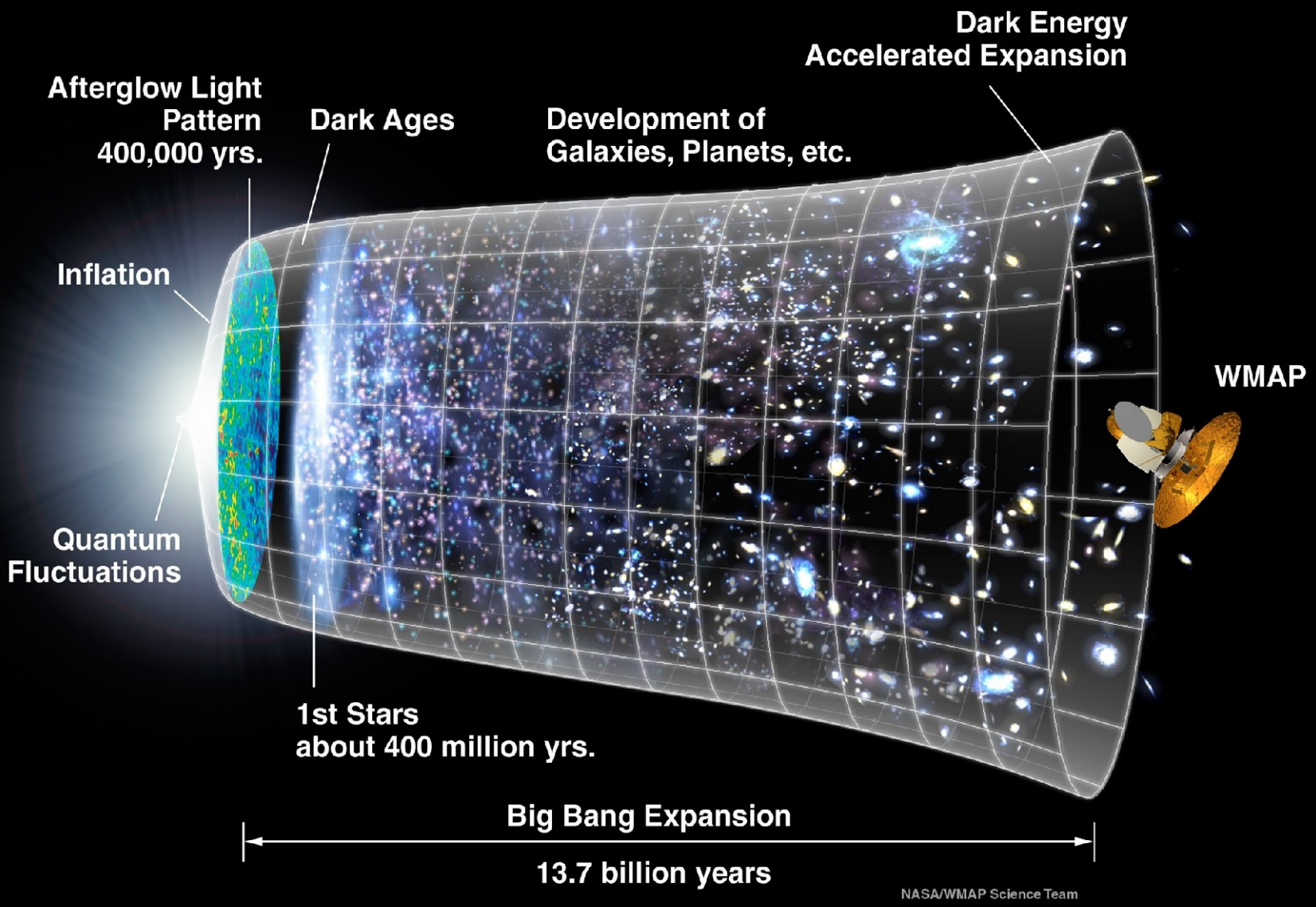


Evolution by Natural Selection

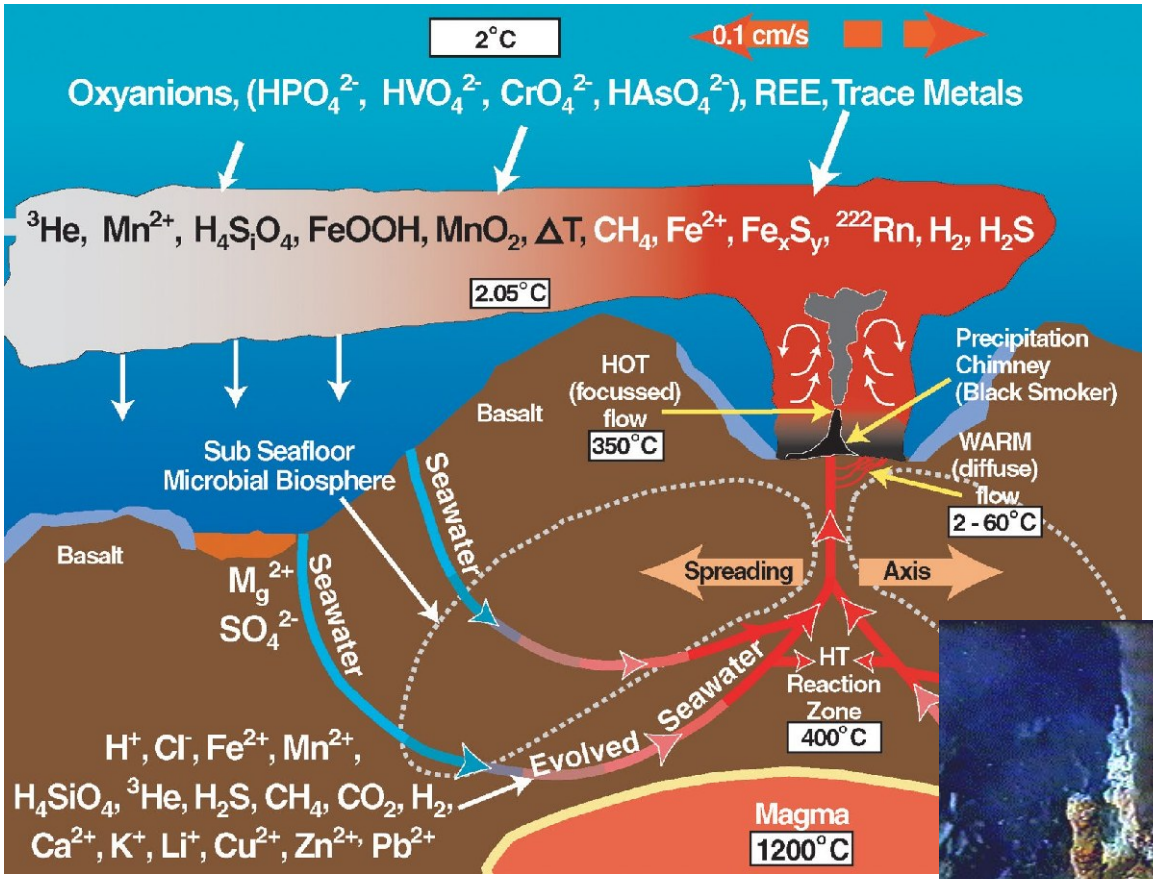
But how are the things that evolve "created" in the first place?

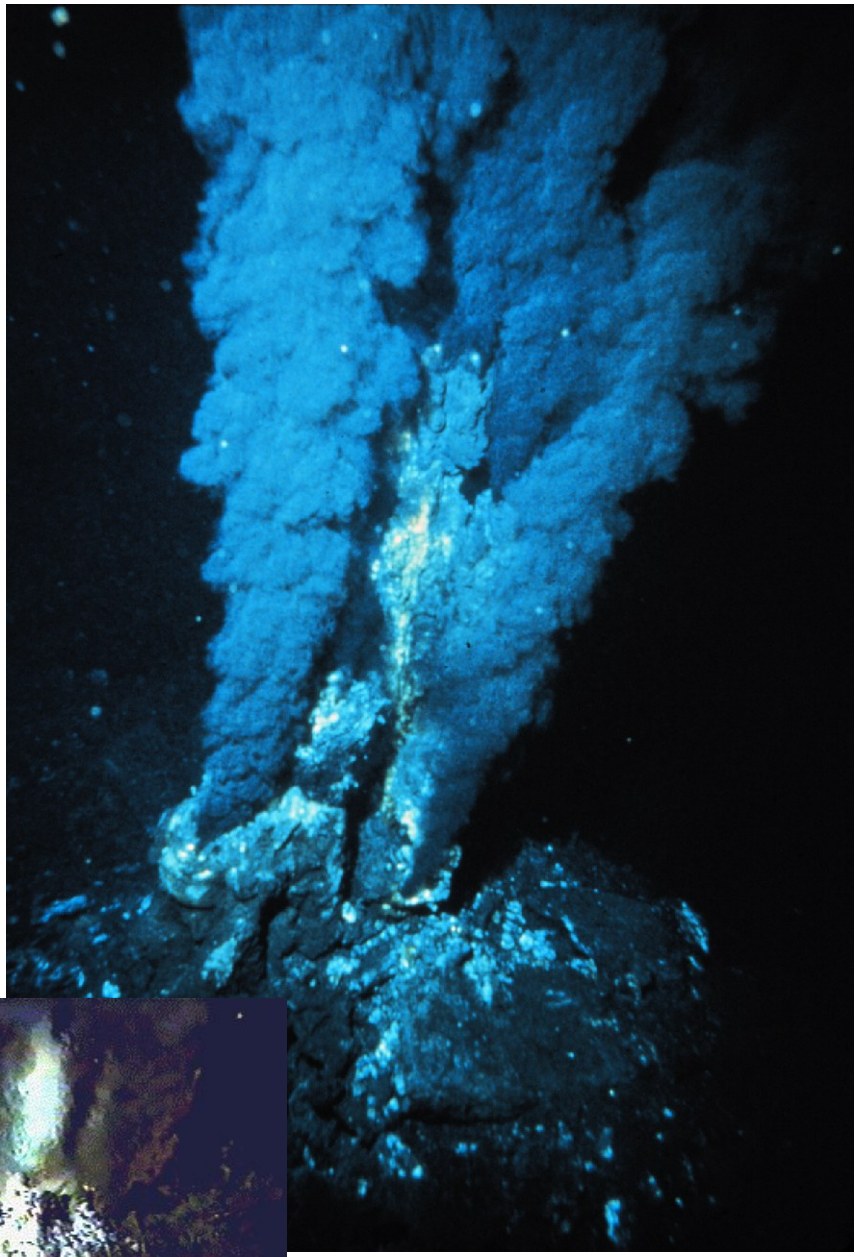
Complexity!

Big Bang

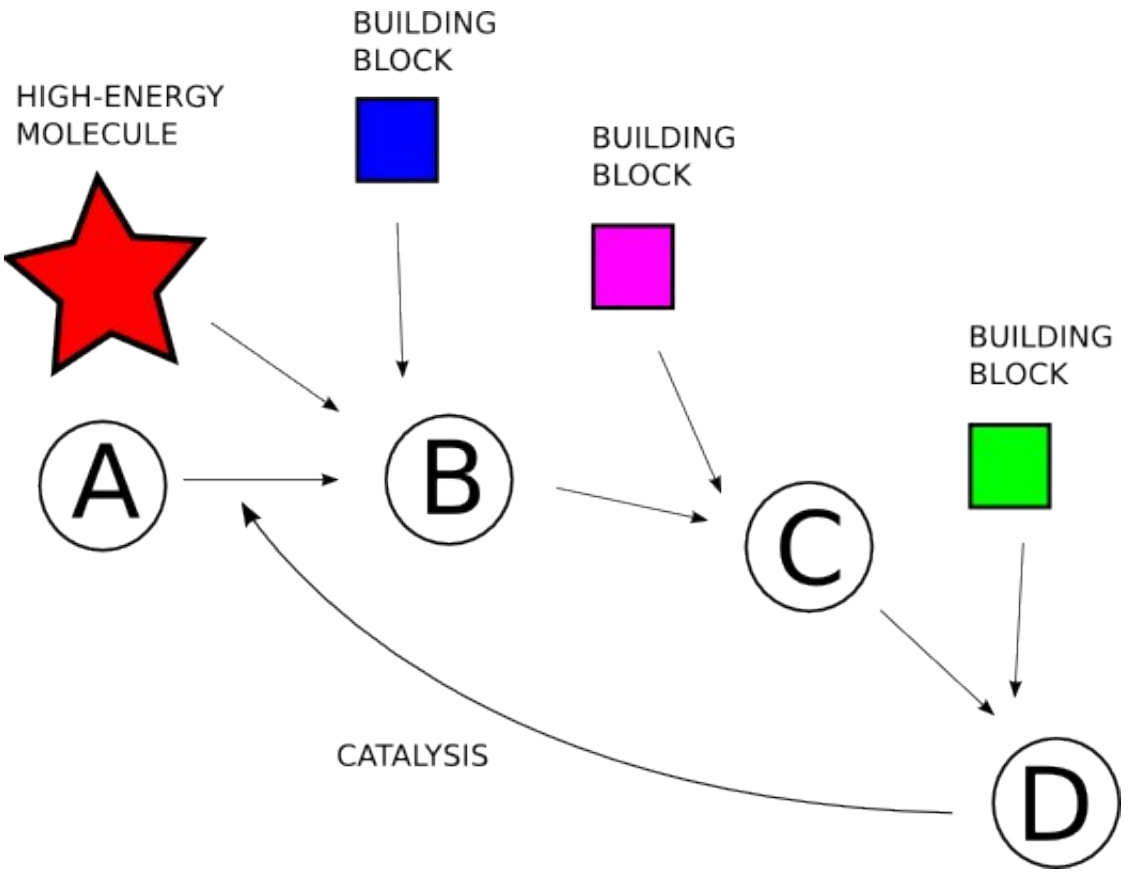

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Deep-Sea Vents

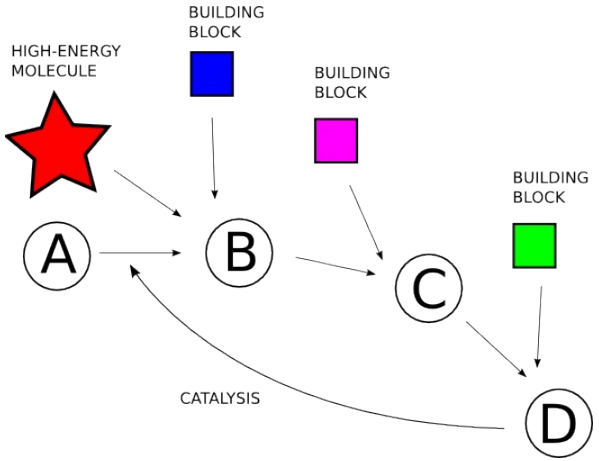


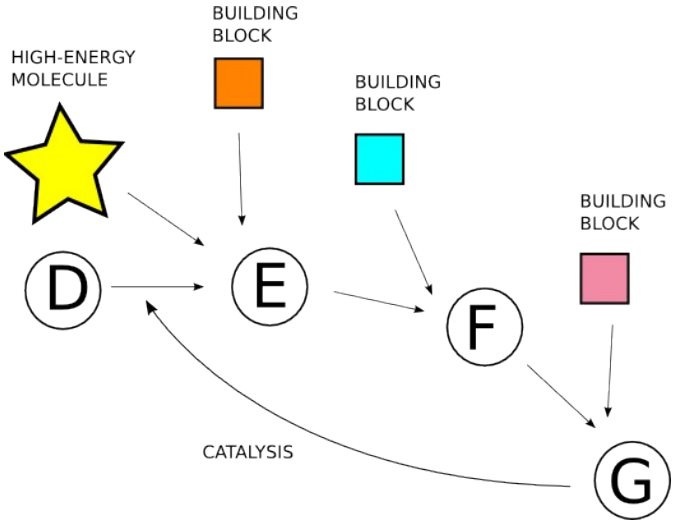


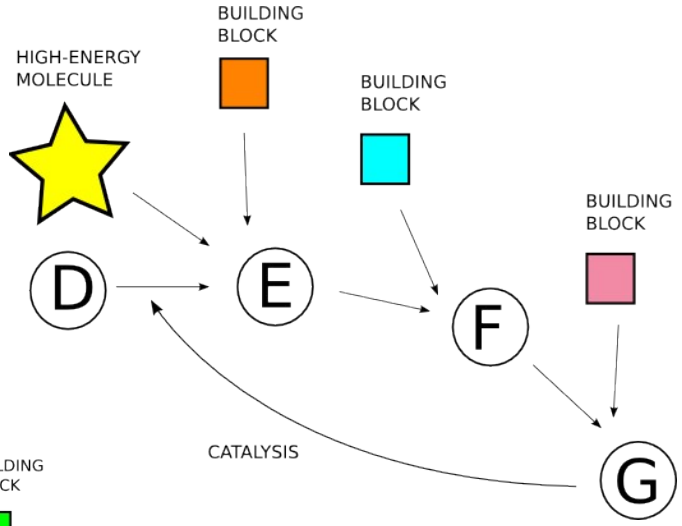
Autocatalytic Set

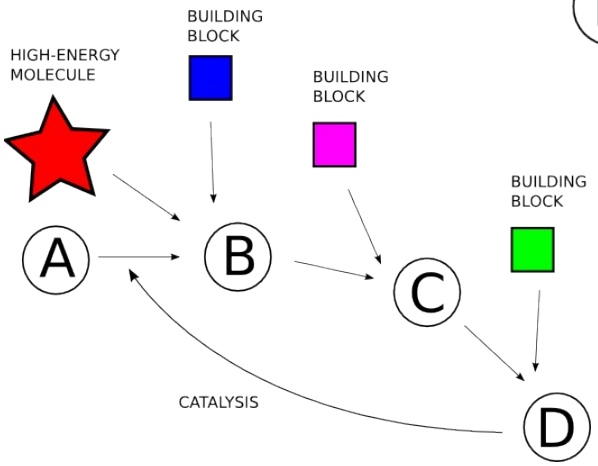


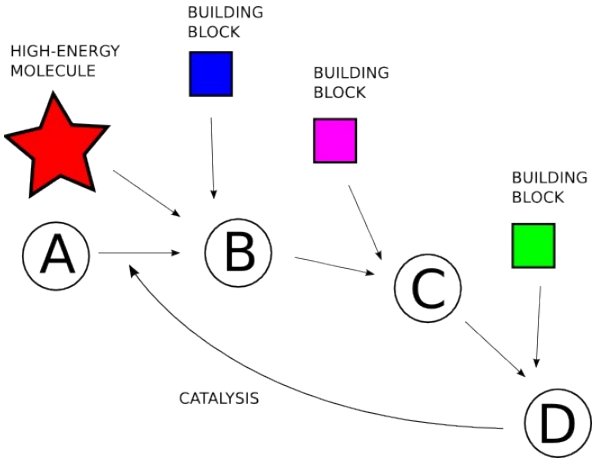
Competition between Autocatalytic Sets



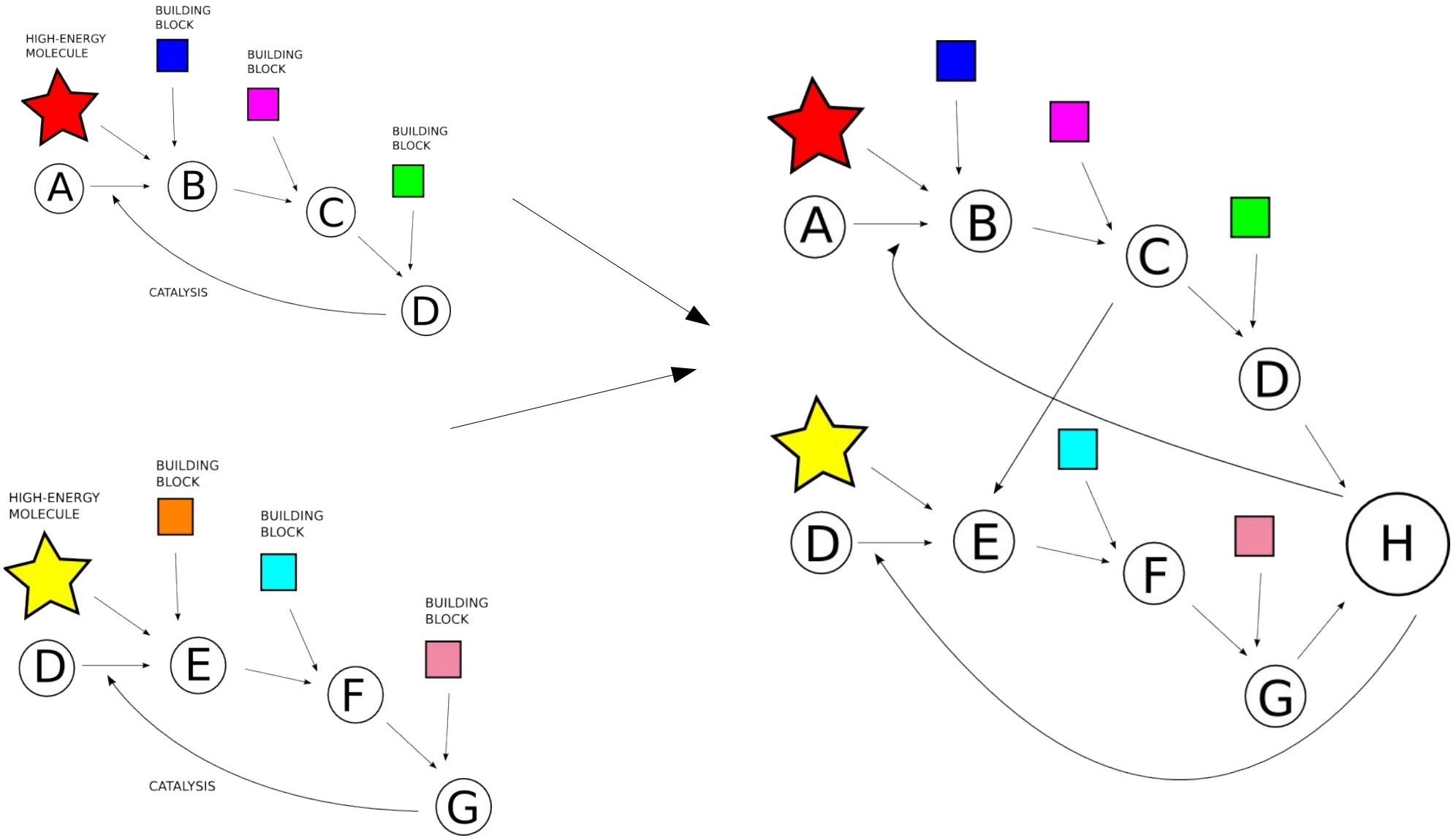




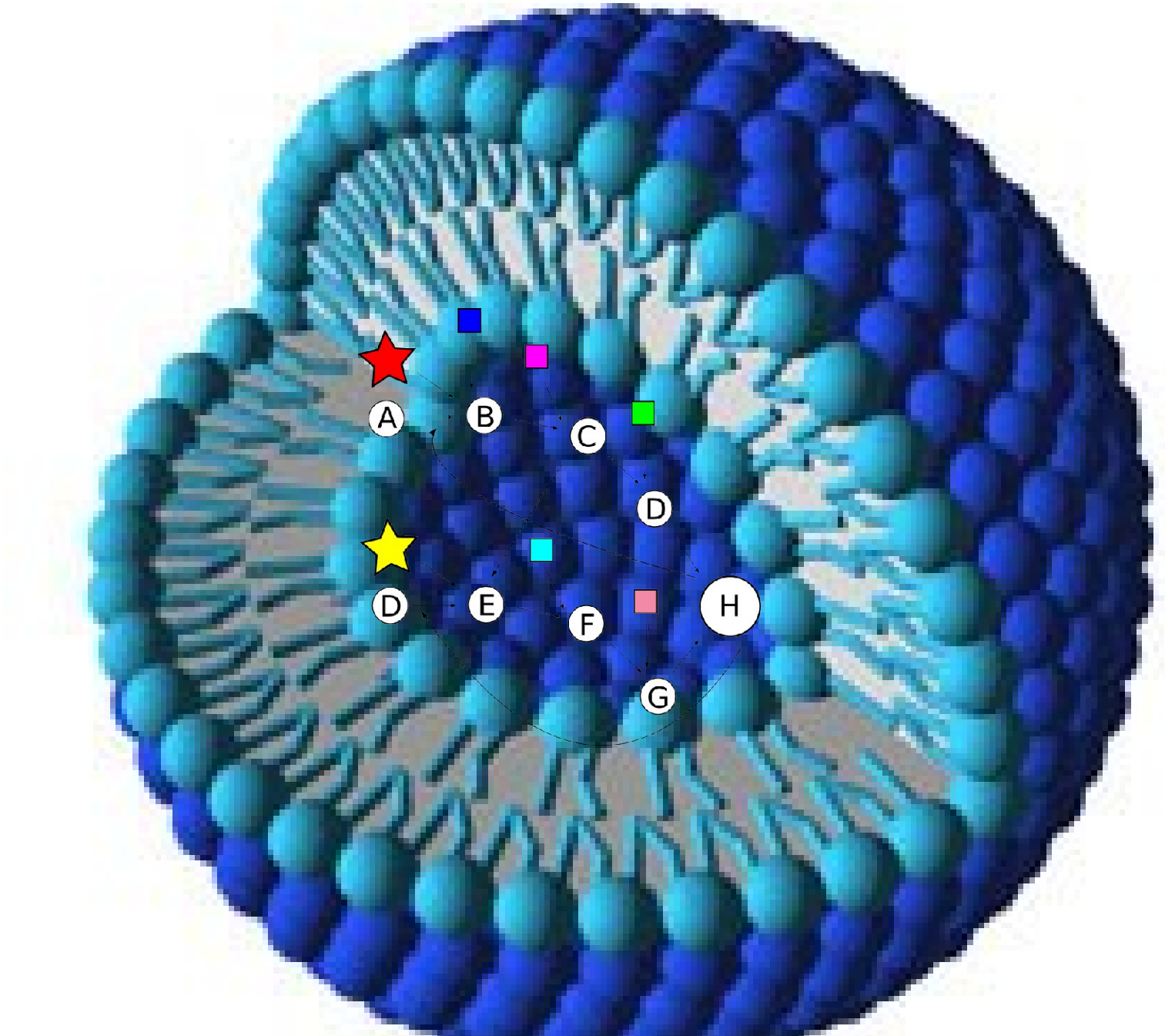




Evolution and Coupling of Autocatalytic Sets

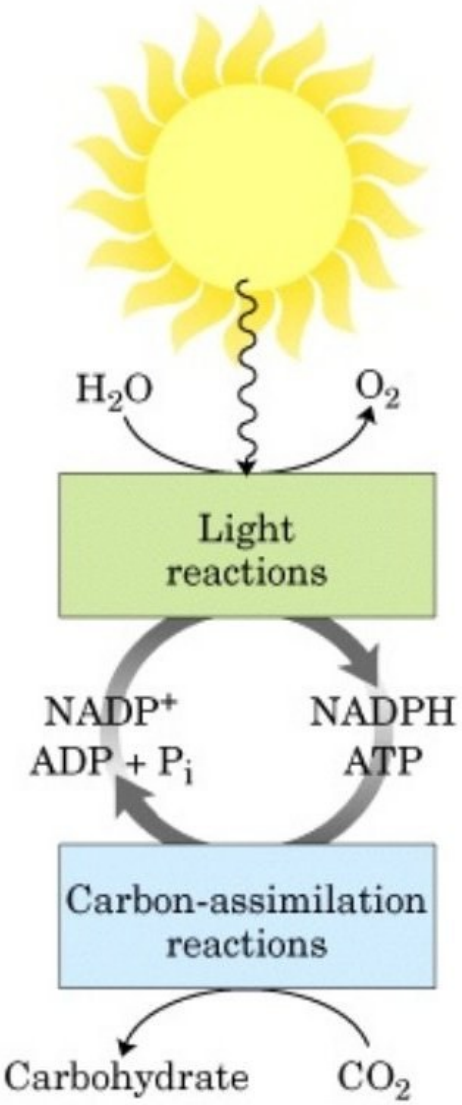


Enclosure by a lipid-bilayer

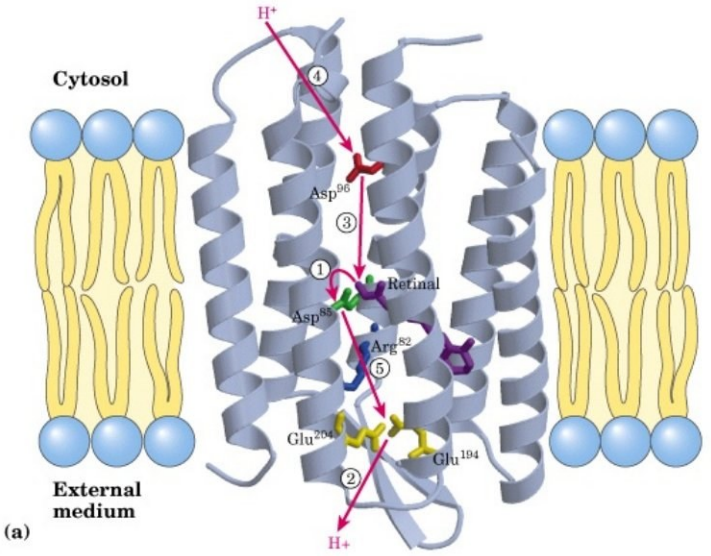


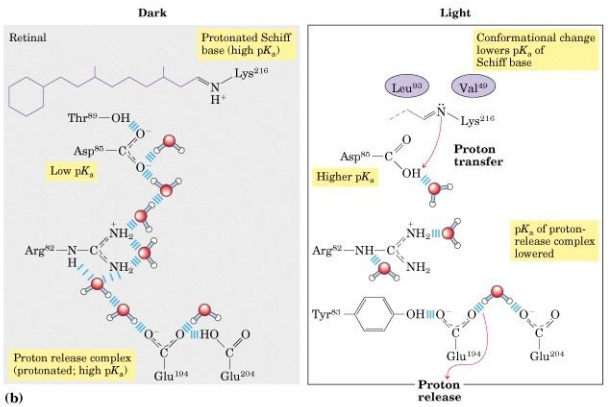
Photosynthesis

Capturing Energy Directly from Sunlight

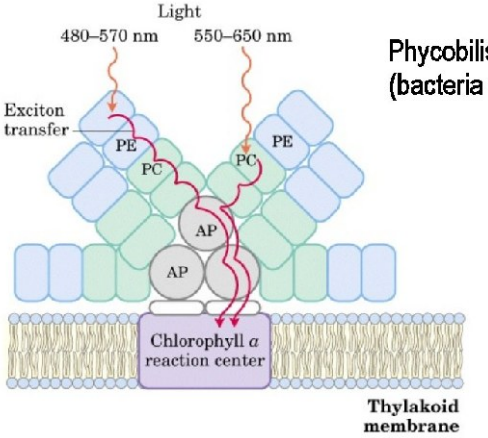


Halobacterium: the simplest light-driven proton pump



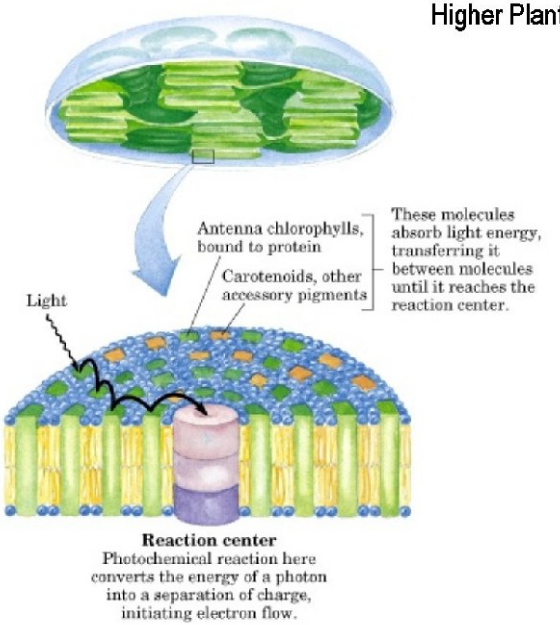


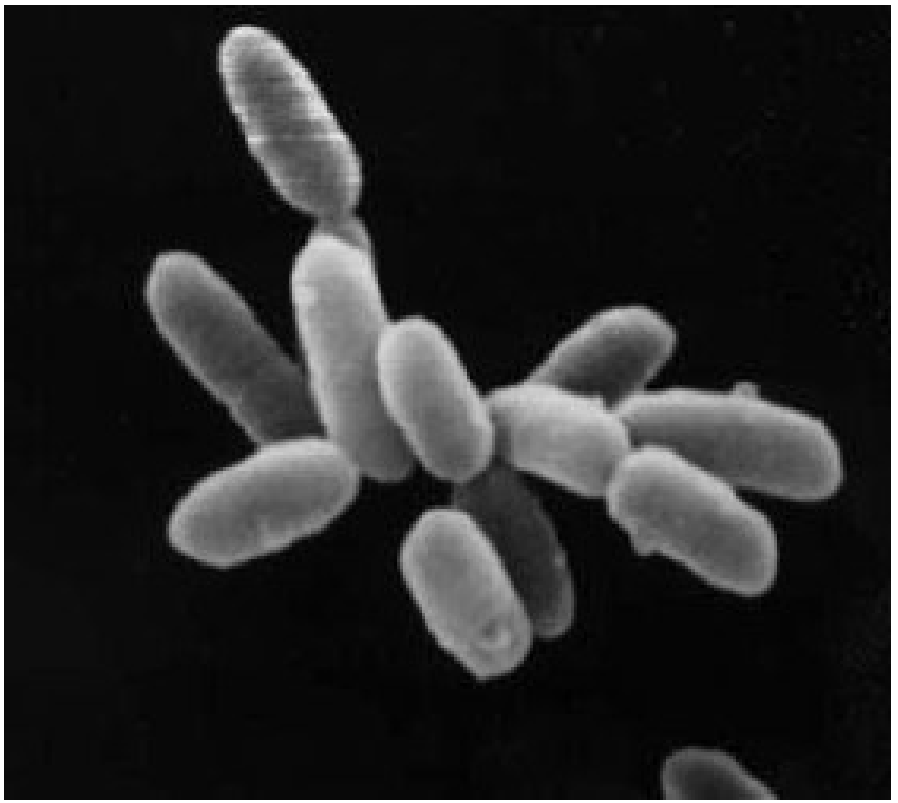
Light harvesting systems



Phycobilisomes (bacteria and algae)

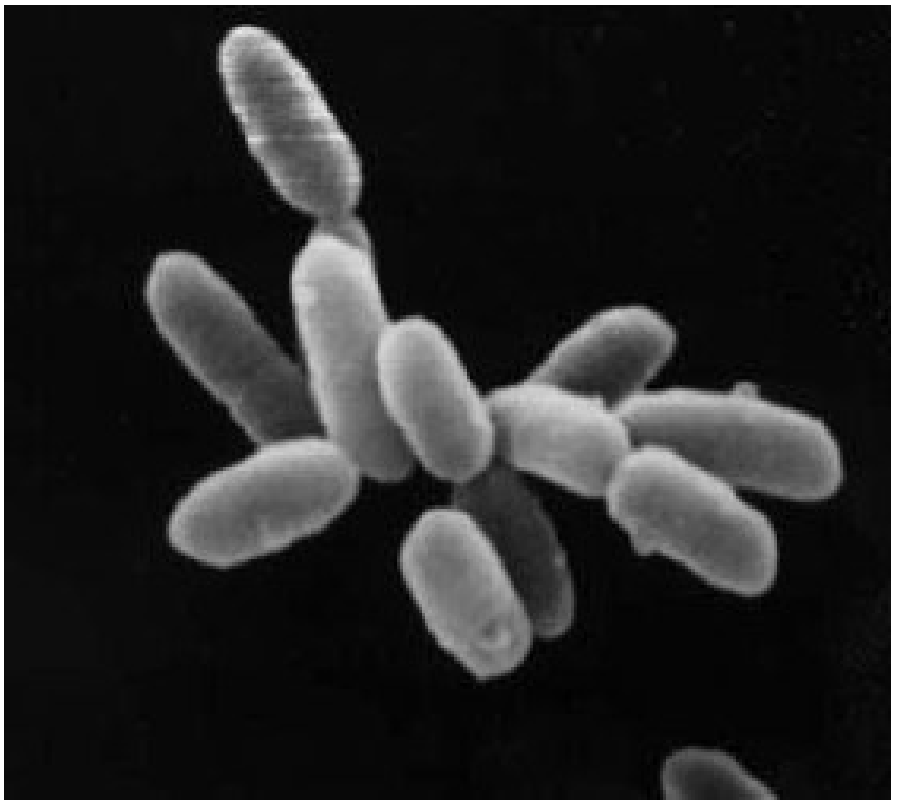
Higher Plants





~ 3,500,000,000 years ago

~ 1,400,000,000 years ago

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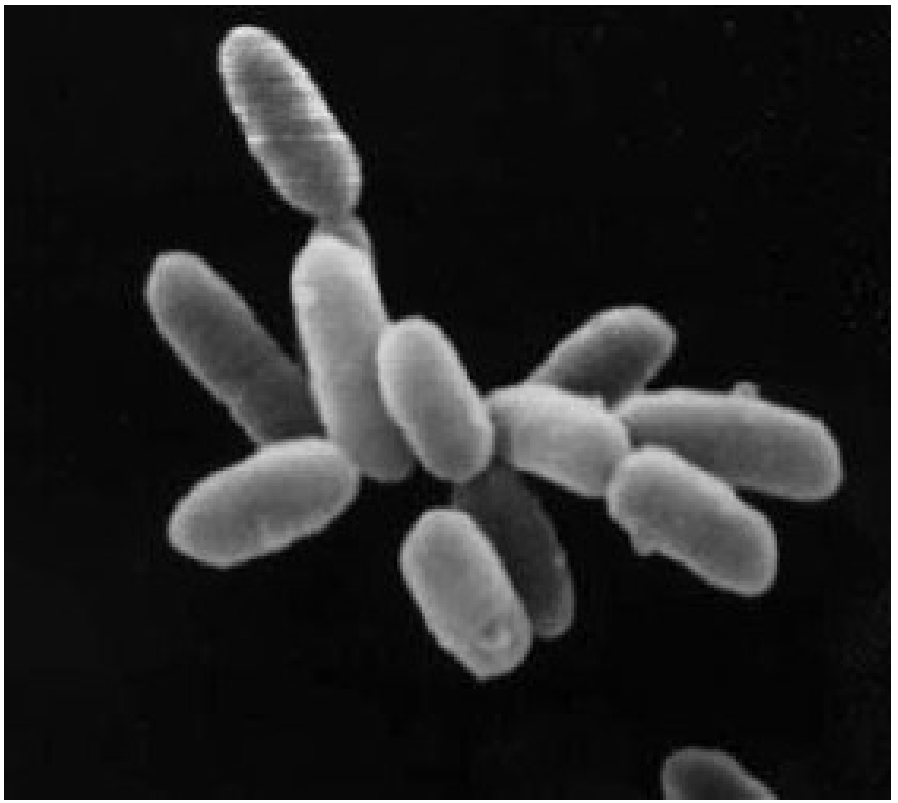

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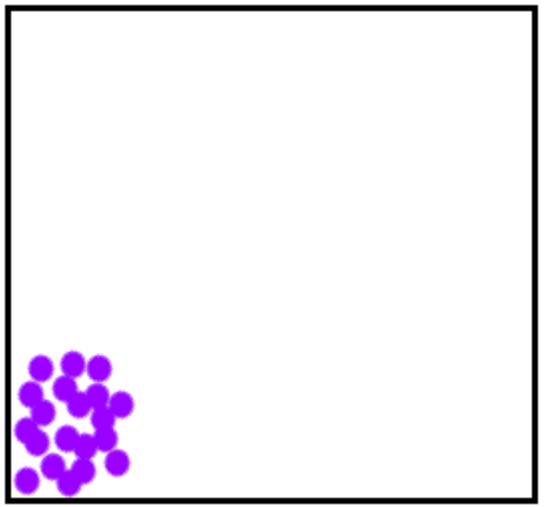
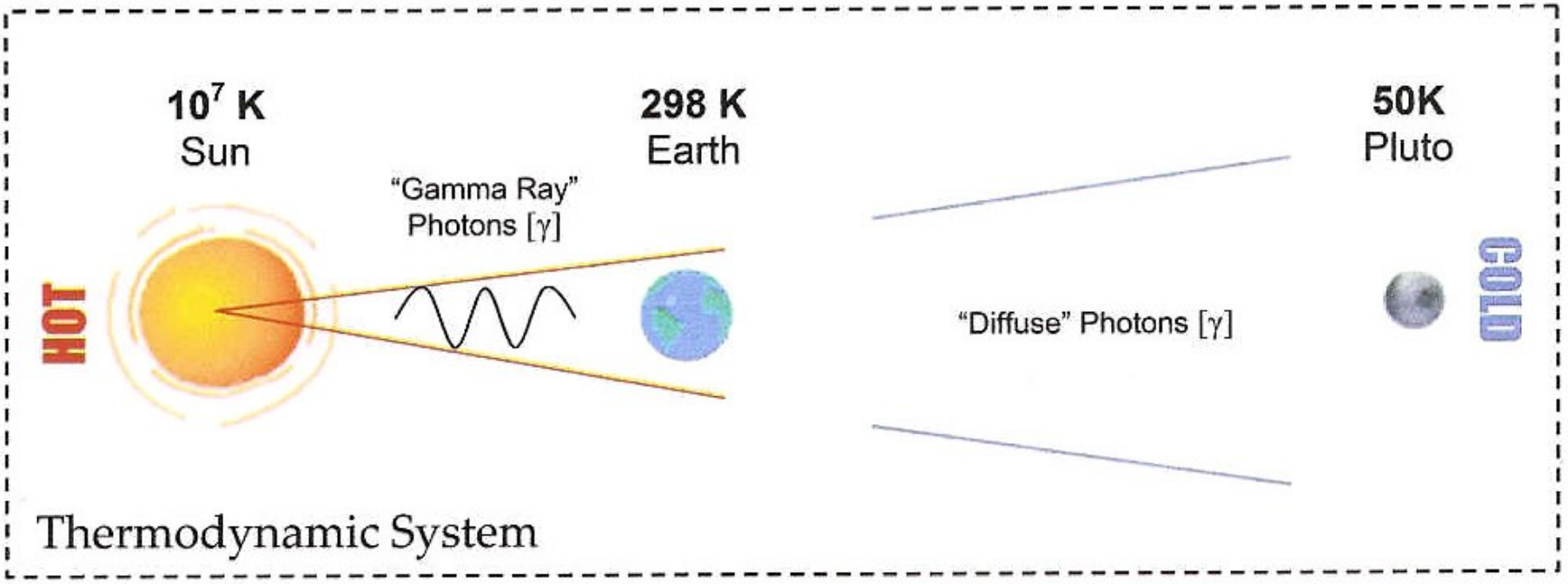
Second Law of Thermodynamics:

Entropy Always Increases

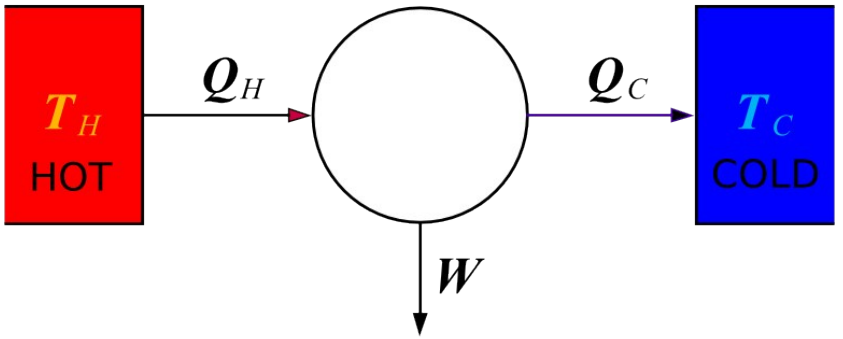


Entropy → Disorder

The Earth is an Open System



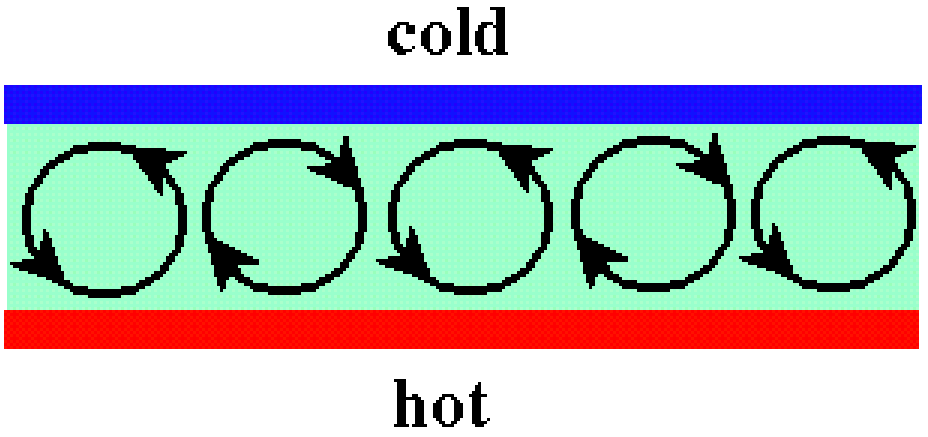
CARNOT HEAT ENGINE

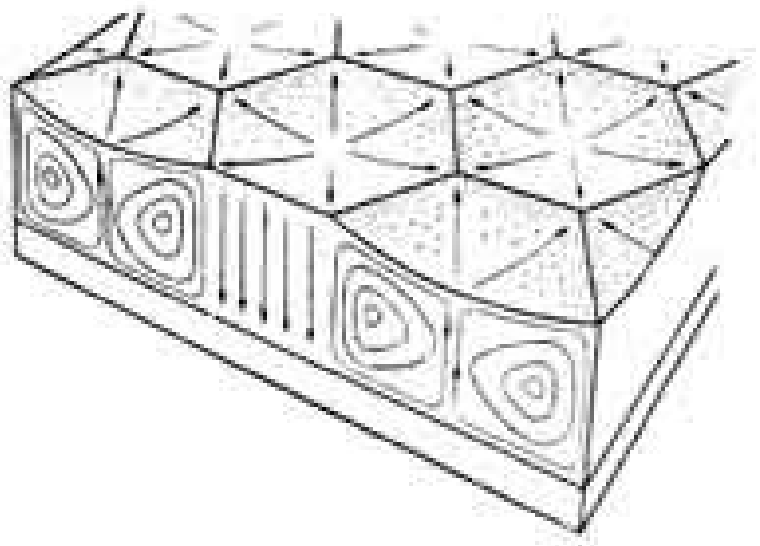


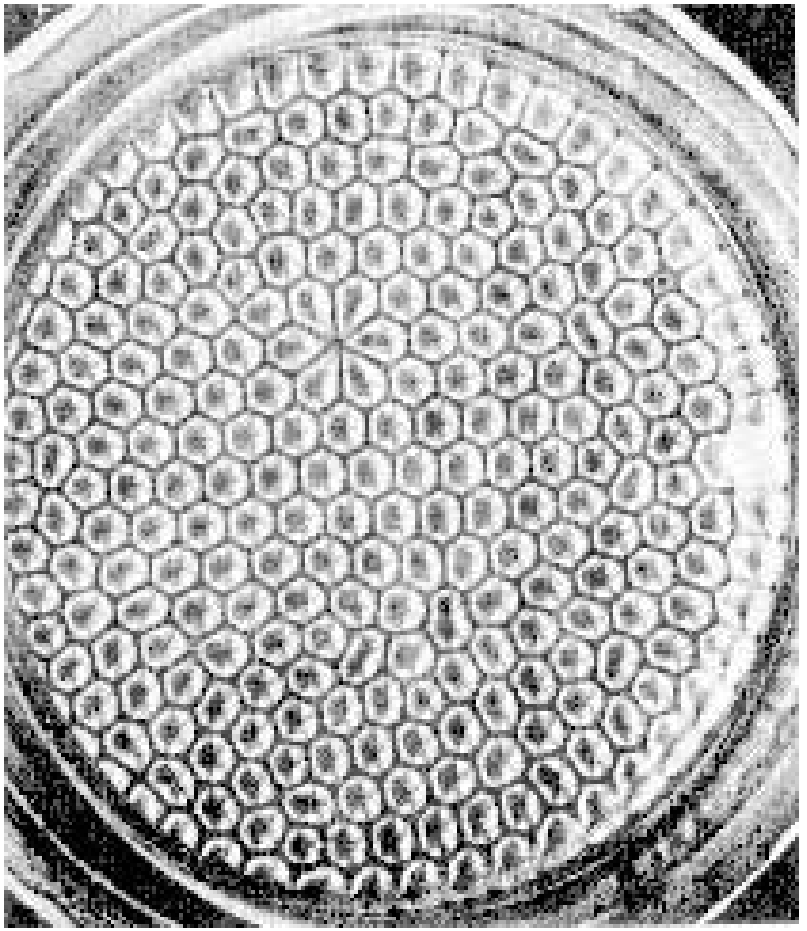
Work done $= Q_H - Q_C$

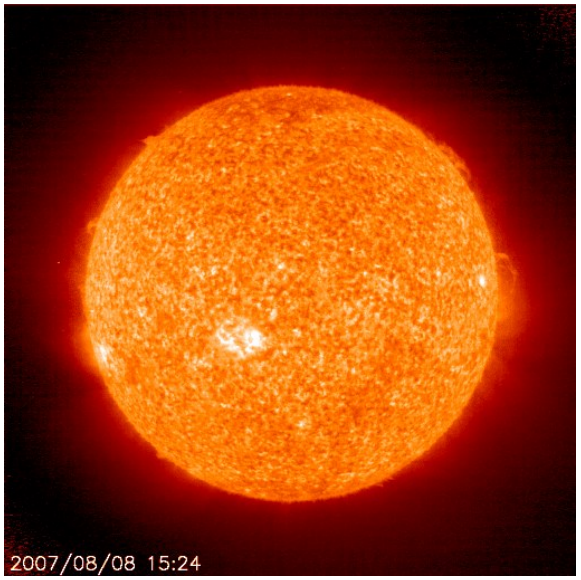
Pattern Formation: Dissipative Structures

Bénard Convection Cells

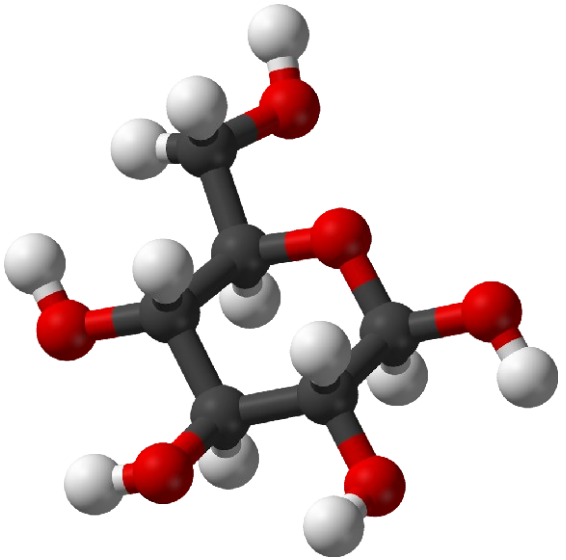


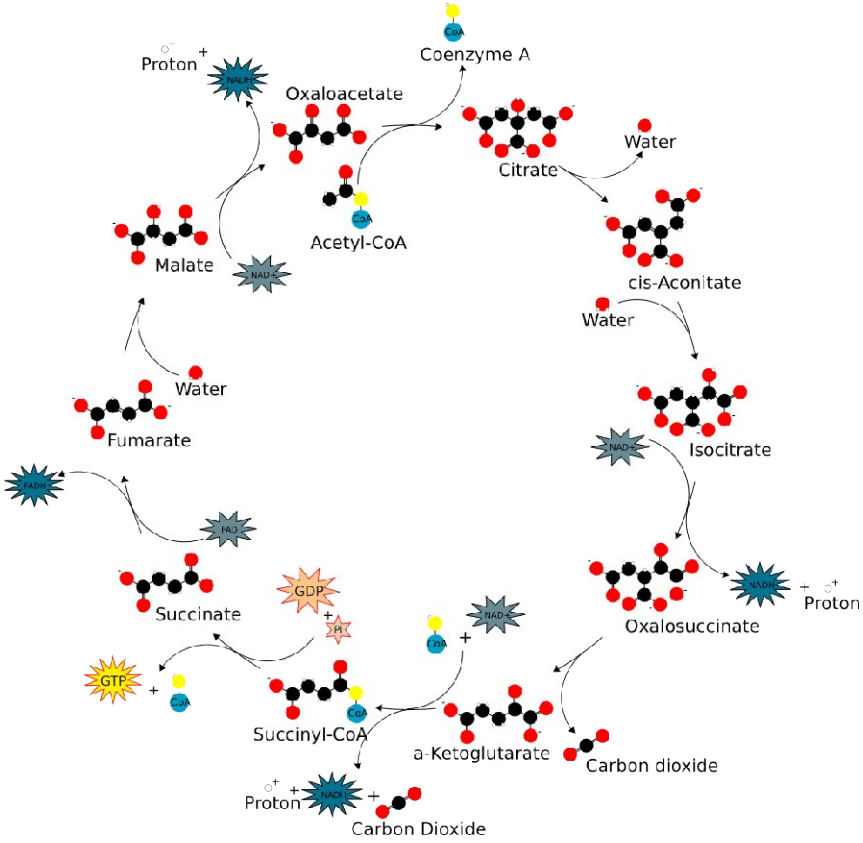




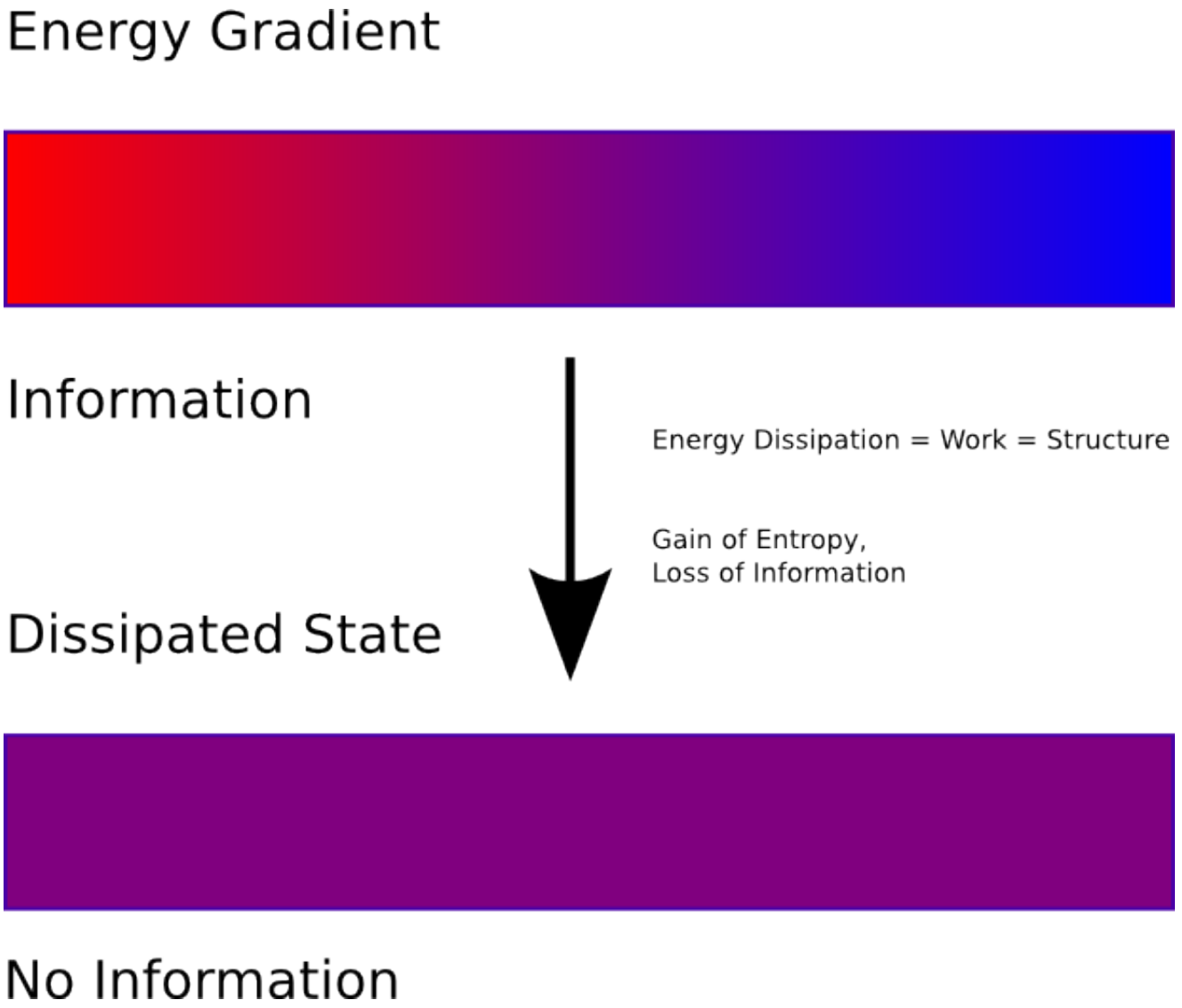


Energy Dissipation by Chemical Reactions

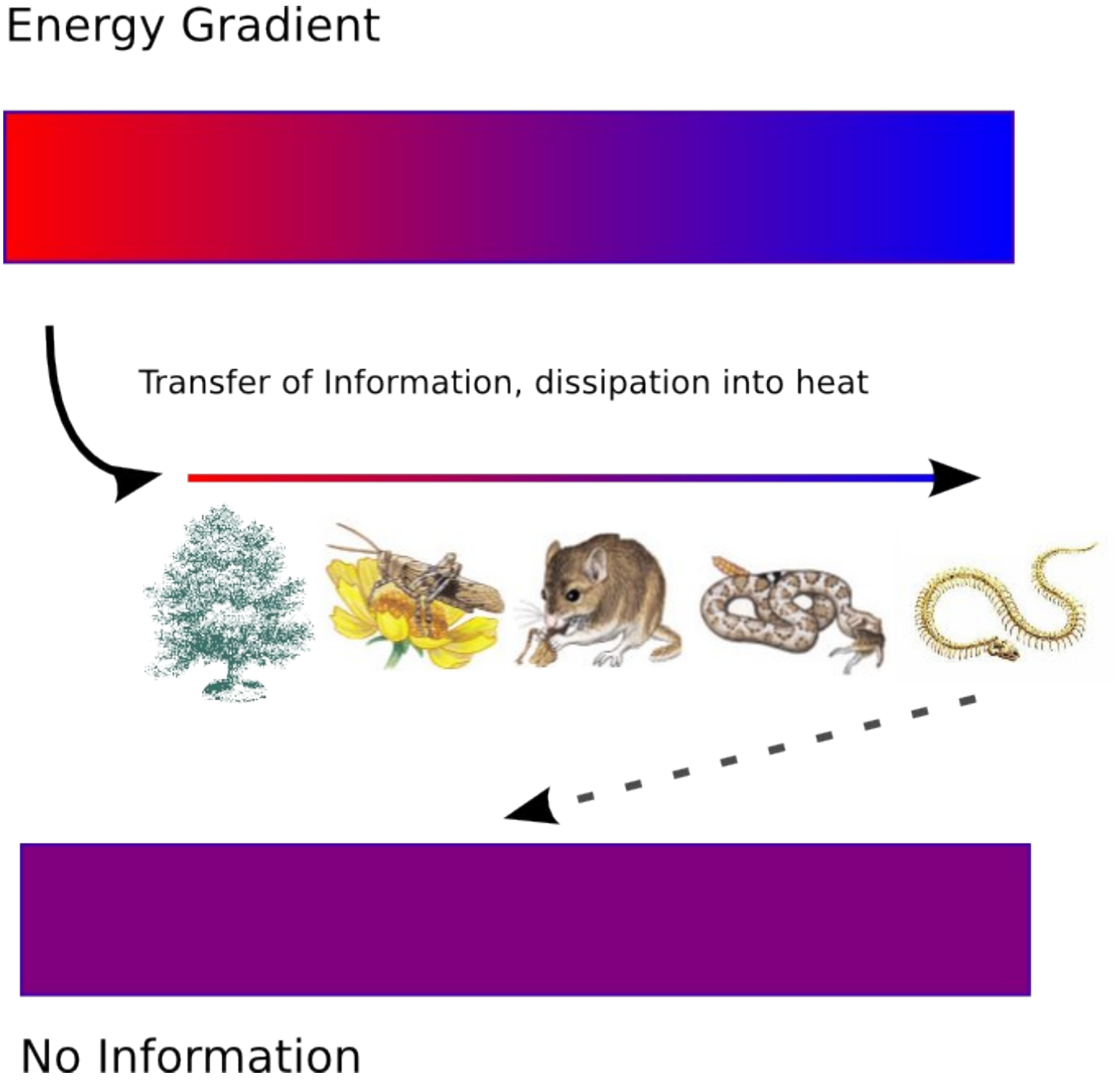




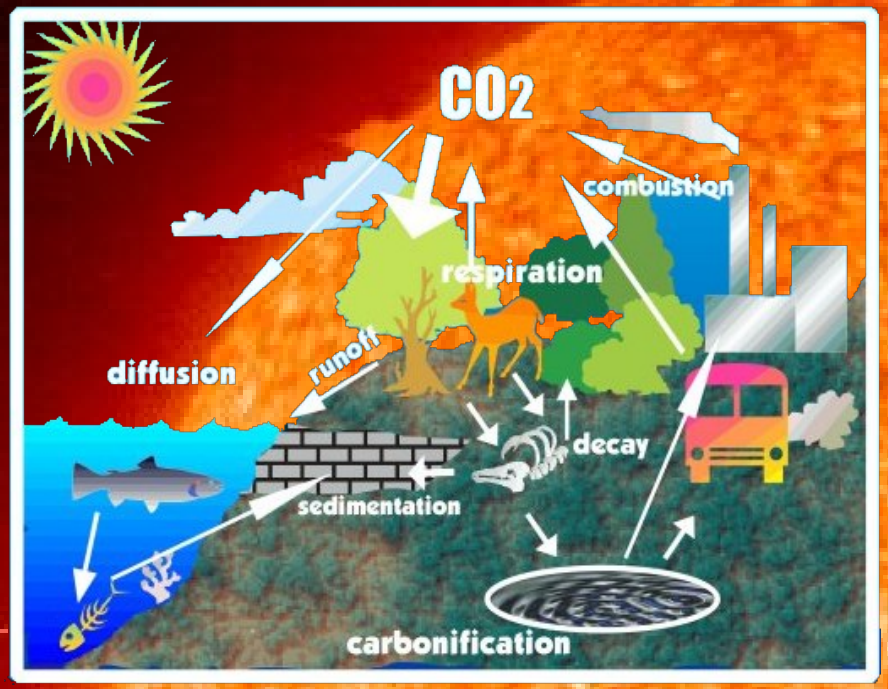
Energy, Entropy and Information



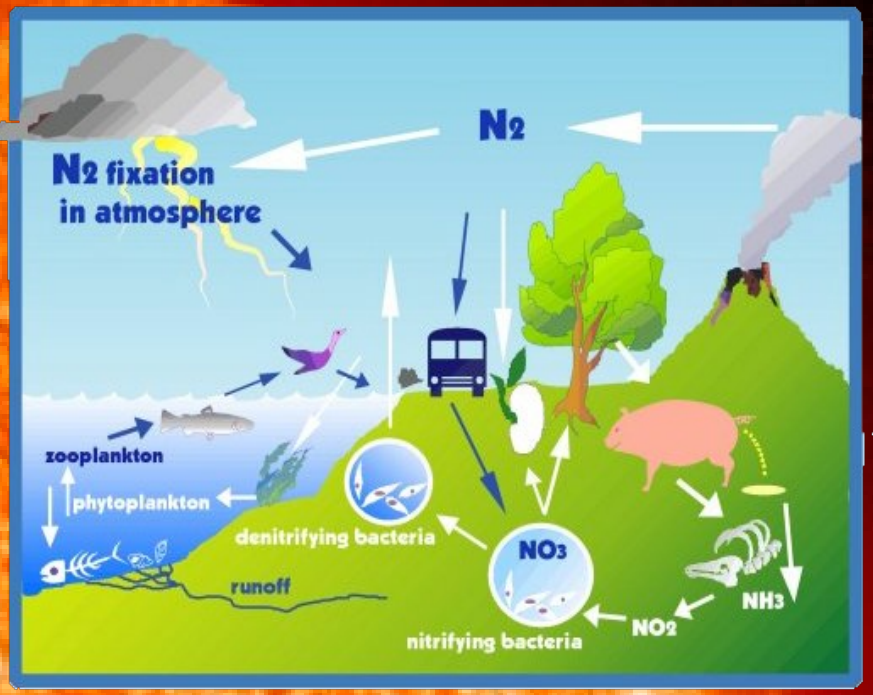
Information and Dissipative Structures



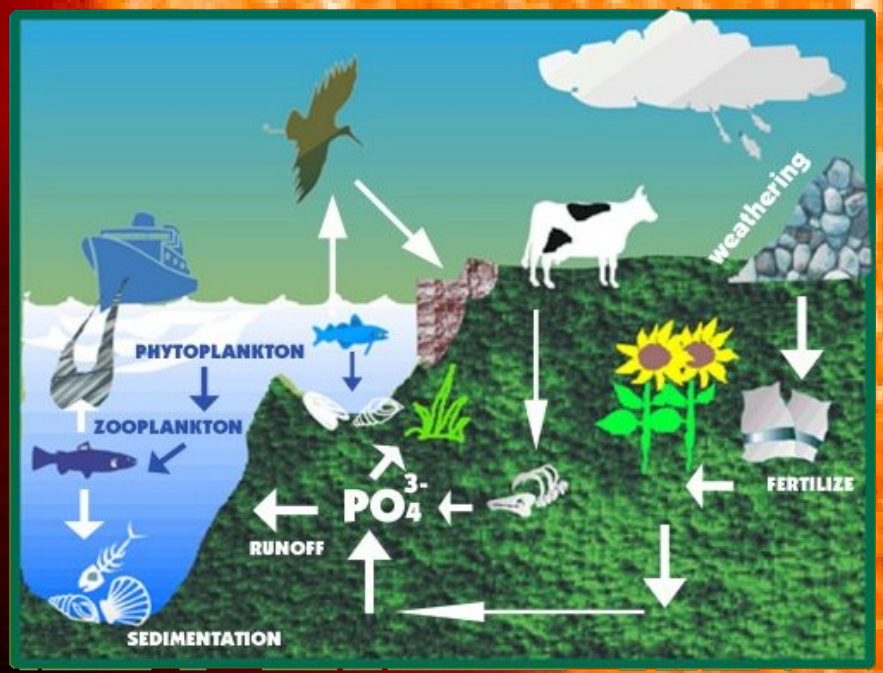
CARBON CYCLE



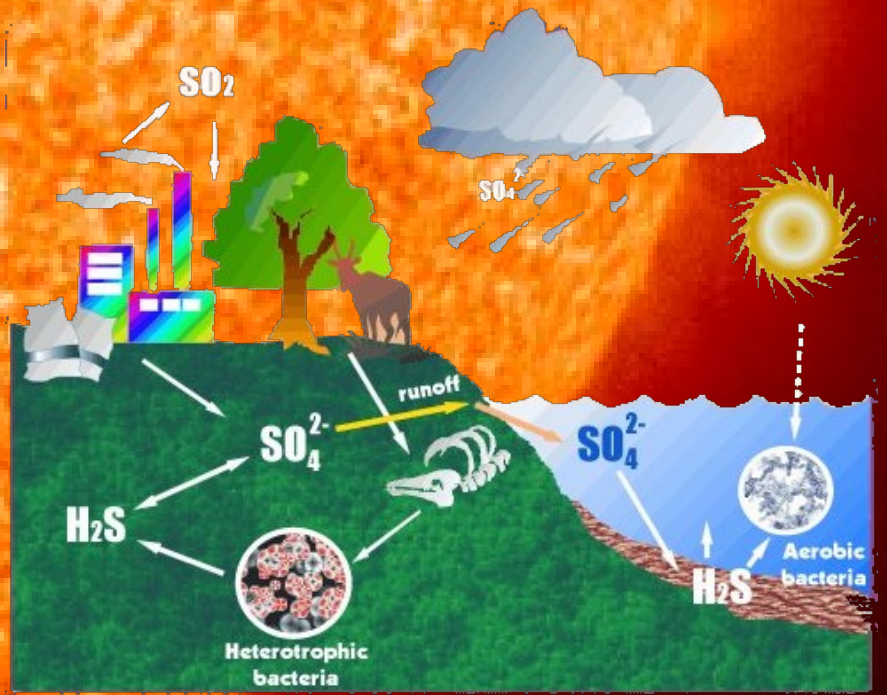
NITROGEN CYCLE



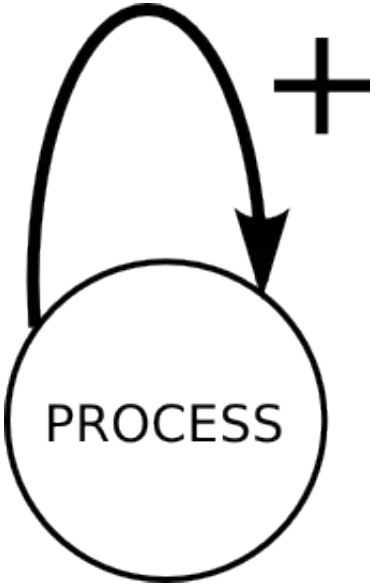
PHOSPHORUS CYCLE



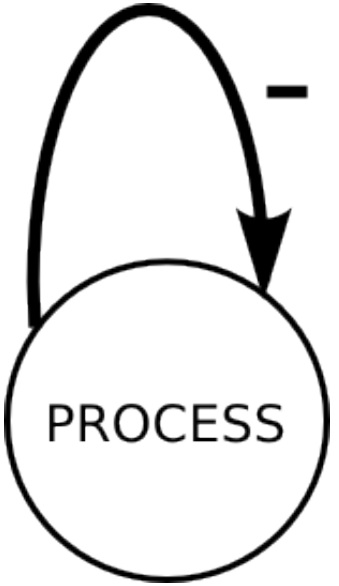
SULPHUR CYCLE



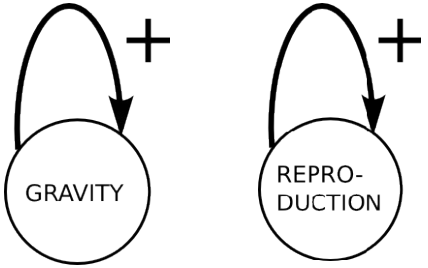
Pattern Formation: Feedback Processes



Positive Feedback

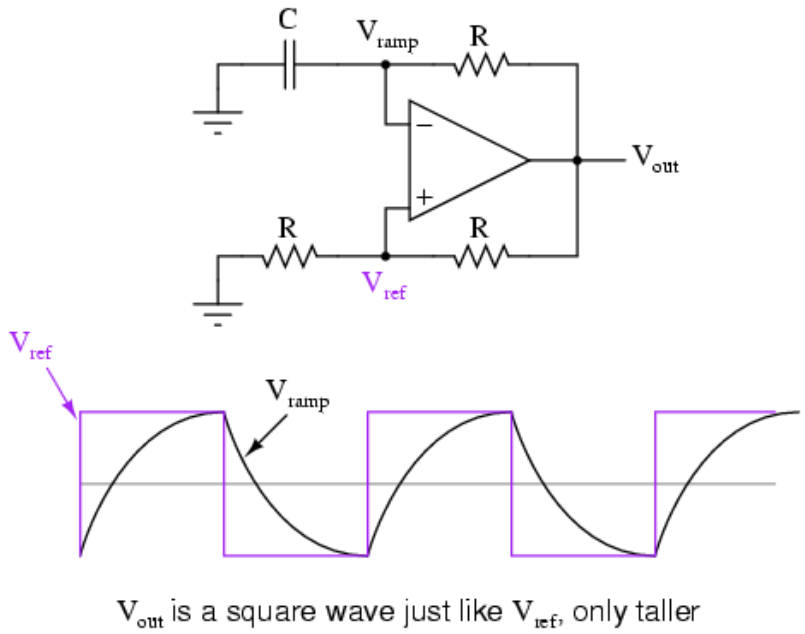


Negative Feedback

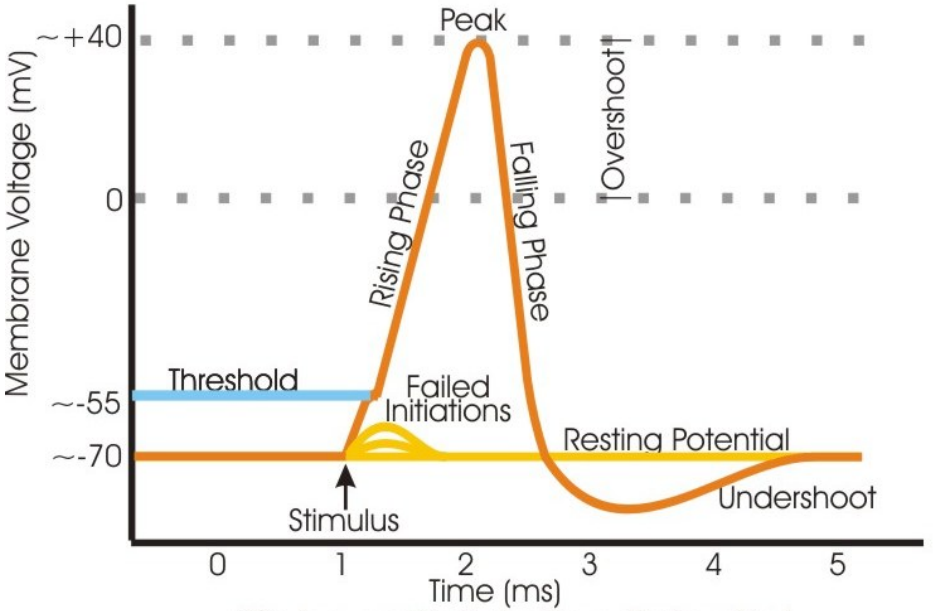


Positive and Negative Feedback Combined in Time

Oscillator circuit using positive feedback

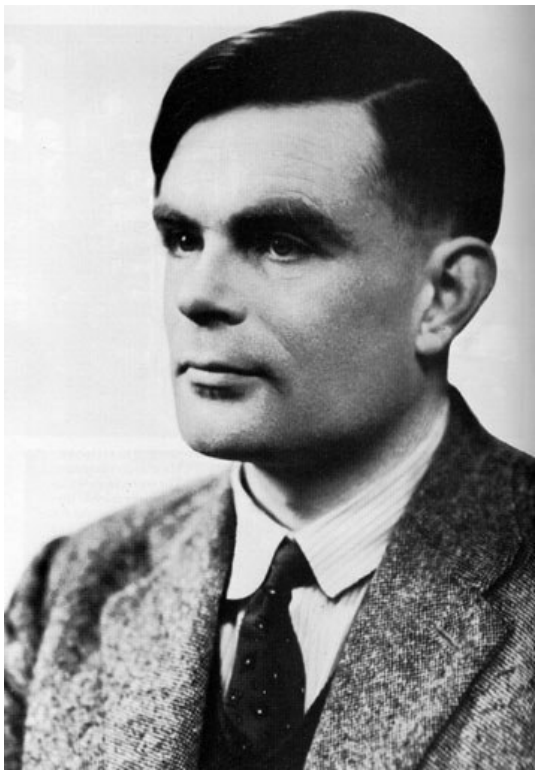


V_{out} is a square wave just like V_{ref}, only taller

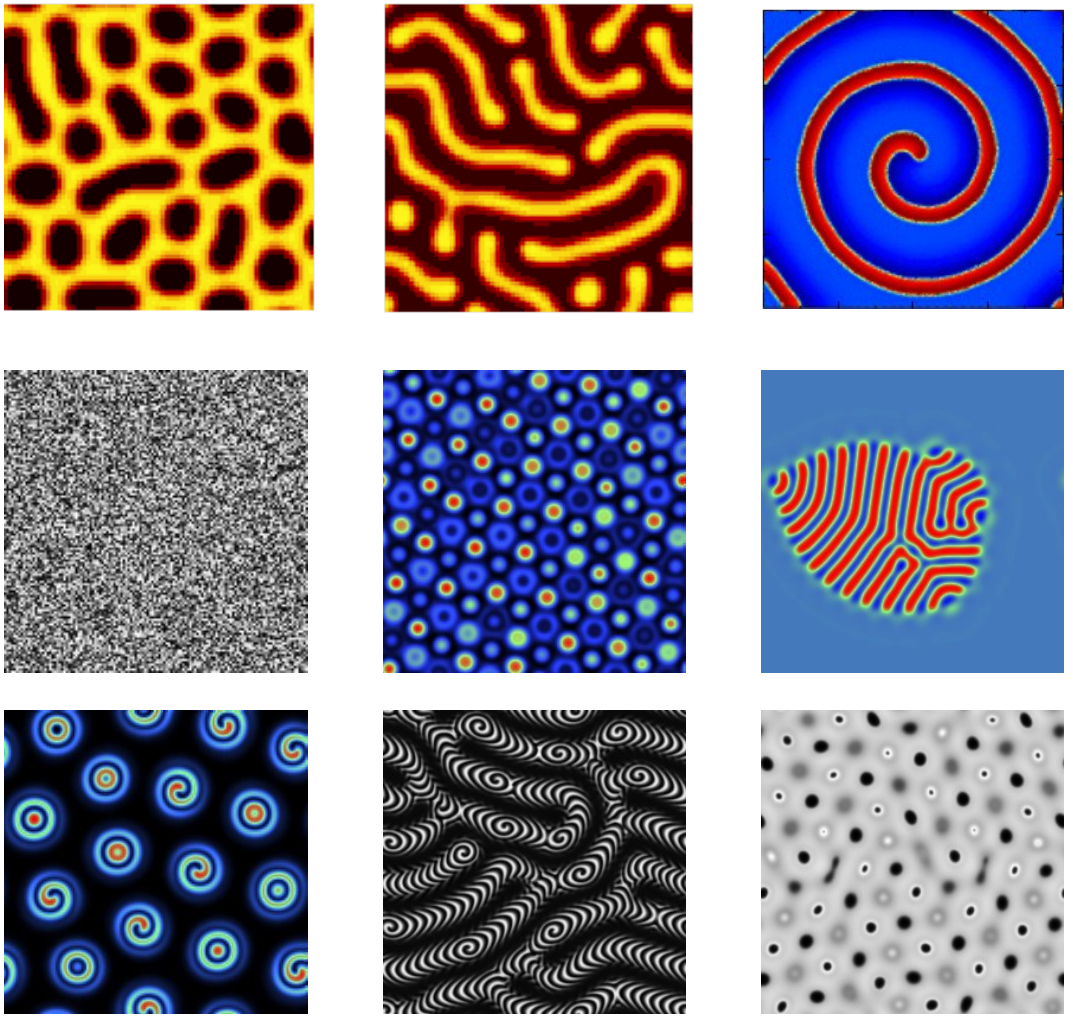


"Schematic" Action Potential

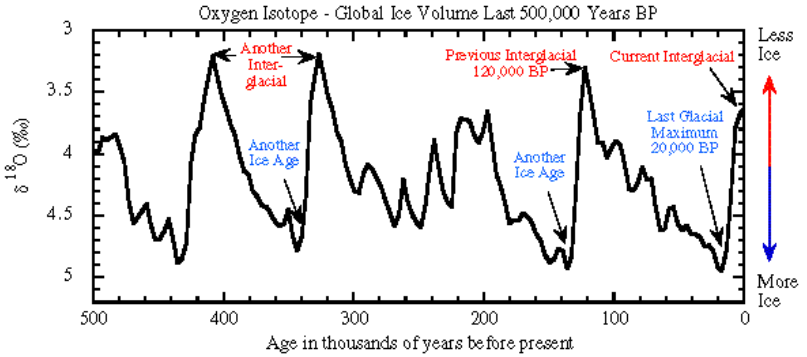
Positive and Negative Feedback Combined in Time and Space

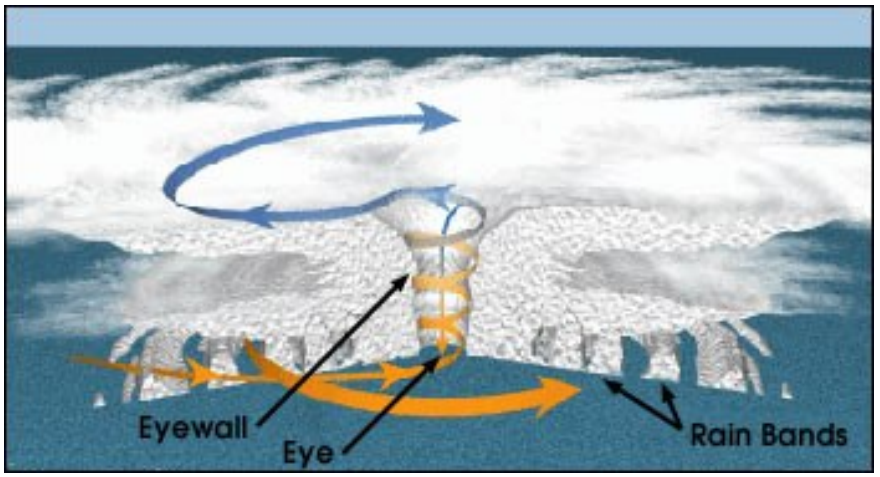


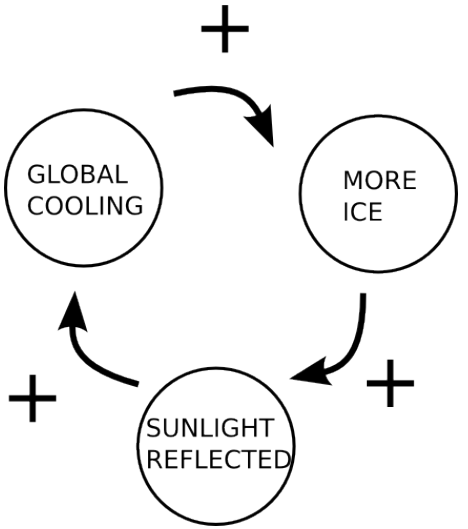
Alan Turing



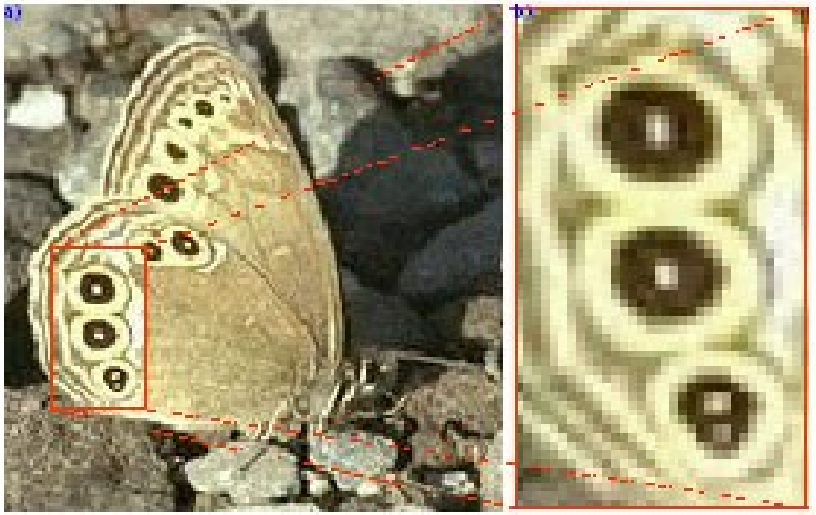
Positive and Negative Feedback Combined in Time and Space

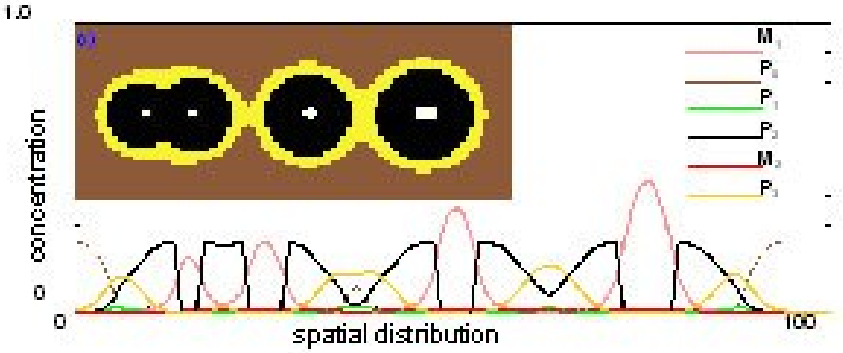


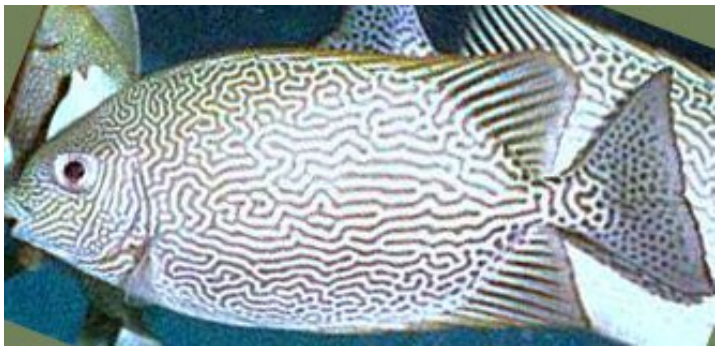


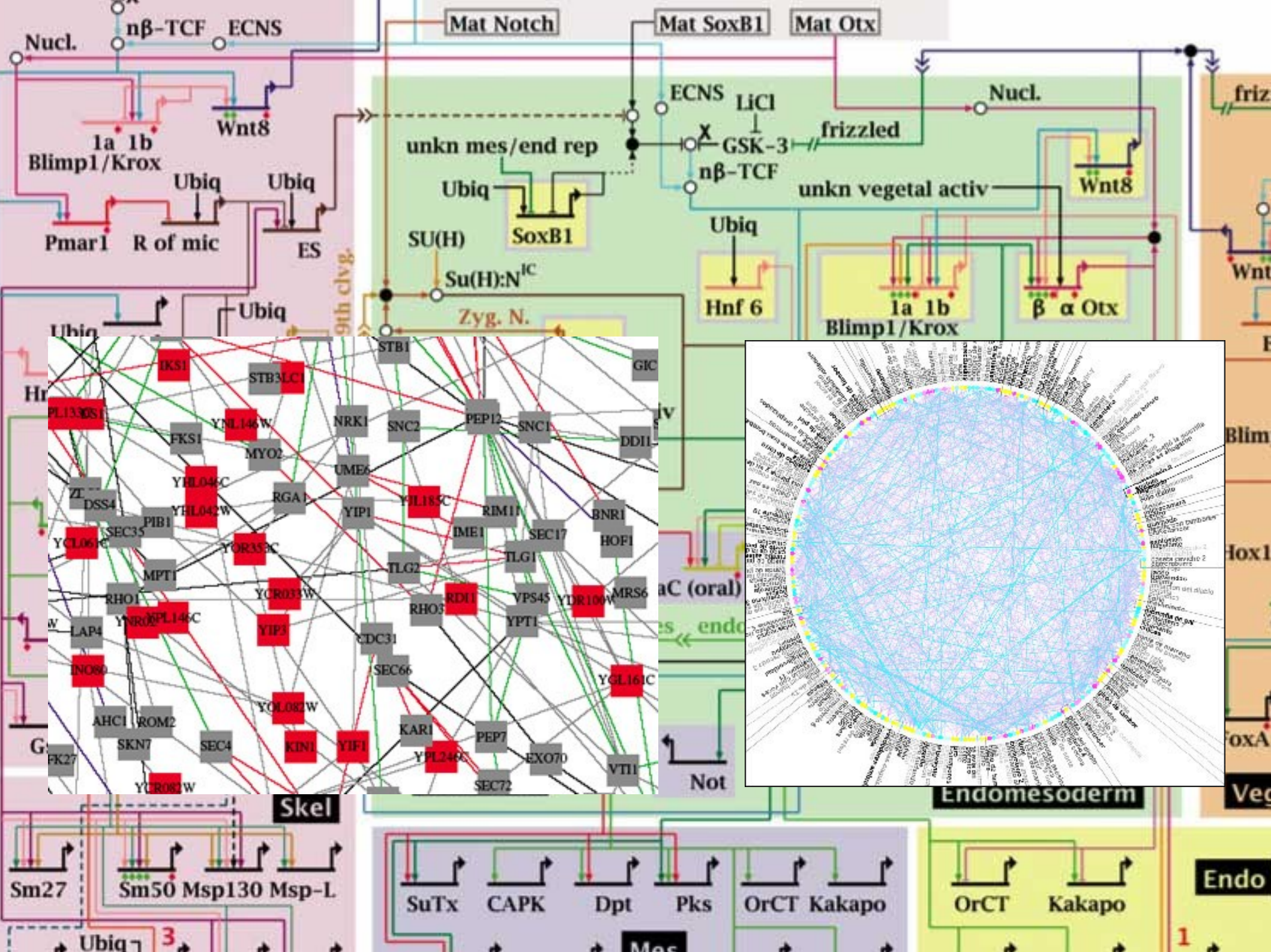


Positive and Negative Feedback Combined in Time and Space

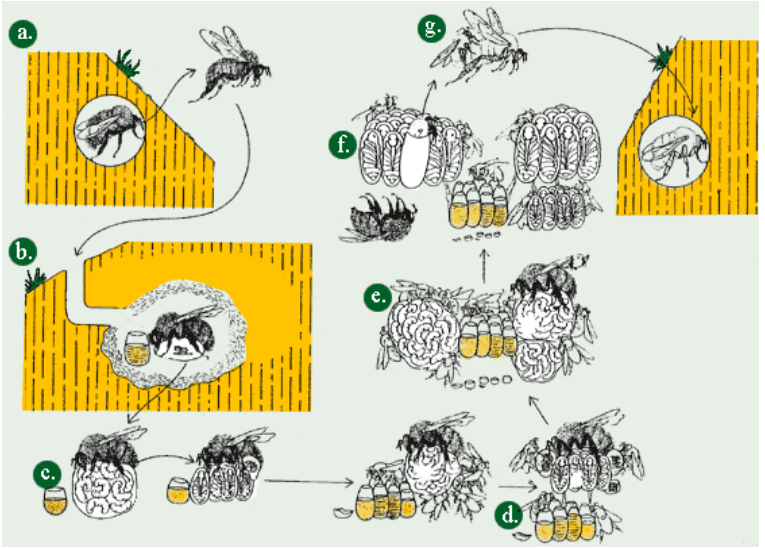


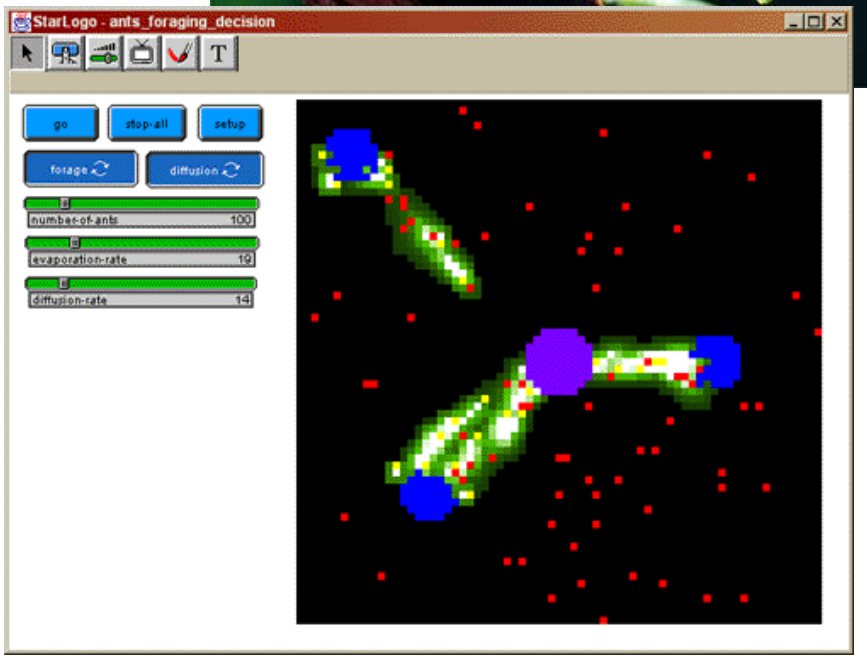




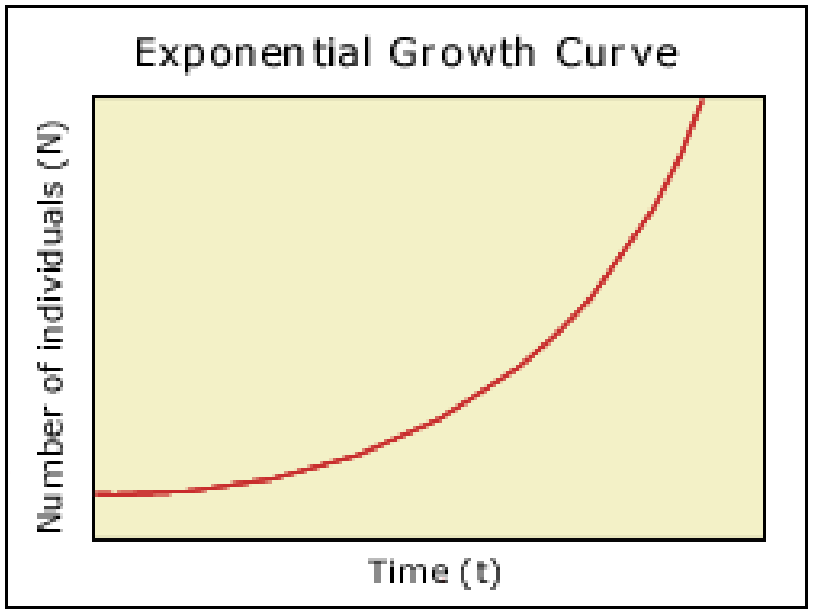

Mat Notch
Mat SoxB1
Mat Otx
nβ-TCF
ECNS
Nucl.
Wnt8
1a 1b
Blimp1/Krox
Ubiq
Pmar1
R of mic
ES
unkn mes/end rep
SoxB1
SU(H)
Su(H):N^IC
Zyg. N.
LiCl
GSK-3
frizzled
unkn vegetal activ
Hnf 6
β α Otx
Not
Endomesoderm
Skel
Sm27
Sm50 Msp130 Msp-L
SuTx
CAPK
Dpt
Pks
OrCT
Kakapo
Endo

Positive and Negative Feedback Combined in Time and Space

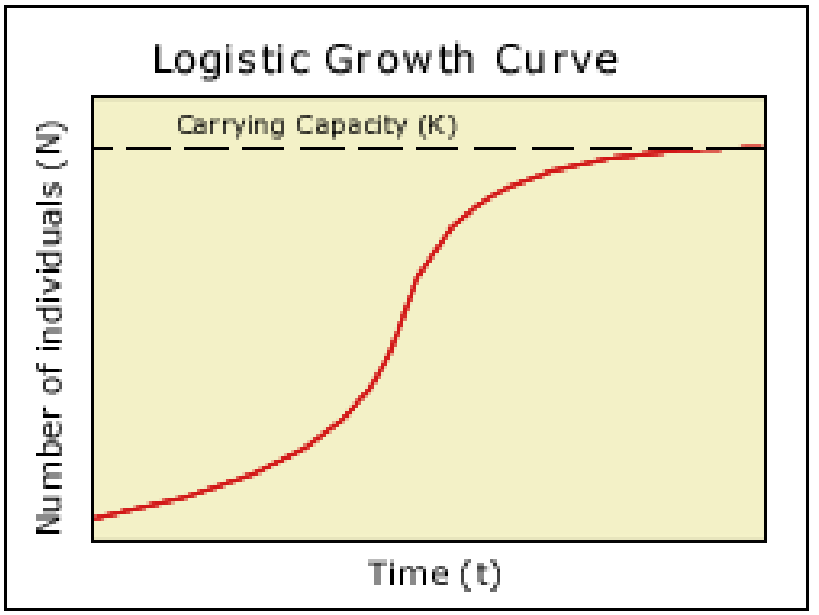




Positive and Negative Feedback Combined in Time and Space

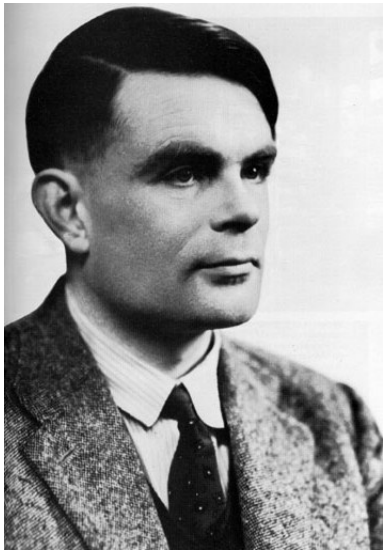


Positive Feedback Causes Growth



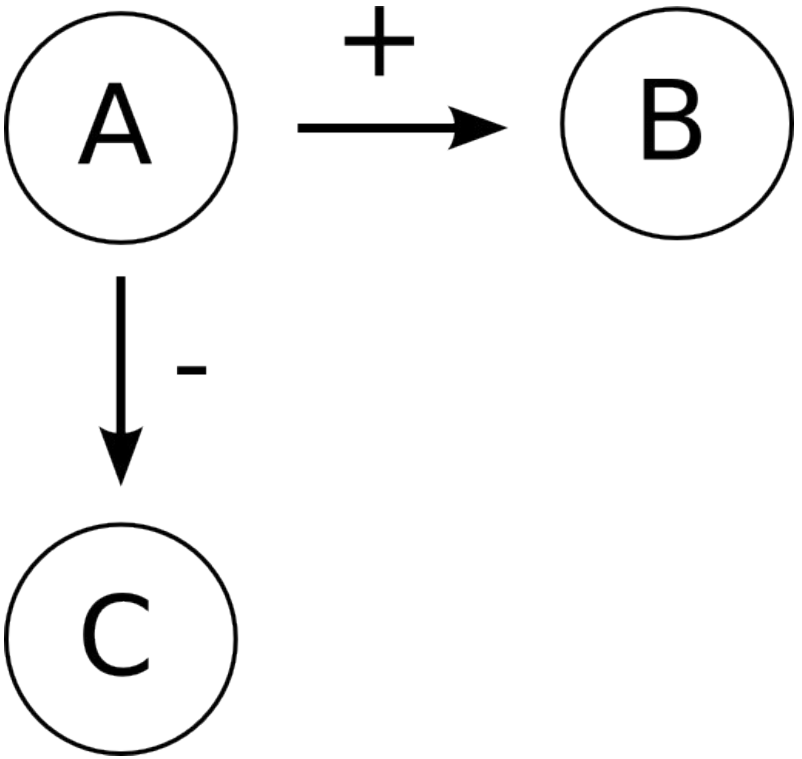
Negative Feedback Causes Selection

But... There's More Than Just Feedback



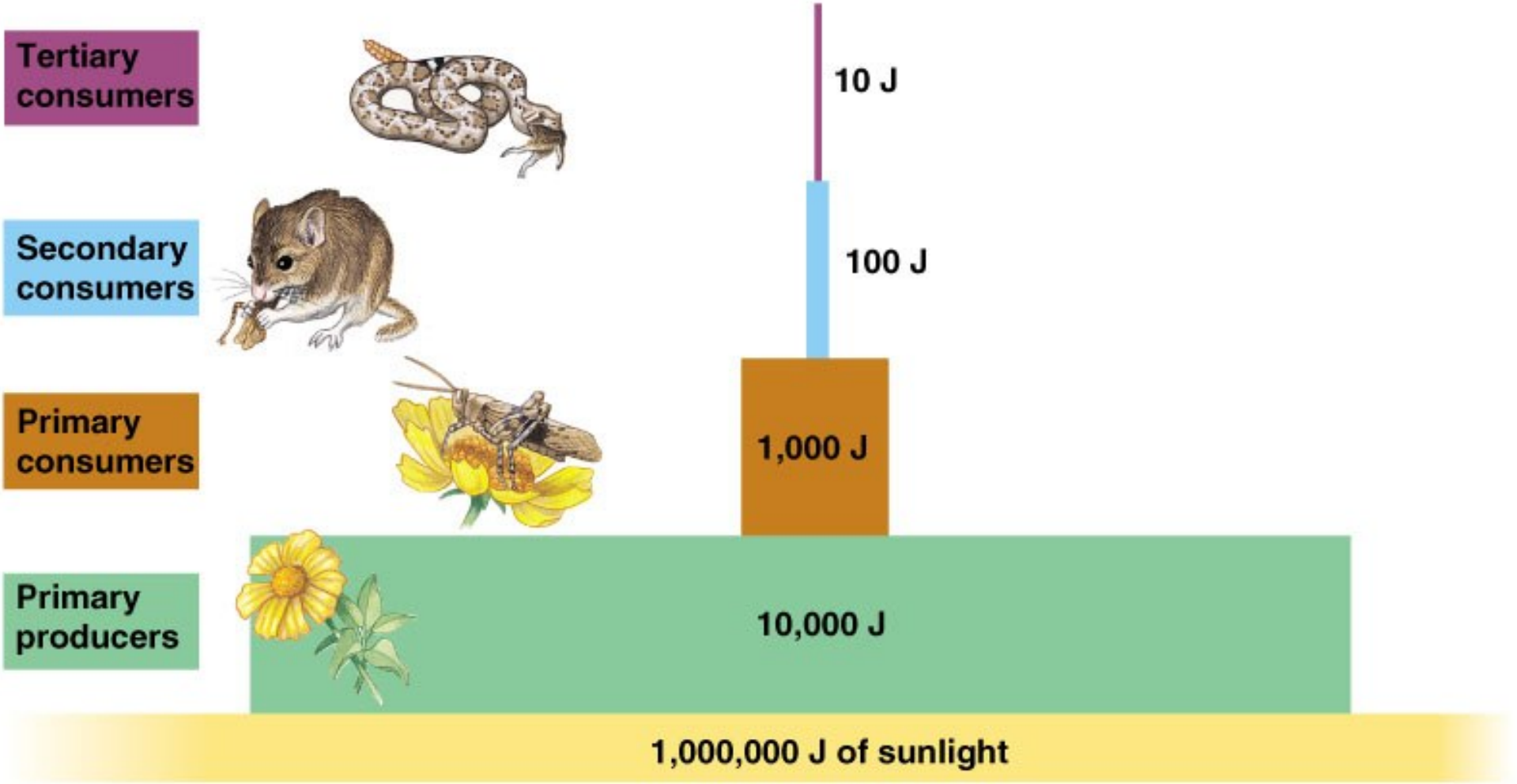
“The stripes are easy, but the horse part is harder to explain”

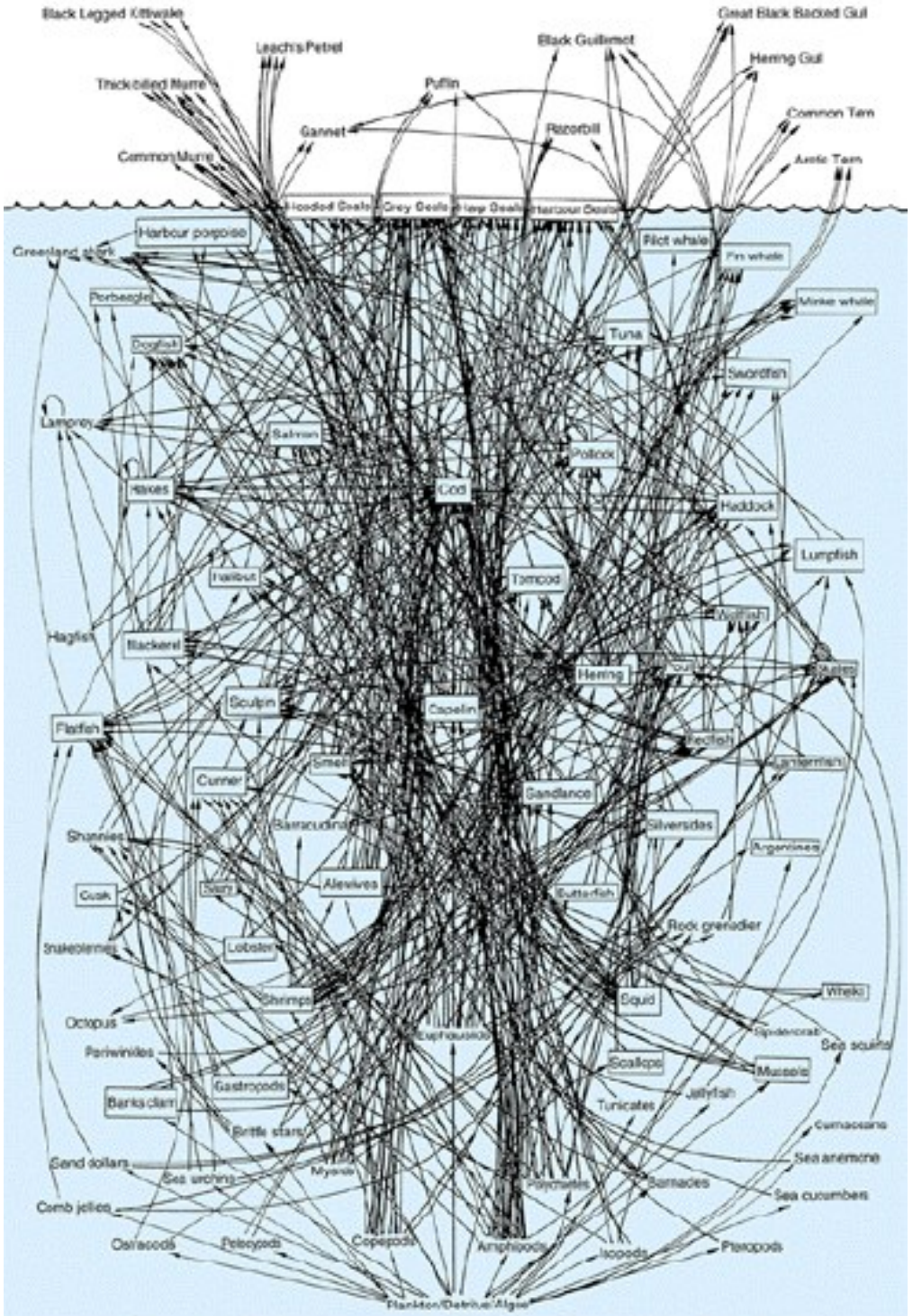
Pattern Formation: Interactions



Trophic Interactions

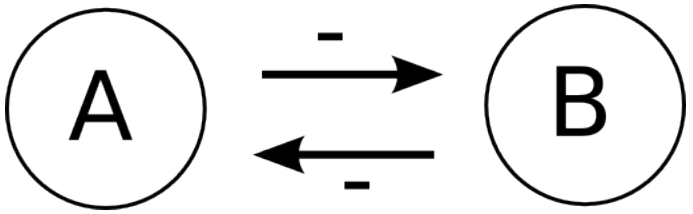
"Eating and Being Eaten"

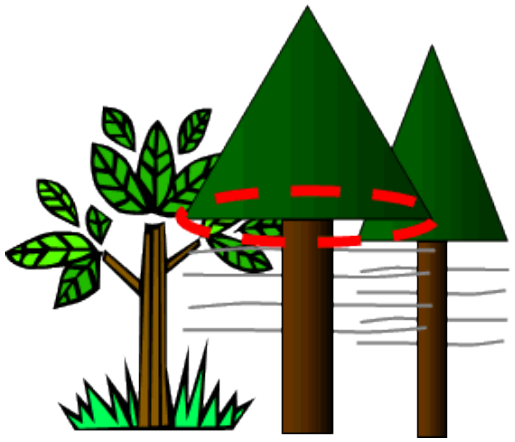


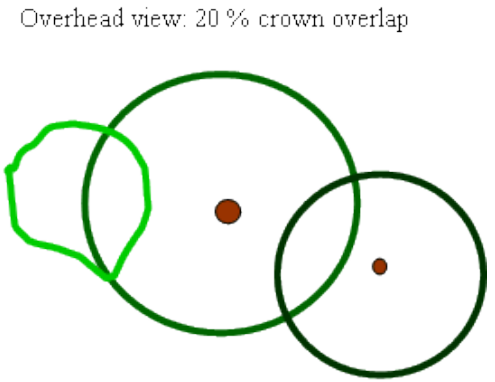


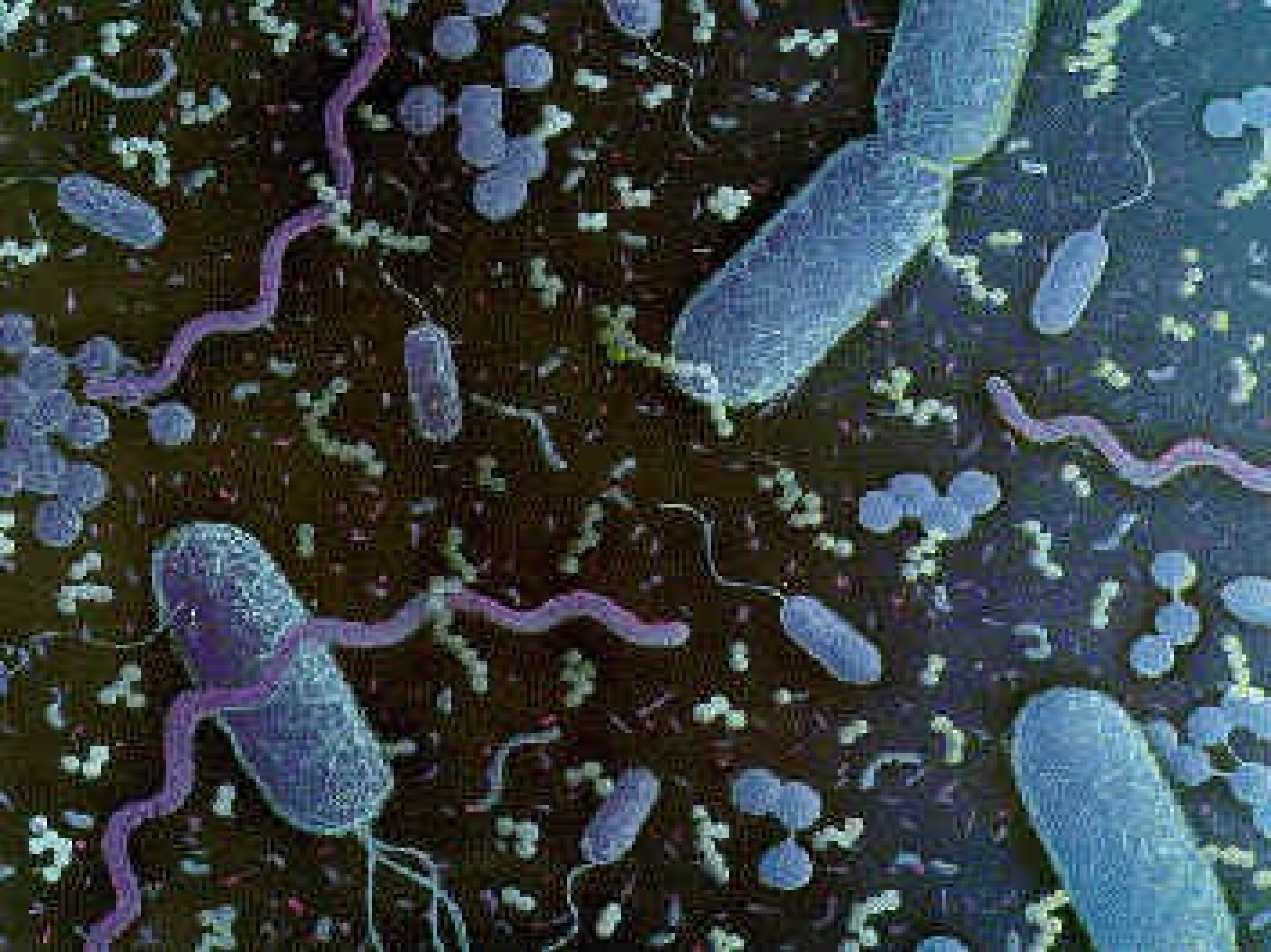
A simplified food web for the Northwest Atlantic

Competitive Interactions

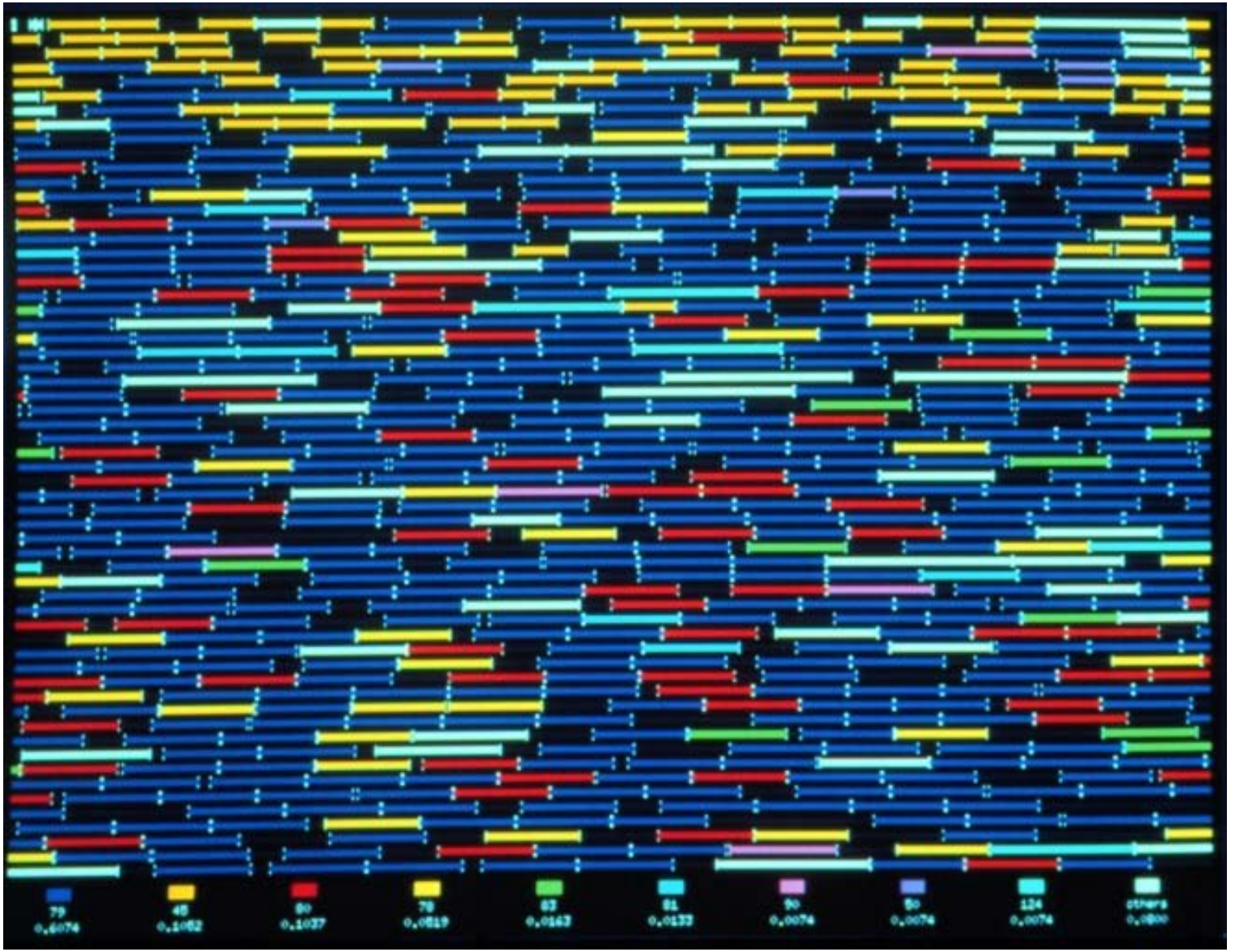






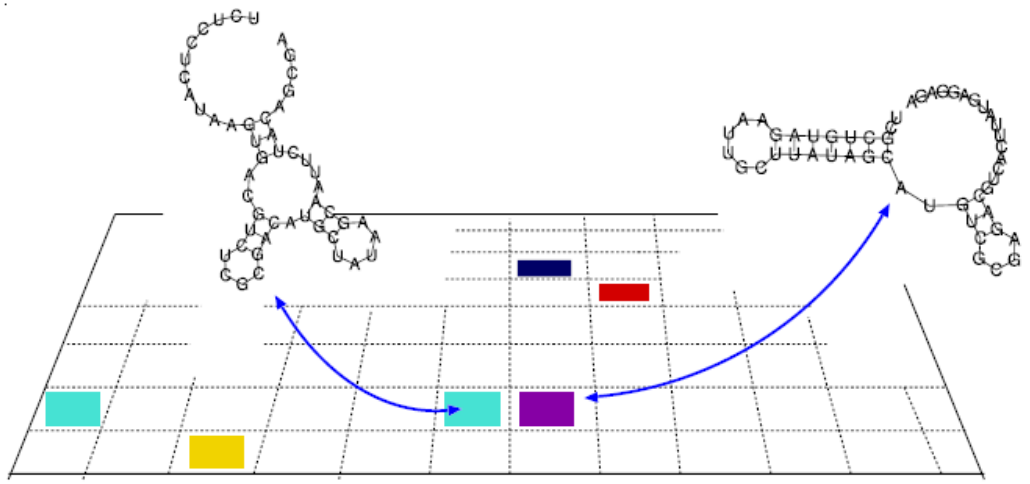


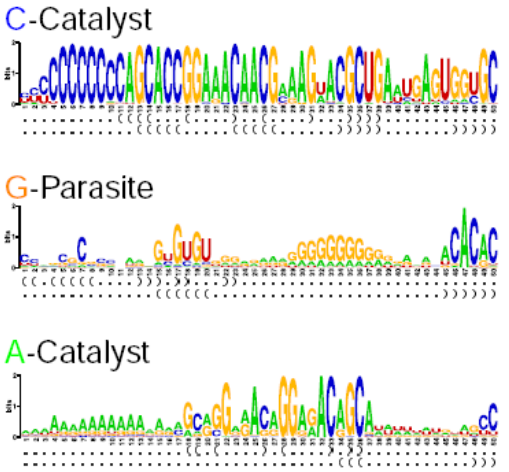
Interactions in a Virtual System: Tierra

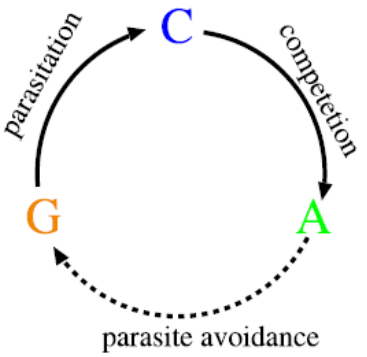


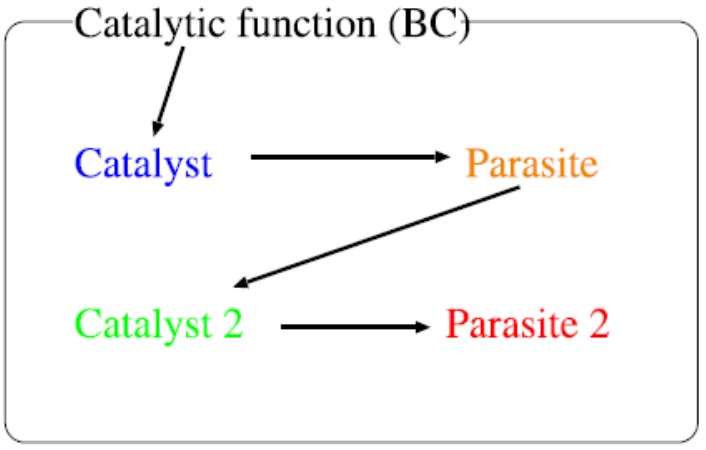
Interactions Between RNA Molecules

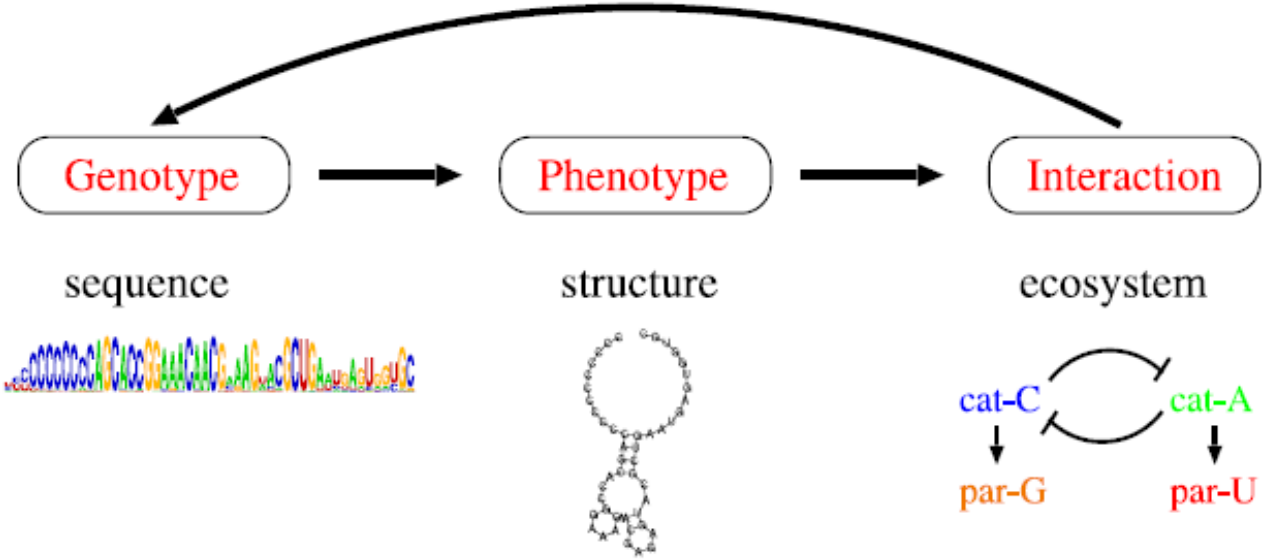
Nobuto Takeuchi and Paulien Hogeweg



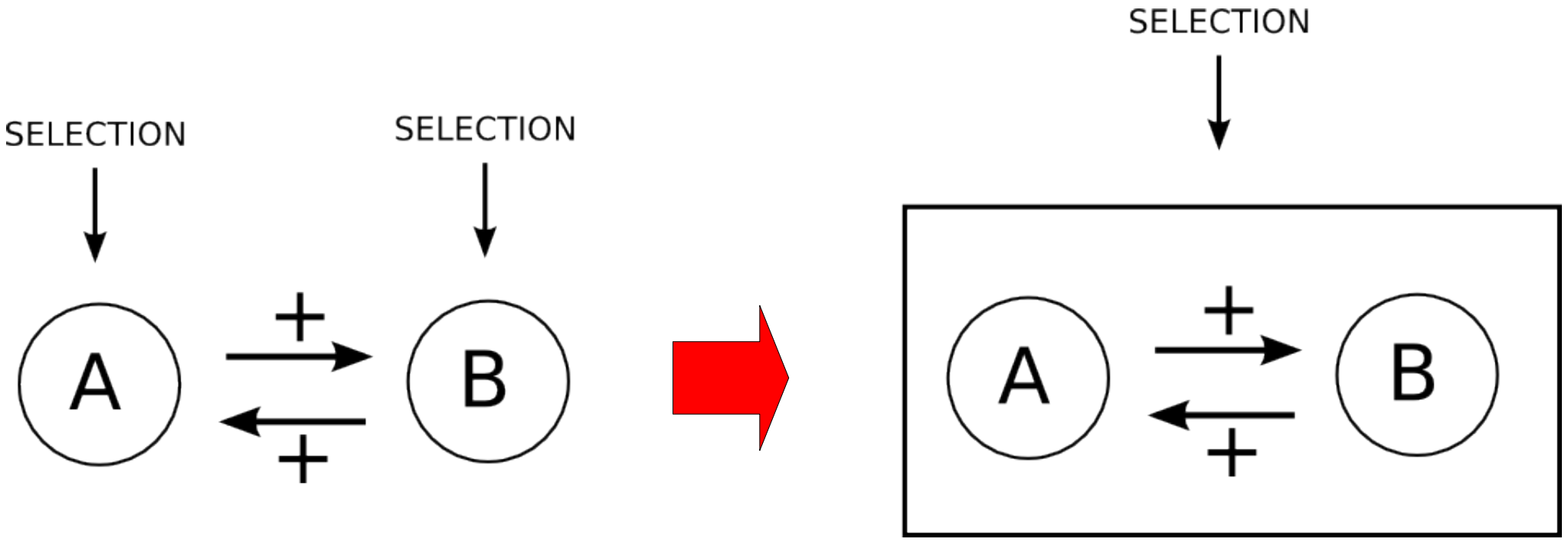






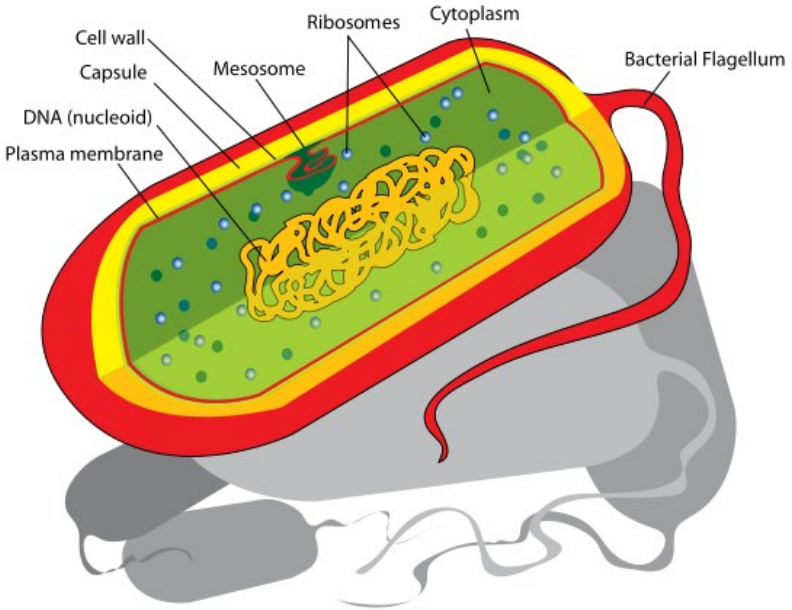


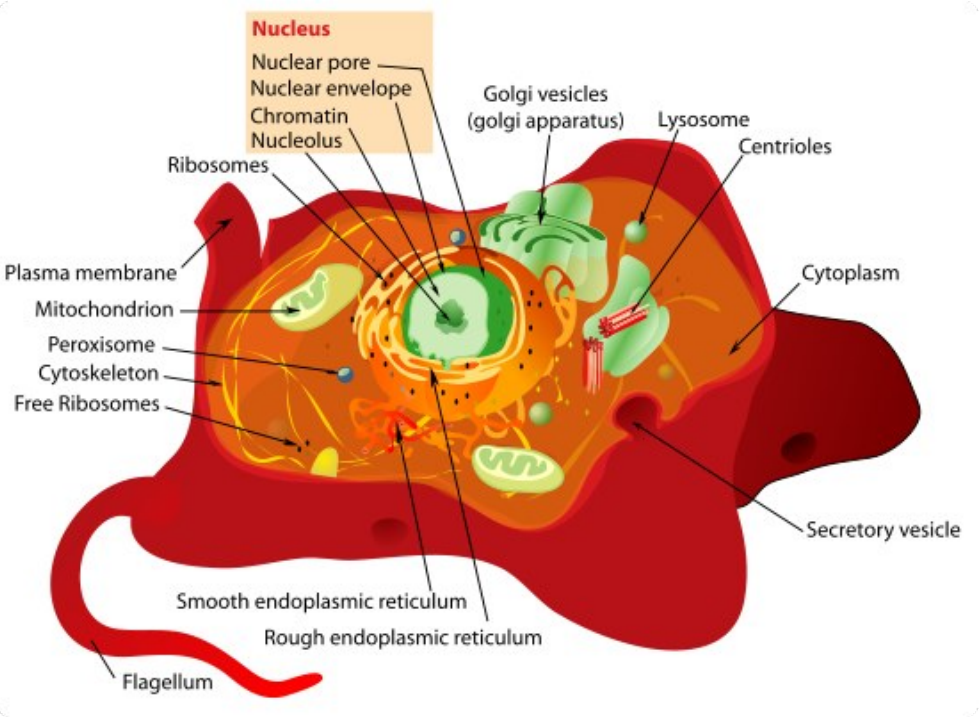
Interactions Can Get Selected For



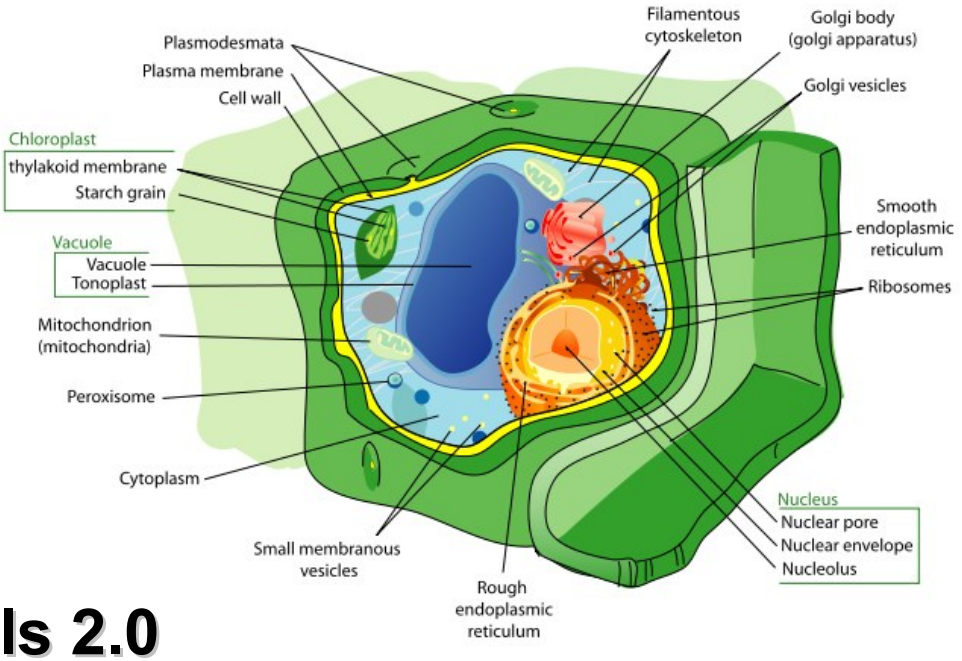
New Level of Selection
and Organisation

Cells 1.0
The Prokaryotic Cell





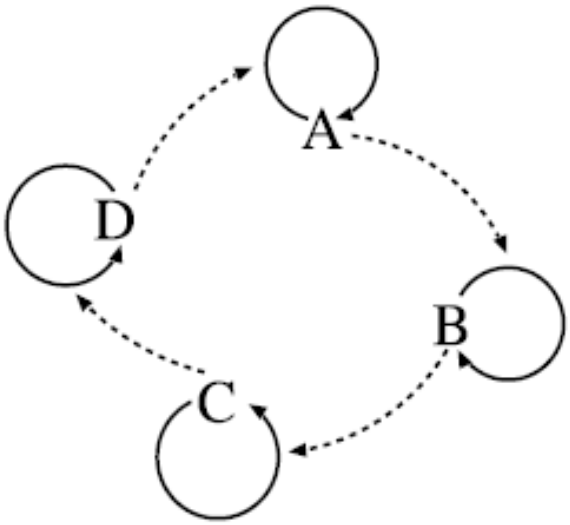
New Level Formed by Cooperation



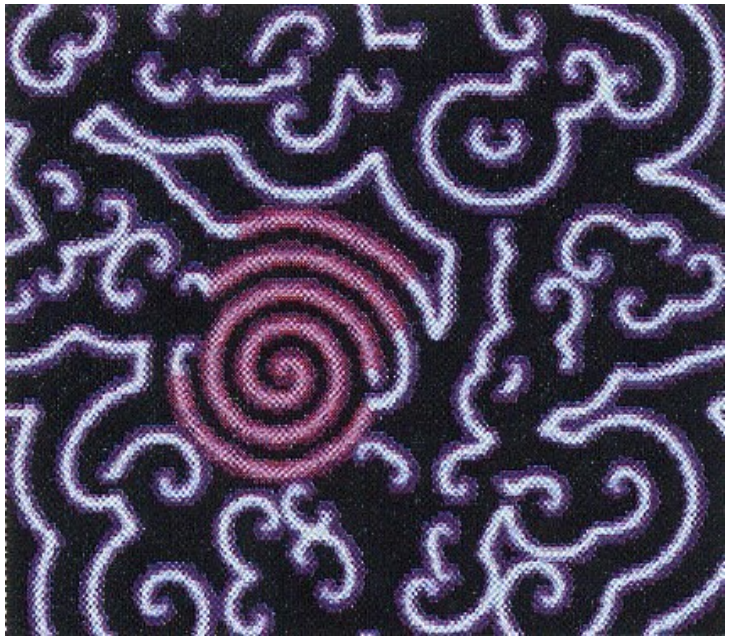
Cells 2.0
The Eukaryotic Cell

New Level Formed by Dynamics

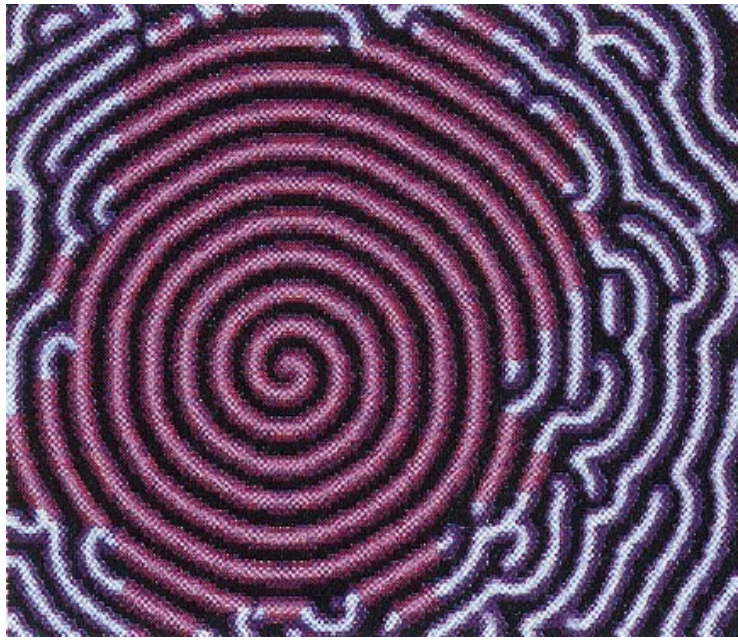
Spiral Selection



Hypercycle



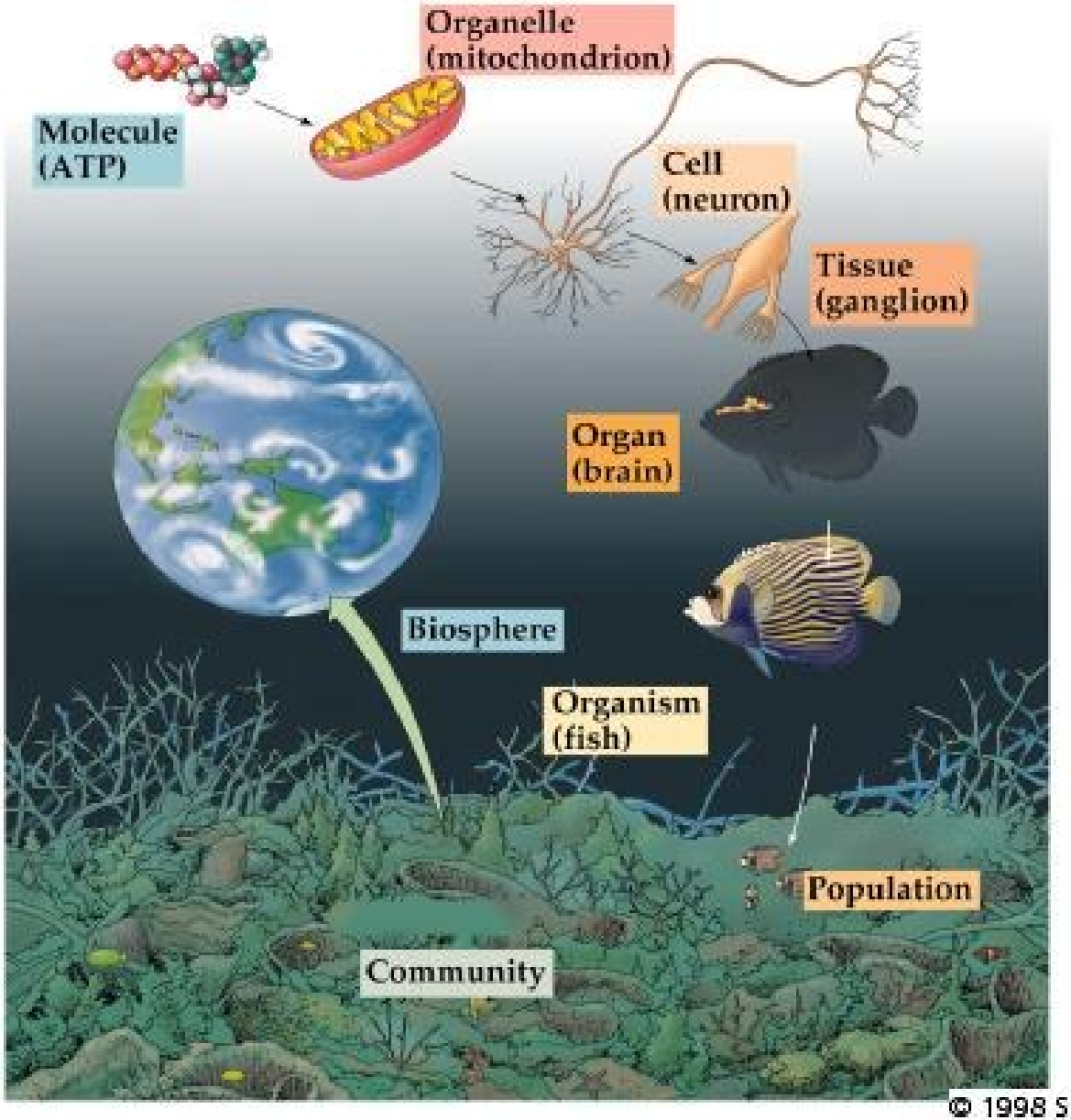
Hypercycles Organise
Into Spirals

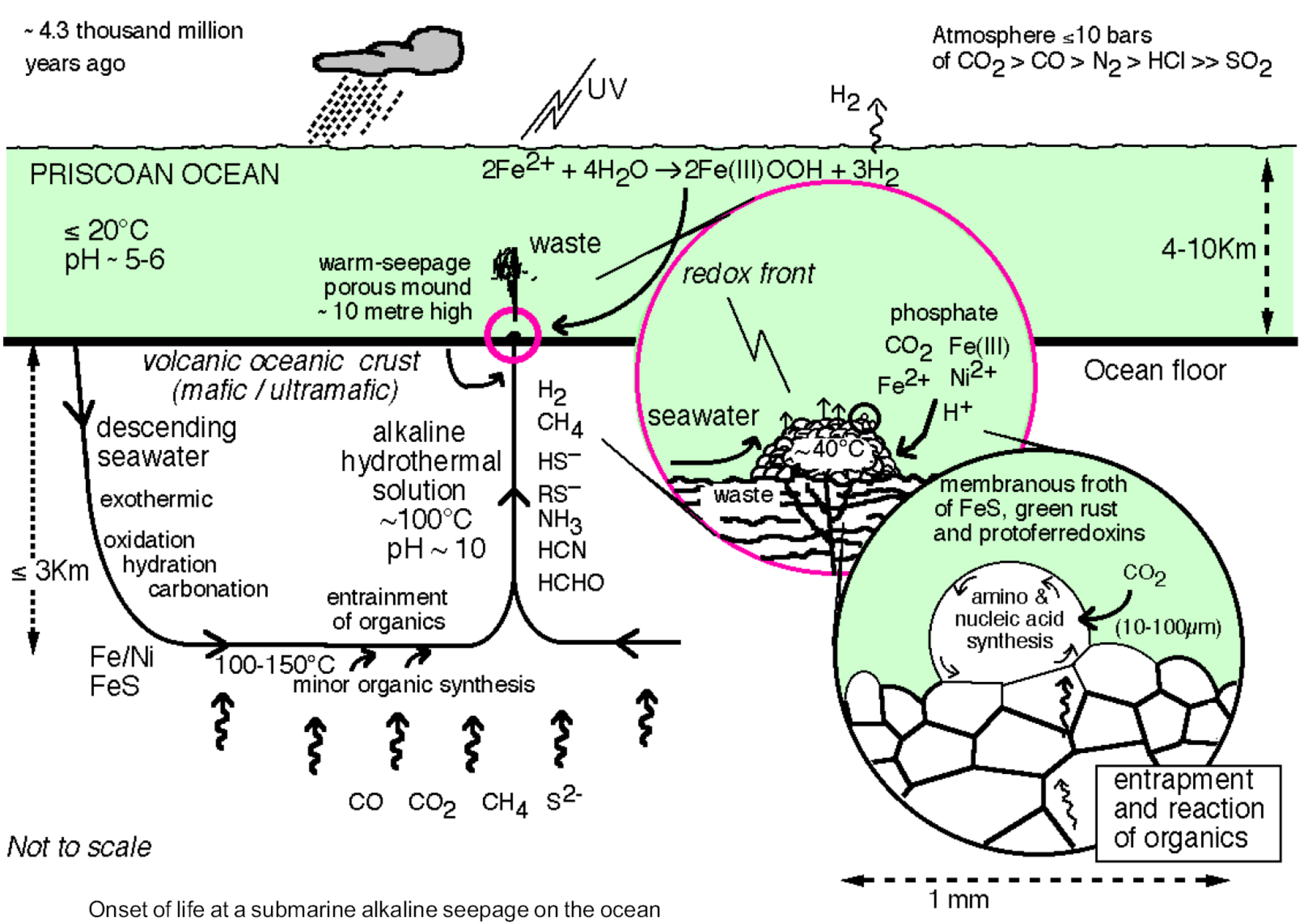


Spirals Compete

Maarten Boerlijst and Paulien Hogeweg, 1993

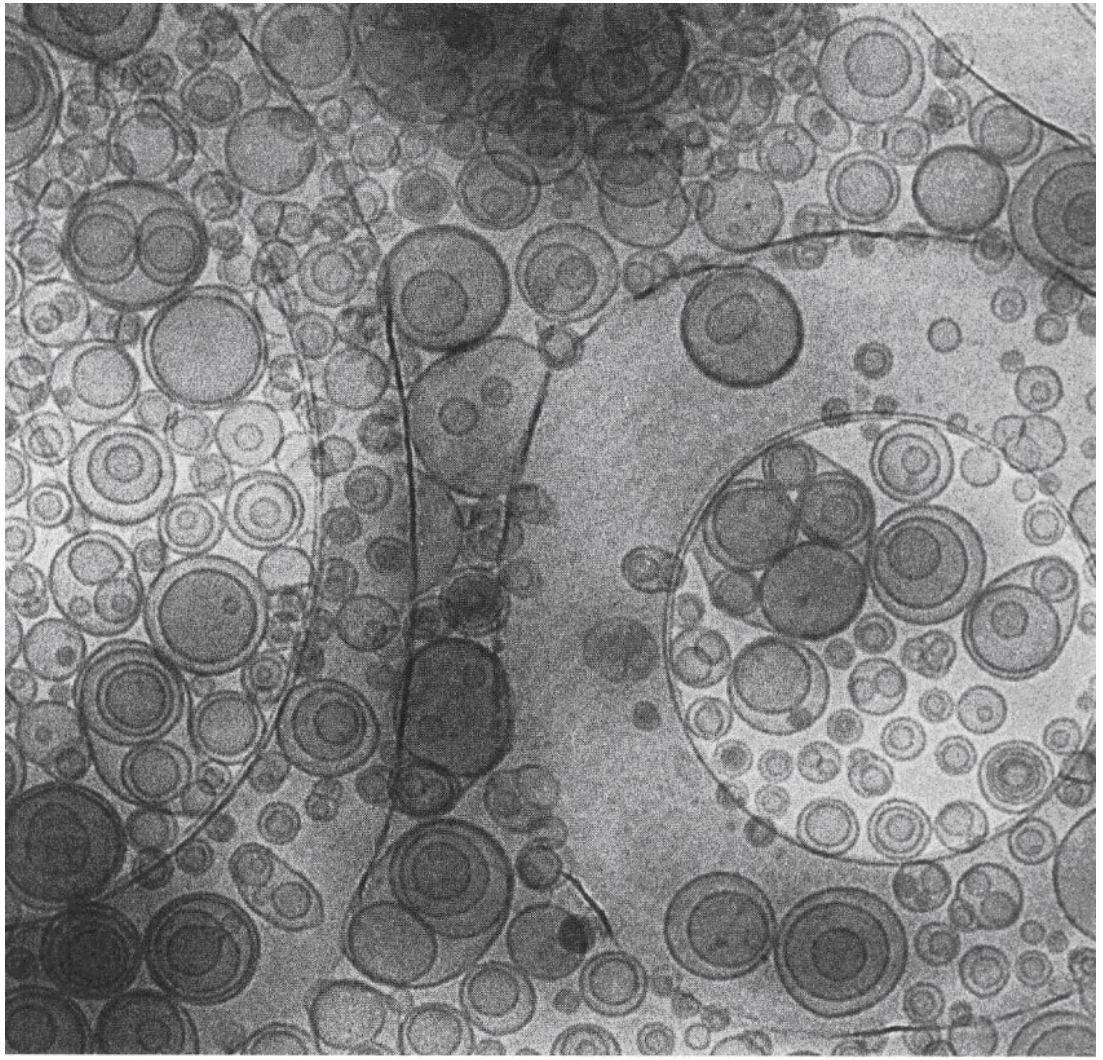
A Hierarchy of Organisation Levels

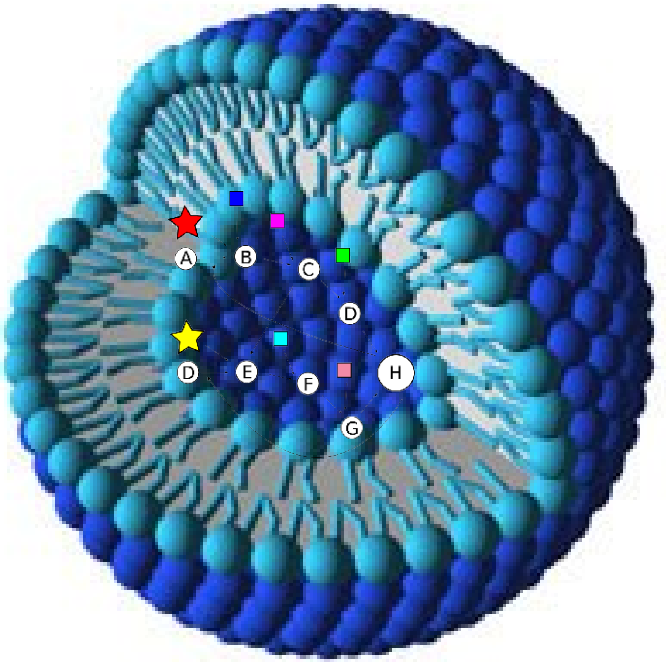


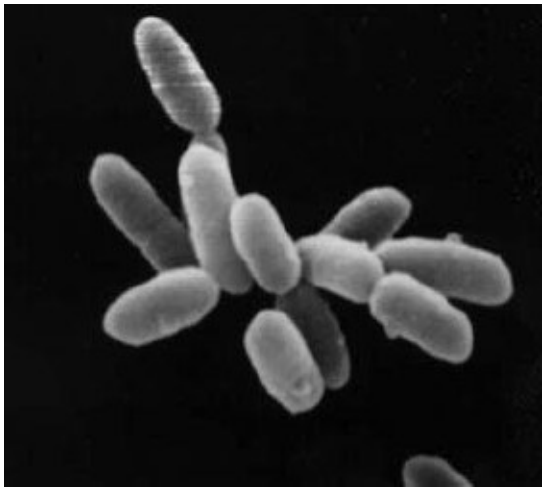


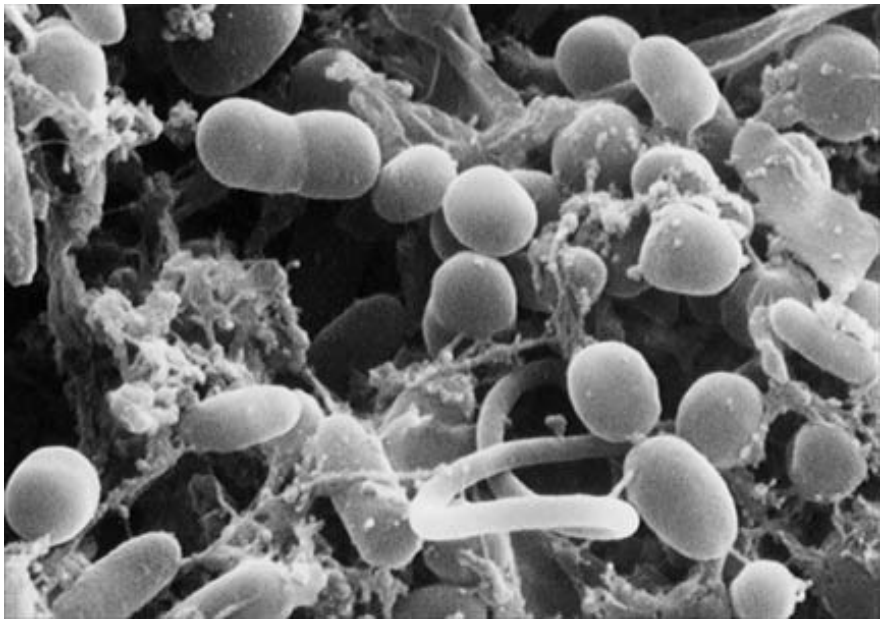
Onset of life at a submarine alkaline seepage on the ocean floor (Russell et al. 2002).

3.5 billion years ago



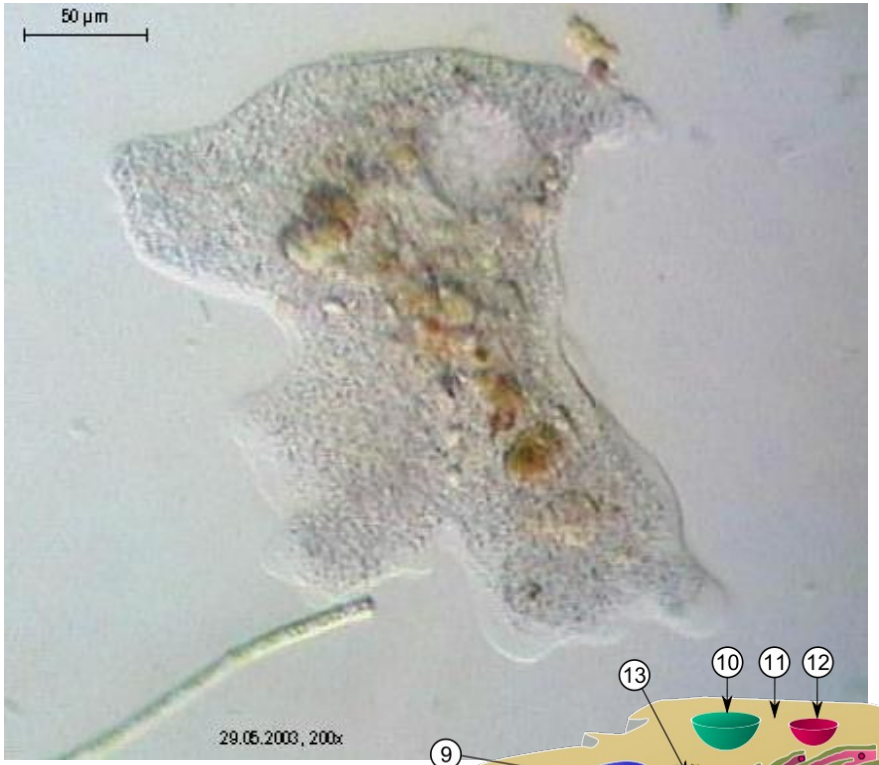


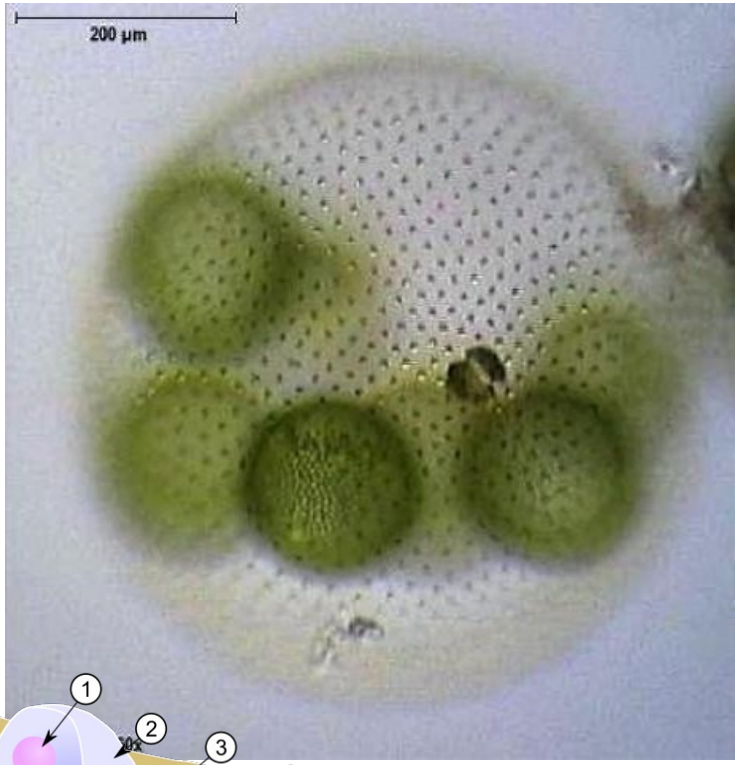


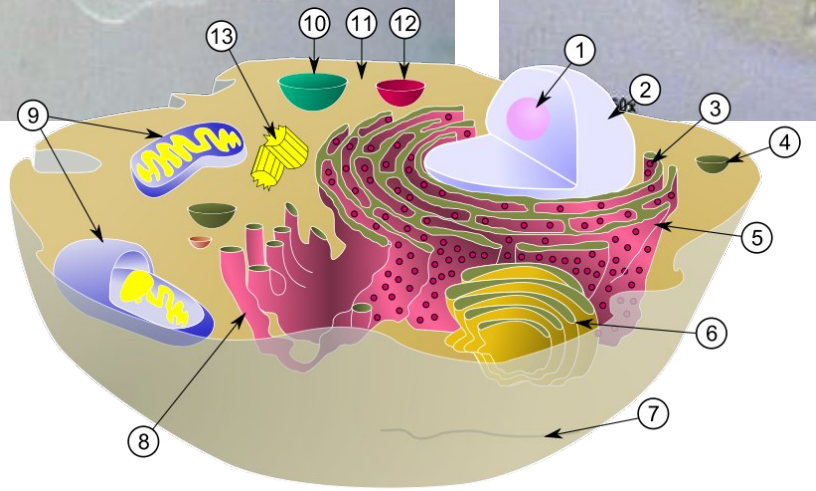



25 µm

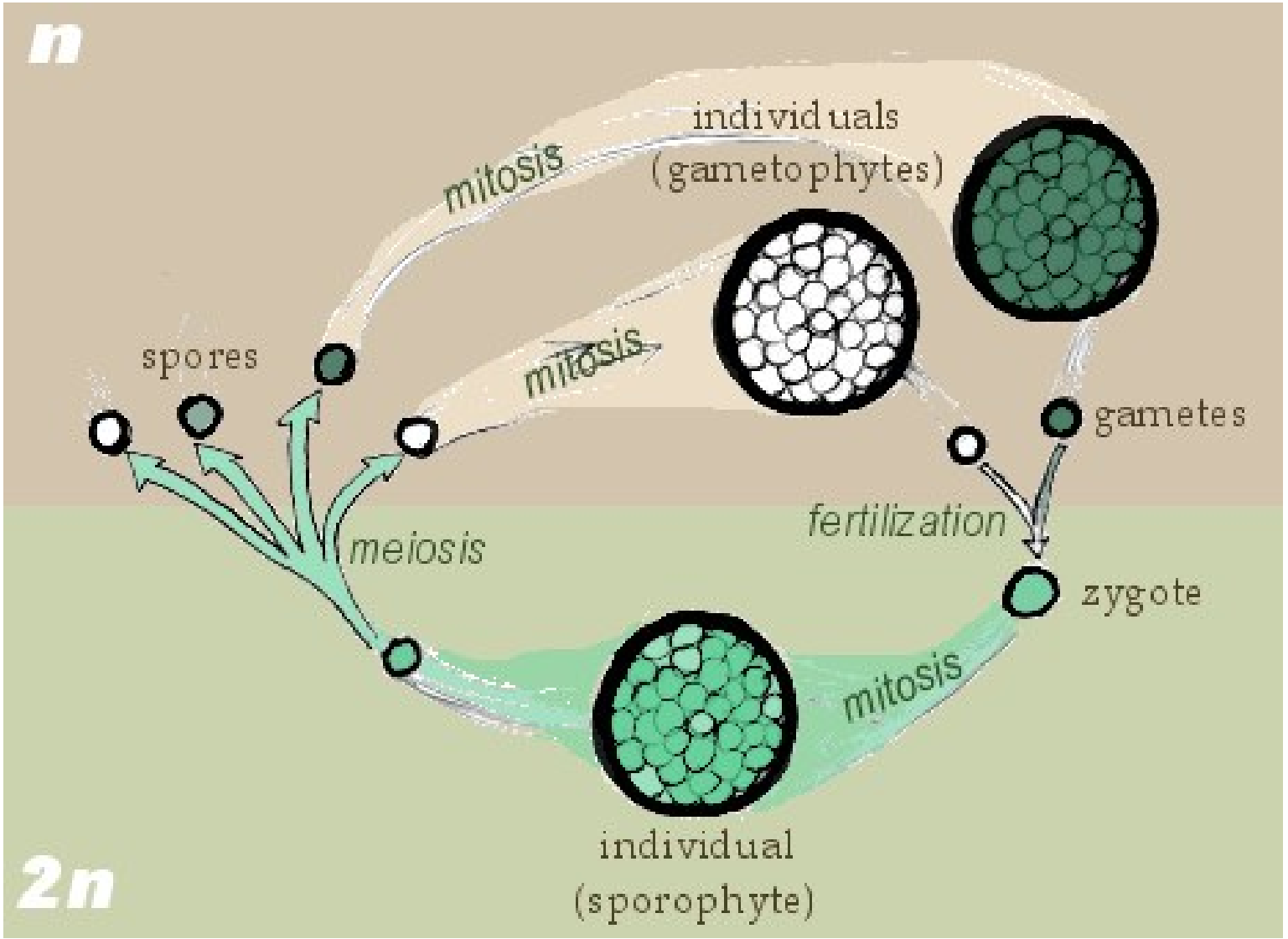
2.5 billion years ago



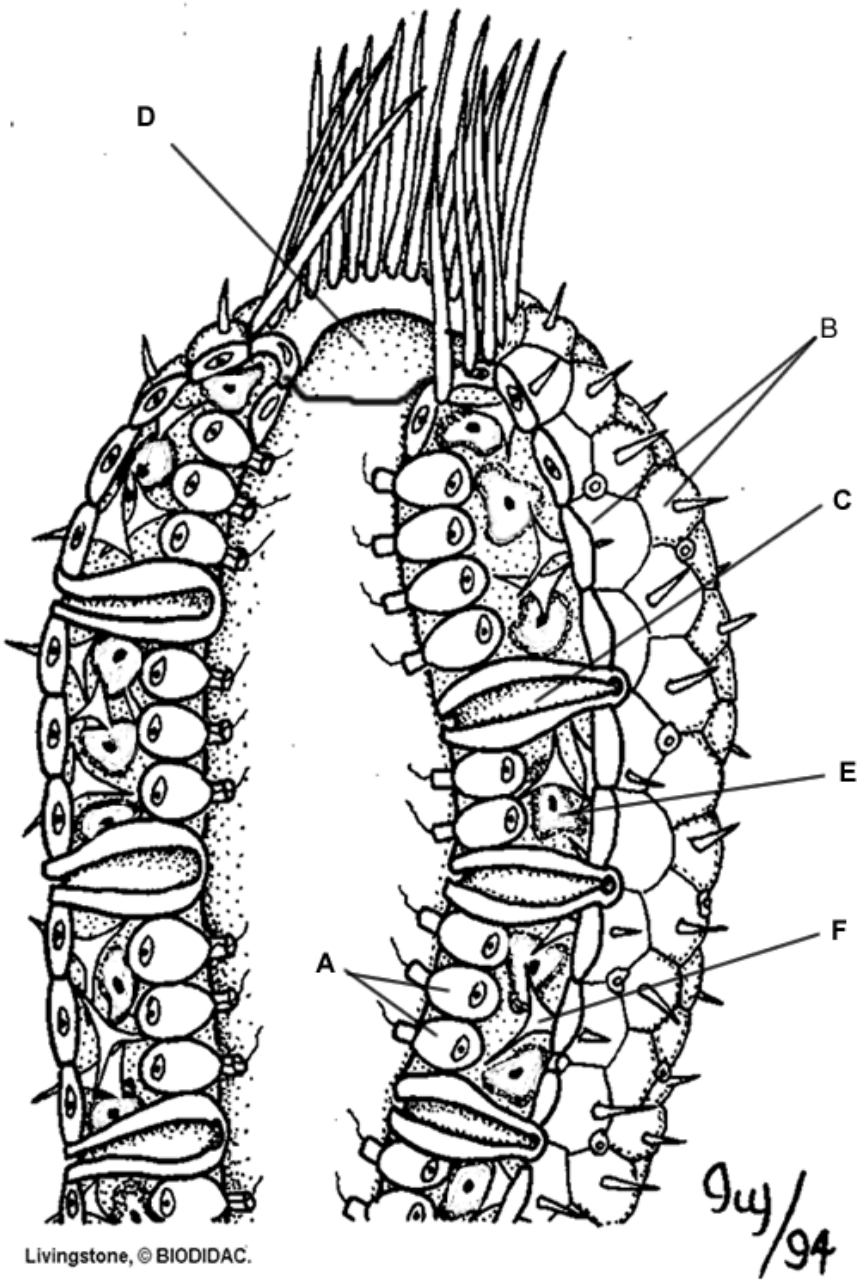


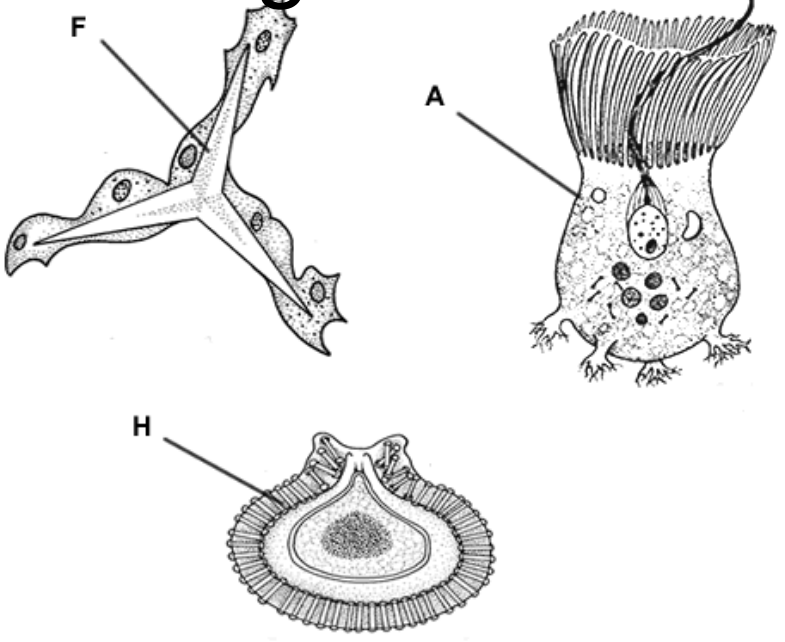


1.8 billion years ago

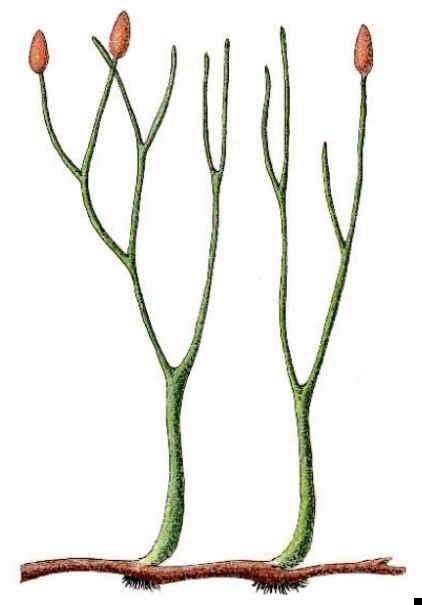


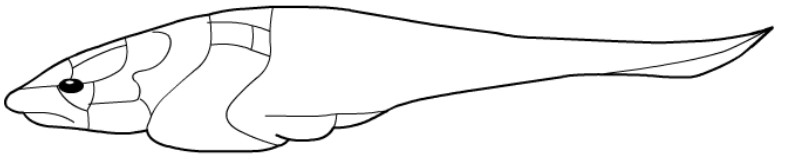
1.4 billion years ago



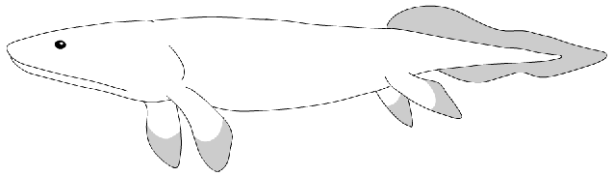



600 million years ago

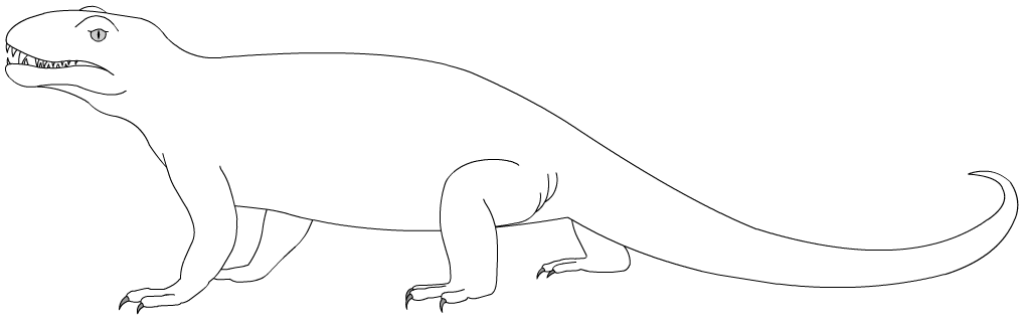




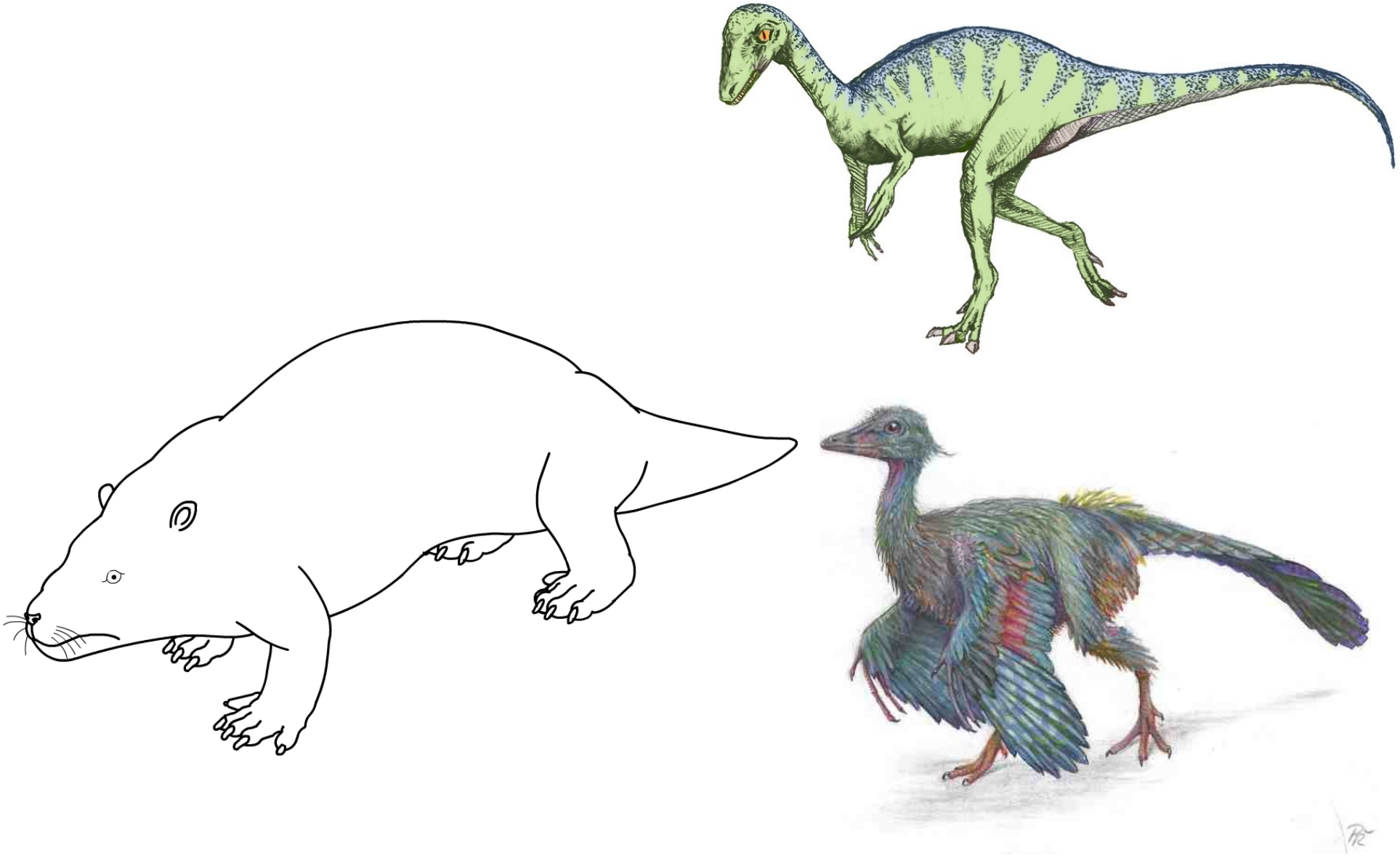
425 million years ago




University of Michigan Exhibit Museum of Natural History Diroama

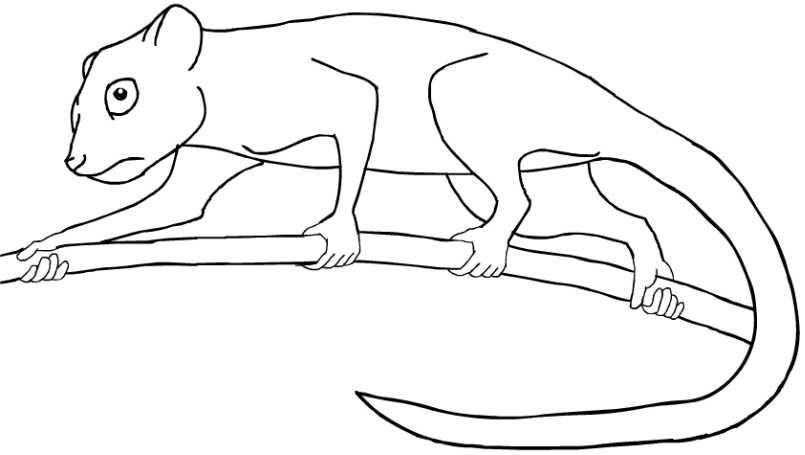


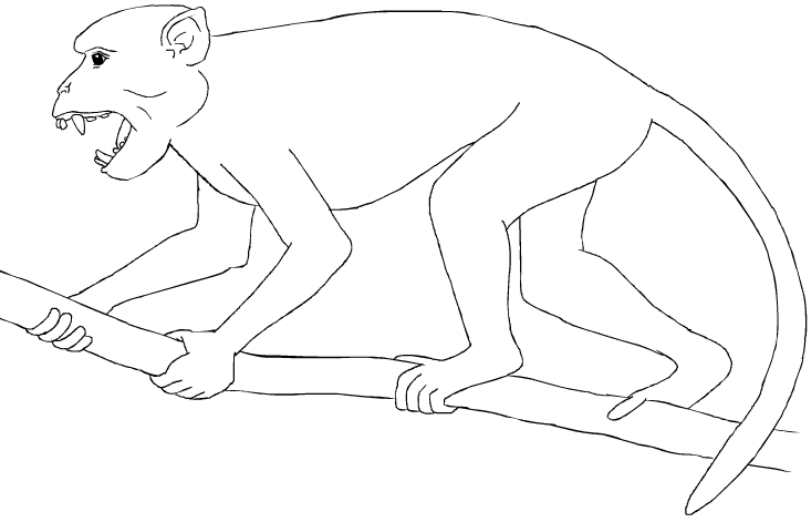
200 million years ago

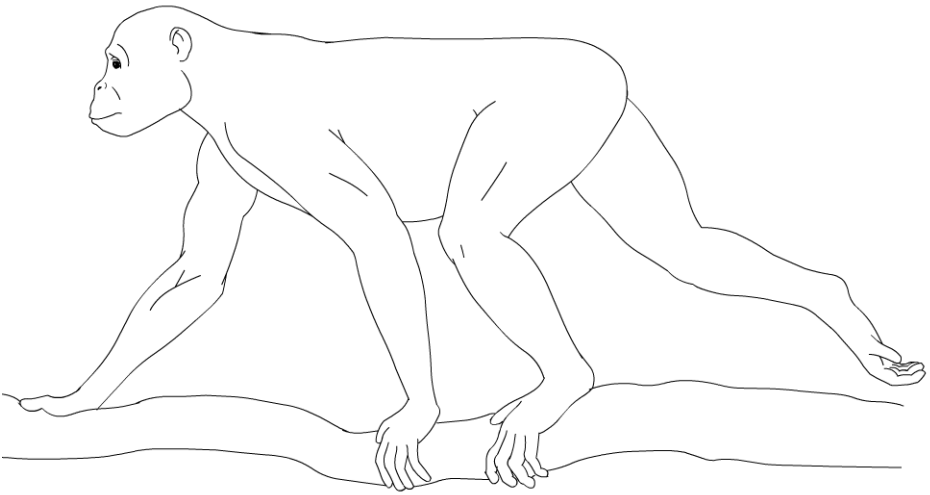


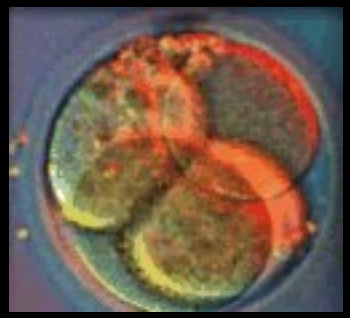
65 million years ago

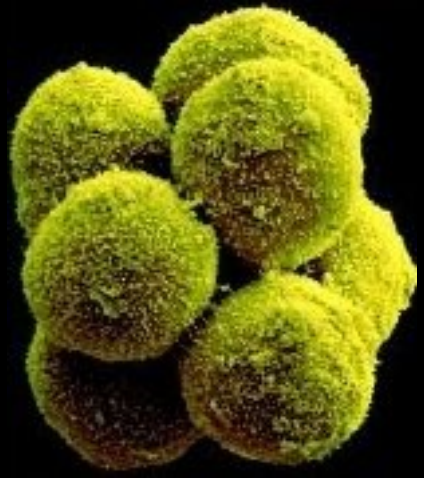

ALL YOUR BASE ARE
BELONG TO US.

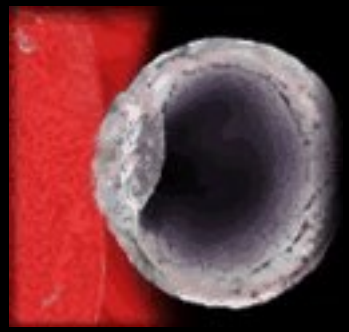


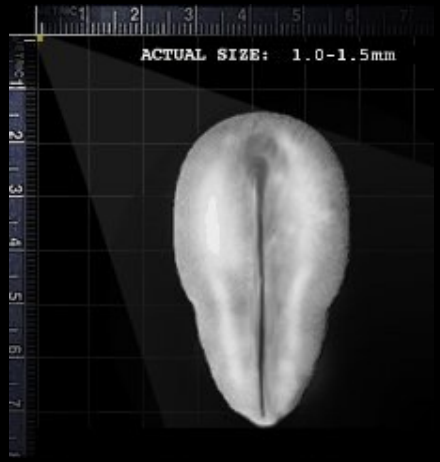


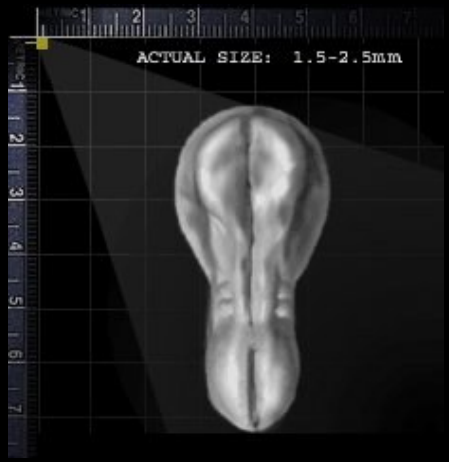


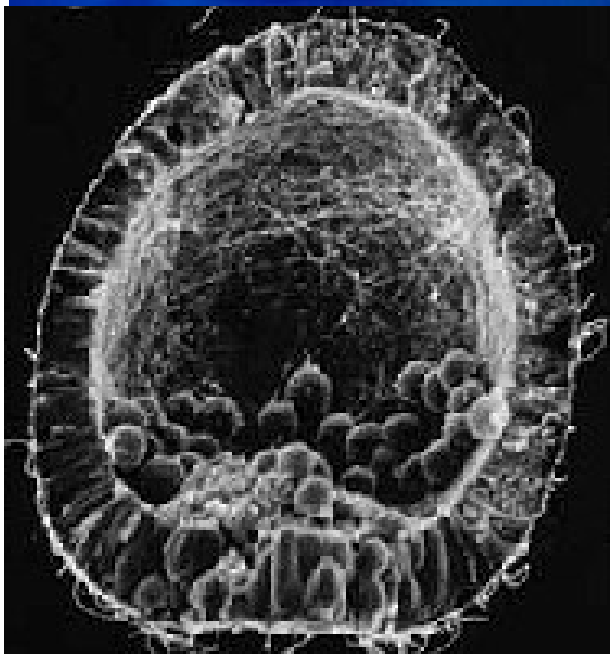




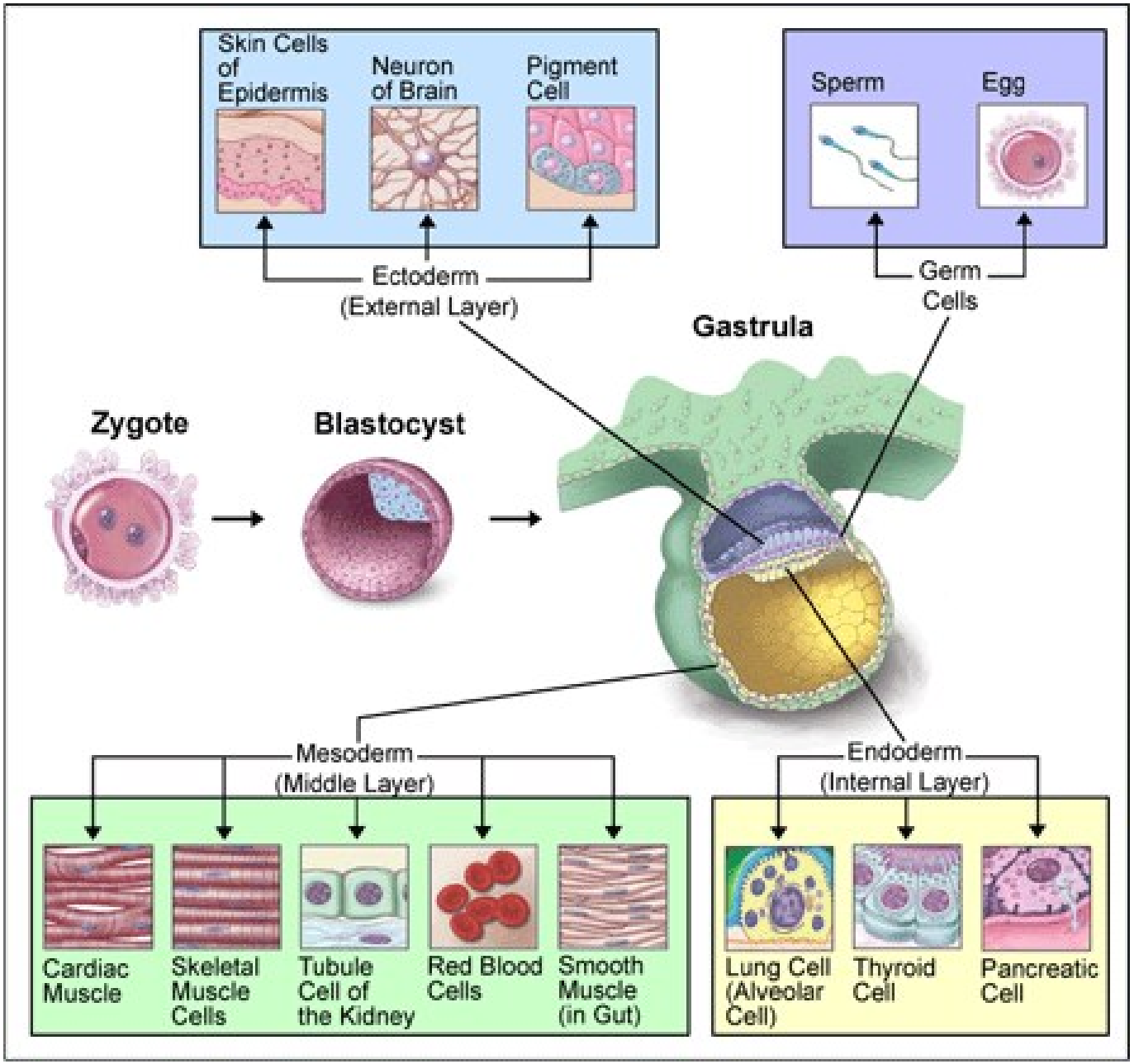








Sea Urchin Development



Human Development

Stage 14 Human Embryo
(approx. 32 days)

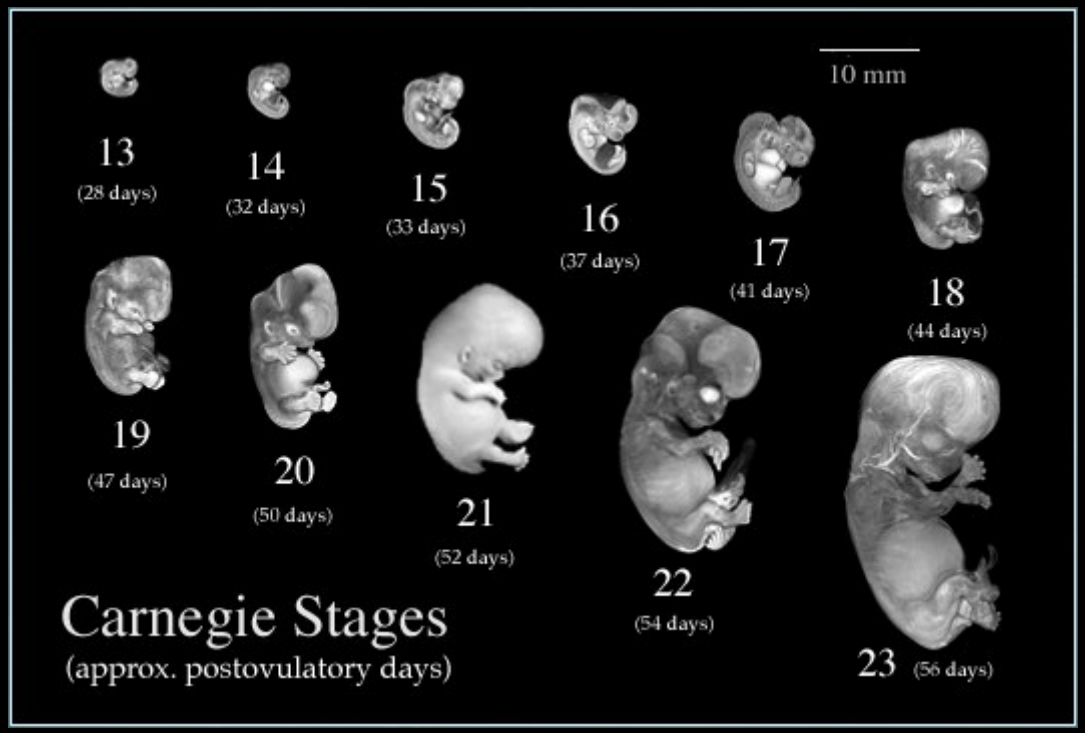
0.5 mm

Stage 15 Human Embryo
(approx. 33 days)

1 mm

Stage 16 Human Embryo
(approx. 37 days)

1 mm



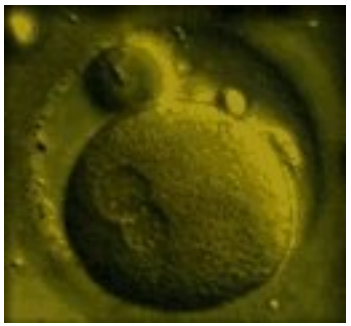
Stage 17 Human Embryo
(approx. 41 days)

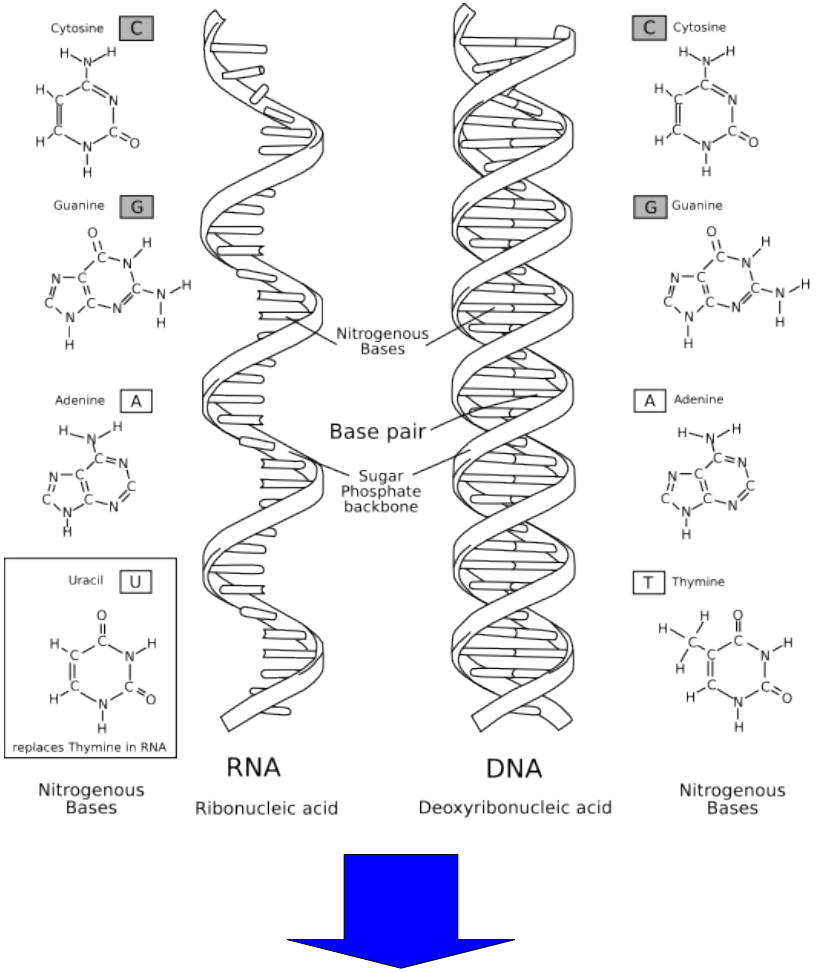
2 mm

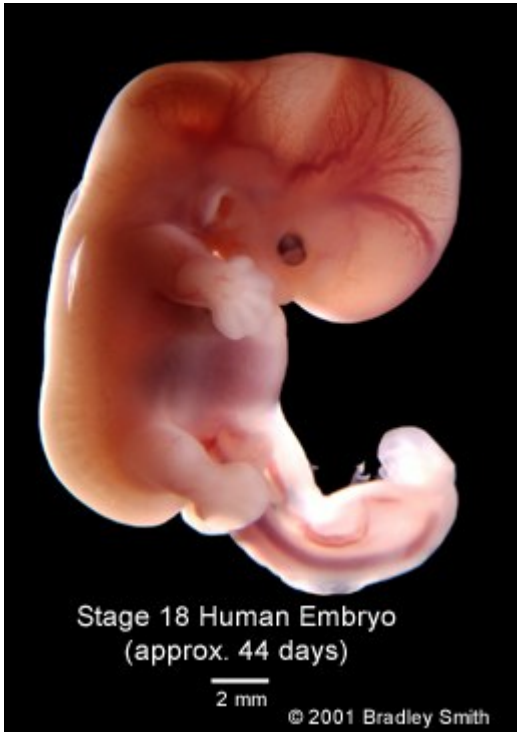
Stage 18 Human Embryo
(approx. 44 days)

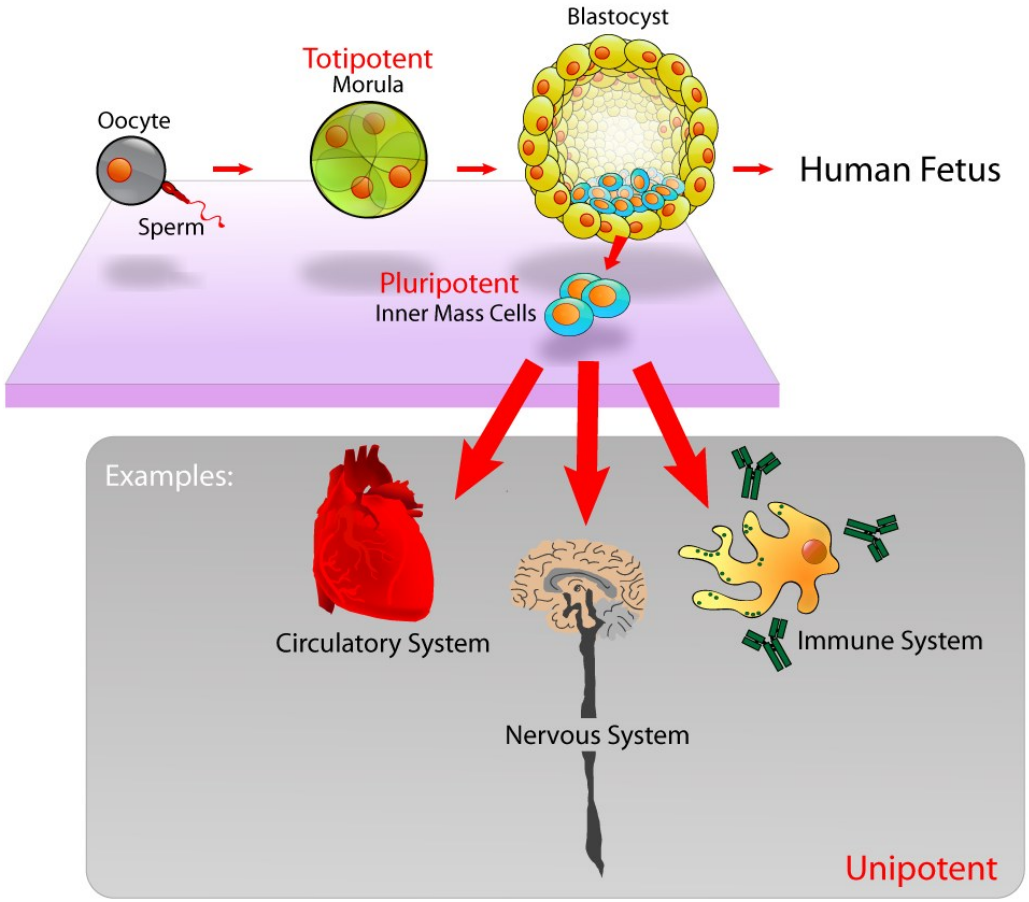
2 mm

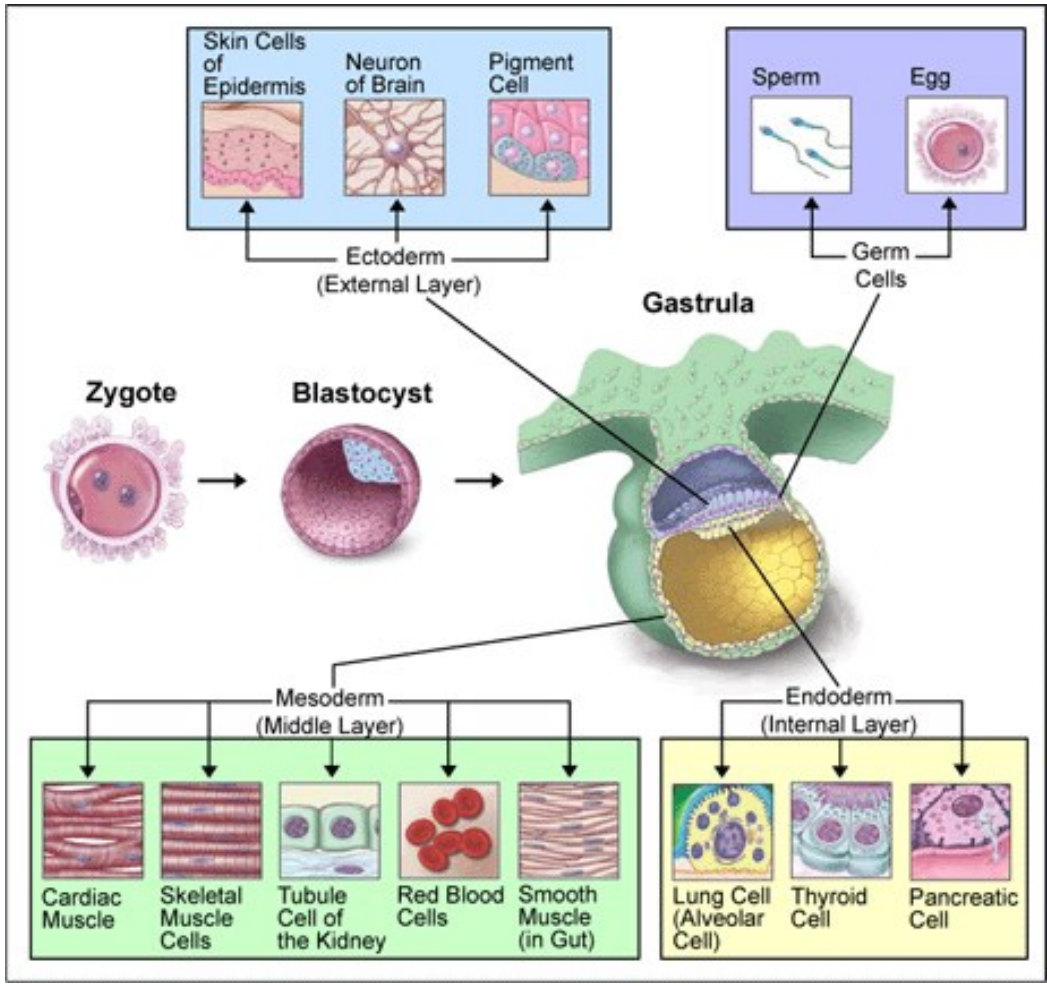
Life = Information?

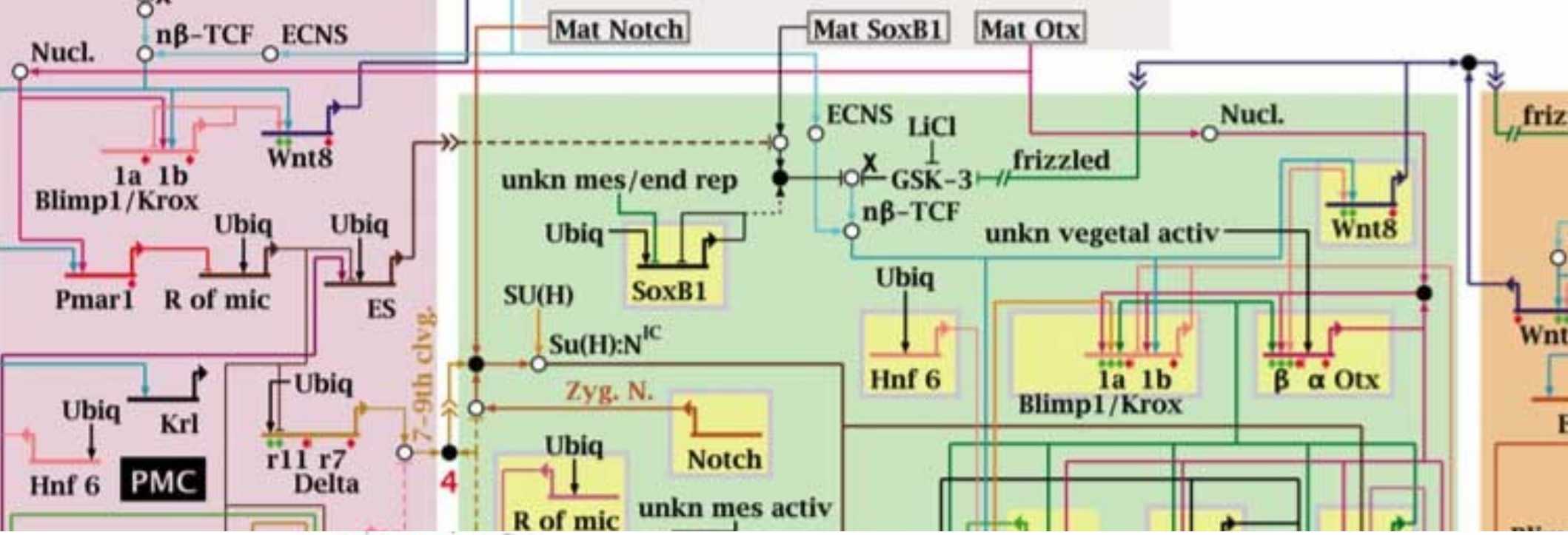


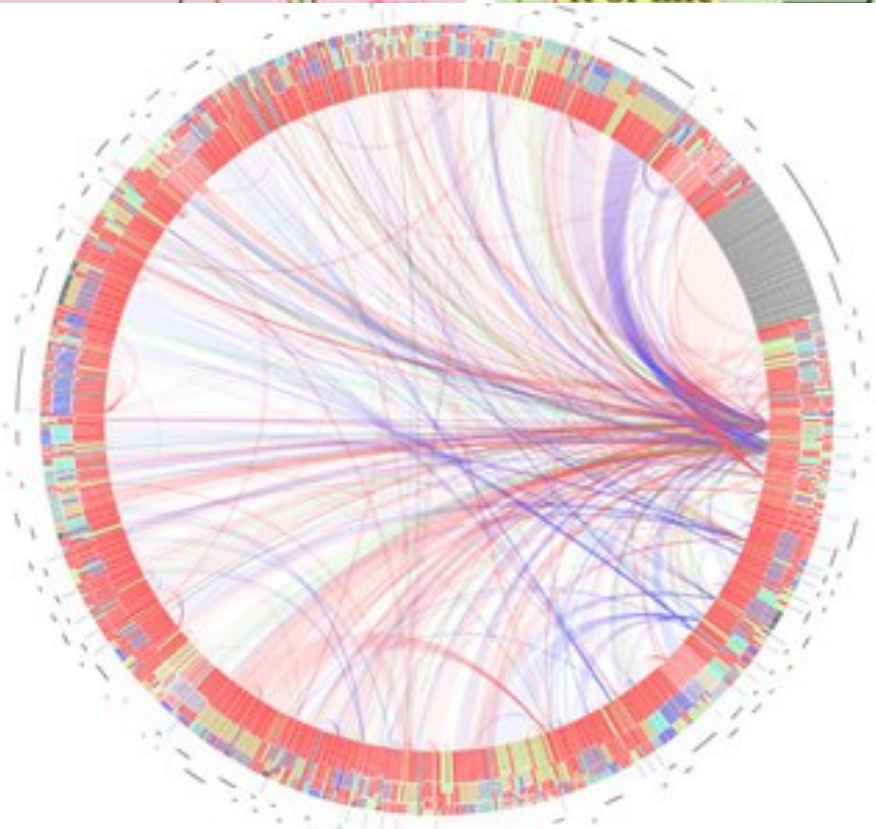


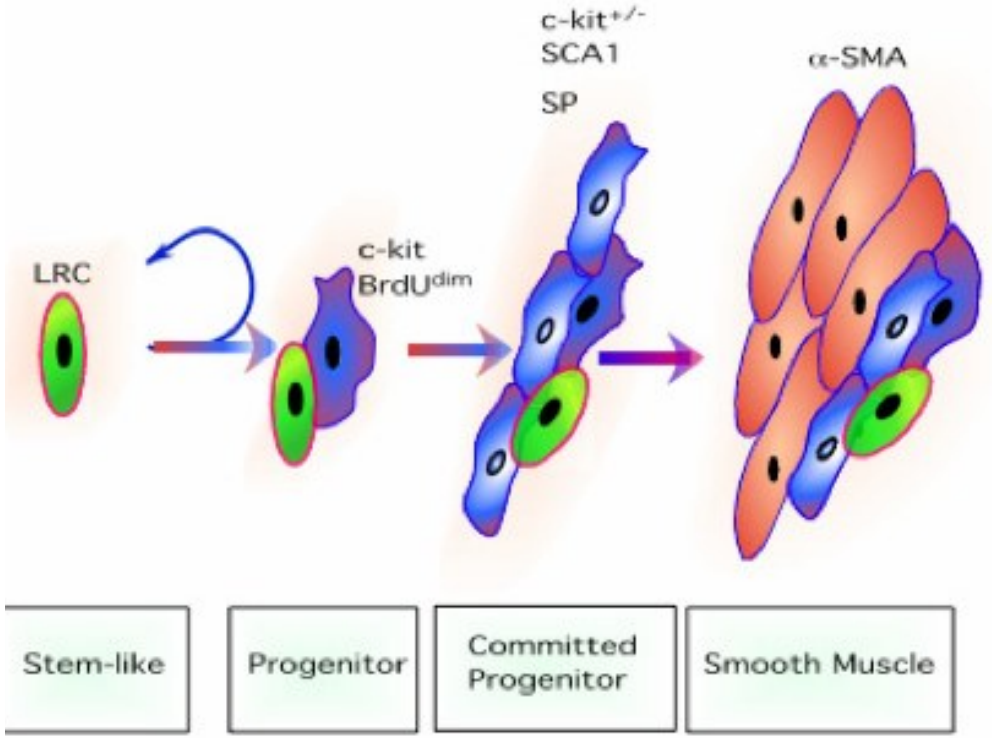



Oocyte
Sperm
Totipotent
Morula
Blastocyst
Human Fetus
Pluripotent
Inner Mass Cells
Examples:
Circulatory System
Nervous System
Immune System
Unipotent

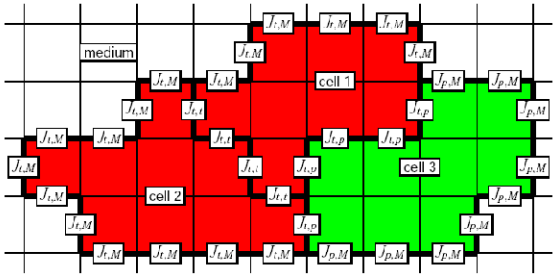

Skin Cells of Epidermis
Neuron of Brain
Pigment Cell
Ectoderm (External Layer)
Sperm
Egg
Germ Cells
Gastrula
Zygote
Blastocyst
Mesoderm (Middle Layer)
Endoderm (Internal Layer)
Cardiac Muscle
Skeletal Muscle Cells
Tubule Cell of the Kidney
Red Blood Cells
Smooth Muscle (in Gut)
Lung Cell (Alveolar Cell)
Thyroid Cell
Pancreatic Cell


Nucl.
nβ-TCF
ECNS
Mat Notch
Mat SoxB1
Mat Otx
1a 1b
Blimp1/Krox
Wnt8
ECNS
LiCl
GSK-3
frizzled
Nucl.
unkn mes/end rep
nβ-TCF
Ubiq
SoxB1
unkn vegetal activ
Wnt8
Ubiq
Ubiq
Pmar1
R of mic
ES
SU(H)
Su(H):N^IC
Ubiq
Hnf 6
1a 1b
Blimp1/Krox
β α Otx
Ubiq
Krl
Ubiq
Zyg. N.
7-9th clvg.
r11 r7
Delta
Notch
Hnf 6
PMC
4
Ubiq
R of mic
unkn mes activ



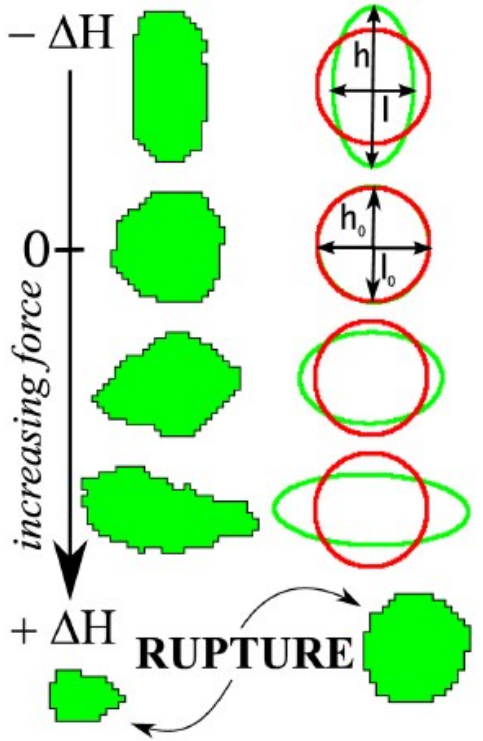

c-kit+/-
SCA1
SP
α-SMA
LRC
c-kit
BrdU^dim
Stem-like
Progenitor
Committed Progenitor
Smooth Muscle

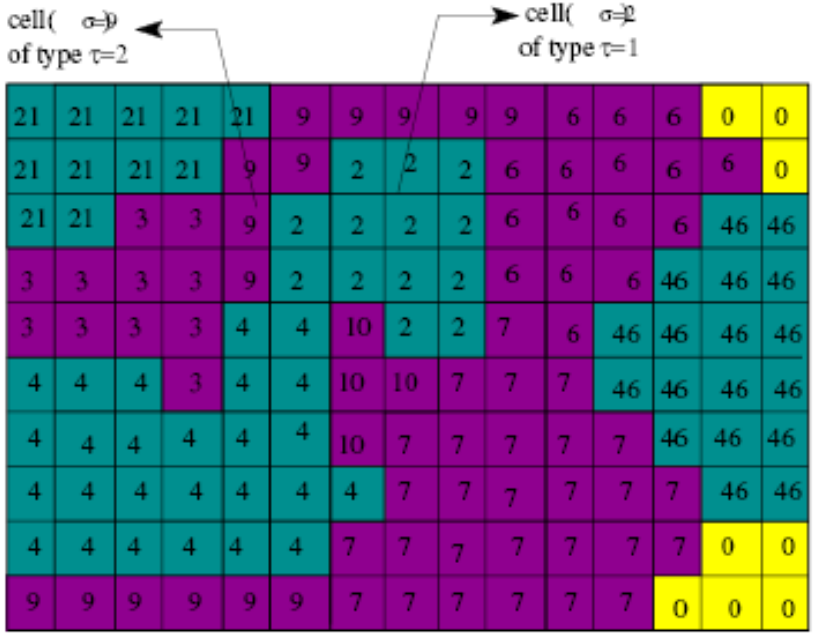

Ubiq
3
Mes
1

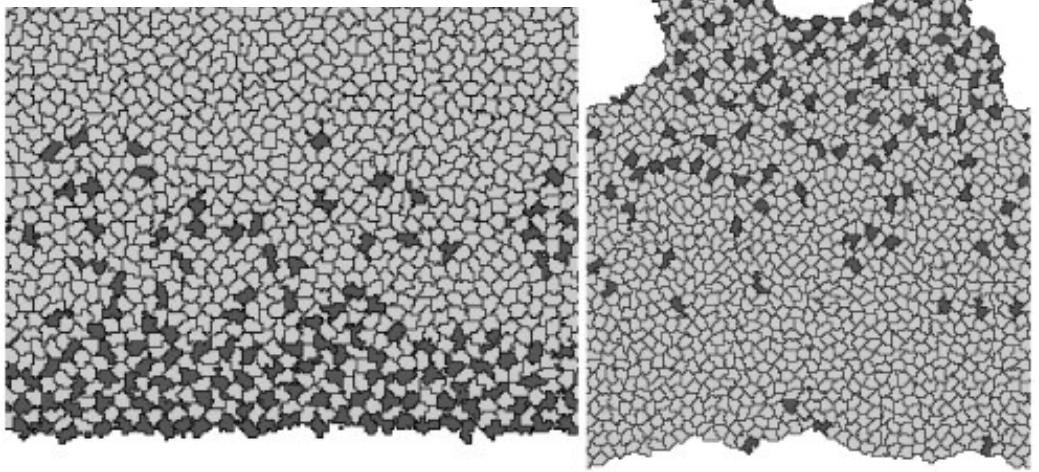


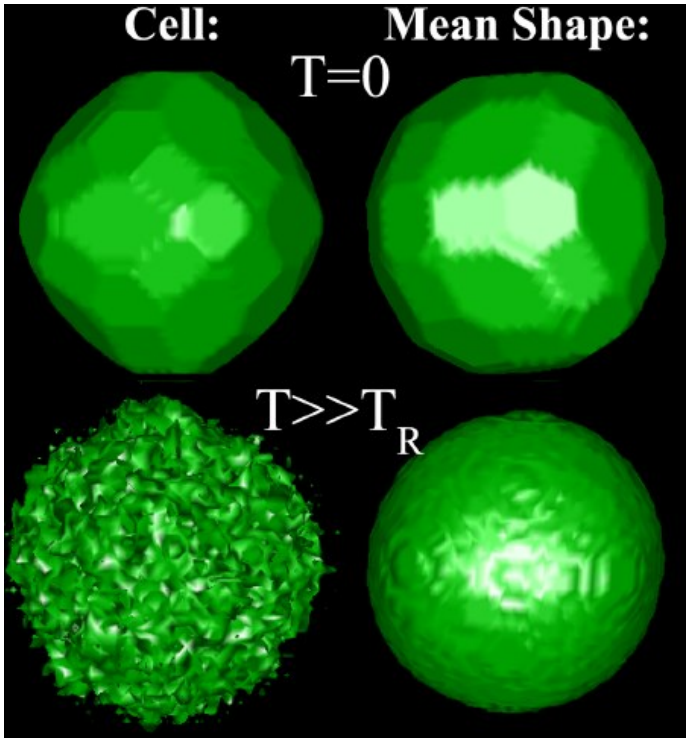
Cellular Potts Model

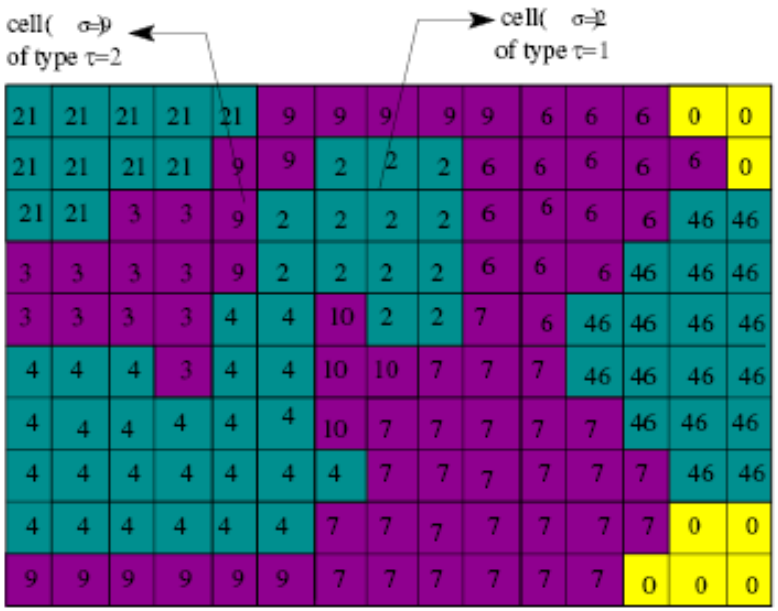
Glazier & Graner (1992, 1992)

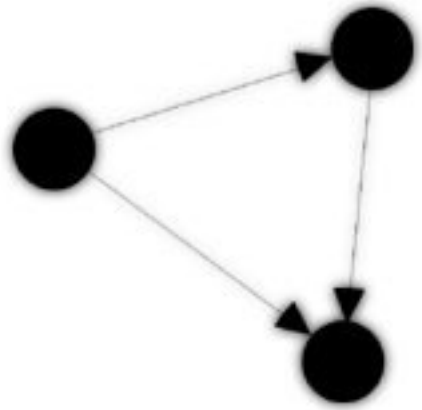


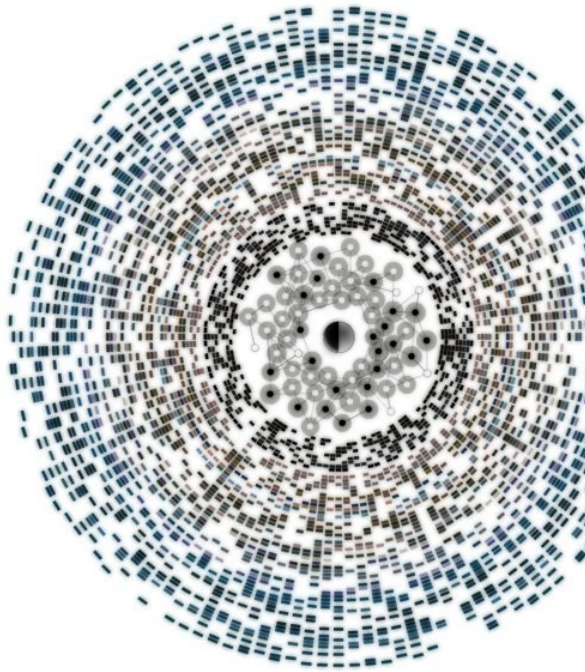






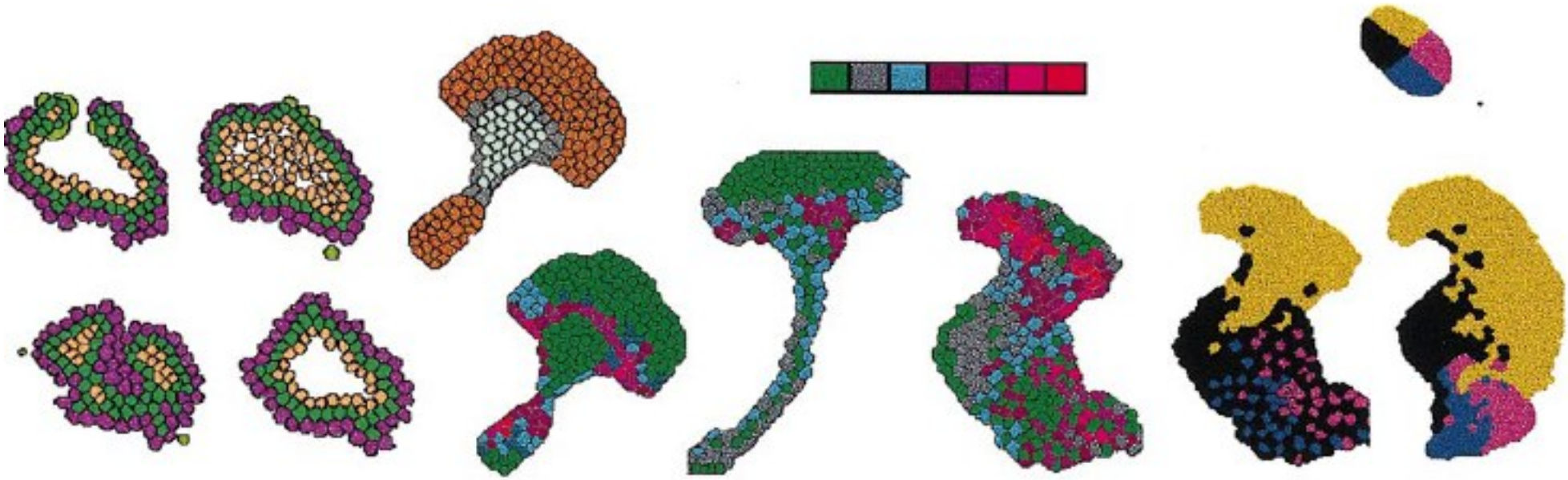






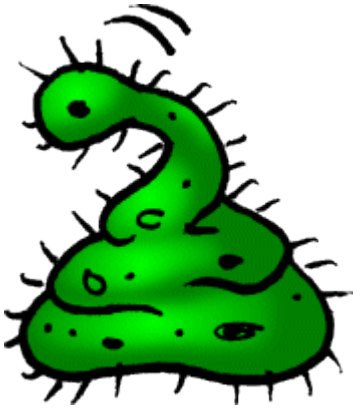
Cell Interactions + Genetic Interactions + Evolution = Morphogenesis

Paulien Hogeweg (2000)



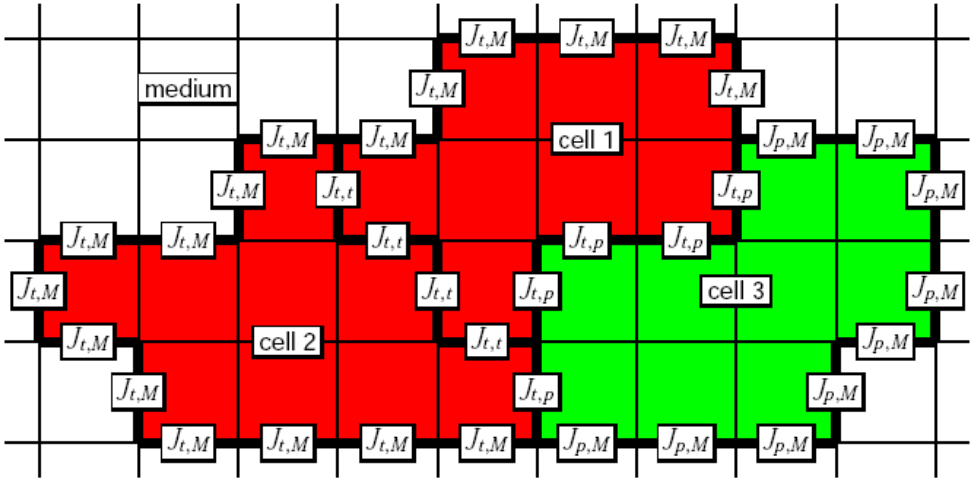
Cellular Slime Mold

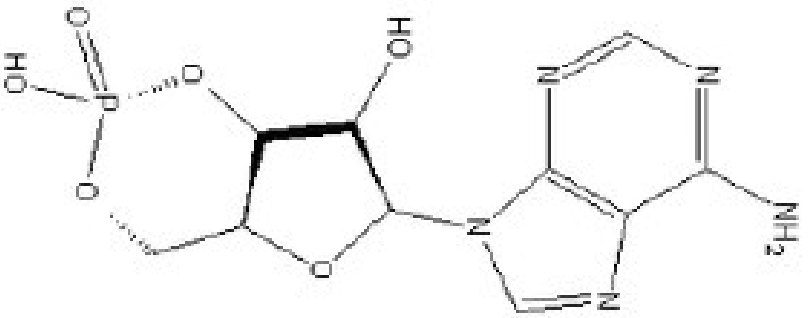
Dictyostelium discoideum

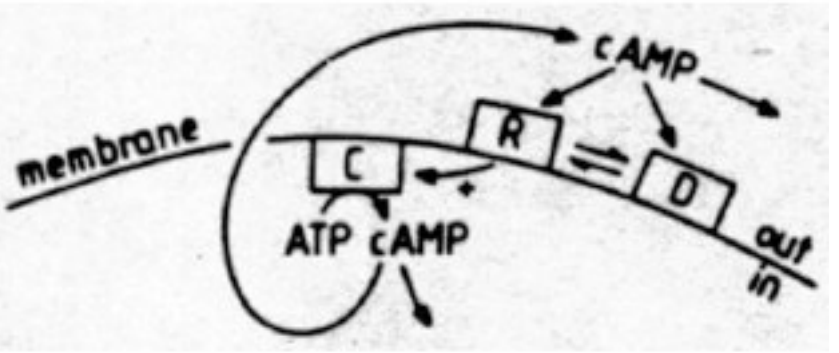


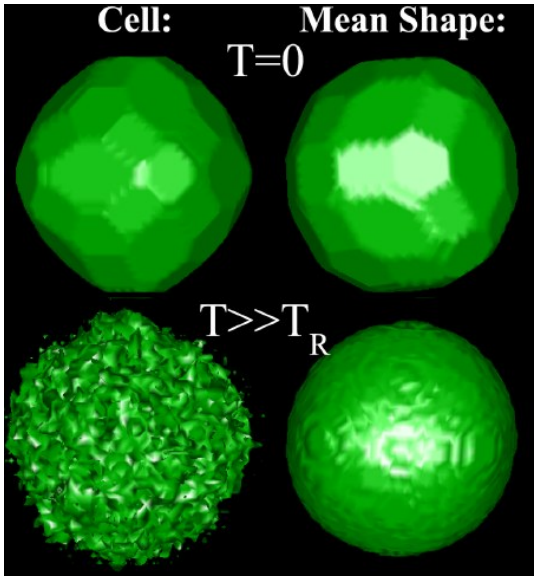
Modelling an Organism

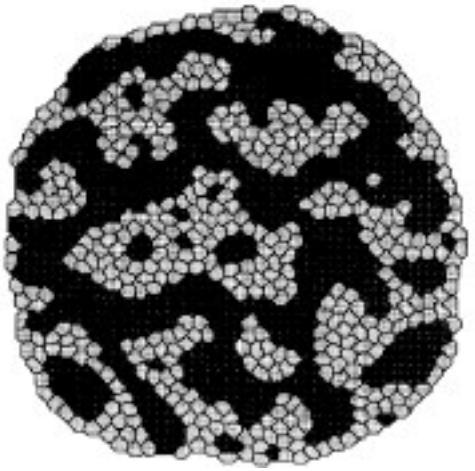
Stan Mareé, Paulien Hogeweg, and Nick Savill









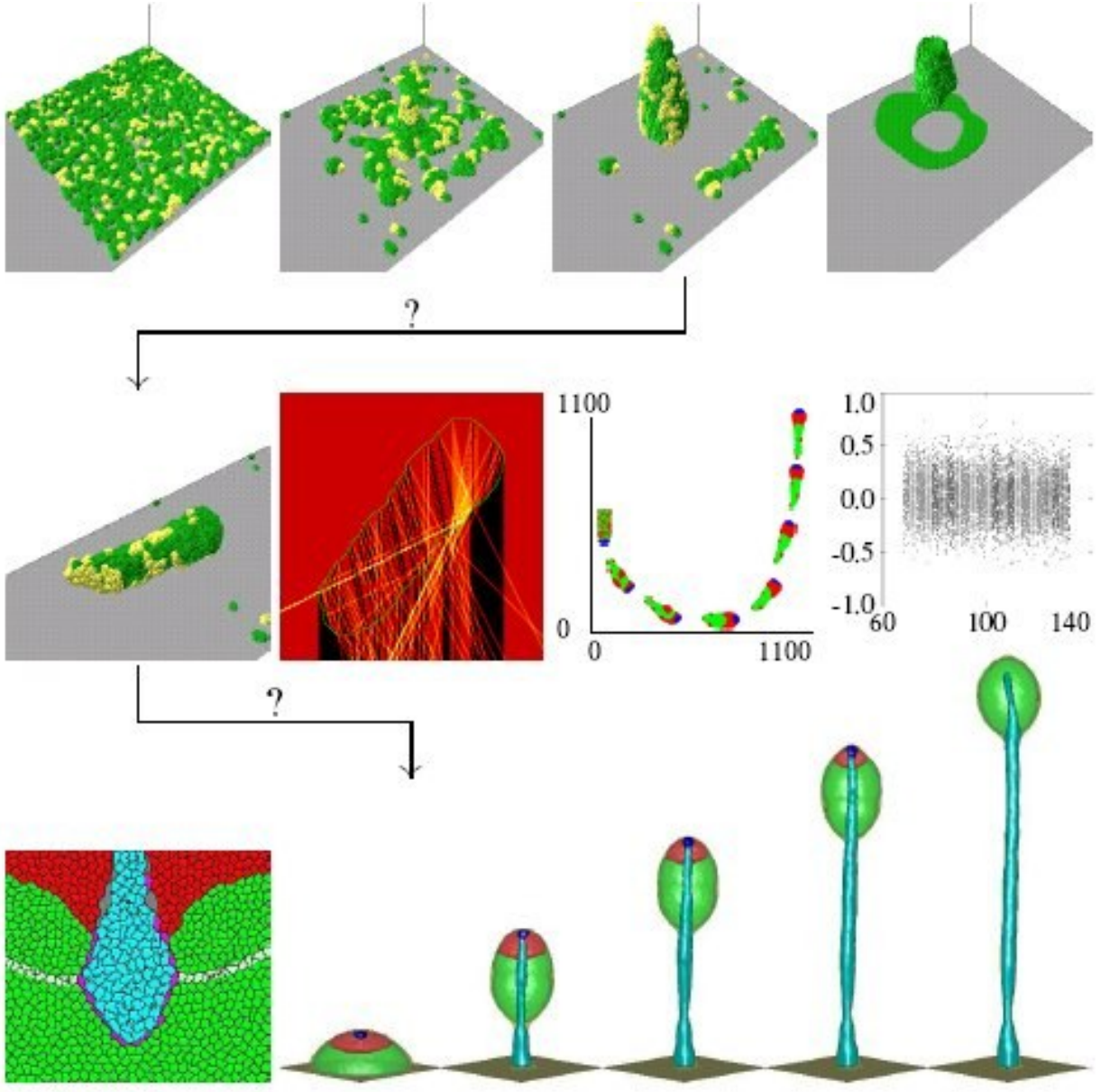


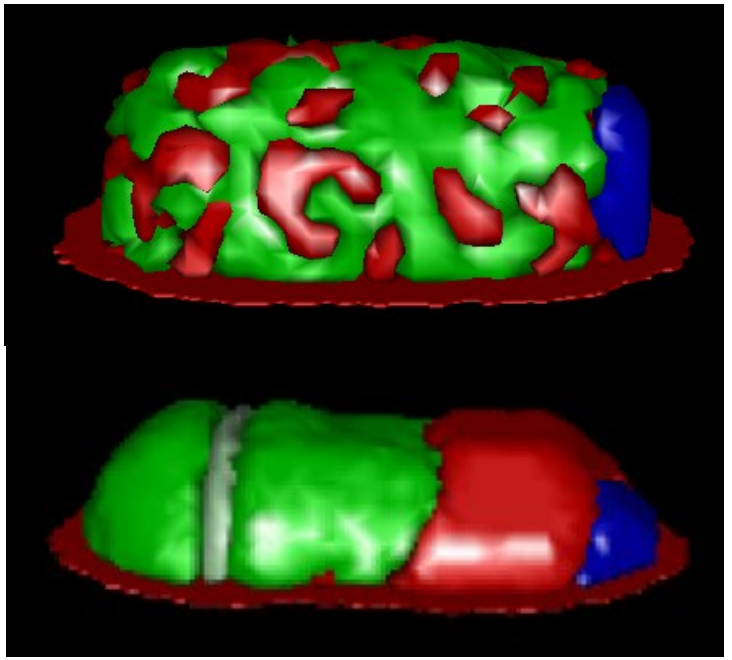
$$\frac{\partial c}{\partial t} = D_c \Delta c - f(c, a_\tau, \cdots) - r \quad ,$$

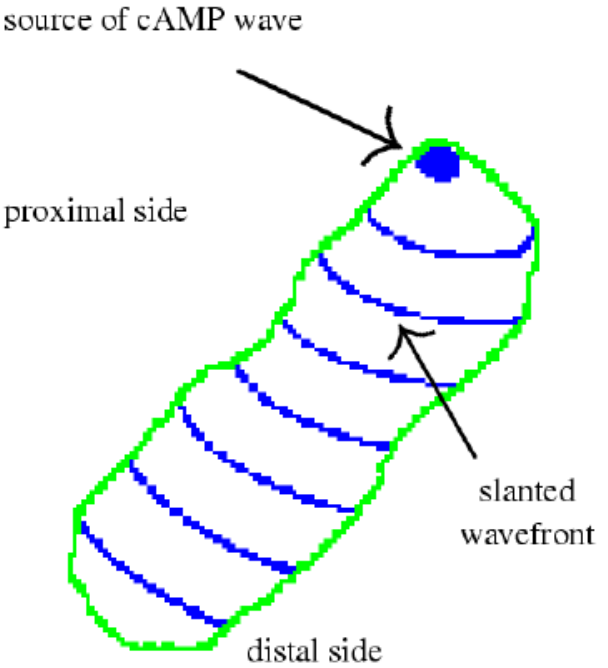
$$\frac{\partial r}{\partial t} = \varepsilon(c)(kc - r) \quad .$$

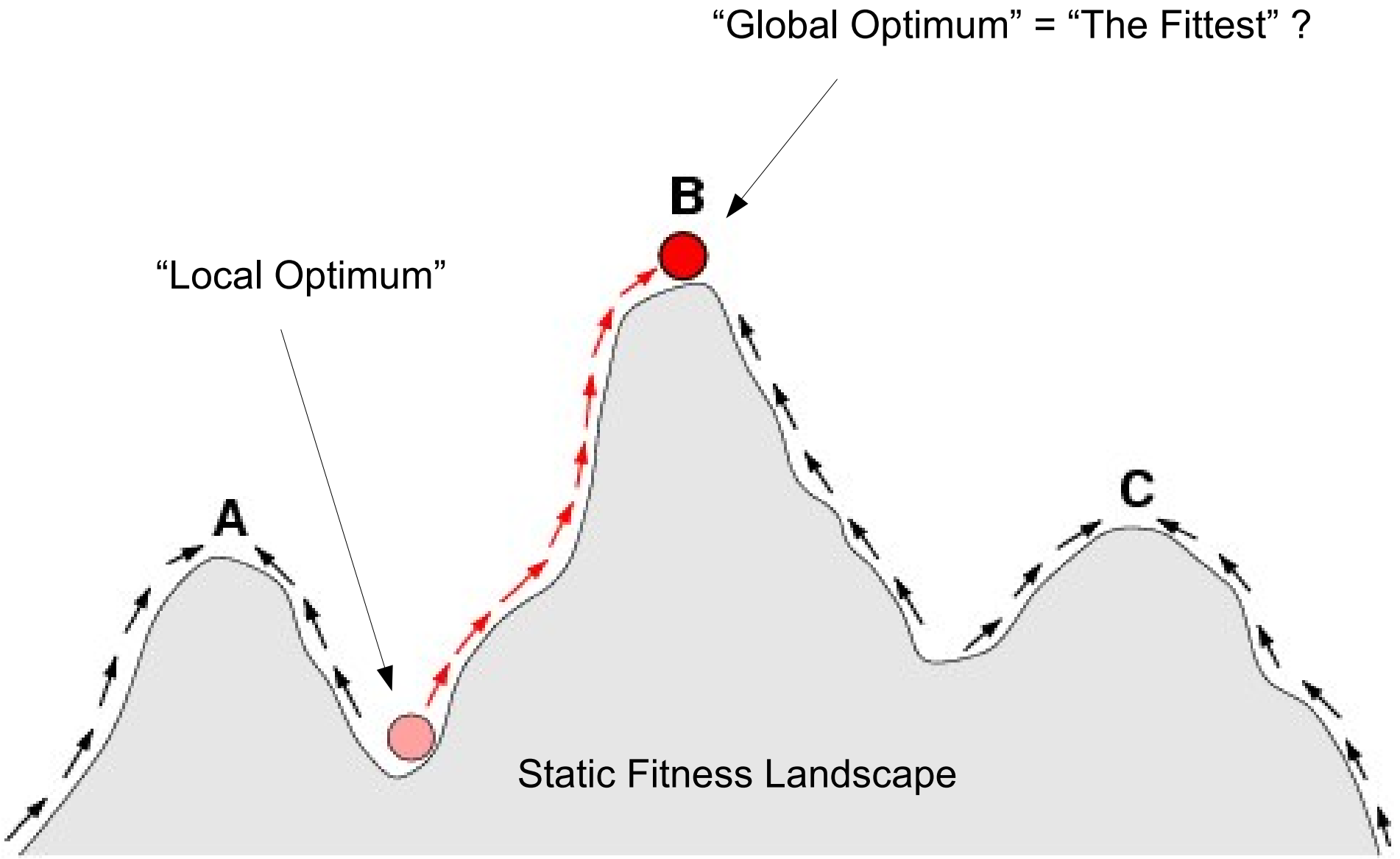
Modelling an Organism

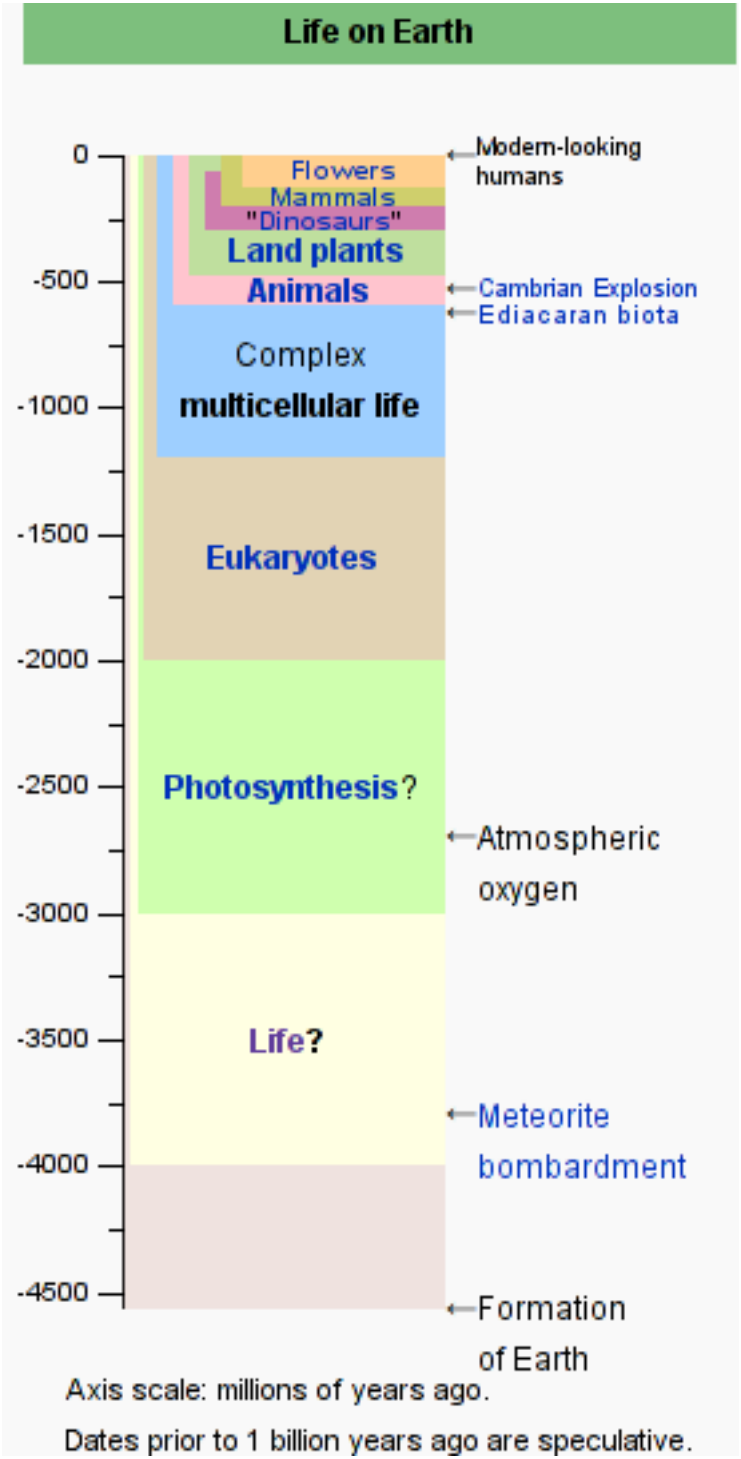
Stan Mareé, Paulien Hogeweg, and Nick Savill

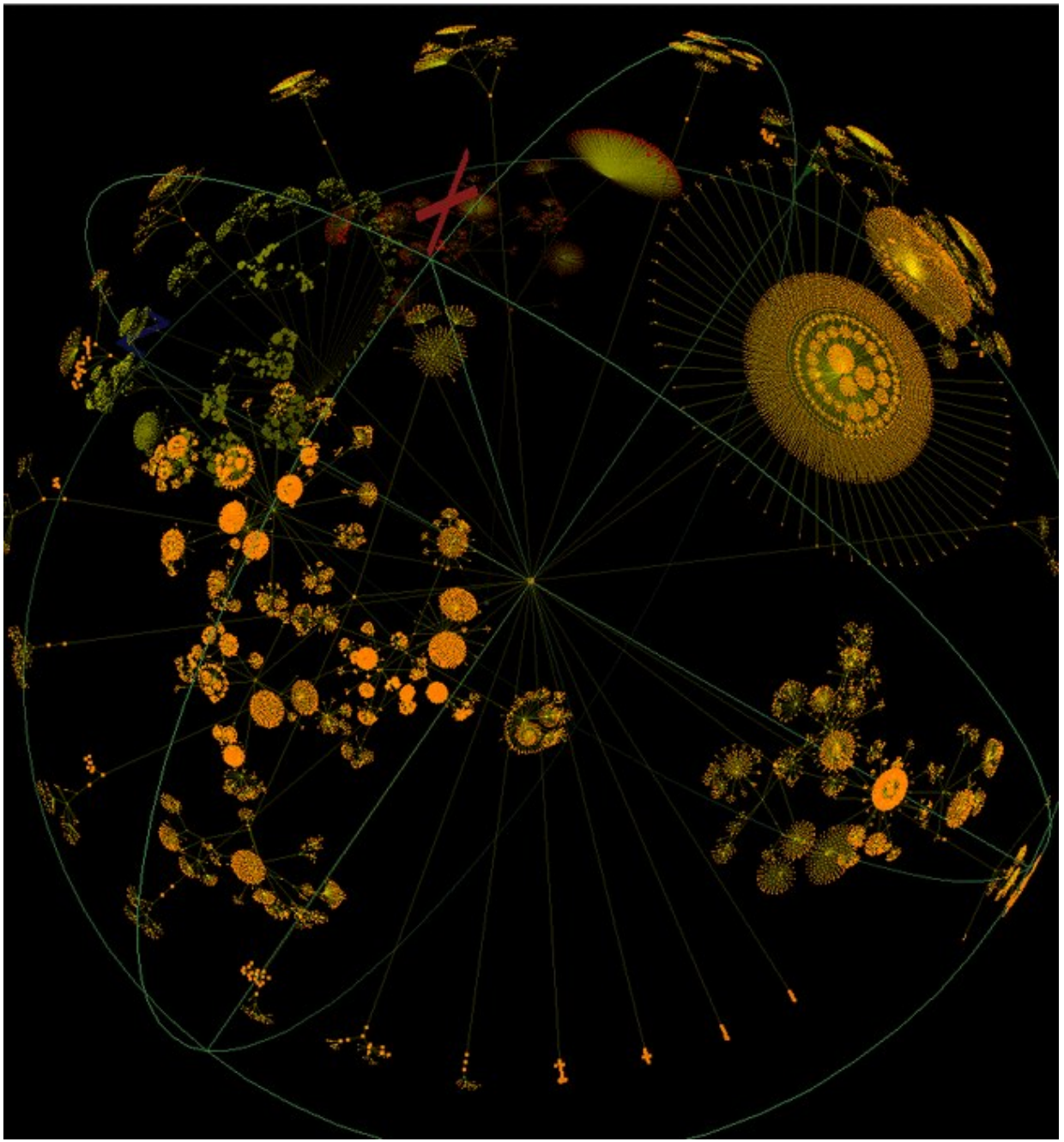




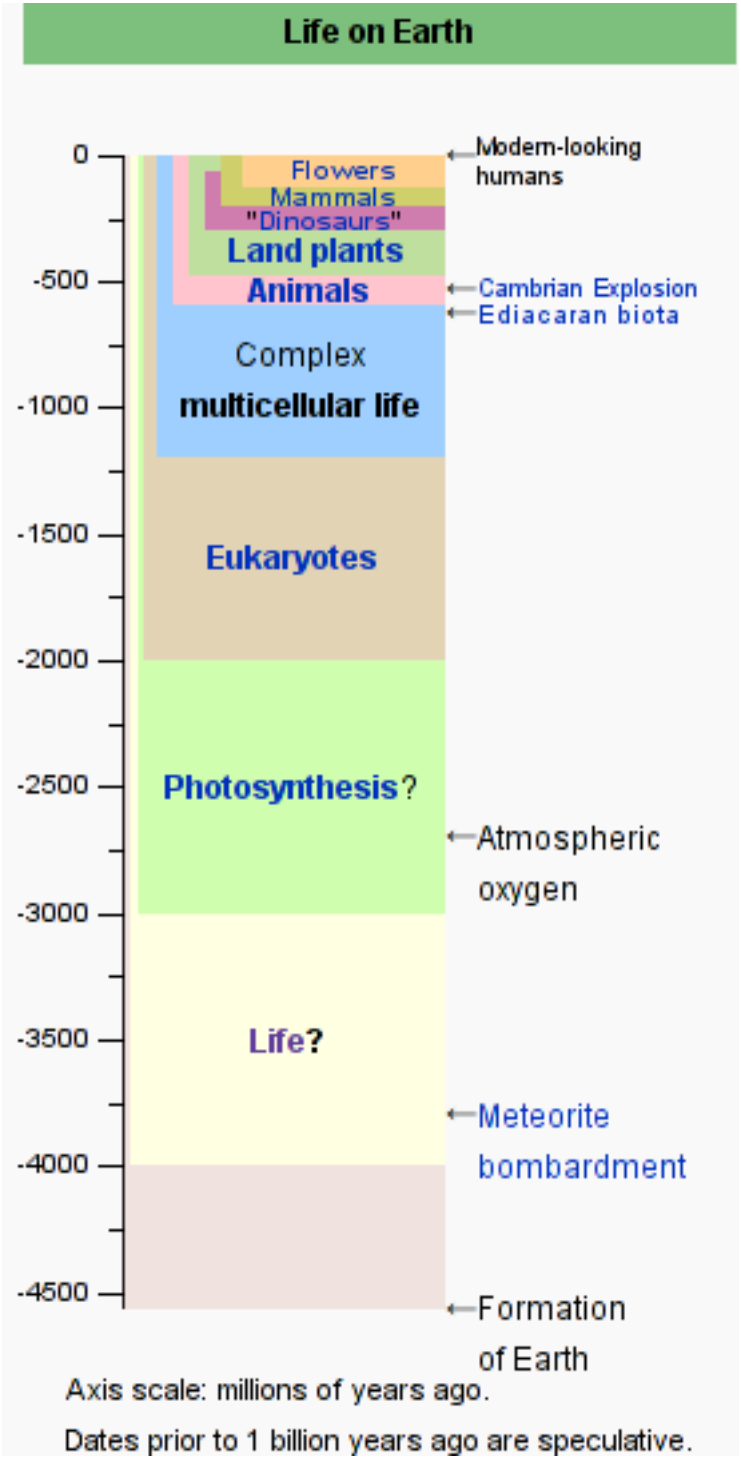


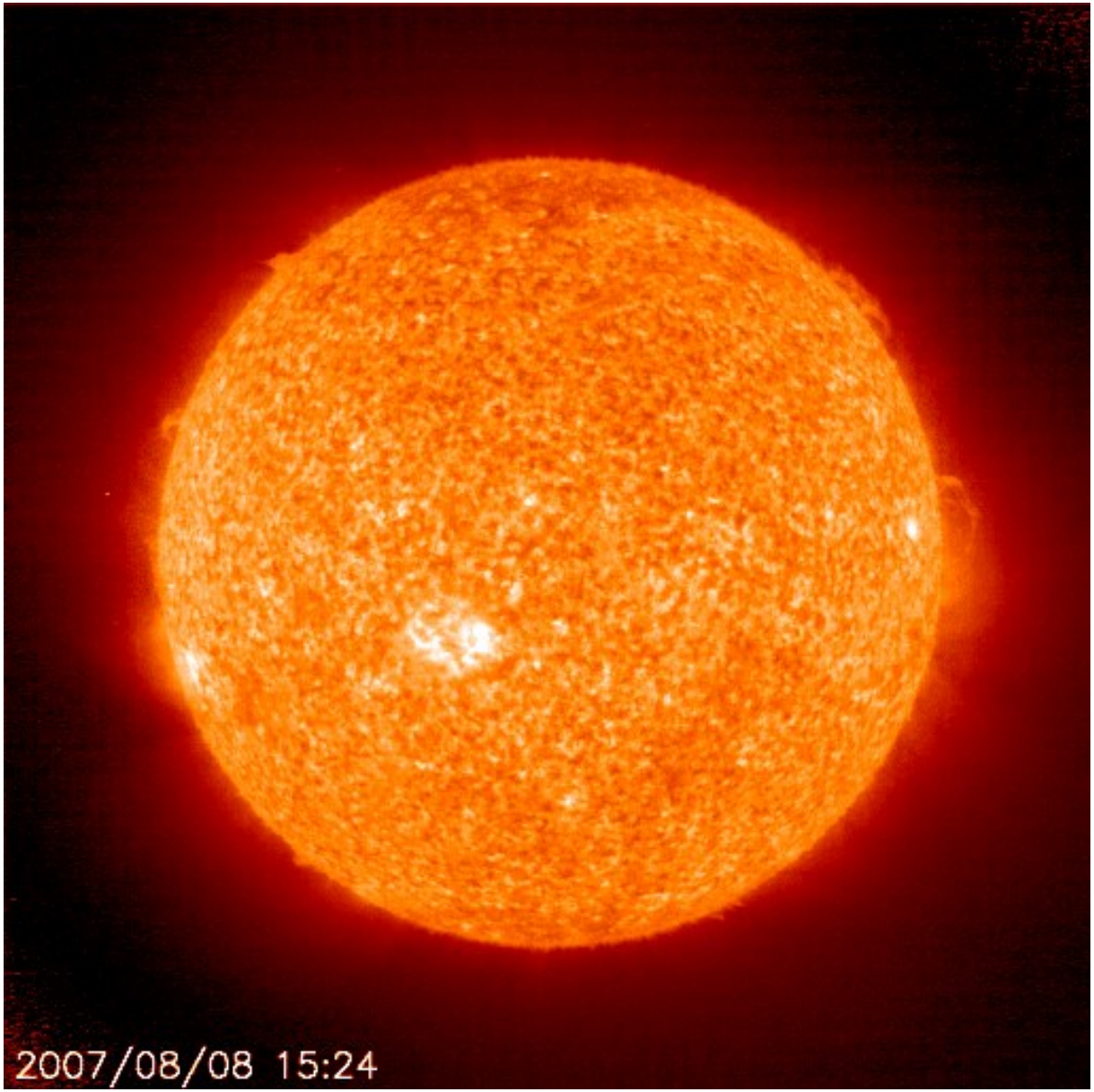

“Global Optimum” = “The Fittest” ?
B
“Local Optimum”
A
C
Static Fitness Landscape





The Evolutionary “Tree of Life”


Life on Earth
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
Flowers
Mammals
"Dinosaurs"
Land plants
Animals
Complex
multicellular life
Eukaryotes
Photosynthesis?
Life?
Modern-looking humans
Cambrian Explosion
Ediacaran biota
Atmospheric oxygen
Meteorite bombardment
Formation of Earth
Axis scale: millions of years ago.
Dates prior to 1 billion years ago are speculative.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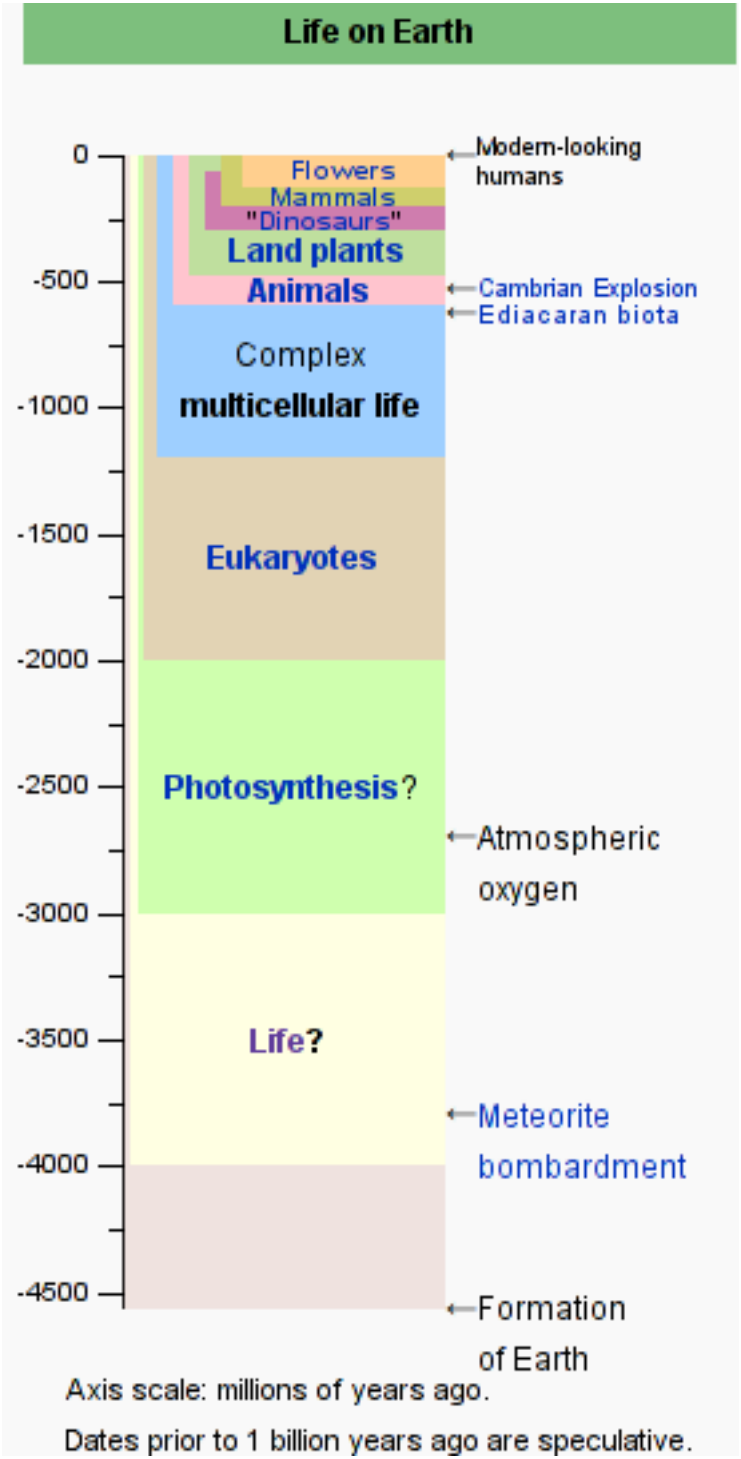
Life on Earth
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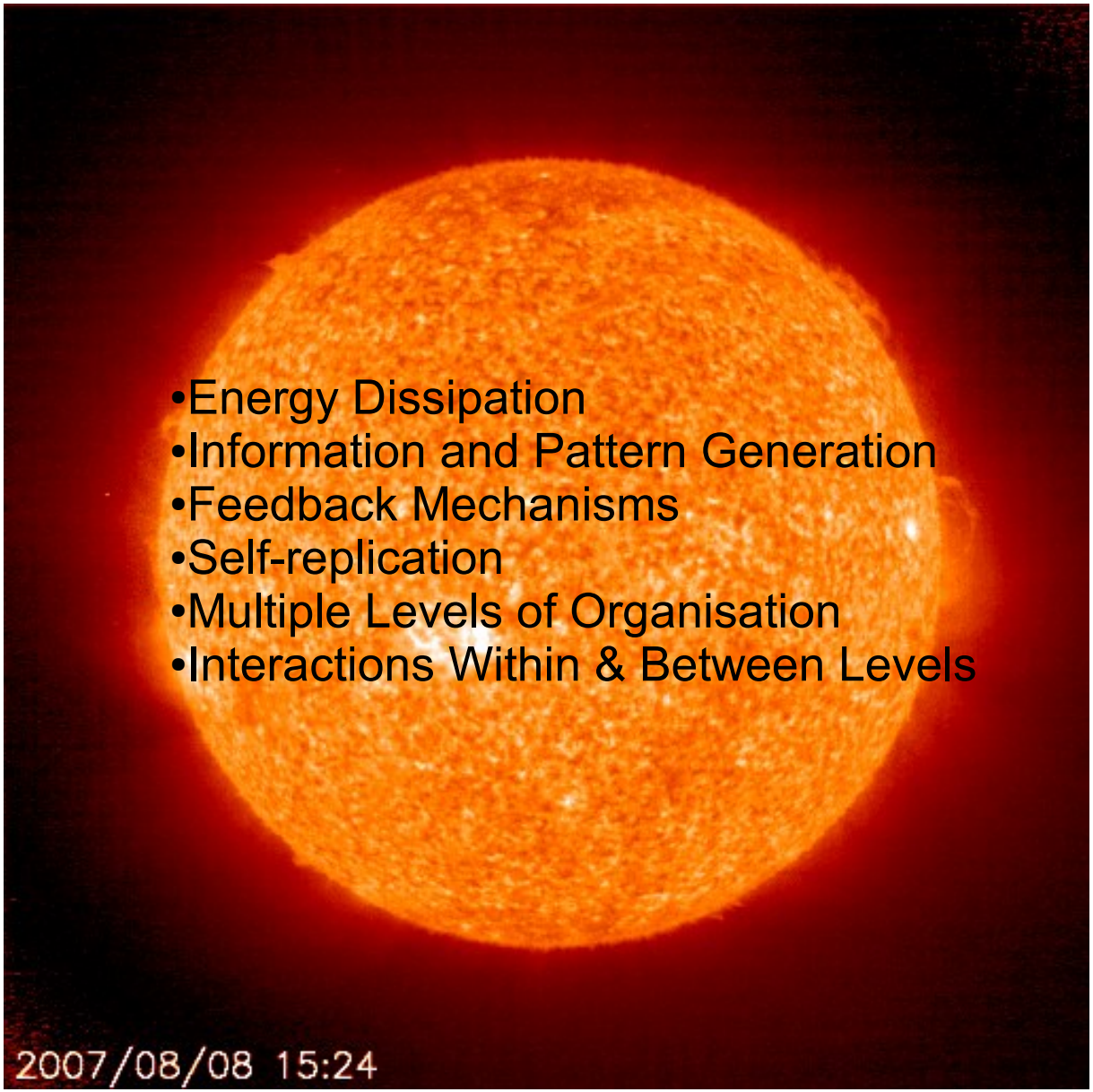
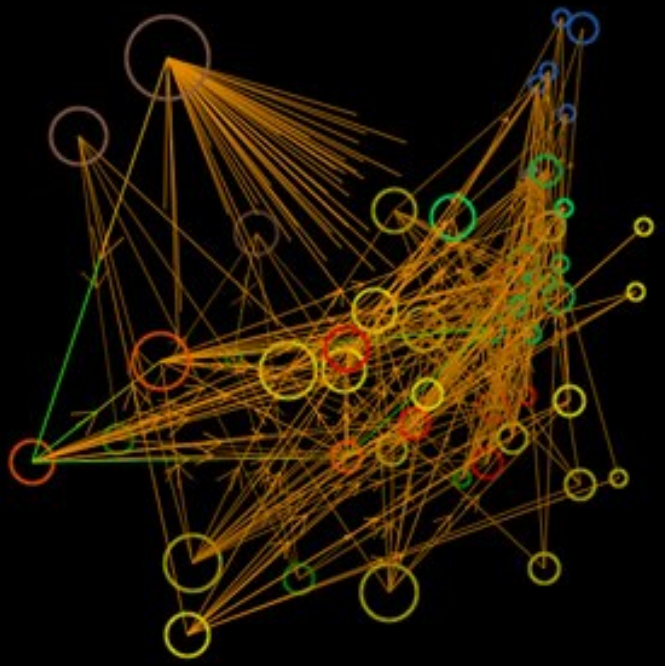
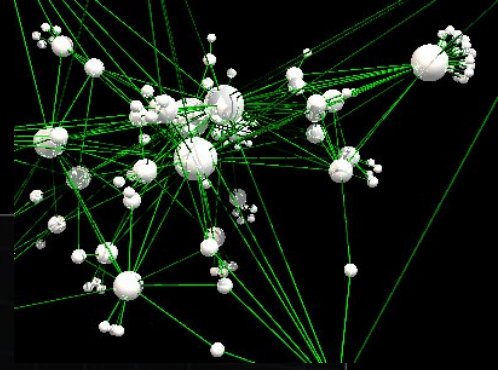
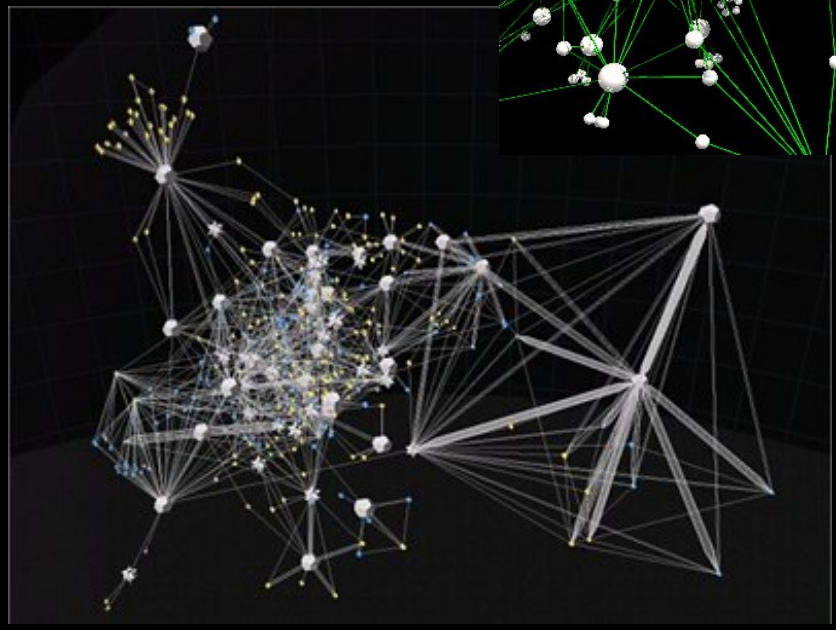
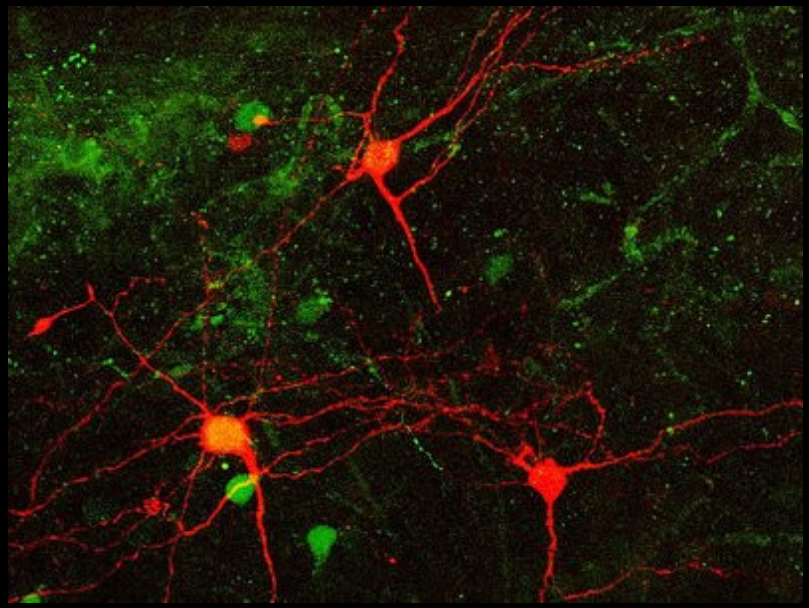

•Energy Dissipation
•Information and Pattern Generation
•Feedback Mechanisms
•Self-replication
•Multiple Levels of Organisation
•Interactions Within & Between Levels
2007/08/08 15:24



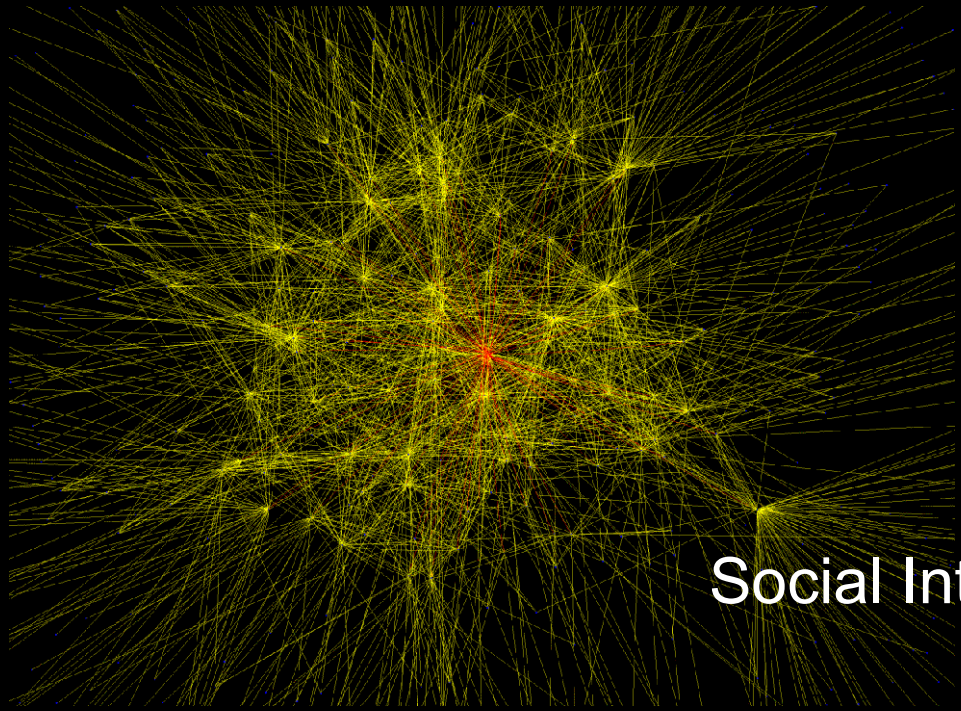
Computers







Biology



Social Interactions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Acknowledgements

Much of this talk is based upon lectures and work by
Prof. Dr. Paulien Hogeweg and Dr. Stan Marée,
as well as on the works and writings of many others.

Click on the blue names in the slides to go to their related websites.