Emergence of Life

Lecture 1&2

Acknowledgements:

Alberts - Molecular Biology of the Cell

Scitable by Nature Education

Nature Resources

Internet resources

Outline of the Lecture

Objective

- Retrace the assembly of matter to form life

Topics

- Introduction and background
  - Some scientific/philosophic questions
- Concept of order
  - Physical, Chemical and Biological Parameters
- Information encoding in biomolecules
- The “creation” of the cell

Was life supposed to evolve?

- What we normally think of as life is based on chains of carbon atoms with a few other primary atoms such as oxygen, hydrogen, nitrogen and phosphorous.
- What about silicon-based life?
  - Yes, maybe! but carbon-based seems the most favorable because it has the richest chemistry

The Anthropic Principle:

For a given universe, it is possible that the values of the physical constants, will allow the existence of objects like carbon atoms that can act as the building blocks of living systems

https://www.youtube.com/watch?v=KtRcAuunEMg

Why did life occur?

- **We don't have an answer! Its like asking – Does God Exist?**
- The *anthropic principle* tells us that LIFE would have happened if not on planet earth, then on some other planet
- We do know, by observation, what are the properties that define life
  - Have a set of instructions that tell the system how to sustain and reproduce itself
  - A mechanism to carry out the instructions
- **By the second law of thermodynamics, to do this, we need to have order**

What is the role of "Order" in the creation of the first cell?

- How do you determine if a system has order - in the sense of structured-ness and organization ?
  - Self Organization
  - Complexity
  - Emergence of new properties
    - **One of the most fundamental problems in biology concerns the origin of forms and their associated functions**
    - **It has been an important question of developmental biology**

Third law of Thermodynamics states that the entropy (disorder) of the universe is continuously increasing with time.

Therefore, decrease of entropy, as in a cell, is permitted if the corresponding increase in entropy in the environment is greater.

The history of life

- And it took 2.5 billion years for life to evolve from the earliest cells to multi cell animals
  - Another 1 billion years to evolve through fish and reptiles to mammals
  - Then evolution seemed to have speeded up
    - **took about a hundred million years to develop from the early mammals to us**

We will examine how “Order” occurs

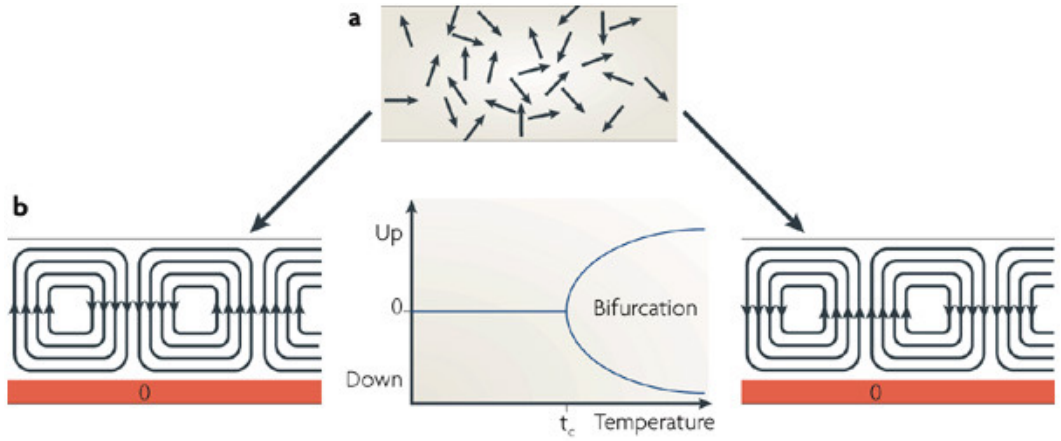
In-animate Systems

- Physical systems
- Chemical systems
- Biological self-assembled systems

Living Systems

- The cell

Order in inanimate systems: Physical Systems

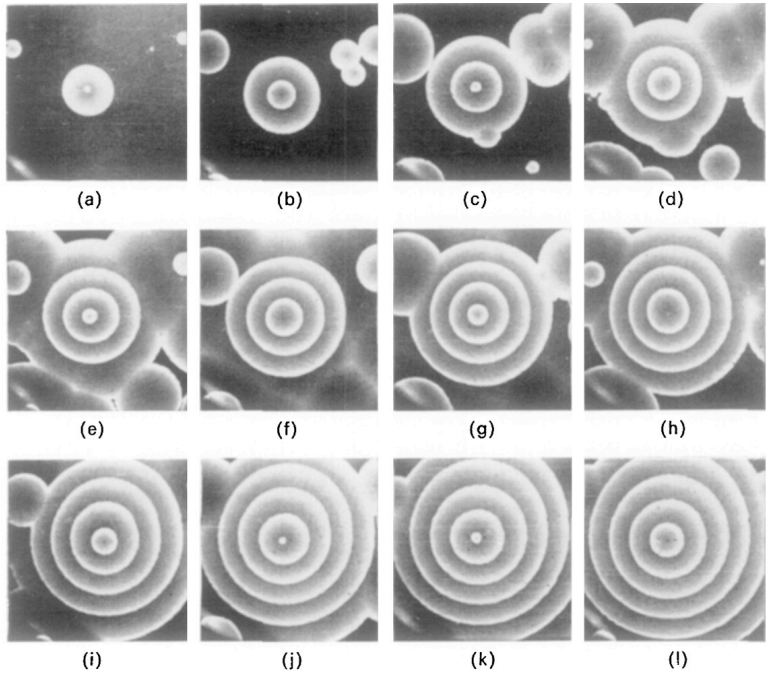


Nature Reviews | Molecular Cell Biology

a) In a liquid layer, molecules are agitated by thermal motion.

b) The molecules in the liquid layer are heated from below (red zone) and self-organize into rolls (drawn in cross-section) when the temperature reaches a critical value (t_c). At this value, the molecules start to move collectively either up or down at point 0, which determines the alternative orientation of the rotation of the rolls throughout the layer. The orientation of the rotation choice is unpredictable and determined by local fluctuations at t_c

Order (Self Organization) in Chemical Reactions



In the system, propagation of a single wave was observed under following conditions:

$NaBrO_3$ = 0.23 M, bromomalonic acid = 0.16 M, (Ferroin) $Fe(phen)_3$ = 0.003 M, H_2S0_4 = 0.26 M, T = 14°C.

The wave velocity equalled approximately 0.01 cm/s.

Photographs taken at 30 s intervals

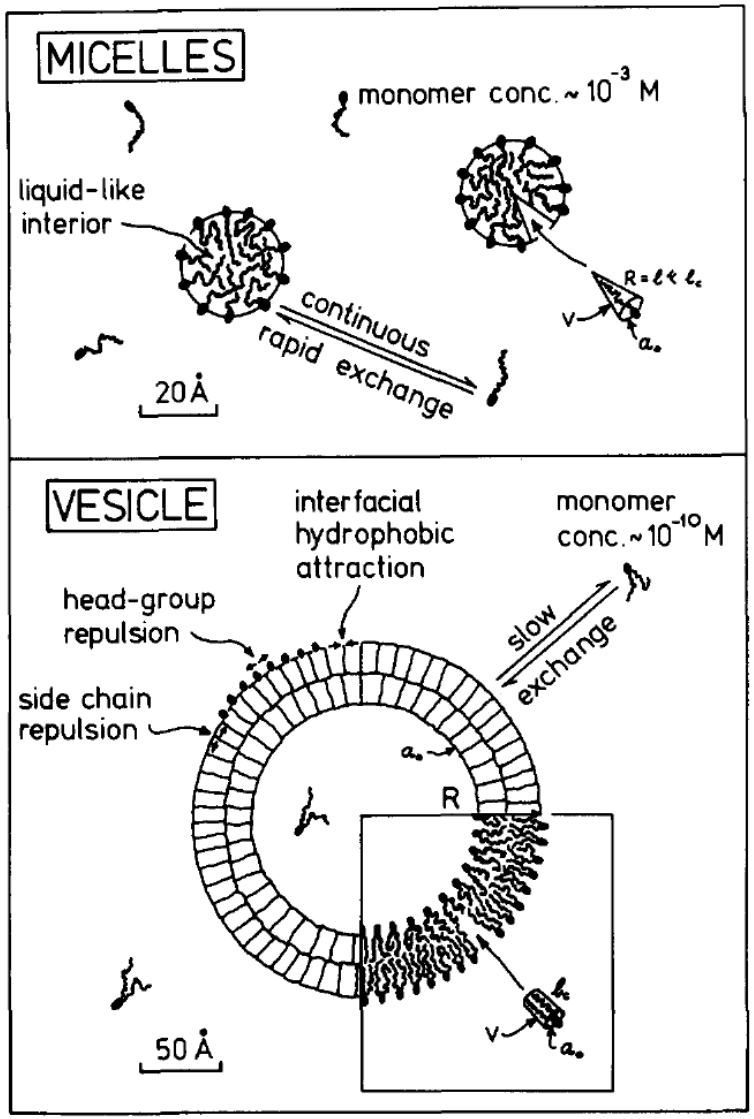
Belousov–Zhabotinsky reaction J. Theor. Biol. (1973) 40, 45-61

In class demonstration of the B-Z reaction
https://www.youtube.com/watch?v=o72GGxQqWt8

Self-assembled systems that occur in Biological world

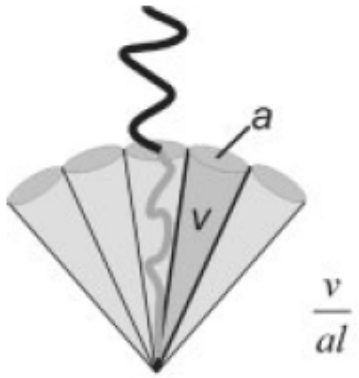
The boundary: inanimate to animate

- The concepts of interaction free energies, molecular geometry and entropy, when taken together, furnish a framework for *a theory of self-assembly or self-organization*
- Micelles and bilayer vesicles assembly are driven by hydrophobic and hydrophilic interaction - of two 'opposing forces"
- Size of the micelle is determined by "optimal surface area" per head group at which the total interaction free energy per lipid molecule is a minimum.

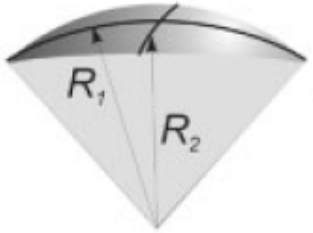


Biochimica et Biophysica Acta, 470 (1977) 185--201

Some basic rules for micelle shapes



$$\frac{v}{al}$$



$$H = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

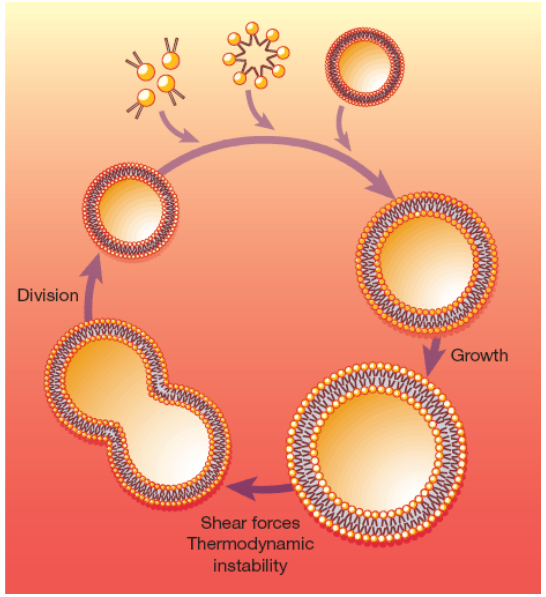
$$K = \frac{1}{R_1 R_2}$$

Shape	$v/(al)$	H	K
Sphere	1/3	$1/R$	$1/R^2$
Cylinder	1/2	$1/(2R)$	0
Bilayer	1	0	0

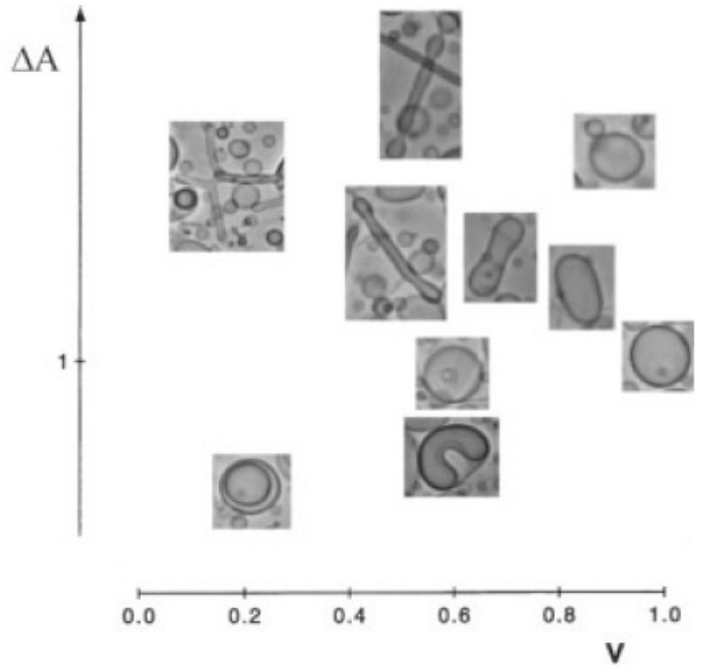
Adv Mater 2003 15 (16)

- Surfactant first forms a bilayer and then closes to form a vesicle
- The ratio of the hydrophobic to hydrophilic portion of the molecule determines the radius of curvature at the interface

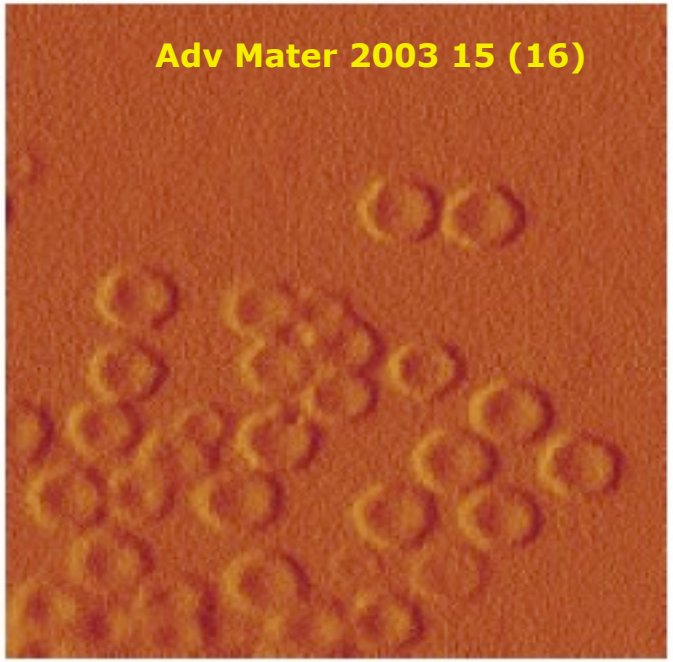
$$\frac{v}{al} = 1 + Hl + \frac{Kl^2}{3}$$



Vesicle Size and Shape

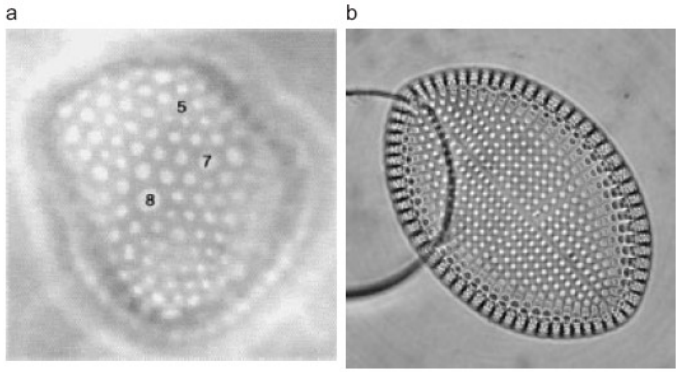


- Depends on mixing entropies (pull towards many assemblies) and molar bending energies (tends towards a smaller number of vesicles)
- ΔA is the difference in area, v is the dimensionless volume to area ratio



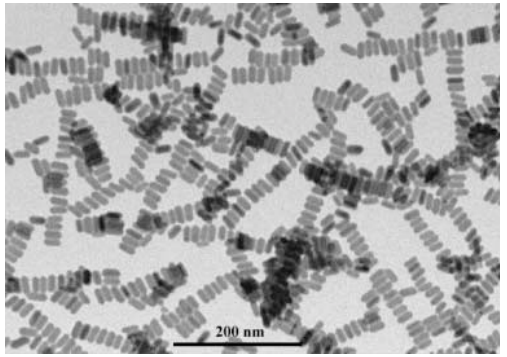
AFM image of a polymer vesicle. The erythrocyte-like shape arises from the evaporation of water from the vesicle interior, leaving the prominent rim

Similarity in structure of self-organized biological and non-biological entities

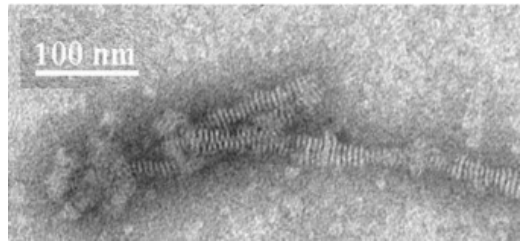


(a) High-genus block copolymer vesicle (b) structure of a diatom [Adv Mater 2003 15 (16)]

- Genus order $g > 100$

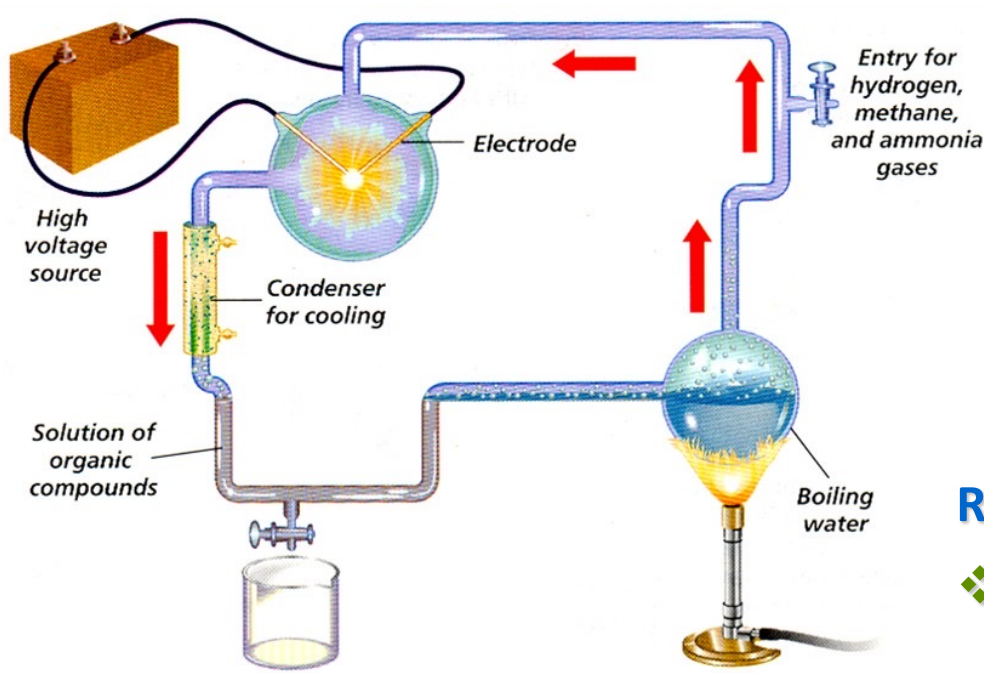


TEM image showing ordered chains of prismatic BaCrO4 nanoparticles prepared in AOT microemulsions Angew. Chem. Int. Ed. 2003, 42, 2350 – 2365



DMPC–apoE CT domain complexes; reconstituted lipoprotein particles were stained with 2% phosphotungstate for visualization [Biochem. J. (2005) 387 (747–754)]

Urey Miller Experiment



Glencoe Biology, The Dynamics of Life, 2002, p. 350.

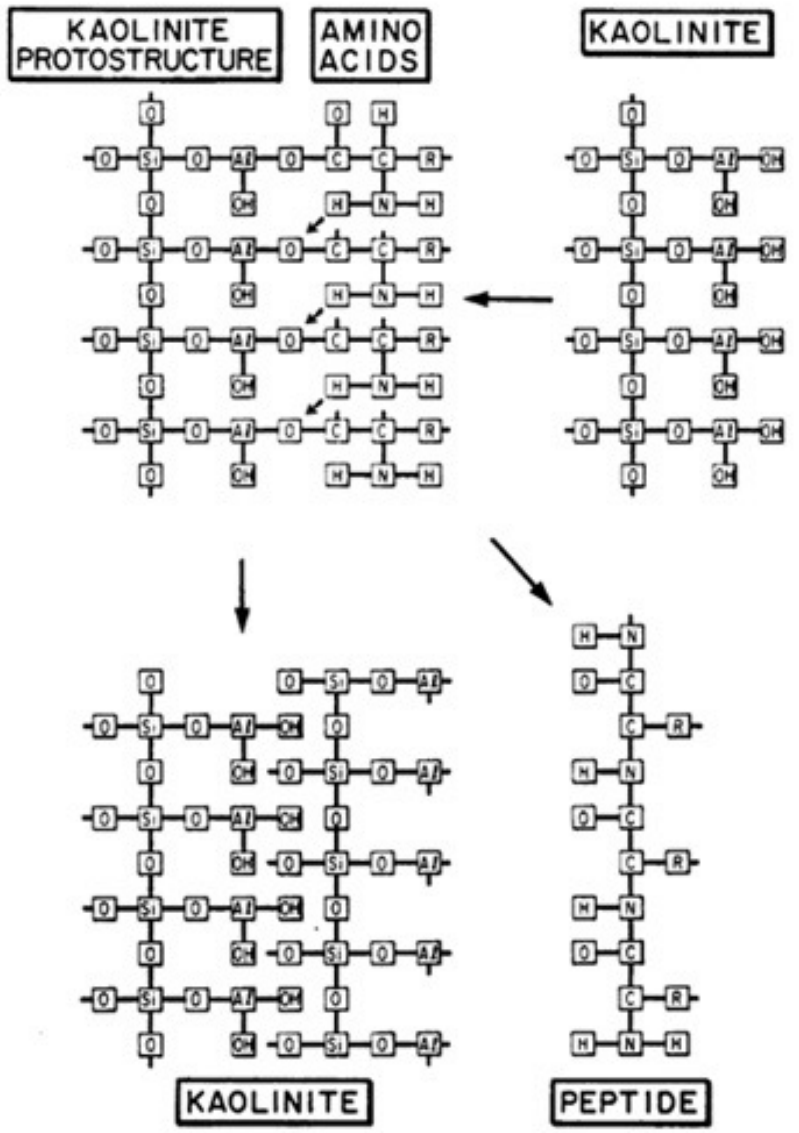
- In 1953 Stanley Miller and Harold Urey performed the first experiment that produced amino acids in what was assumed to be a pre-life atmosphere. They passed a mixture of water vapor, methane, hydrogen and ammonia gases through an electric arc to simulate what would happen if these gases were subjected to lightning.

Result:

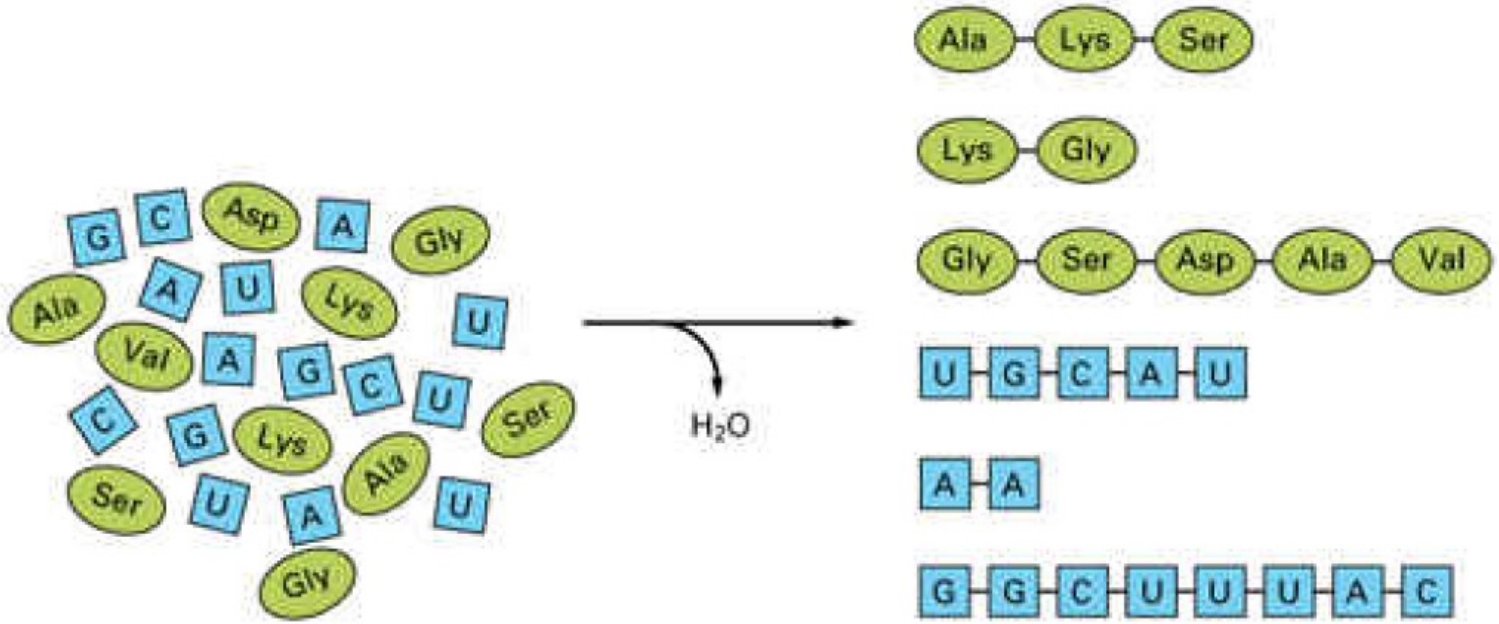
- **10 biologic amino acid types**
  25 non-biologic amino acid types
  Formaldehyde
  Sugars

First proteins

- In the presence of kaolinite, amino acids are picked up from an aqueous solvent and brought into solid solution
  - Amino groups become hydrogen bonded to structural oxygen
  - In water, amino acids cannot polymerize because of dipole-dipole interactions
  - In solid solution, however, amino acids will polymerize, because the solvent medium does not interfere
  - about 1000 times more amino acids were polymerized to peptides
- Kaolinite is also instrumental in preferentially synthesizing pentoses and hexoses from formaldehyde and transforming them into polysaccharides
- Preferential polymerization of L-amino acids on kaolinite can be attributed to the inherent enantiomorphism of the edges of the octahedral layer of kaolinite

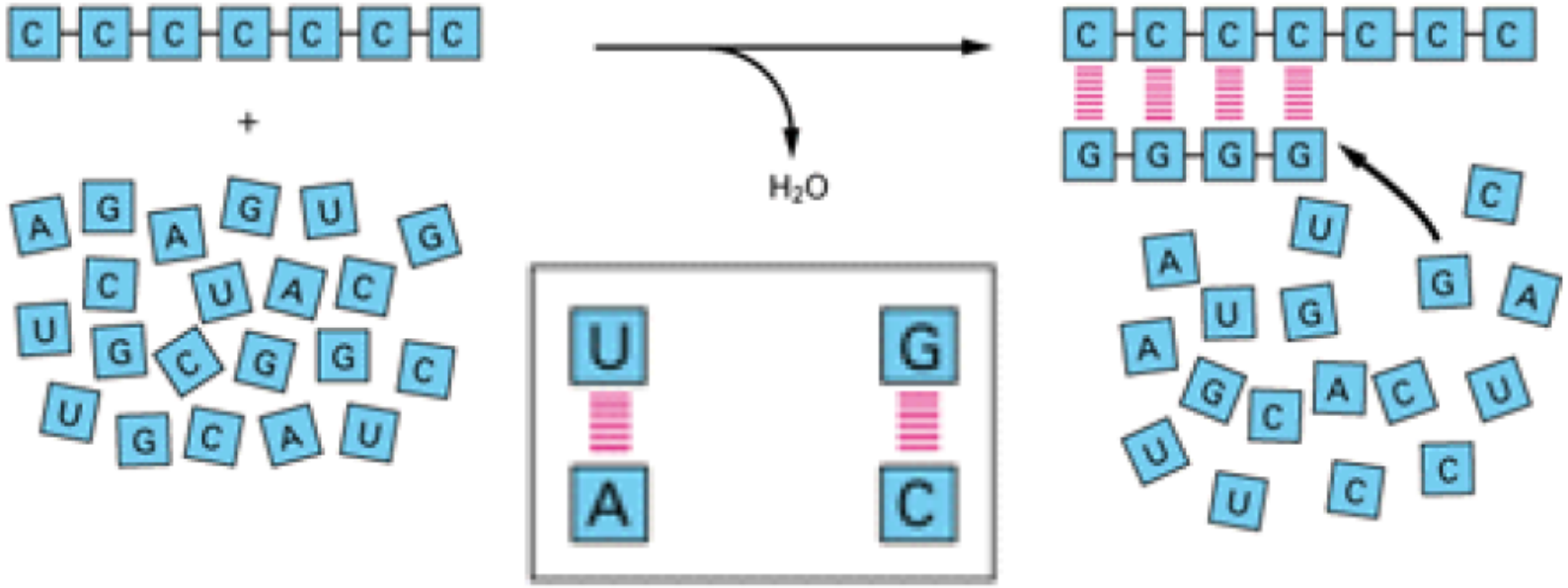


Formation of polynucleotides and polypeptides



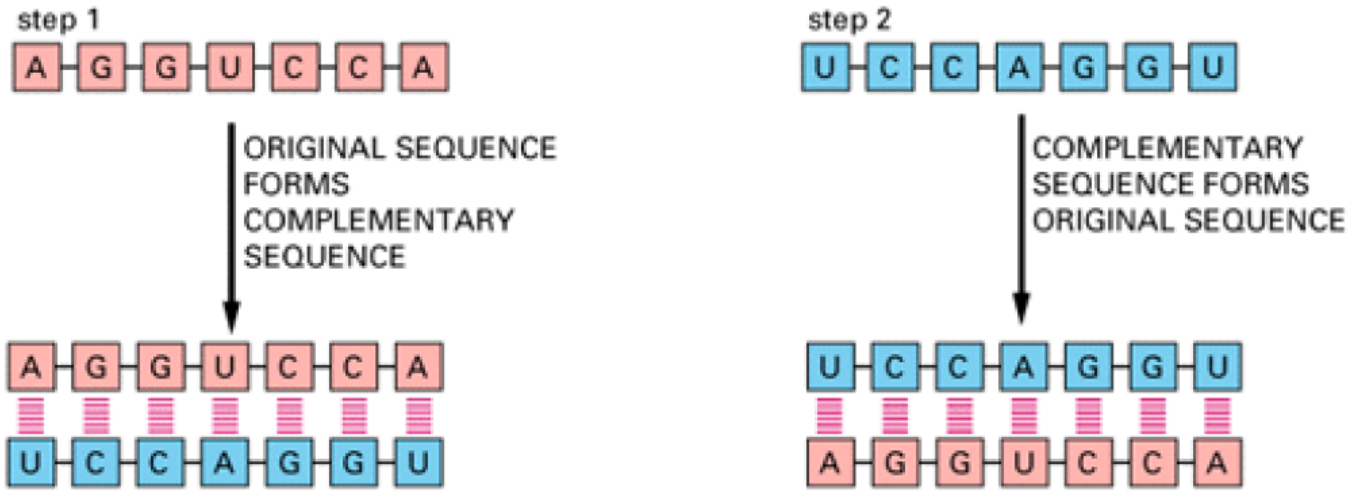
- Nucleotides of four kinds (here represented by the single letters A, U, G, and C) can undergo spontaneous polymerization with the loss of water. The product is a mixture of polynucleotides that are random in length and sequence.
- Similarly, amino acids of different types, symbolized here by three-letter abbreviated names, can polymerize with one another to form polypeptides. Present-day proteins are built from a standard set of 20 types of amino acids.

Polynucleotides as templates



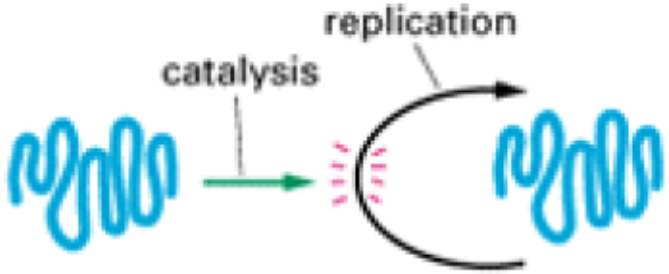
- Preferential binding occurs between pairs of nucleotides (G with C and U with A) by relatively weak chemical bonds

Replication of a polynucleotide sequence

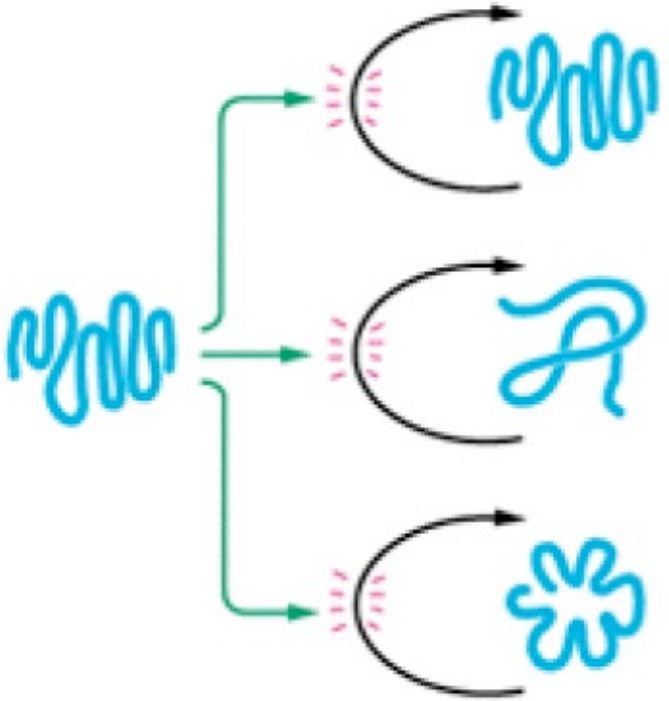


- The original RNA molecule acts as a template to form an RNA molecule of complementary sequence.
- This complementary RNA molecule itself acts as a template, forming RNA molecules of the original sequence. Since each templating molecule can produce many copies of the complementary strand, these reactions can result in the "multiplication" of the original sequence

Conformation of an RNA molecule

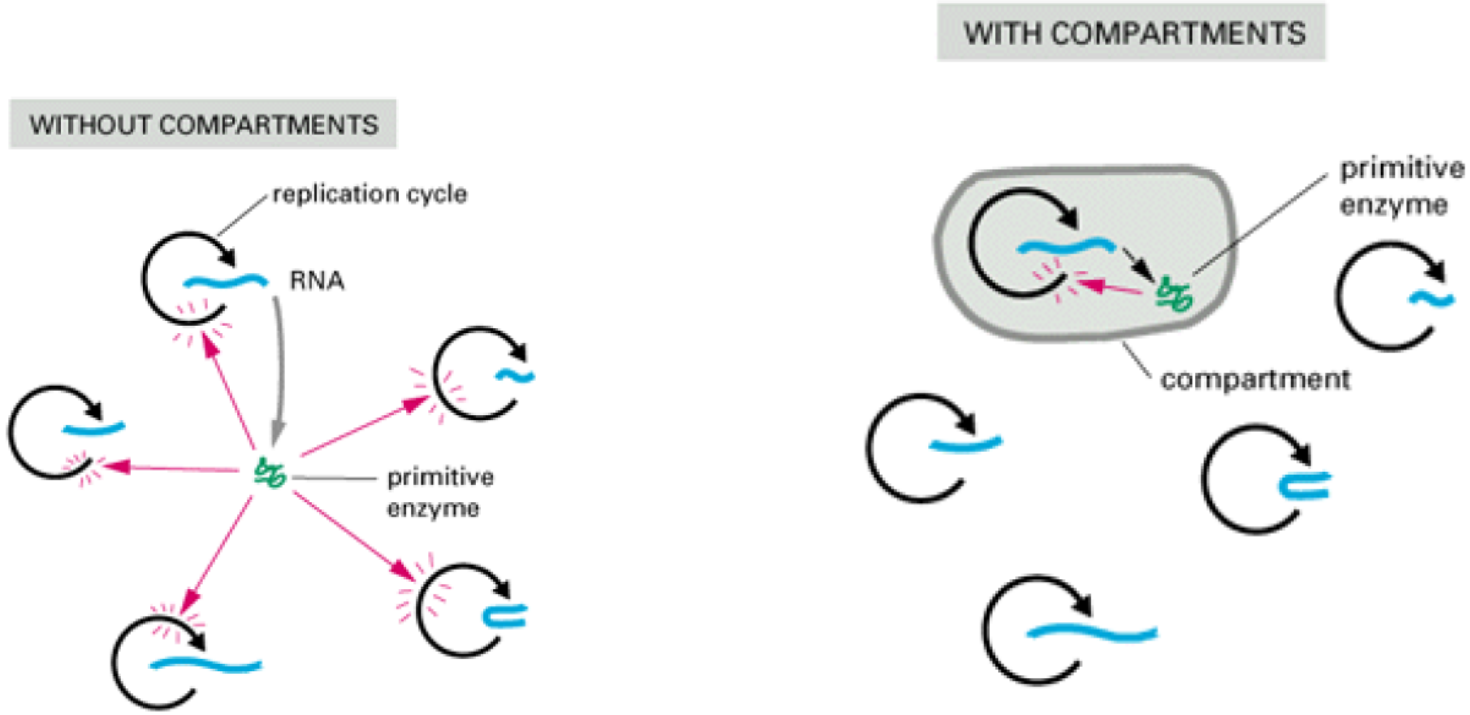


catalytic RNA molecule that joins together nucleotides to reproduce its own nucleotide sequence and therefore its shape



family of mutually supportive catalytic RNA molecules, one catalyzing the reproduction of the others

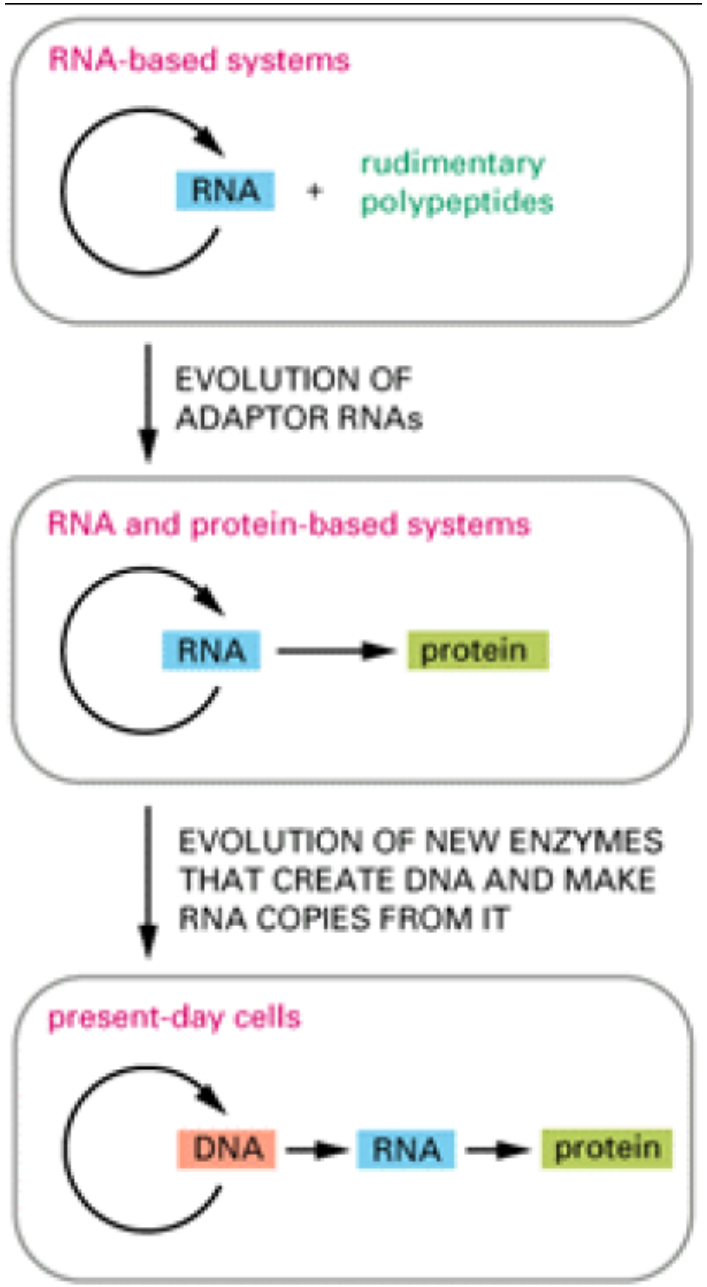
Evolutionary significance of cell-like compartments



- Any improved form of RNA that is able to promote formation of a more useful protein must share this protein with its neighboring competitors.
- If the RNA is enclosed within a compartment, such as a lipid membrane, then any protein the RNA causes to be made is retained for its own use; the RNA can therefore be selected on the basis of its guiding production of a better protein.

Central Dogma

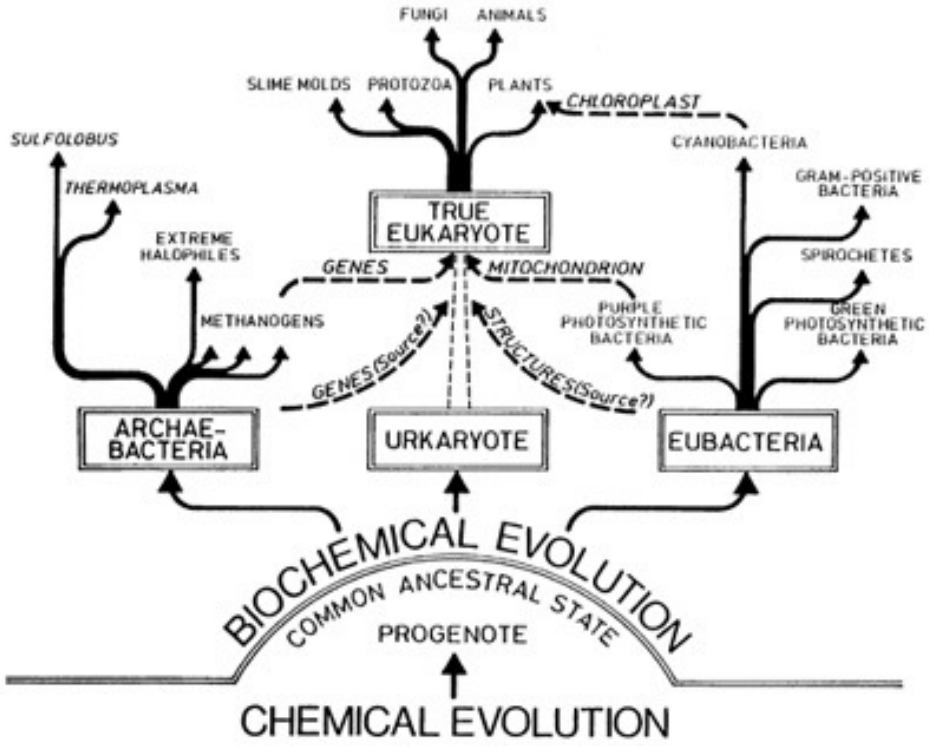
Suggested stages of evolution from simple self-replicating systems of RNA molecules to present-day cells. Today, DNA is the repository of genetic information and RNA acts largely as a go-between to direct protein synthesis



Last Universal Common Ancestor

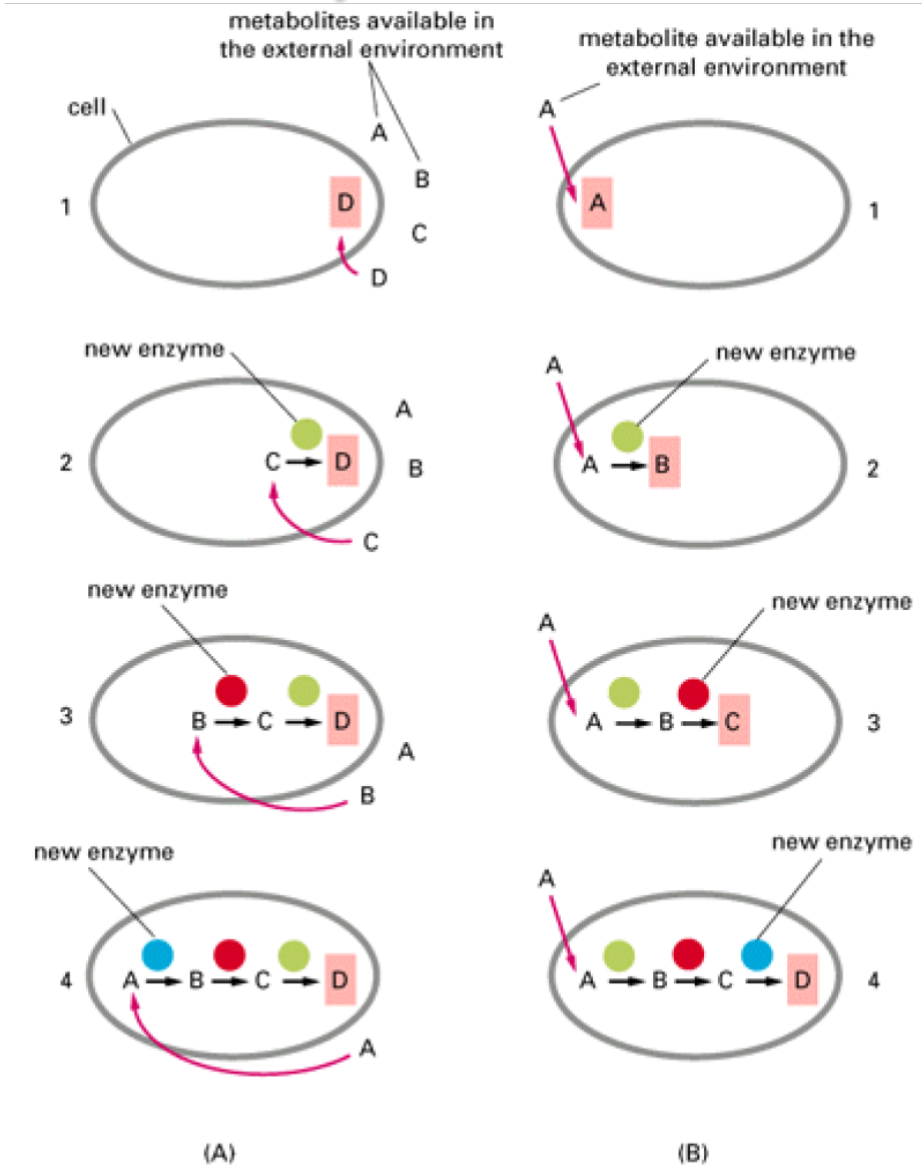
- The evolution of the translation apparatus occurred in a series of increasingly complex stages, rather than all at once,
- The stages subsequent to the establishment of the basic mechanism were concerned by and large with increasing the mechanism's accuracy, and possibly speed as well

J. Mol Evol 10, 1-6, 1977

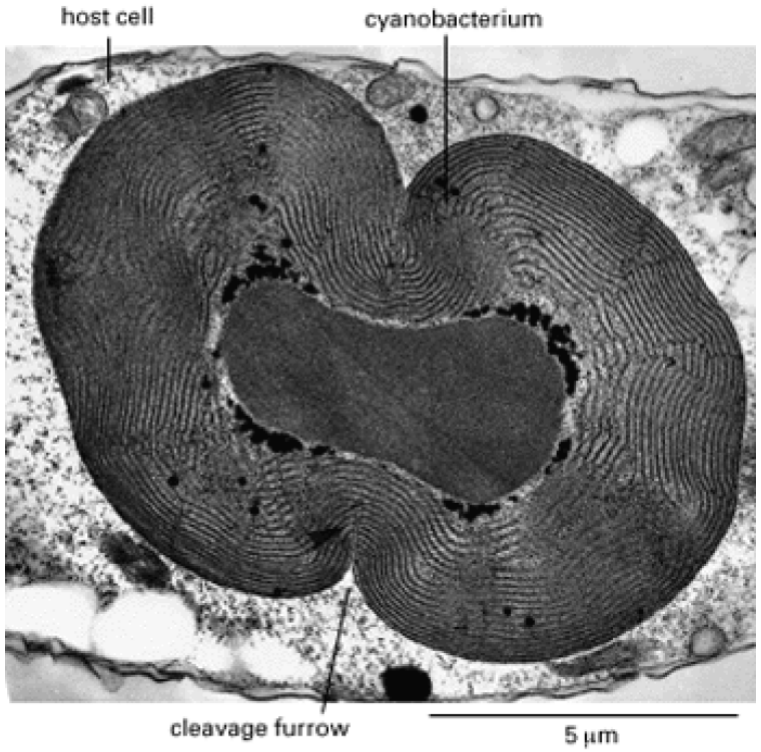


Evolution of Metabolic Pathways

- The cell on the left is provided with a supply of related substances (A, B, C, and D) produced by prebiotic synthesis. One of these, substance D, is metabolically useful. As the cell exhausts the available supply of D, a selective advantage is obtained by the evolution of a new enzyme that is able to produce D from the closely related substance C. Fundamentally important metabolic pathways may have evolved by a series of similar steps.
- On the right, a metabolically useful compound A is available in abundance. An enzyme appears in the course of evolution that, by chance, has the ability to convert substance A to substance B. Other changes then occur within the cell that enable it to make use of the new substance. The appearance of further enzymes can build up a long chain of reactions.

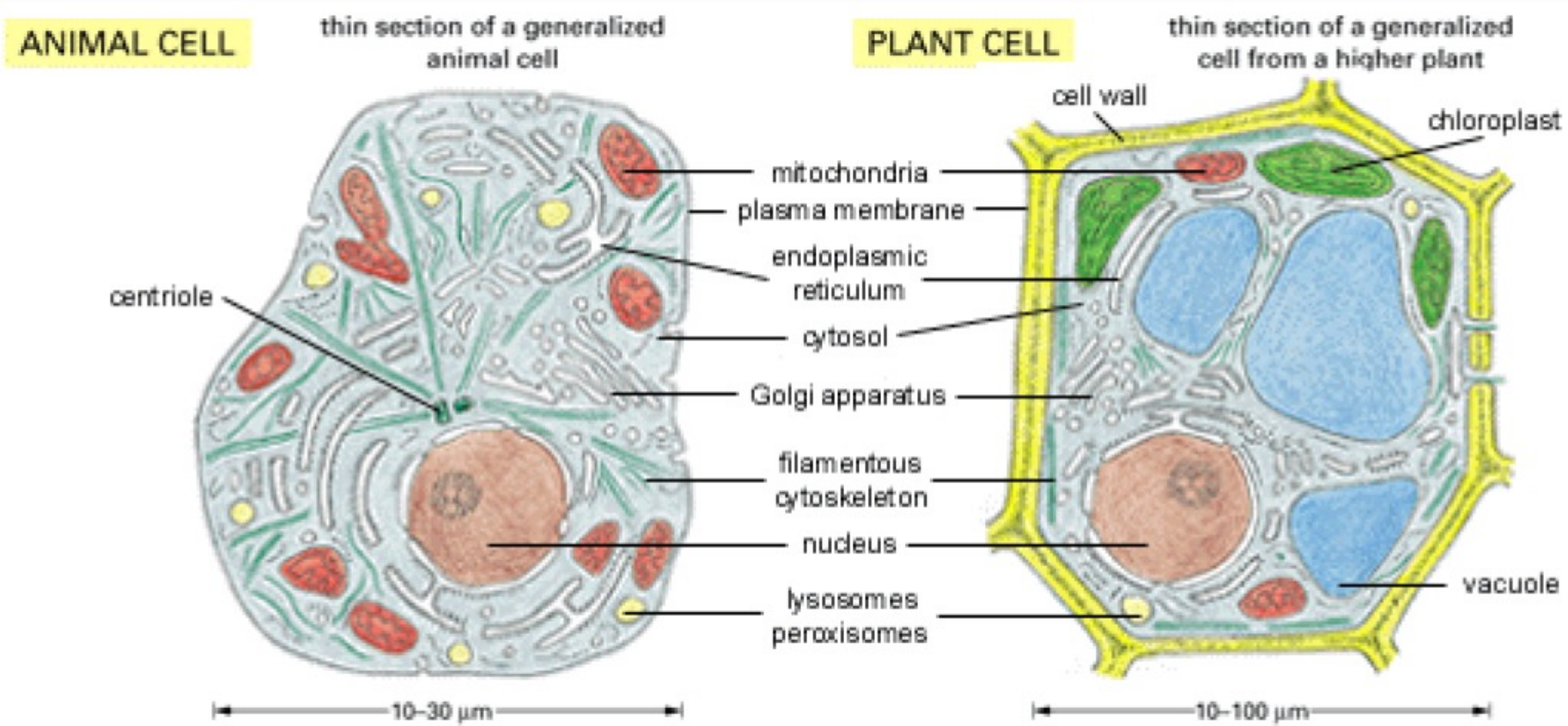


Predation to new cellular structures



- A close relative of present-day cyanobacteria that lives in a permanent symbiotic relationship inside another cell. The two organisms are known jointly as *Cyanophora paradoxa*
- The "cyano-bacterium" is in the process of dividing

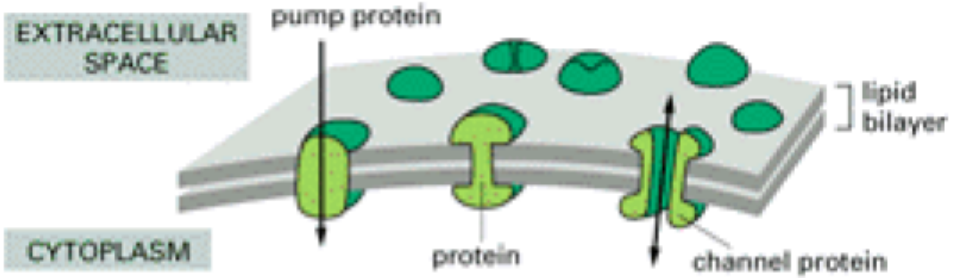
Animal and Plant Cell structures



Cellular Membrane System

PLASMA MEMBRANE

The outer boundary of the cell is the plasma membrane, a continuous sheet of phospholipid molecules about 4–5 nm thick in which various proteins are embedded.

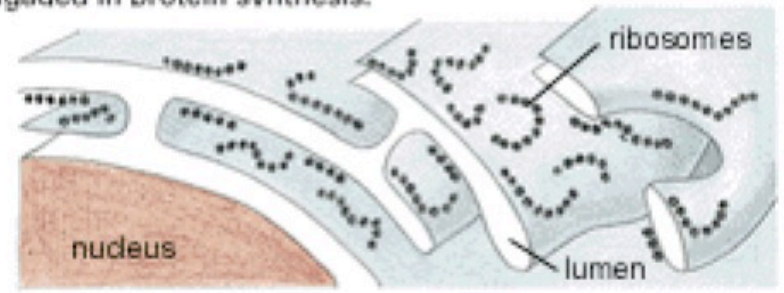


Some of these proteins serve as pumps and channels for transporting specific molecules into and out of the cell.

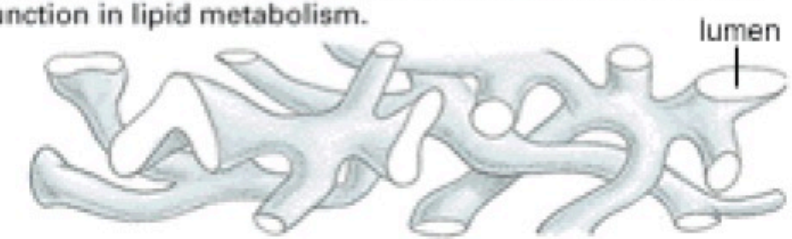
ENDOPLASMIC RETICULUM

Flattened sheets, sacs, and tubes of membrane extend throughout the cytoplasm of eucaryotic cells, enclosing a large intracellular space. The ER membrane is in structural continuity with the outer membrane of the nuclear envelope, and it specializes in the synthesis and transport of lipids and membrane proteins.

The rough endoplasmic reticulum (rough ER) generally occurs as flattened sheets and is studded on its outer face with ribosomes engaged in protein synthesis.



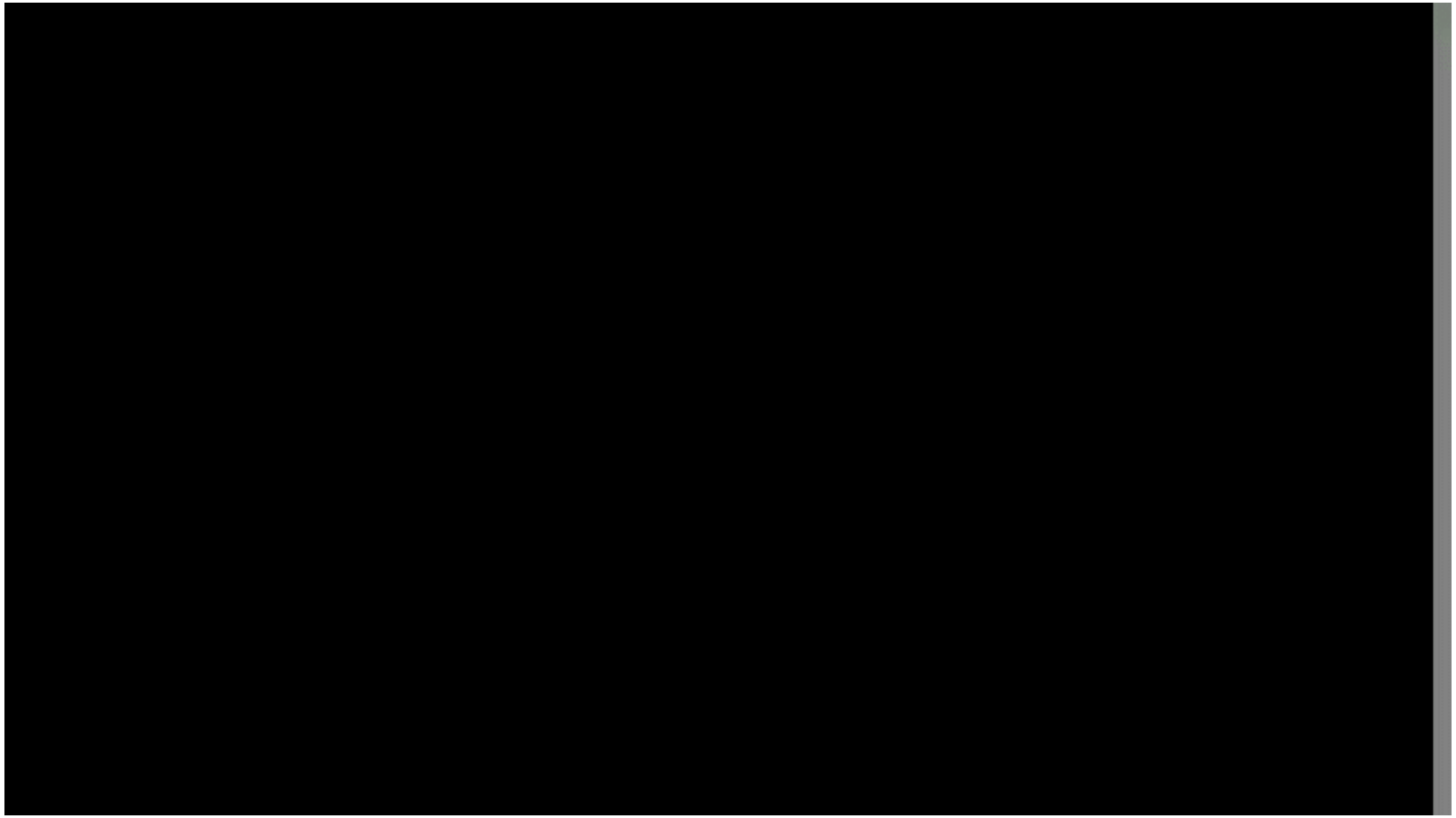
The smooth endoplasmic reticulum (smooth ER) is generally more tubular and lacks attached ribosomes. It has a major function in lipid metabolism.



Summary

- Autocatalytic mechanisms fundamental to living systems began with the evolution of families of RNA molecules that could catalyze their own replication.
- Families of cooperating RNA catalysts developed the ability to direct synthesis of polypeptides.
- Accumulation of additional protein catalysts allowed more efficient and complex cells to evolve, the DNA double helix replaced RNA as a more stable molecule for storing the increased amounts of genetic information required by such cells
- Present-day living cells are classified as procaryotic (bacteria and their close relatives) or eucaryotic.

Inner Life of a Cell



Full version

https://www.youtube.com/watch?v=FzcTgrxMzZk