

Lecture Series 14 Origins of Life, Early Earth & Prokaryotic Diversity

The Chemical Aspects of The Origin of Life

Life is the cumulative product of interactions among the many kinds of chemical substances that make up the cells of an organism.

The abiotic chemical evolution of life follows four major hurdles:

1. The abiotic synthesis and accumulation of small organic molecules, or monomers, such as amino acids and nucleotides.
2. The joining of these monomers into polymers, including proteins and nucleic acids.
3. The aggregation of abiotically produced molecules into droplets, e.g., protobionts, that had chemical characteristics different from their surroundings.
4. The origin of heredity or information transference.

To understand how the origin of life from abiotic material occurred, we have to consider two critical concepts:

1. The extension of the idea of natural selection to the chemical level.
2. The realization that the condition of the early Earth when life first arose must have been vastly different from present:
 - (a) Non-oxidizing atmosphere: present level of oxygen, which began to accumulate around 2.1 billion years ago with the presence of cyanobacteria, would have been lethal to primitive organisms
 - (b) Abundant resources produced non-biologically
 - (c) Long time scale without competition

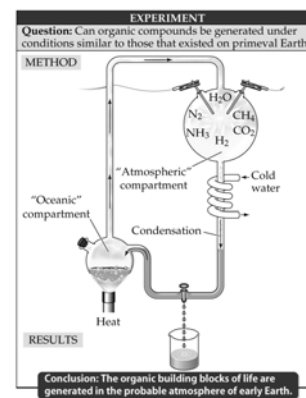
The Molecular Clues to the Origin of Life on Earth

- o Molecules of living organisms are rich in **hydrogen-containing carbon** compounds that are highly reduced. This suggests that there were little or no free molecular oxygen on primitive Earth.
- o All **amino acids** exist in both the right-handed and left-handed state. However, only 20 amino acids of the left-handed variety are used by living organisms in proteins. Therefore, suggesting there was a single origin of life.
- o **DNA & RNA** are the universal informational basis of all life forms on Earth.
- o **ATP** is the universal energy currency of all living organisms; suggesting a common origin of metabolism.
- o In any cell, first steps of carbohydrate metabolism involve **fermentation**, with the last steps in aerobic organisms the usage of oxygen via **respiration** – suggesting that aerobic organisms evolved from anaerobic ones.

Necessary Conditions for the Origin of Life

- Earth at the time of life's origin had a reducing atmosphere. Under conditions that resemble Earth's early atmosphere, small molecules essential to living systems form and polymerize.

Diagram of Stanley Miller's apparatus



Necessary Conditions for the Origin of Life

- Before life appeared, polymerization reactions generated the carbohydrates, lipids, amino acids, and nucleic acids of which organisms are composed. These molecules accumulated in the oceans.
- Originally “Darwin’s Warm Pond” Hypothesis

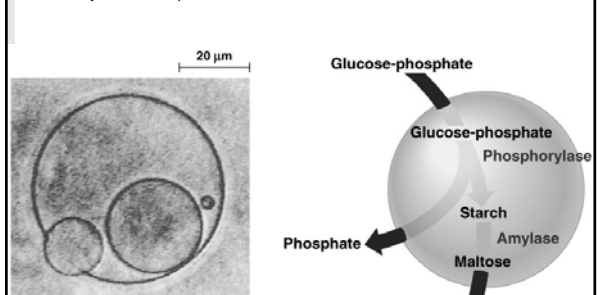
A painting of early Earth showing volcanic activity and photosynthetic prokaryotes in dense mats



Protobionts: Enclosing Prebiotic Systems

- The earliest protobionts probably had lipid-based membranes.

Laboratory versions of protobionts



(a) Simple reproduction

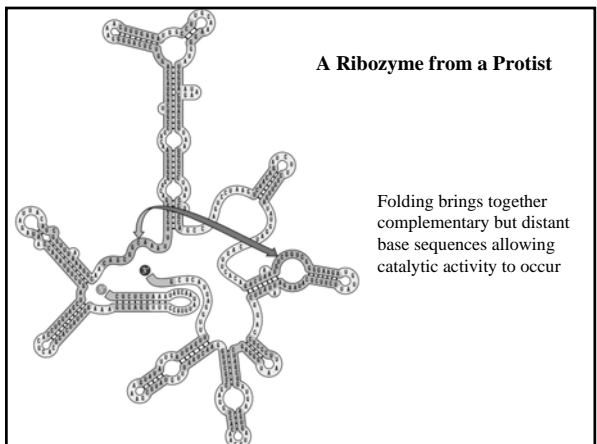
(b) Simple metabolism

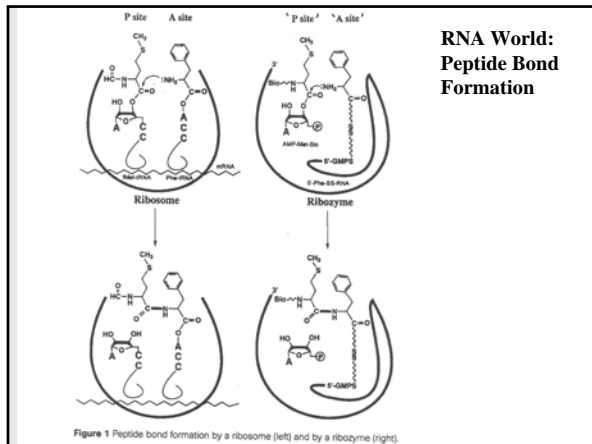
Putative “Metabolism” of a Coacervate Drop

Protobionts: Enclosing Prebiotic Systems

- The first genetic material may have been RNA that had a catalytic function and an information transfer function. Some RNA’s—called ribozymes—have catalytic functions today.

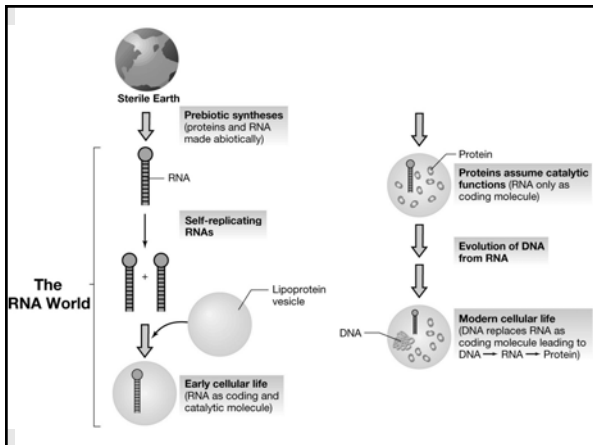
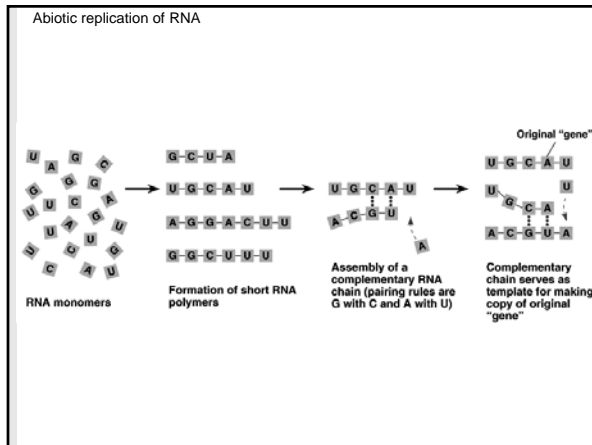
A Ribozyme from a Protist





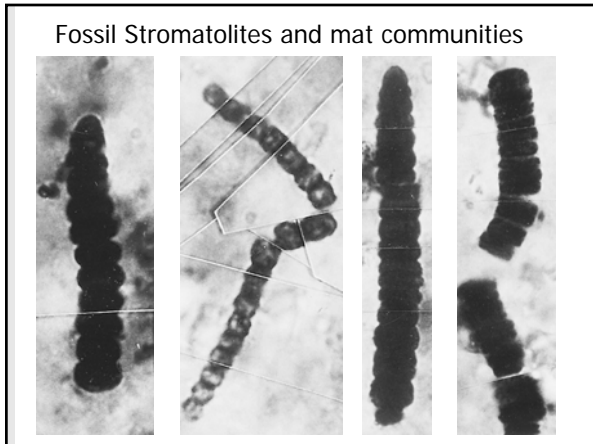
Protobionts: Enclosing Prebiotic Systems

- DNA probably evolved after RNA-based life became surrounded by membranes that provided an environment in which DNA was stable.



Photosynthesis Is the Source of Atmospheric O₂

- Cyanobacteria, which evolved the ability to split water into hydrogen ions and O₂, created atmospheric O₂. Accumulation of free O₂ in the atmosphere made possible the evolution of aerobic metabolism.



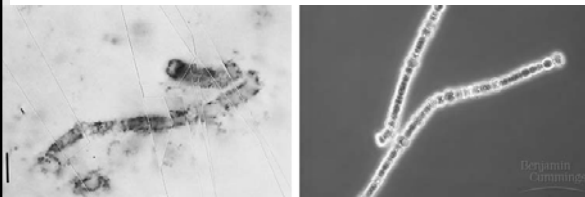
Living columnar stromatolites, Shark Bay, Western Australia



Modern Stromatolites from Yellowstone Natl. Park



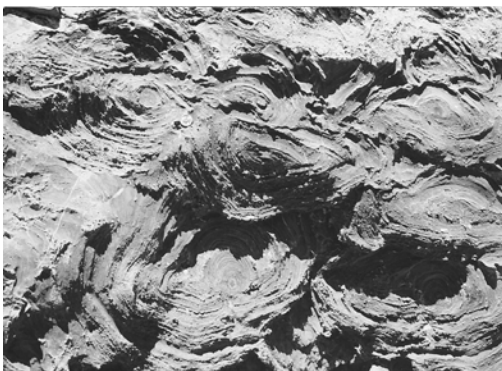
Early (left) and modern (right) prokaryotes



Microbial mat communities

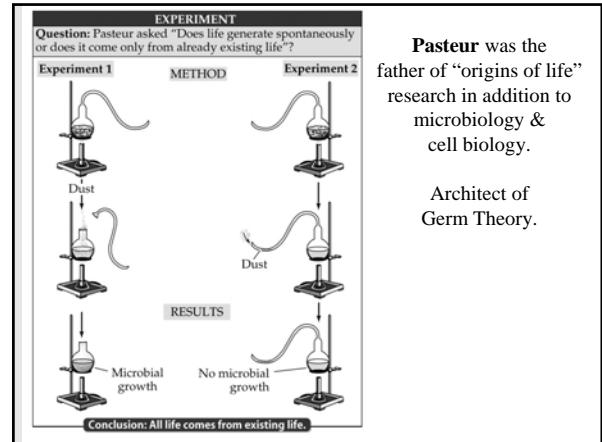
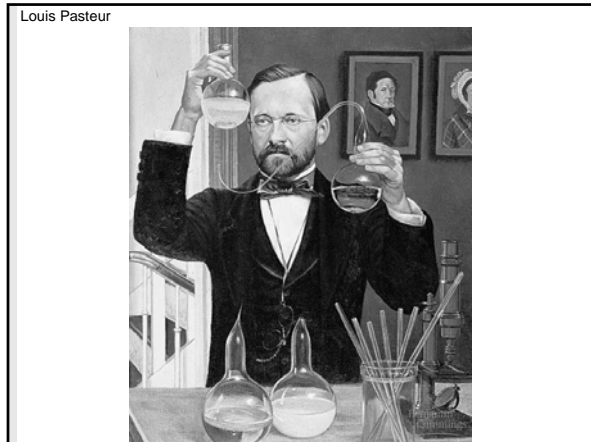


Fossil Stromatolites from Glacier Natl. Park



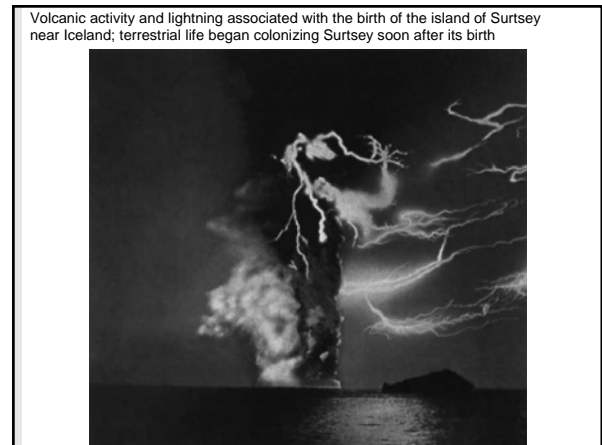
Is Life Evolving from Nonlife Today?

- Because most of the chemical reactions that gave rise to life occur readily under the conditions that prevailed on early Earth, life's evolution was "probably" inevitable.
- Experiments by Louis Pasteur and others convinced scientists that life does not come from nonlife on Earth today.



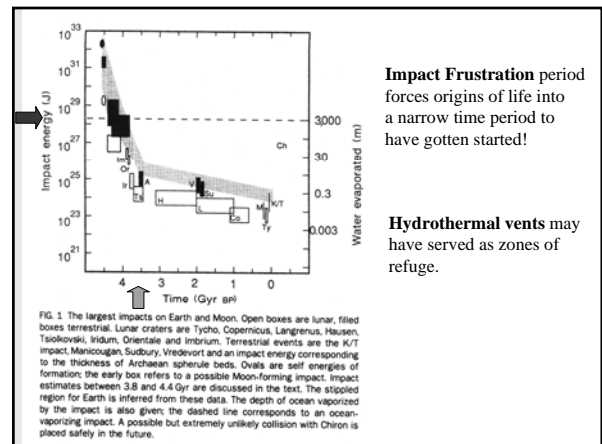
Is Life Evolving from Nonlife Today?

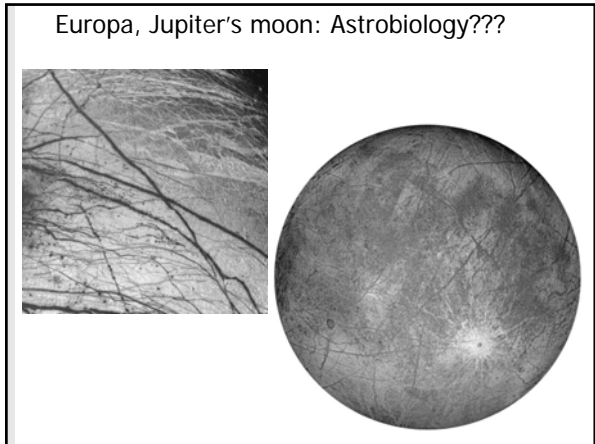
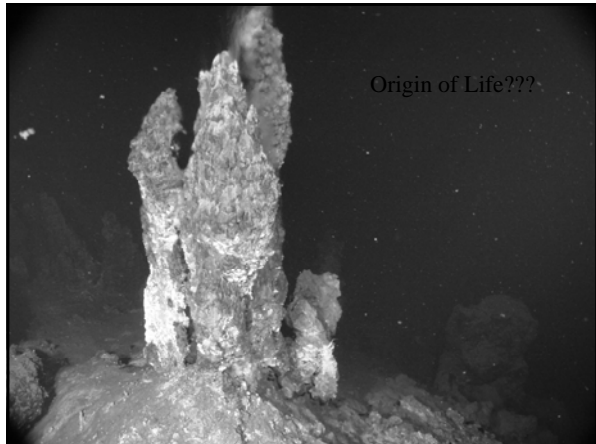
- New life is no longer being assembled from nonliving matter because simple biological molecules that form in today's environment are oxidized or consumed by existing life.
- Now we have competition & oxygen!



Does Life Exist Elsewhere in the Universe?

- Conditions that permit the evolution and maintenance of simple prokaryotic life may be widespread in the universe, but multicellular life has more stringent requirements, including a planet with a relatively circular orbit, a rapid rate of spin, nearby planets that intercept impacts, and a large moon that stabilizes the planet's orbit. Such conditions may be very rare.



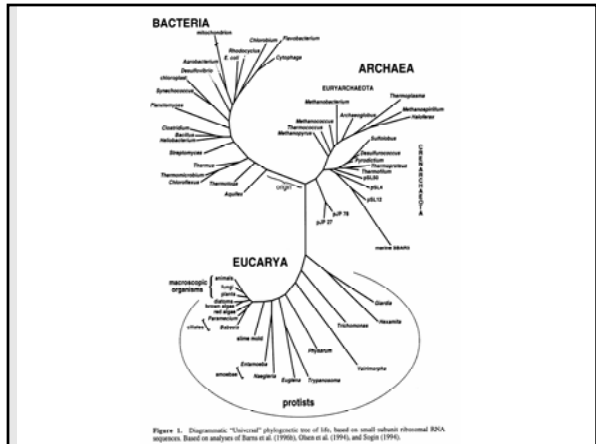


Does Life Exist Elsewhere in the Universe?

- Although conditions on Earth have fluctuated greatly, they have been suitable for multicellular organisms for nearly a billion years.

Why Three Domains?

- Living organisms can be divided into three domains: Bacteria, Archaea, and Eucarya. The prokaryotic domains (Archaea and Bacteria) differ from each other more radically than the Archaea from the Eucarya.



Why Three Domains?

- Evolutionary relationships of the domains were revealed by rRNA sequences. Their common ancestor lived more than 3.6 - 3.8 billion years ago, prior to that of the common ancestor of the Archaea and Eucarya.

**Some Lessons from the BIG TREE:
Map of the Biological Record**

Single origin for all life on Earth...

- o Central Dogma intact
- o ATP and PMF are universal themes
- o Uniformity among chiral carbon compds (sugars & AAs)
- o Hot start origin...
- o Also Cyanobacteria did not arrive first on the scene!
- o Now estimated at 2.5 –2.1 bya

**Some Lessons from the BIG TREE:
Map of the Biological Record**

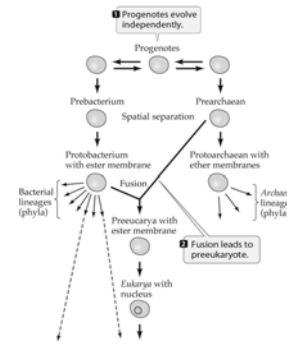
General topology implies:

- o Three “primary lines of evolutionary descent.”
- o The Eucarya “nuclear” lineage almost as old as the prokaryote lines.
- o Prokaryotes split between *Bacteria* and *Archaea*.
- o Shown for only a limited number of representative org’s.
- o Mitochondria and chloroplasts proven to be of bacterial origin.

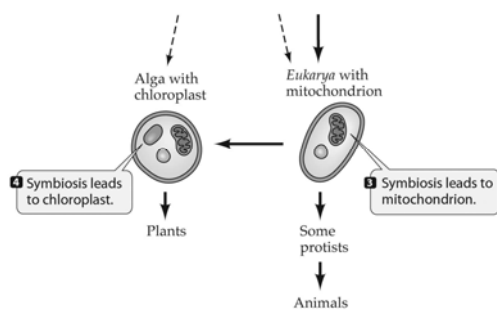
A Comparison of the Three Domains of Life

CHARACTERISTIC	DOMAIN		
	Bacteria	Archaea	Eukarya
Nuclear envelope	Absent	Absent	Present
Membrane-enclosed organelles	Absent	Absent	Present
Peptidoglycan in cell wall	Present	Absent	Absent
Membrane lipids	Unbranched hydrocarbons	Some branched hydrocarbons	Unbranched hydrocarbons
RNA polymerase	One kind	Several kinds	Several kinds
Initiator amino acid for start of protein synthesis	Formyl-methionine	Methionine	Methionine
Introns (noncoding parts of genes)	Absent	Present in some genes	Present
Response to the antibiotics streptomycin and chloramphenicol	Growth inhibited	Growth not inhibited	Growth not inhibited
Histones associated with DNA	Absent	Present	Present
Circular chromosome	Present	Present	Absent
Ability to grow at temperatures >100°C	No	Some species	No

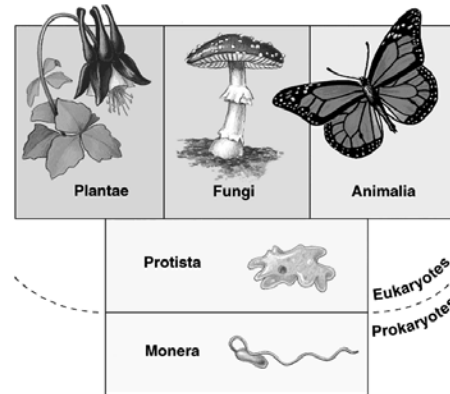
Evolution of the main lines of descent

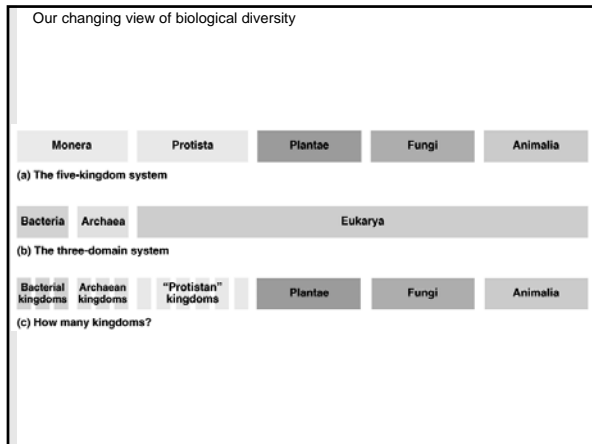


Evolution of the main lines of descent



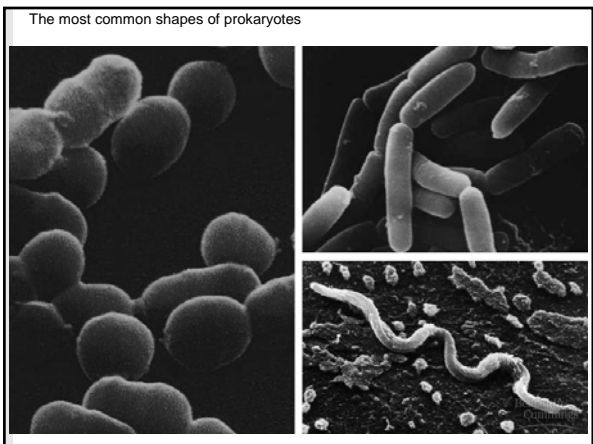
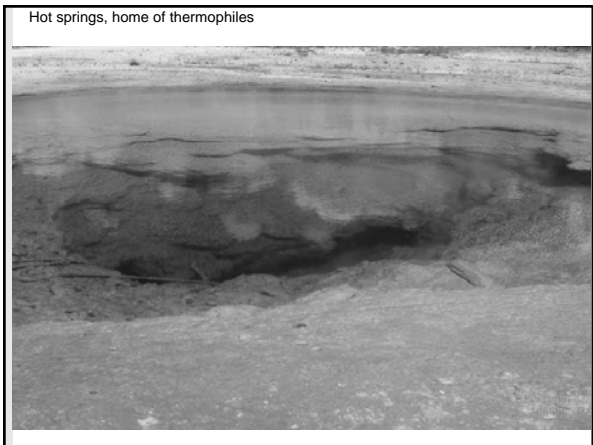
Whittaker's five-kingdom system





General Biology of the Prokaryotes

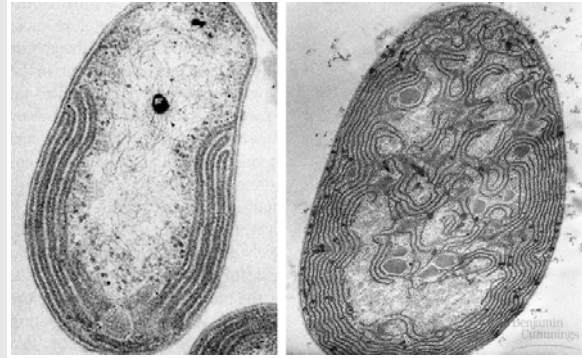
- The prokaryotes are the most numerous organisms on Earth, occupying an enormous variety of habitats.
- Most prokaryotes are cocci, bacilli, or spiral forms. Some link together to form associations, but very few are truly multicellular.



General Biology of the Prokaryotes

- Prokaryotes lack nuclei, membrane-enclosed organelles, and cytoskeletons. Their chromosomes are circular. They often contain plasmids. Some contain internal membrane systems.
- Prokaryotes reproduce asexually by binary fission, but also exchange genetic information.

Specialized membranes of prokaryotes



General Biology of the Prokaryotes

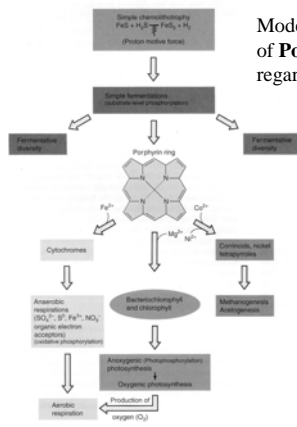
- Prokaryotes' metabolic pathways and nutritional modes include obligate and facultative anaerobes, and obligate aerobes. Nutritional types include photoautotrophs, photoheterotrophs, chemoautotrophs, and chemoheterotrophs. Some base energy metabolism on nitrogen- or sulfur-containing ions.

Major Nutritional Modes

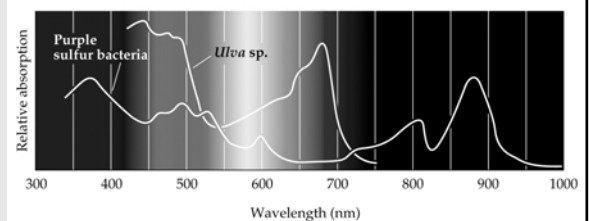
Table 27.1 Major Nutritional Modes

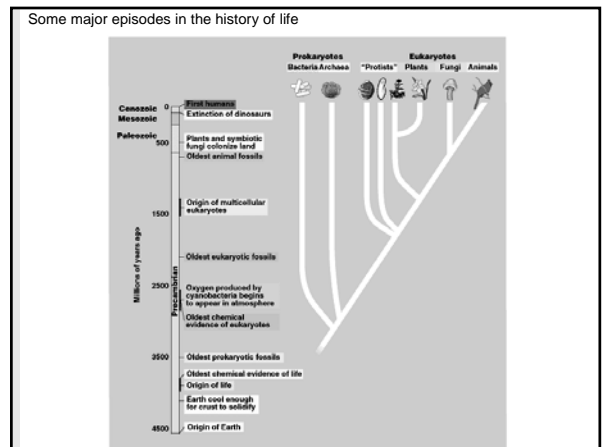
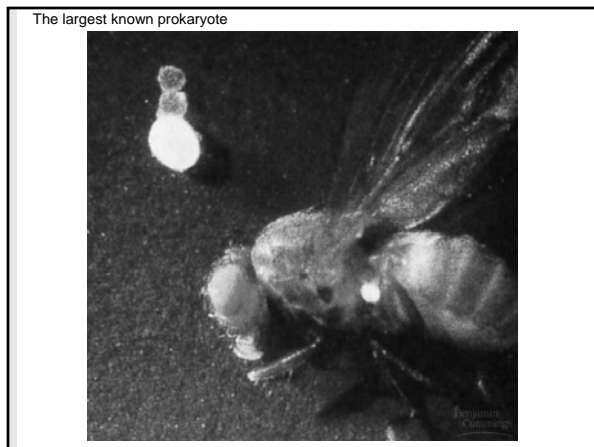
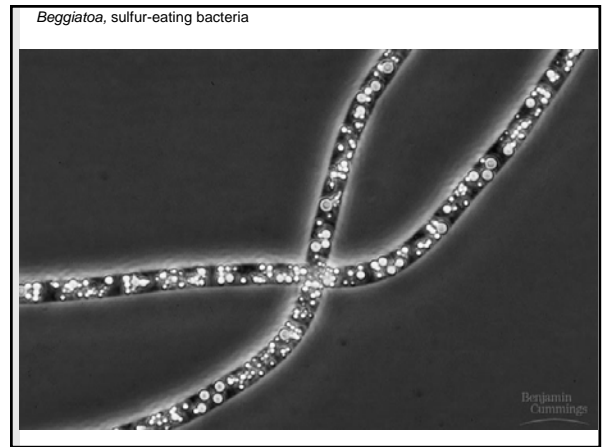
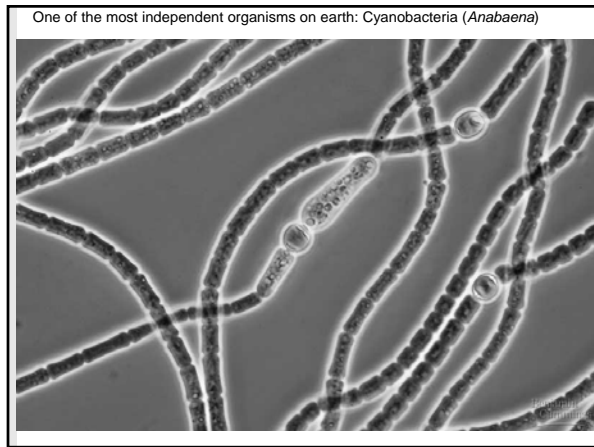
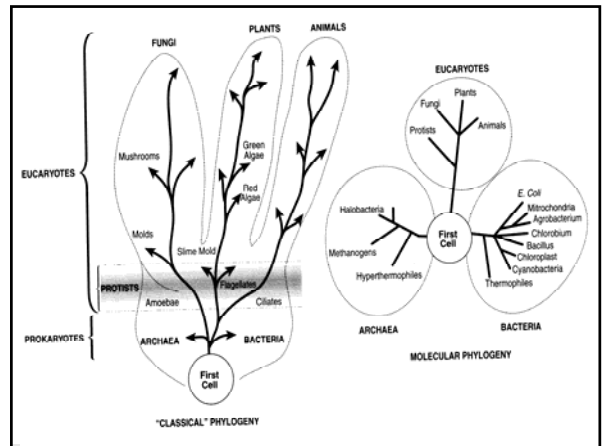
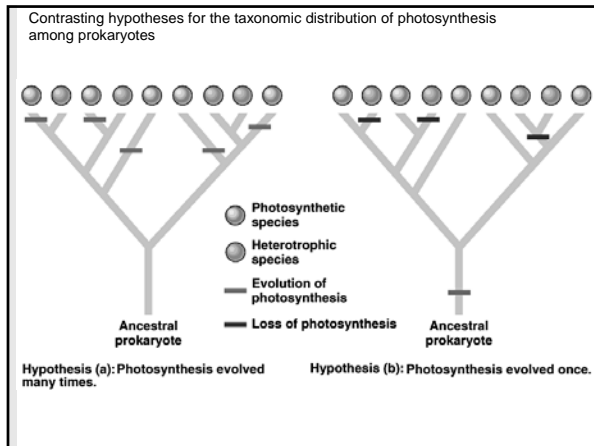
Mode of Nutrition	Energy Source	Carbon Source	Types of Organisms
Autotroph			
Photo-autotroph	Light	CO ₂	Photosynthetic prokaryotes, including cyanobacteria; plants; certain protists (algae)
Chemo-autotroph	Inorganic chemicals	CO ₂	Certain prokaryotes (for example, <i>Sulfolobus</i>)
Heterotroph			
Photo-heterotroph	Light	Organic compounds	Certain prokaryotes
Chemo-heterotroph	Organic compounds	Organic compounds	Many prokaryotes and protists; fungi; animals; some parasitic plants

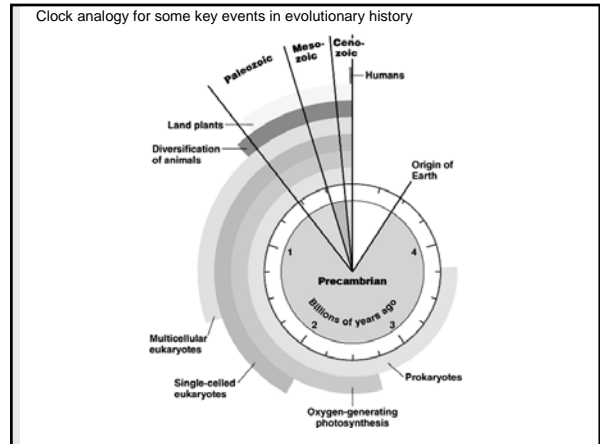
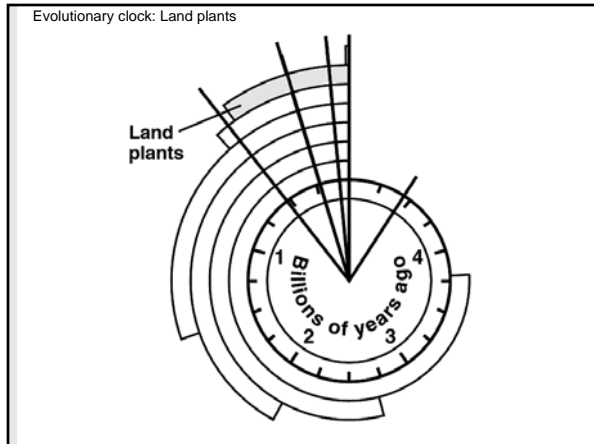
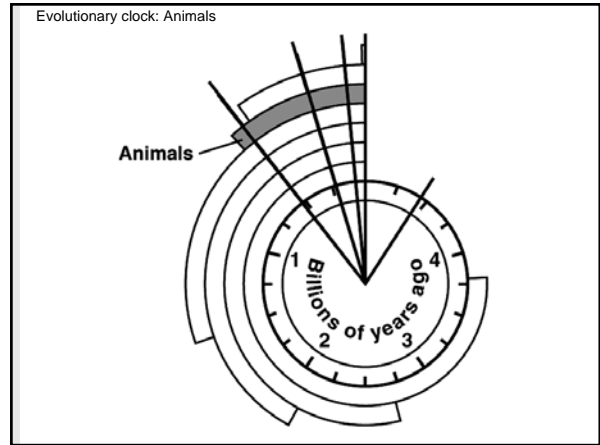
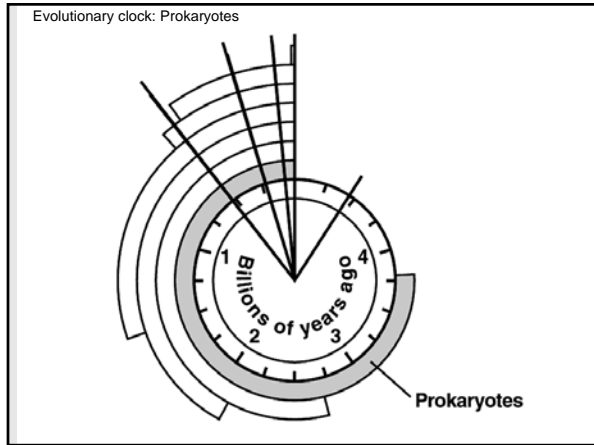
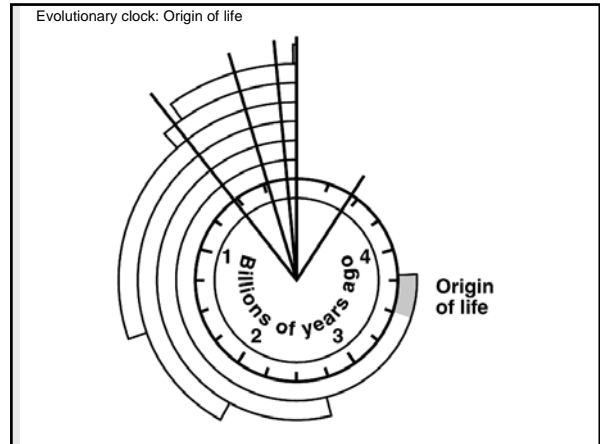
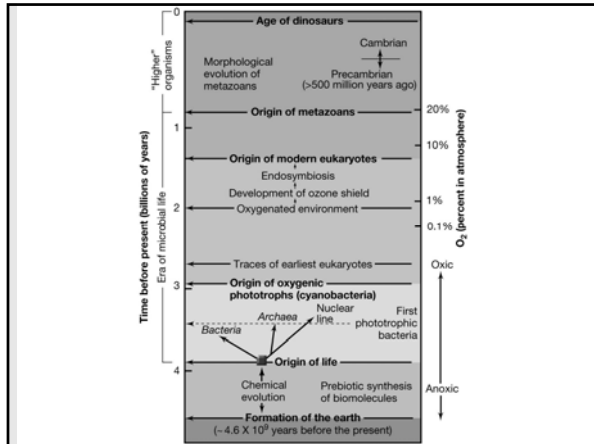
Model for the development of **Porphyrin Ring** diversity regarding metabolic pathways

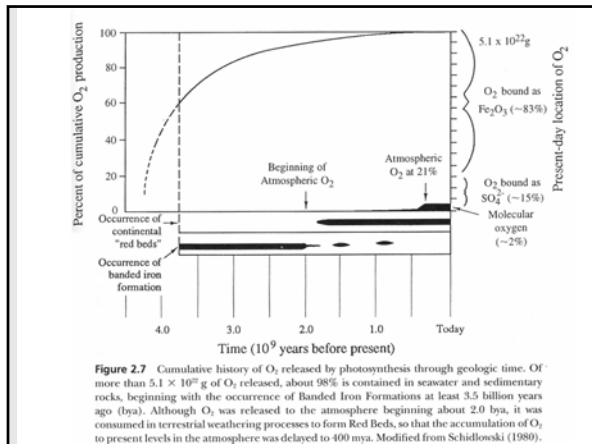


Action Spectra

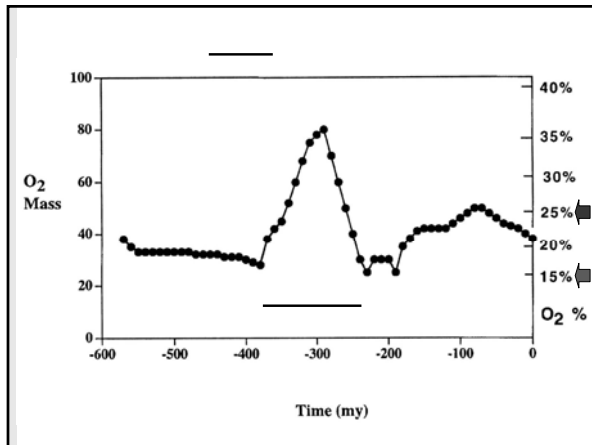








Banded iron formations are evidence of the vintage of oxygenic photosynthesis



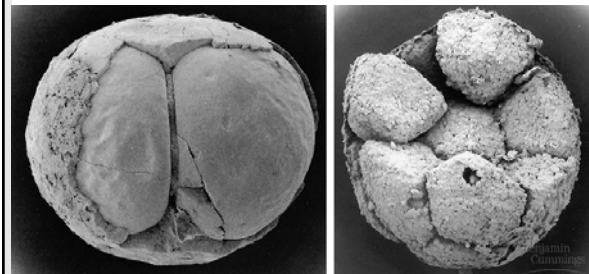
Patterns of Evolutionary Change

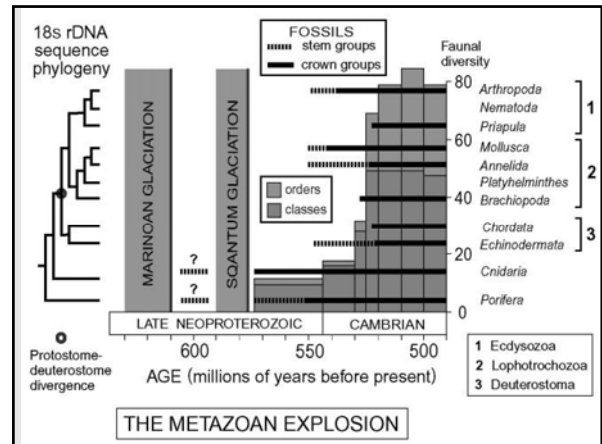
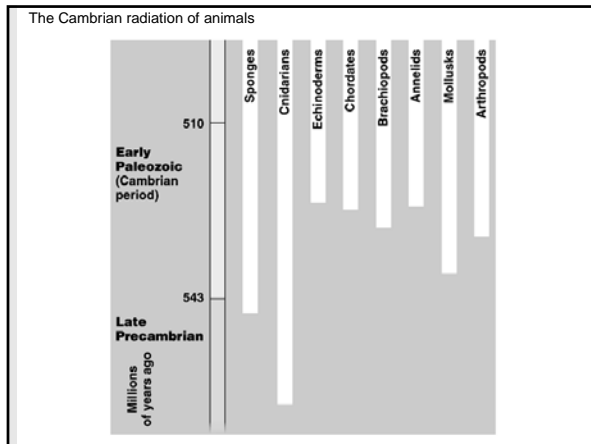
- The Oxygen "Blip" @ ~300 mya resulted from the invasion of land by plants!
- This gave rise to:
 - Gigantic Insects
 - Origin of Flight
 - Invasion of land by animals

Patterns of Evolutionary Change

- Truly novel features of organisms have evolved infrequently. Most evolutionary changes are the result of modifications of already existing structures.

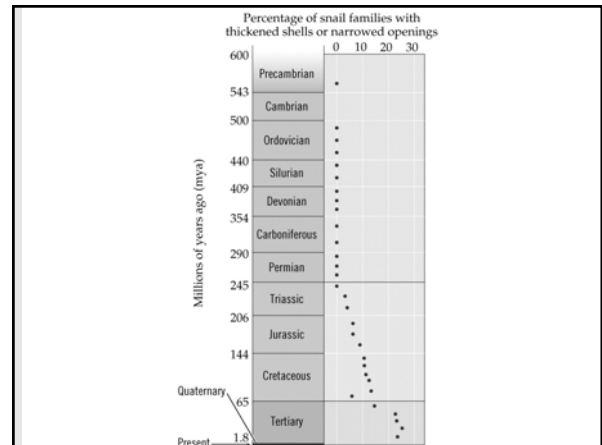
Fossilized animal embryos from Chinese sediments 570 million years old





Patterns of Evolutionary Change

- Over evolutionary time, organisms have increased in size and complexity. Predation rates have also increased, resulting in the evolution of better defenses among prey species.



The Future of Evolution

- The agents of evolution continue to operate today, but human intervention, both deliberate and inadvertent, now plays an unprecedented role in the history of life.
- Global Warming???
- The Human Bolide???