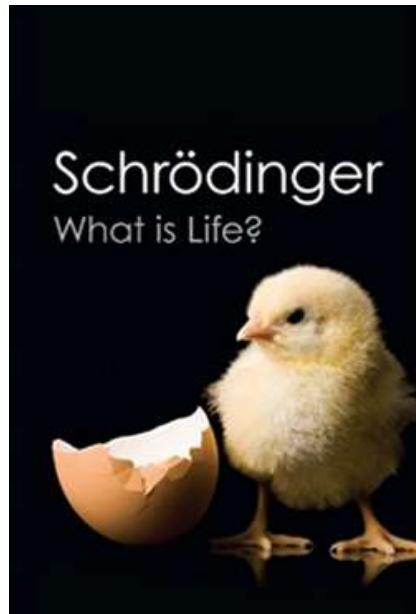
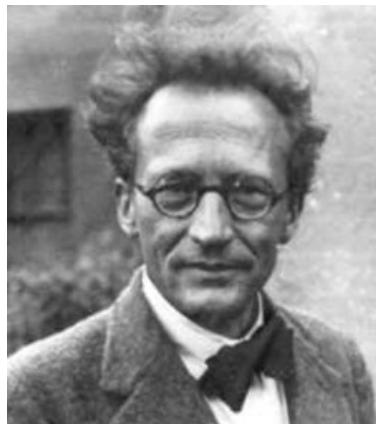


# A network perspective on the origin and major transitions of life

Béla Suki

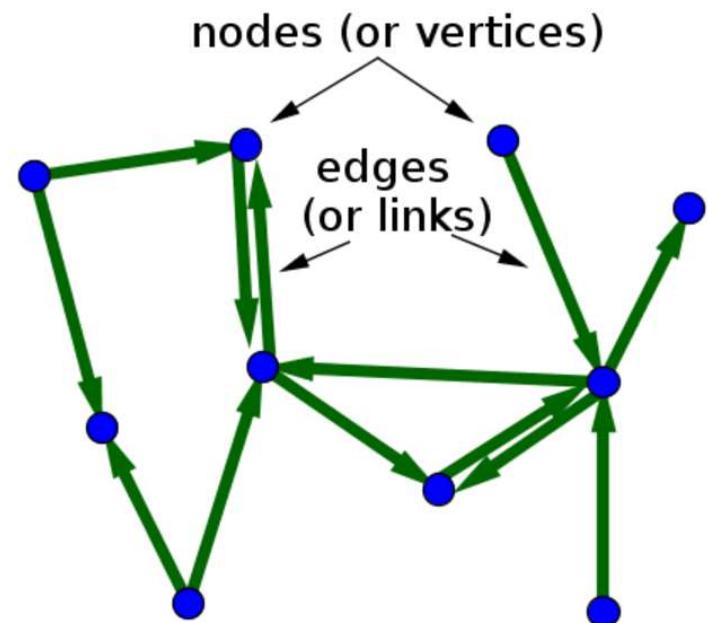
Department of Biomedical Engineering  
Boston University



- How does order develop from order?  
“aperiodic crystal”
- How does order develop from disorder?  
“Entropy reduction”

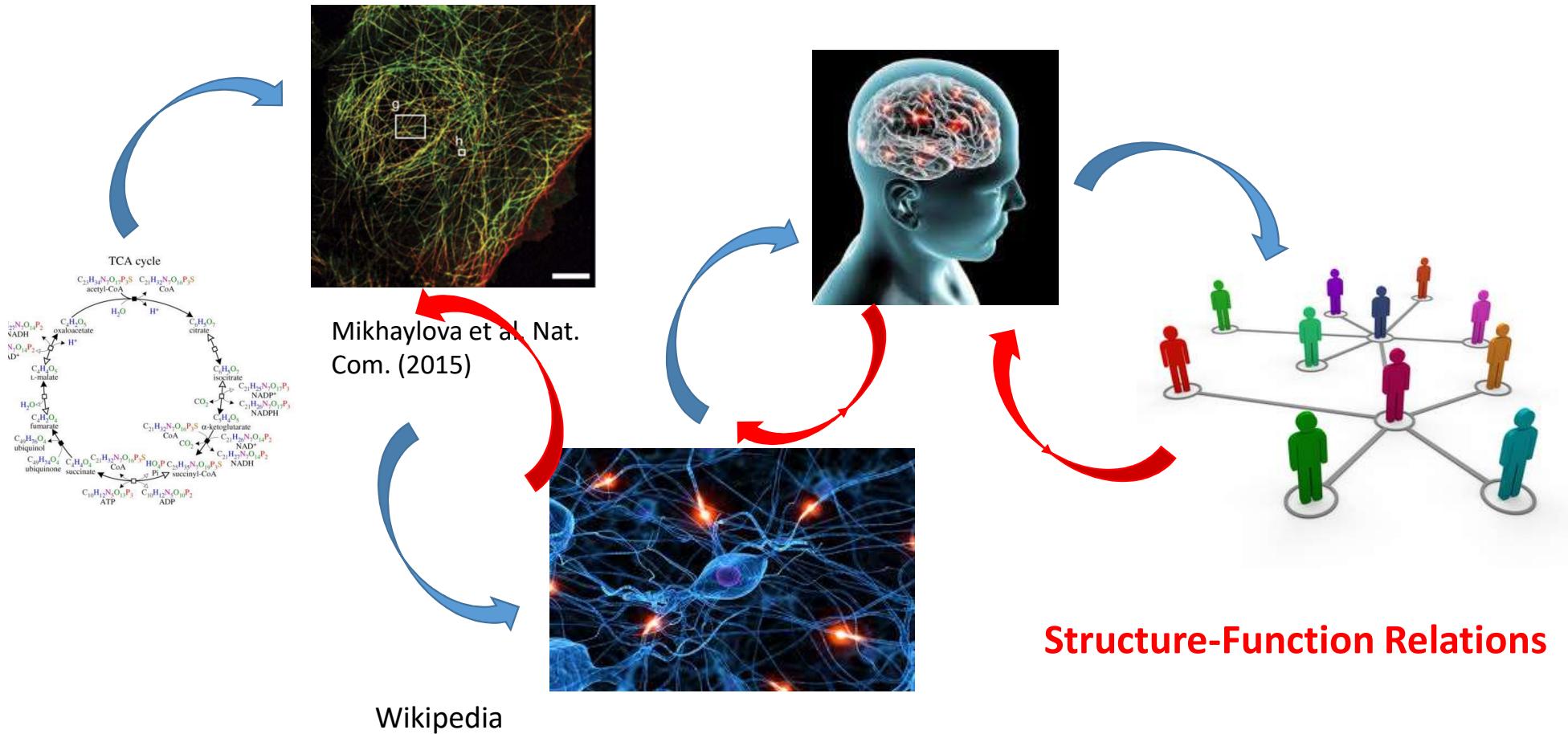


# What is a network?

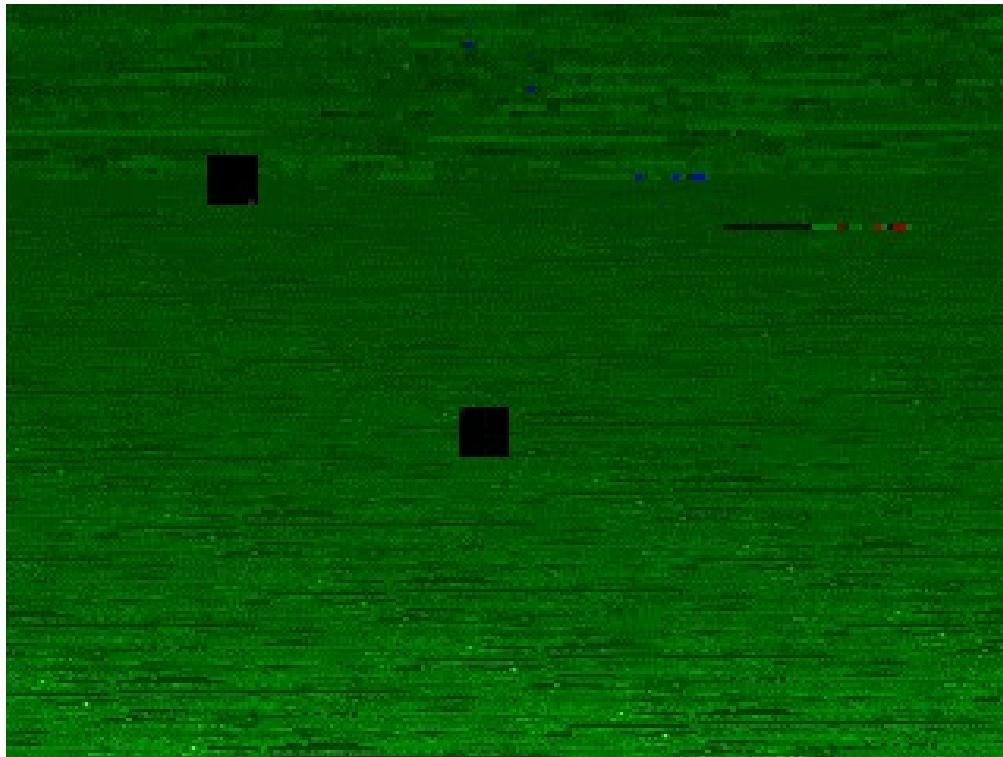


<http://mathinsight.org/definition/network>

# Basis of Life: Network hierarchy

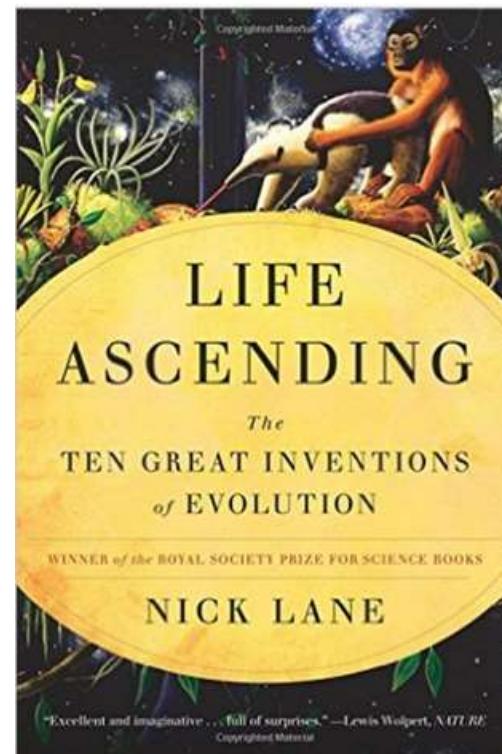
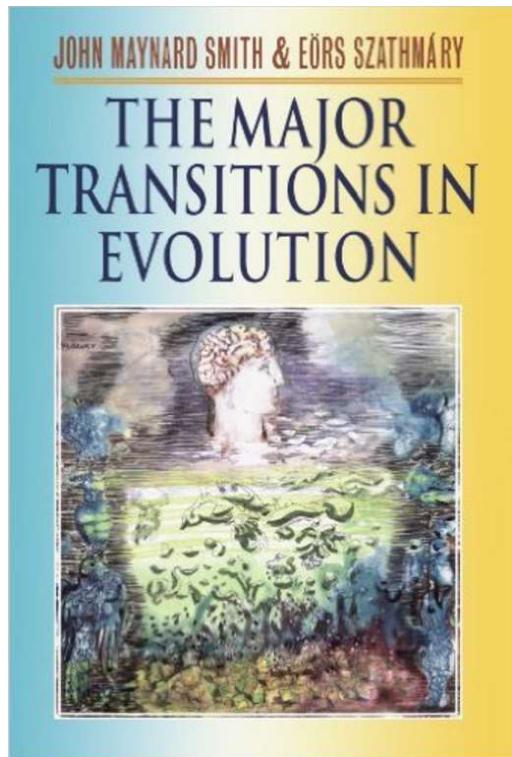


# Increasing complexity by Darwinian evolution



*Carl Sagan: Cosmos*  
*Permission by Druyan-Sagan Associates, Inc*

# The major transitions

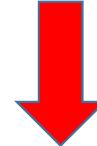


# What are the major transitions?

## Emergence of

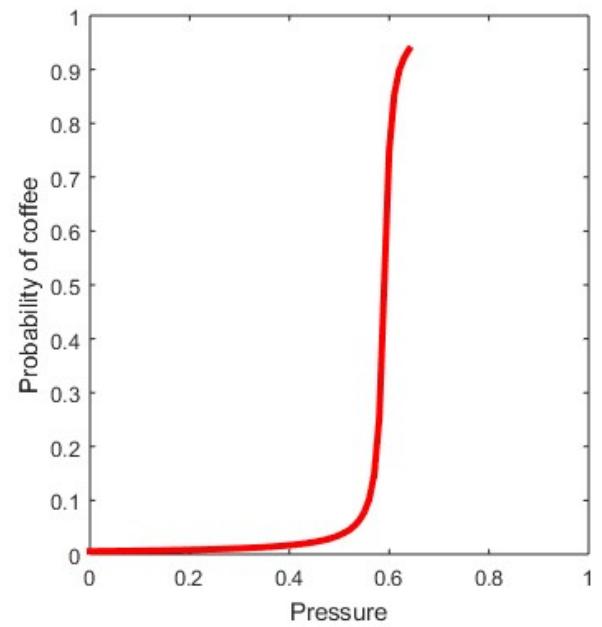
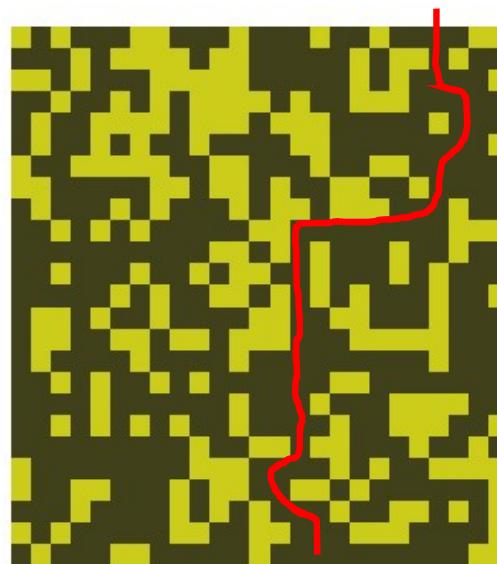
- Life
- Genetic code
- Eukaryotic cell
- Sex
- Multicellular life
- Vision
- Motion
- Consciousness
- Death
- Culture

Change in network structure; phase transition



Emergence of new function

# Coffee making: network transition



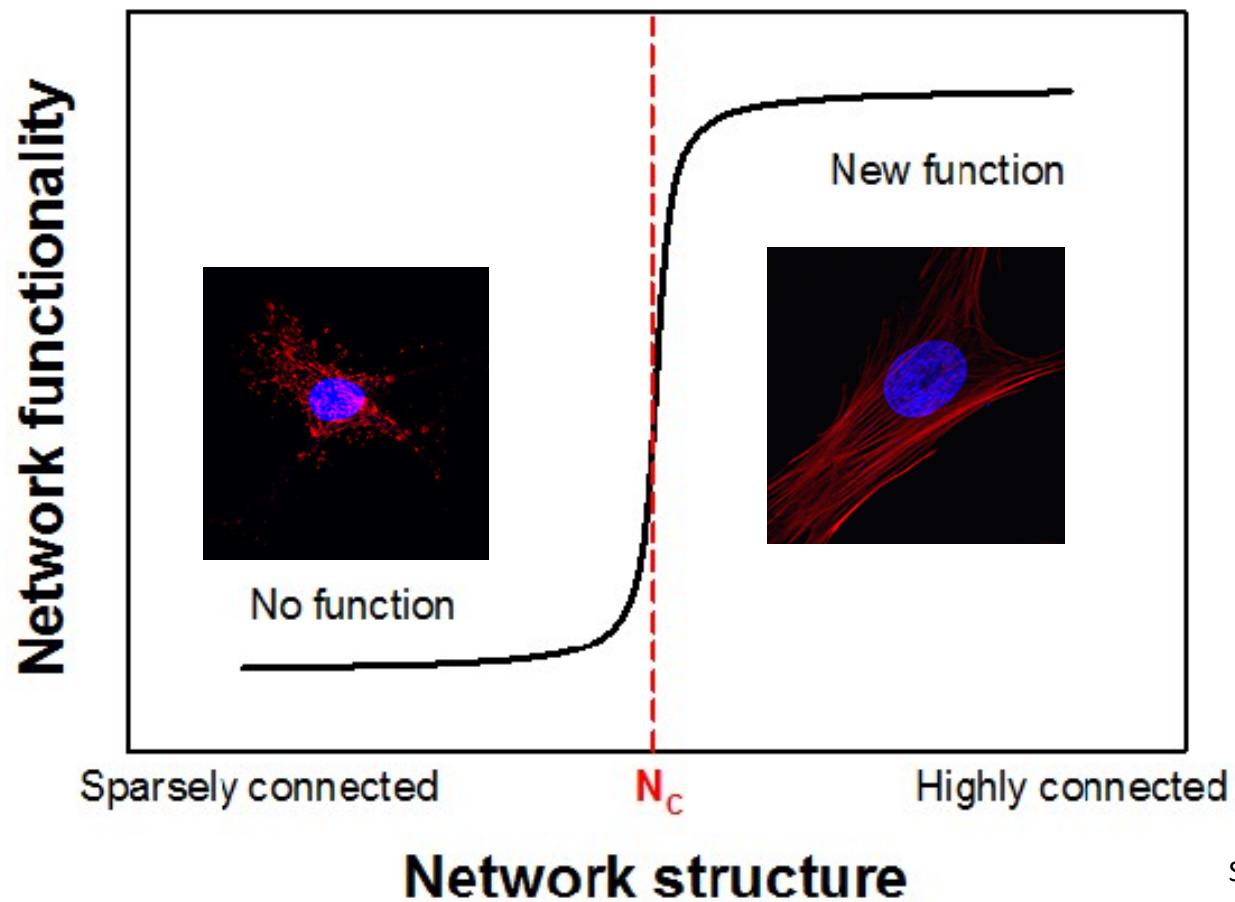
The structure of air pockets form a structure that allows coffee with probability 1.

# Example of emergence



Emergence of the metal man!

# Emergence of new function from structure



# Origin of life

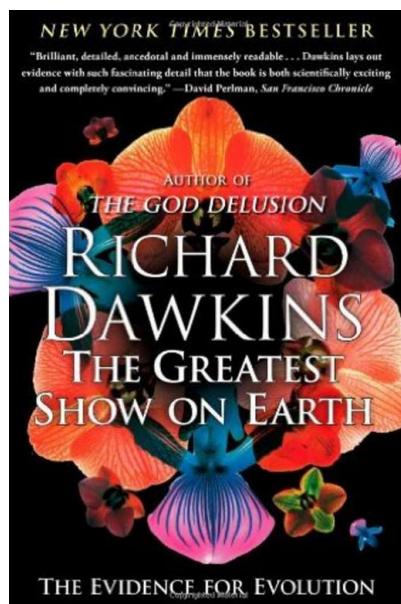


***How life on Earth really got its start.***

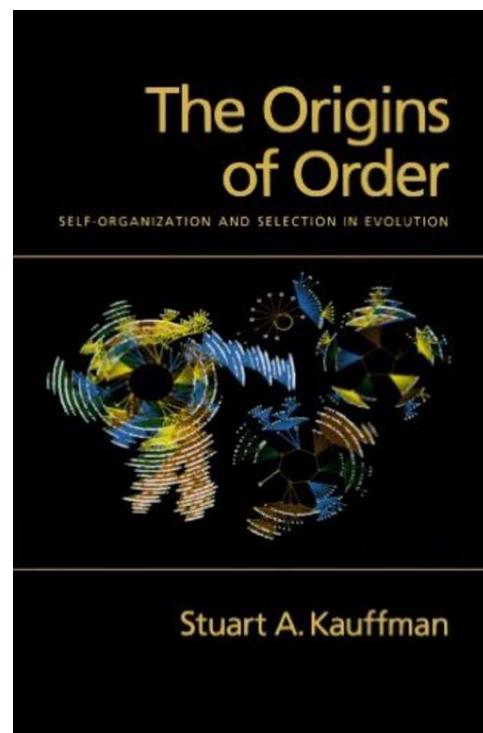
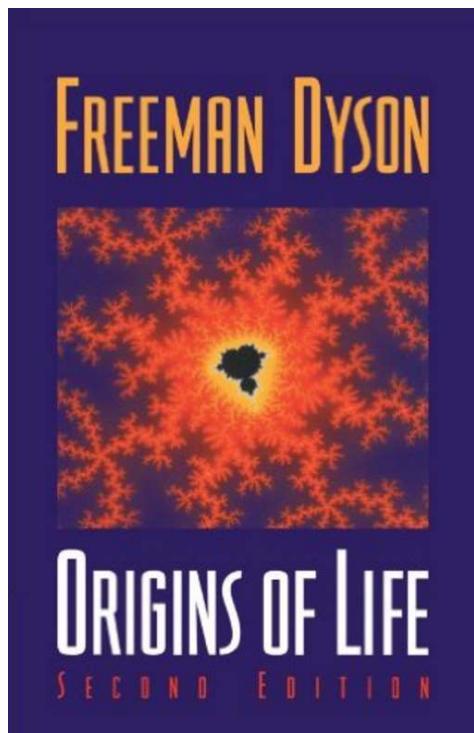
Picture Citation:

<http://2.bp.blogspot.com/-yOYy08cWAzs/T0uTXJCcsVI/AAAAAAAAB00/vWUb6zcDTIA/s400/Origin+of+Life.jpg>

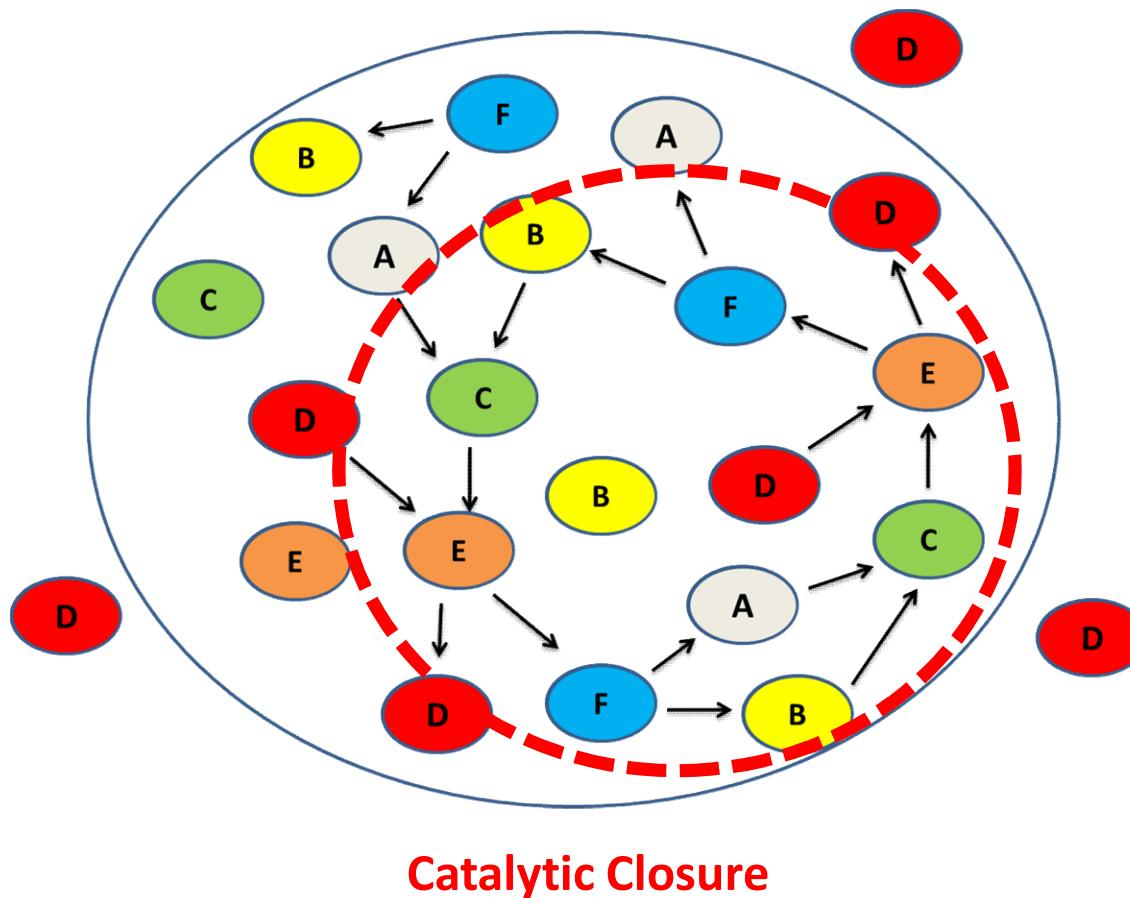
# Origin of life



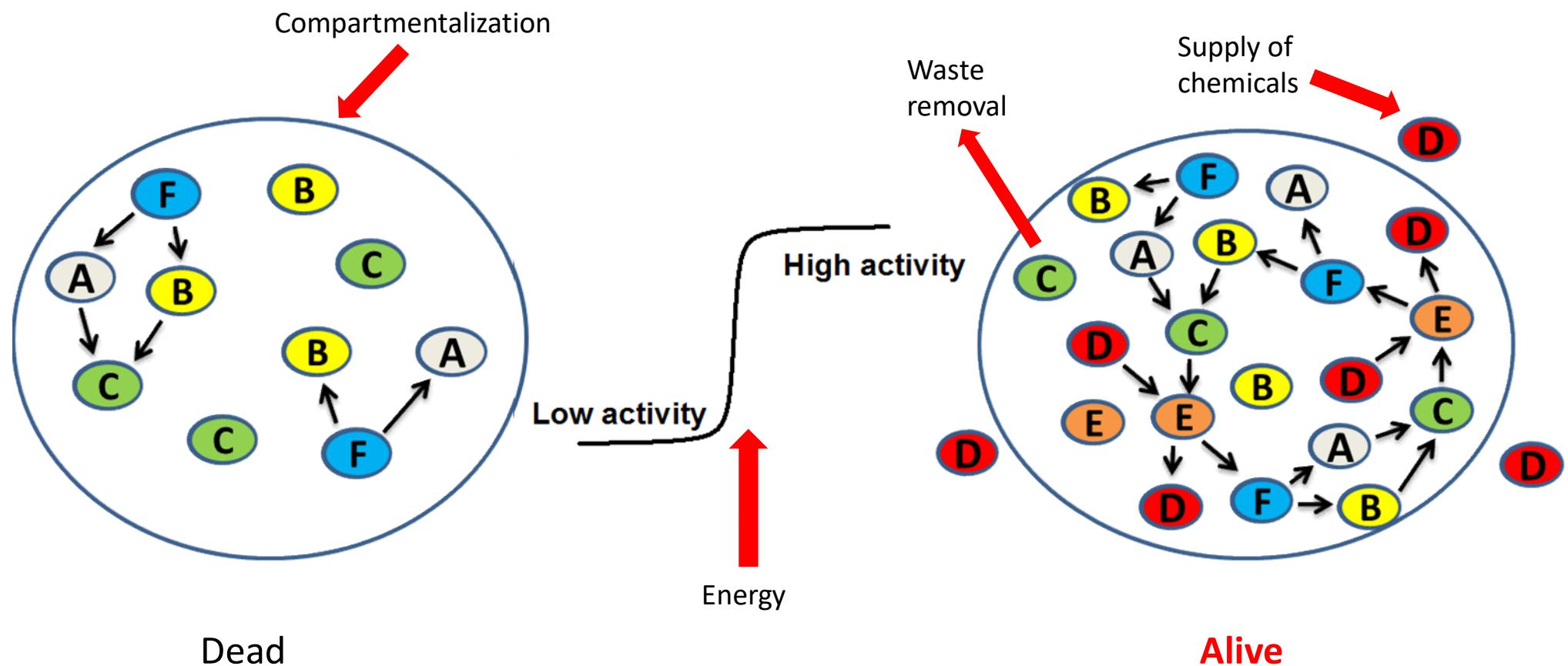
# Network Origin?



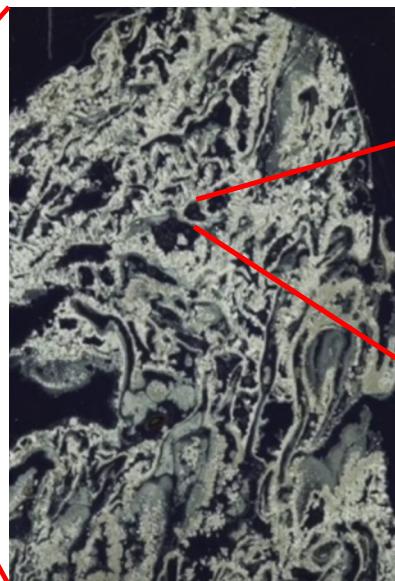
# Reaction networks



# Origin of life

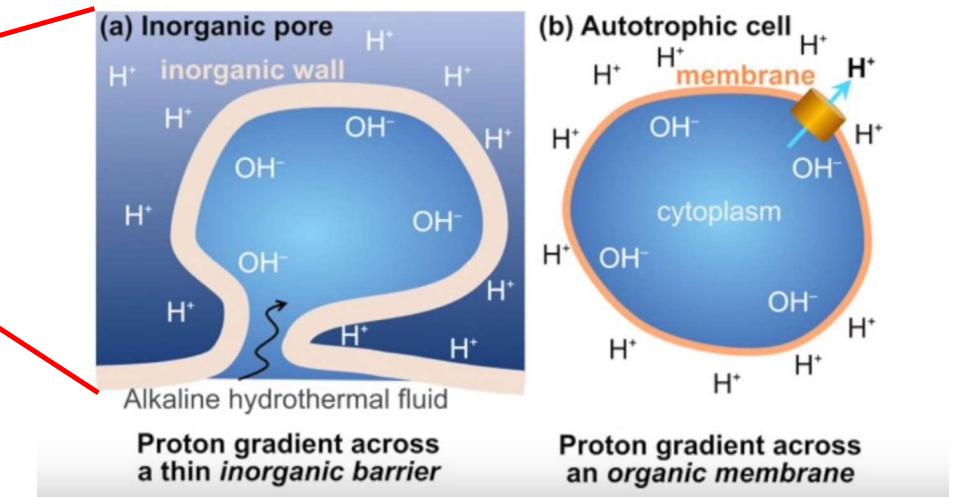


# Deep sea hydrothermal vents



0.5 mm

Mineral 'cells' in vents have **natural proton gradients**



Nick Lane

Deep sea hydrothermal vents provide all this!

# Summary of Origin of Life

Energy supply

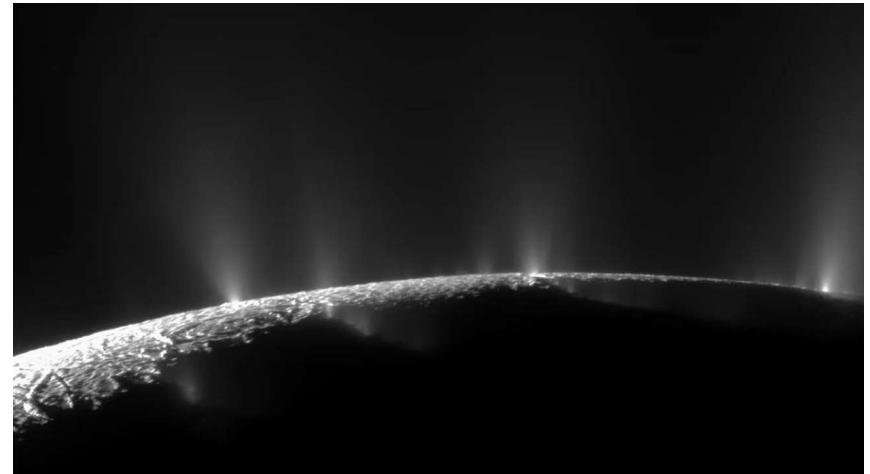
Compartmentalization

Raw materials

Waste removal

## Emergent network phenomenon

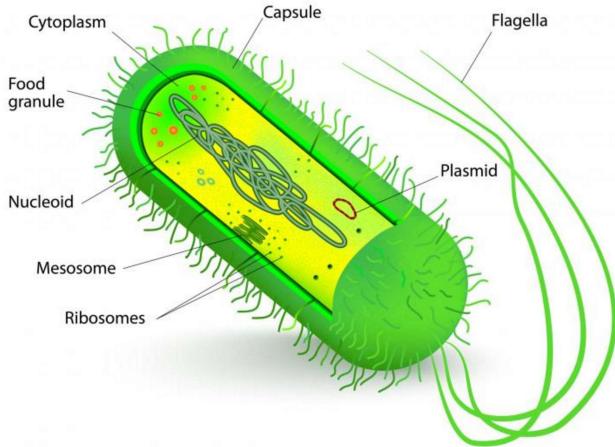
These are criteria for any life anywhere in the cosmos!



Enceladus, Saturn's moon (Science, 2017): Cassini spacecraft revealed the presence of molecular hydrogen ( $H_2$ ) in jets of vapor and particles ejected from a liquid water ocean through cracks in the ice shell. The abundance of  $H_2$  along with previously observed carbonate species suggests a state of chemical disequilibrium in the Enceladus ocean that represents a chemical energy source capable of supporting life.

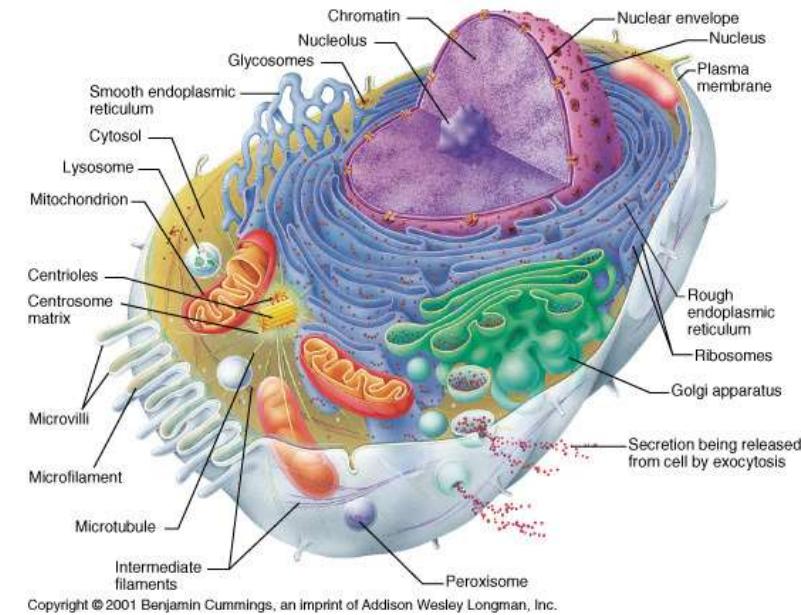
# The rise of the eukaryotic cell

Grow anywhere, but remained structurally simple.



Low  
morphological  
complexity

High  
morphological  
complexity



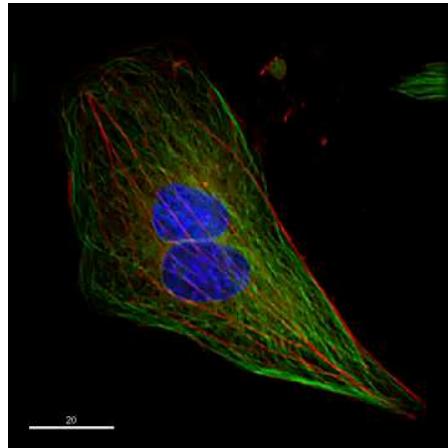
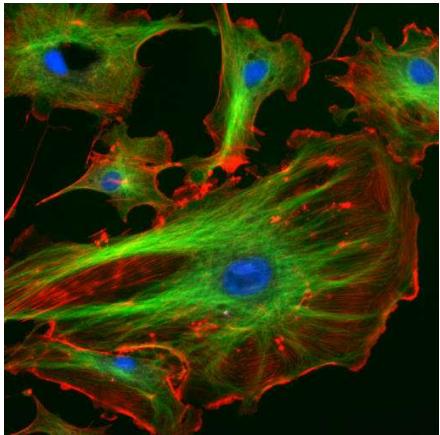
Giant network of embedded loops of biochemical reactions together with structural networks, huge size, compartmentalization, mitochondria and nucleus and large DNA.

# The cytoskeleton and the new functions

Bacteria lost their cell wall

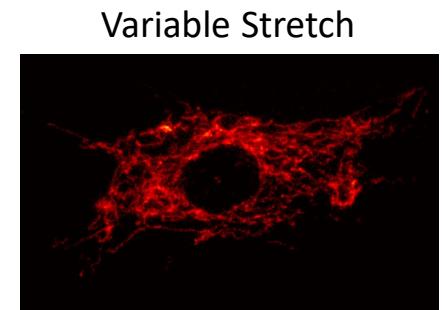
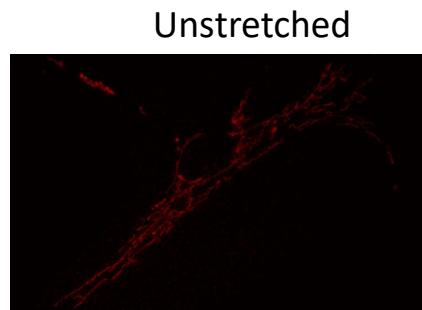
Those that developed cytoskeletal network would survive

Cytoskeletal structure undergoes network transition that is enabling new function.

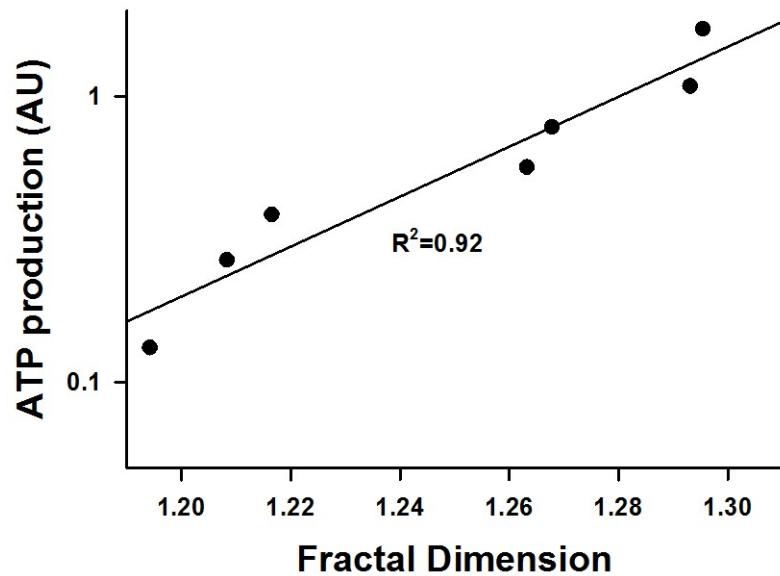


- It took nearly 2 billion years to arise
- It gave rise to a variety of new functions:
  - Mitochondria
  - Sex
  - Phagocytosis
  - Nucleus
  - Movement
  - Sensing
  - Multicellularity

# Mitochondrial complexity and energy dissipation



Bartolák-Suki et al. (Nature Materials, 2015)



Energy production and distribution is more efficient when the mitochondria self-organize themselves into more complex fractal structures. Self-organization can be induced by fluctuations.

Fractal dimension: Self-similarity and space filling capacity of an object.

Monotonous stretch mimic standard laboratory conditions.  
Variable stretch includes beat by beat fluctuations in blood pressure.

# Sex



Fashion



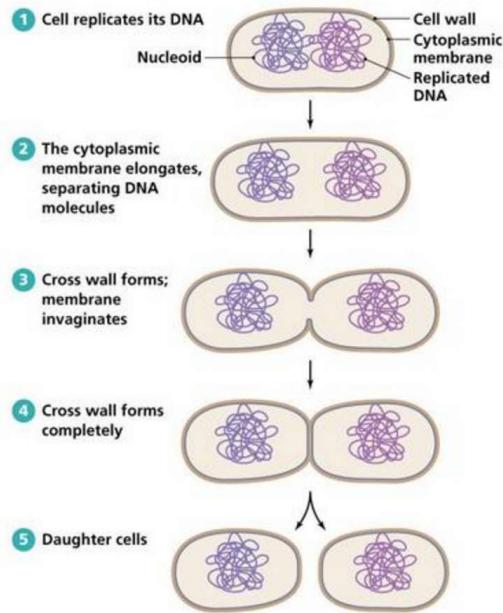
Fight



Death

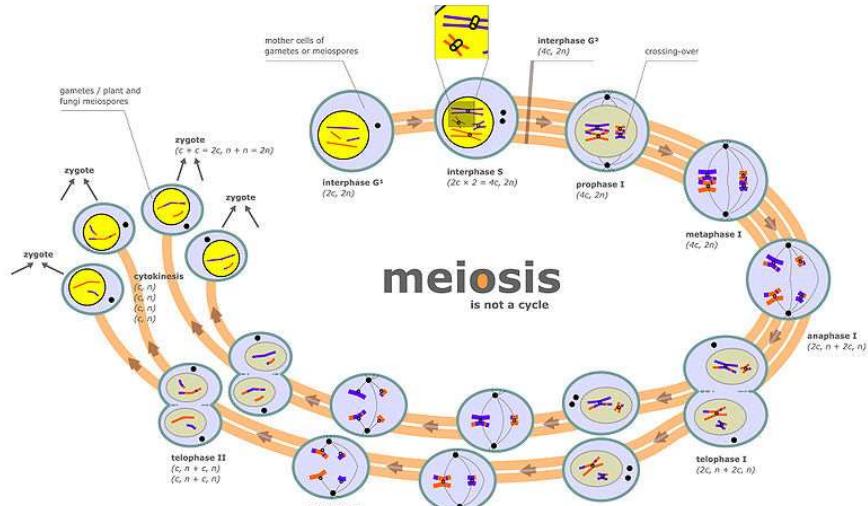
Sex is costly, dangerous and should be avoided!

# Clonal versus Sexual reproduction



Clonal reproduction: gradual accumulation of bad mutations declines population fitness (called Muller's ratchet) and most clonal species die out.

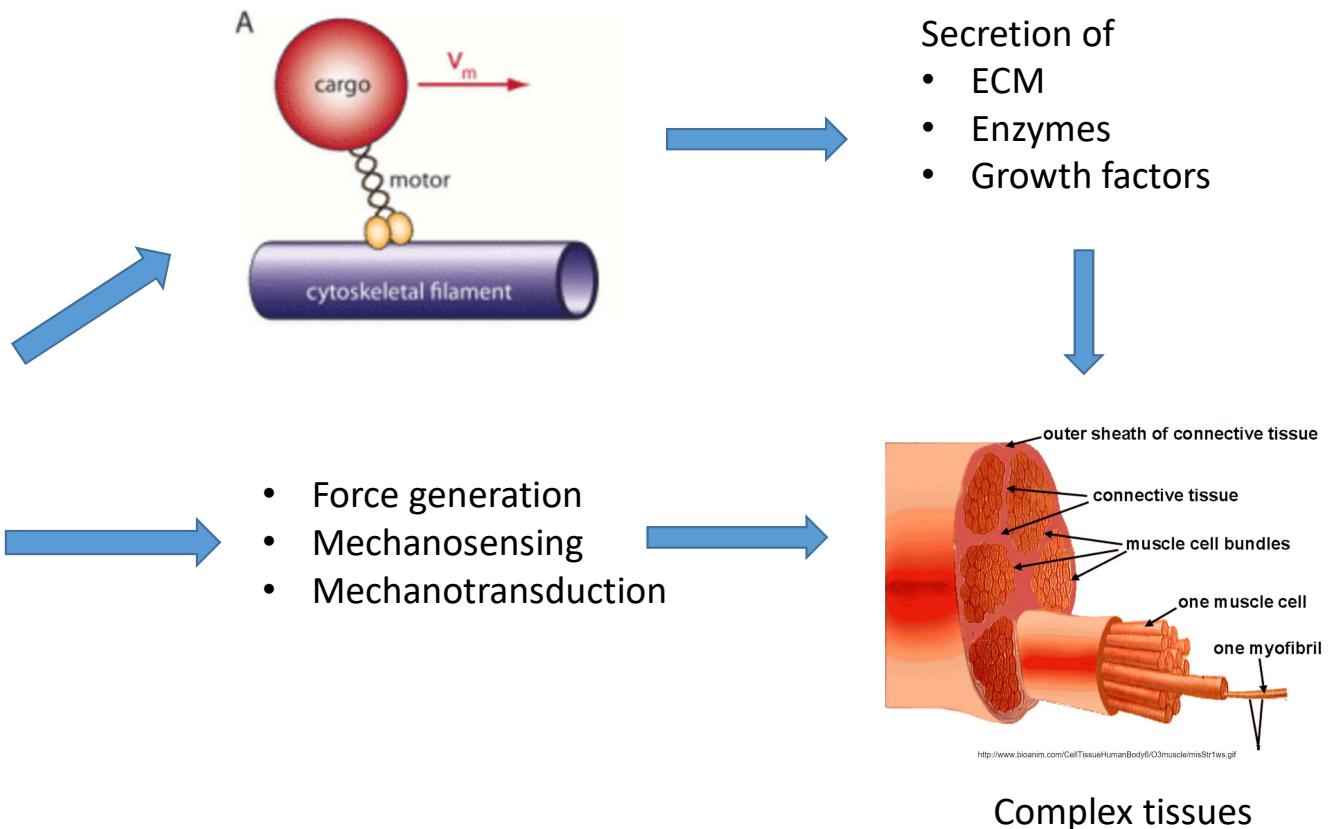
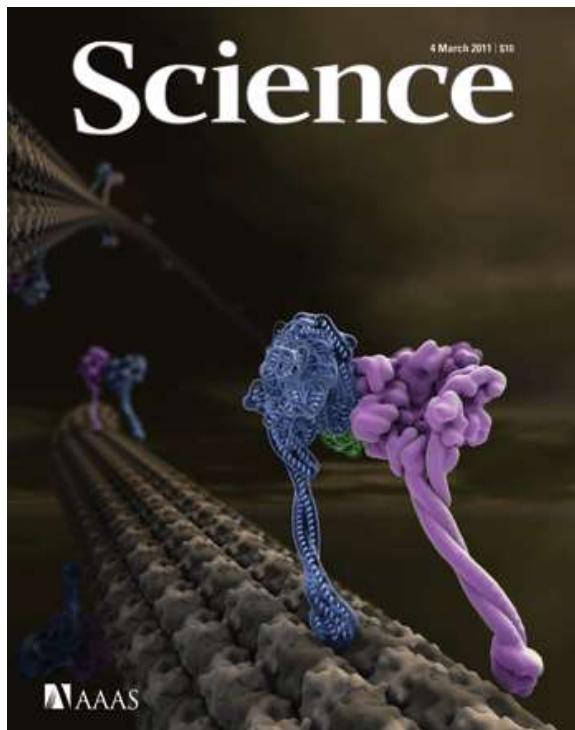
<http://mr-roes.wikispaces.com/Asexual+Reproduction+Webquest>



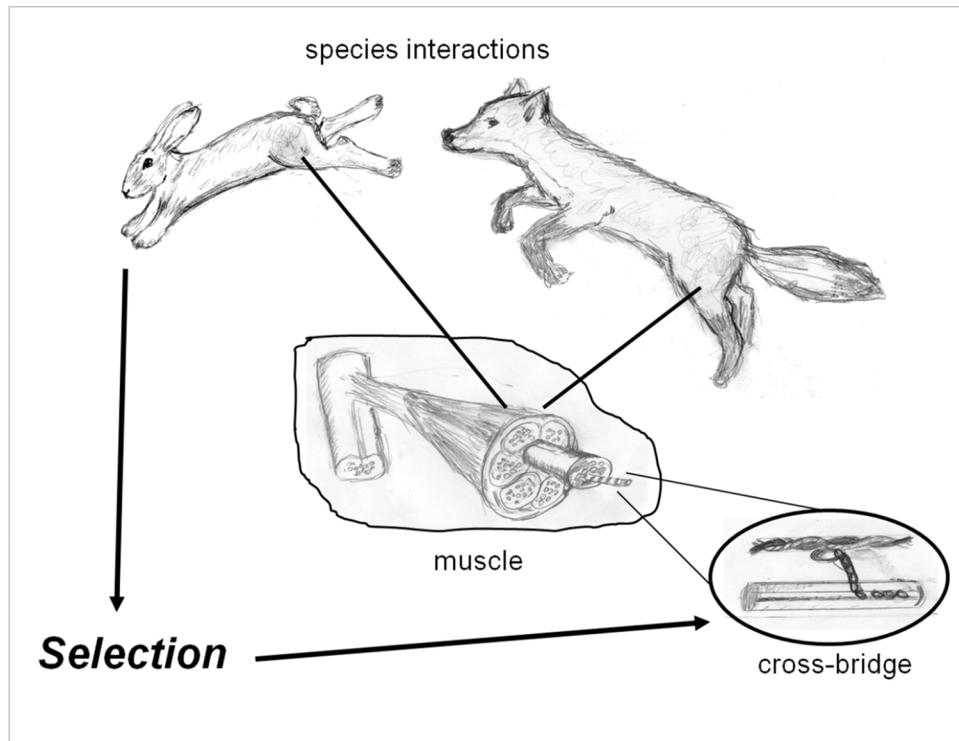
Sexual reproduction: by shuffling genes, which is similar to collision of two genetic networks also helped by a network of other helper proteins, species are able to avoid the Muller's ratchet. Over 99% of species are sexually reproducing.

[http://www.thefullwiki.org/Medical\\_Physiology/Cellular\\_Physiology](http://www.thefullwiki.org/Medical_Physiology/Cellular_Physiology)

# Movement and mechanosensing



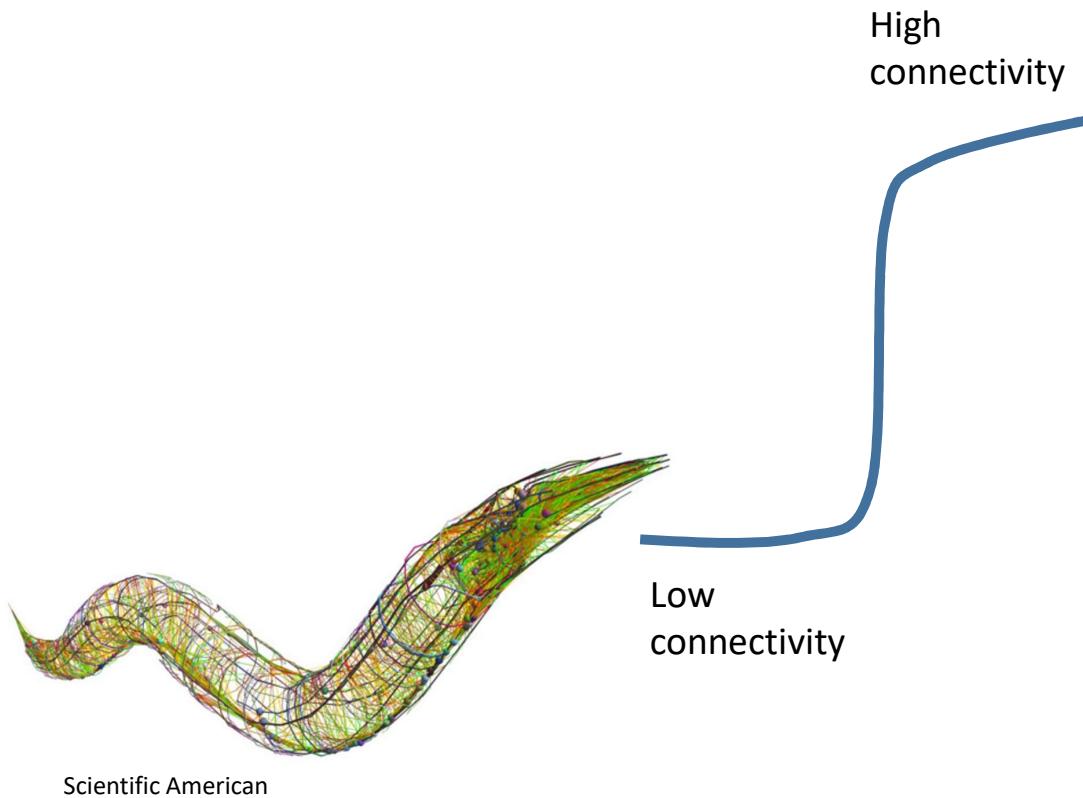
# Multiscale ecosystems



Drawing: Elizabeth Bartolák-Suki

Scales of network function range from nm to thousands of km:  **$10^{15}$  orders!!!!**

# Emergence of the brain



Brain function: control movement  
with 302 neurons.

Cognition is not understood, but neural networks must be enabling it.



Image: Computer artwork of a frontal view of the brain with a neural network of nerve cells firing in the back. (Getty/Science Photo Library - PASIEKA)

Human brain: 20 billion neurons in the cortex  
with 23 trillion connections

- Vision, smell, touch, movement, instinct, fear
- Consciousness, love, language
- Culture, religion, war, science

# Summary of the network transitions

- Network associated phase transitions may be at the heart of the major transitions of life.
- When a critical point is reached in network connectivity, a structural phase transition occurs that allows new functional behavior.
- Natural selection also acts on changes due to major transitions.
- Such transitions may have played an important role in gradual Darwinian evolution.

# Questions of importance

- Can new life form emerge due to human activity?
- Can humans undergo new transitions for example due to symbiosis with robots?
- Can the internet as a network become conscious?
- Can artificial intelligence undergo a transition?
- Can we anticipate and control transitions?