Lecture 28

Origin of Life on Earth

Outline of Lecture 28

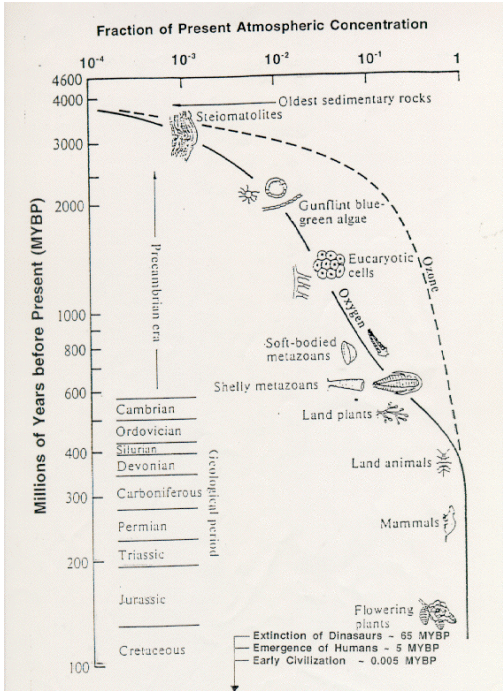
- Modern scientific perspective of transition,

  inanimate matter → animate matter,

  as a physical rather than a divine process.
- Important steps in creation of life:
  - Nonbiological synthesis of organic compounds in nonoxidizing atmosphere.
  - Polymerization by removal of water from chemical joints of monomers.
  - Survival advantage of protocells that can make polymers.
  - Evolution of metabolic chains from back-to-front.
  - Natural selection for objects that have genetic apparatus (nucleic acids) for remembering metabolic recipes that can pass down that apparatus (DNA) to daughter cells.
- Importance of sexual reproduction, eukaryotic cells, and cell differentiation.

Important Geologic Events Leading to Biosphere

- 4.56 - 3.8 Gyr ago -- heavy meteoroid bombardment of Earth
- 4.4 Gyr ago: formation of zircon crystals which require liquid water that was probably outgassed from volcanoes as part of formation of first non-oxidizing atmosphere
- 3.8 Gyr ago -- cessation of heavy bombardment allowing survival of first rocks, no living things yet
- 3.5 Gyr ago -- fossilization of first micro-organisms in stromatolites
- 2.5 - 1.7 Gyr ago -- appearance of eukaryotic cells and precipitation of iron from oceans in banded iron formations (rust beds) when atmosphere became oxidizing
- 540 Myr ago -- Cambrian period: explosion of multicellular lifeforms



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Chesley Bonestell

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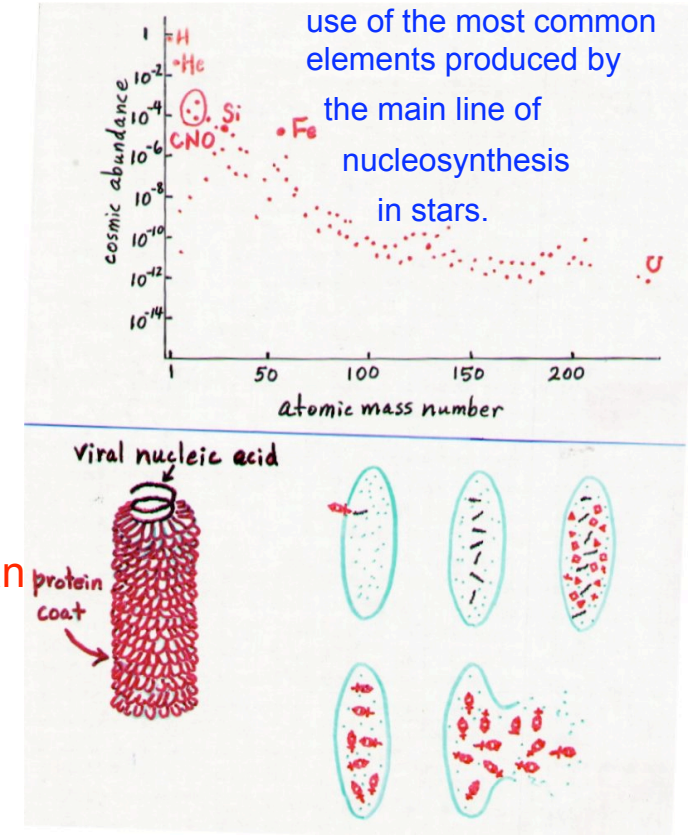
Viruses Lie at the Borderline of Life

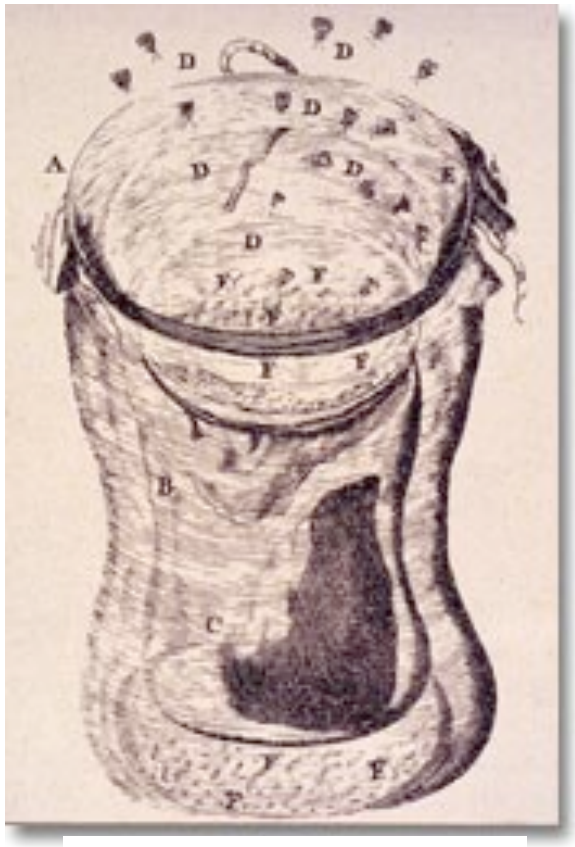
- It is easier to believe that a transition of inanimate matter to animate forms can occur if we have something that lies at the borderline.
- That “something” exists. It is a virus which cannot grow or reproduce on its own, but relies on exploiting a host cell. Example:
  - A virus particle attaches itself to the wall of a cell.
  - The protein coat of the virus makes a hole in the wall.
  - The viral DNA or RNA is injected into the living cell.
  - The viral nucleic acid takes over the machinery of the cell and manufactures many copies of its protein coat, nucleic acid, etc. These are assembled into many copies of the complete virus.
  - The viral particles in contact with the cell wall burst it open, killing the cell and releasing many viruses that can continue the process of infection.
- However, left to its own devices, a virus particle is simply a sophisticated collection of molecules, which cannot even defend itself from oxidation by O_2 in the air; whereas living cells have evolved mechanisms to ward off viral attacks.

One indication of a connection between animate and inanimate world is that both make use of the most common elements produced by the main line of nucleosynthesis in stars.



Historical Context of Ideas

- Before advent of modern science, people's perception of living and nonliving things were blurred: "frogs arising from slime, maggots from decaying meat."
- Careful observation in 17th century demonstrated that complex organisms always originated from parents (e.g., maggots from flies alighting on meat).
- Discovery of single-celled organisms (e.g., bacteria) and Louis Pasteur's (1822-1895) theories of fermentation and disease pushed question of spontaneous generation to microorganisms.
- Pasteur saved French wine industry, invented vaccination against anthrax, found cure for rabies.



Experiment by Francesco Redi, a student of Galileo, showing that maggots did not appear in meat without removing gauze separating meat from eggs laid by flies.

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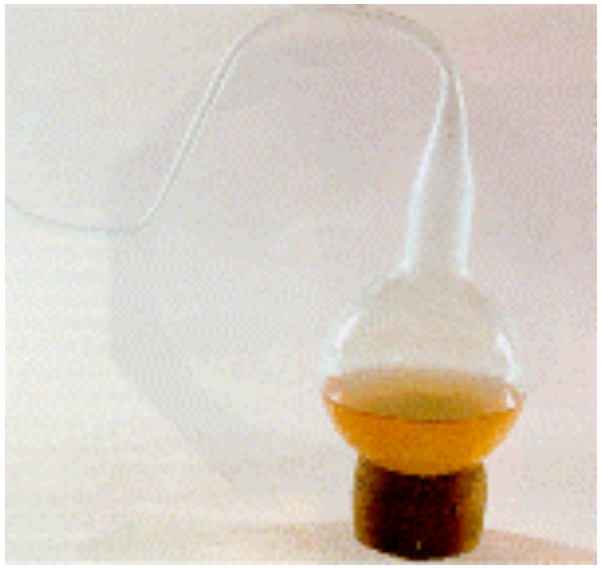
Pasteur's Experiment with a Swan-Neck Flask on Spontaneous Generation

- Boil soup in flask to sterilize it.
- Expose it to air (because some people claimed air to contain substance vital to life).
- In flask with a swan-neck that trapped microbes in air from getting beyond the first turn, the soup does not spoil.
- This experiment shows that spontaneous generation of even single-celled organisms does not occur under today's conditions on Earth.
- But what about at the beginning? Was there a first cell that started everything?



Wikipedia

Importance of Long Timescale and No Competition

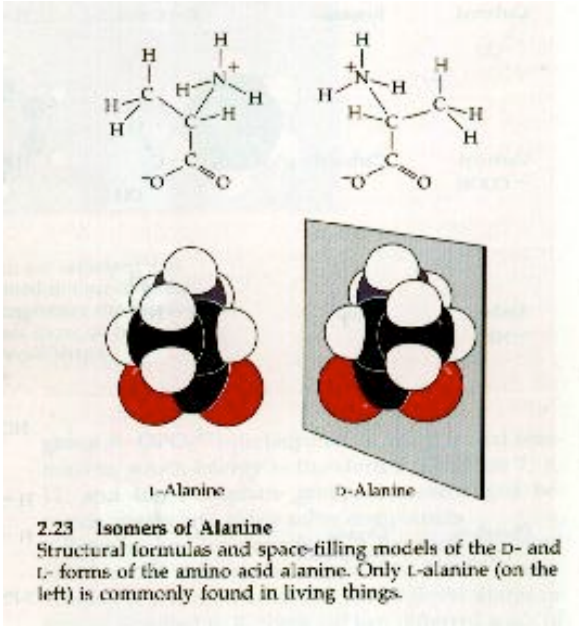
- Charles Darwin, Pasteur's contemporary, in 1871:

  "It is often said that all the conditions for the first production of a living organism are now present, which could ever be present. But if (and oh! what a big if!) we could conceive in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc., present, that a protein compound was chemically formed ready to undergo still more complex changes, at the present day such matter would be instantly devoured or absorbed, which would not have been the case before living creatures formed."
- A. I. Oparin (1894-1980) in Russia and J. B. S. Haldane (1892-1964) in Great Britain stressed the important role of a non-oxidizing atmosphere.

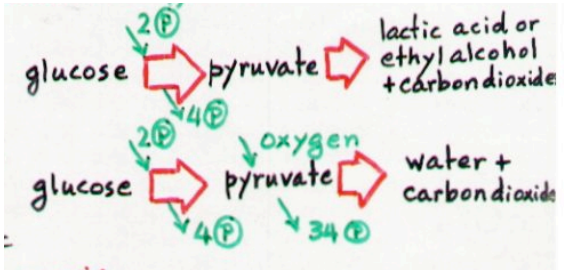
- Two critical ideas:
  - Extension of idea of natural selection to a molecular level.
  - Conditions when life first arose must have been immensely different from what they are today:
    - Very long time scales free from competition with other organisms.
    - Non-oxidizing atmosphere (present O_2 in atmosphere arises from action of plant photosynthesis).
    - Abundant organic resources produced non-biologically.

Molecular Clues to the Origin of Life

- In molecules of importance to living organisms, carbon is often attached to hydrogen rather than to oxygen.
  - Wood and steaks burn; rocks and lakes do not.
  - Suggests that original atmosphere of Earth did not contain free molecular oxygen, as is true even today of Mars and Venus, for example.
- Only 20 amino acids of the left-handed variety found in living things. Suggests a common origin for all living organisms. (Otherwise why aren't right-handed forms used?)
- RNA and DNA are genetic basis for all lifeforms on Earth. Suggests great advantage for this molecular machinery to achieve growth & reproduction.
- ATP is the universal energy currency for all living thins. Suggests a common origin of metabolism.
- In any cell, first steps of carbohydrate metabolism is fermentation process (without O_2). In aerobic organisms, respiration adds on steps using oxygen. Suggests aerobic organisms evolved from anaerobic ones after it became advantageous (factor of 18 in phosphate bonds) to make use of O_2 when the atmosphere became oxidizing (about 2 billion yr ago).



2.23 Isomers of Alanine
Structural formulas and space-filling models of the D- and L- forms of the amino acid alanine. Only L-alanine (on the left) is commonly found in living things.



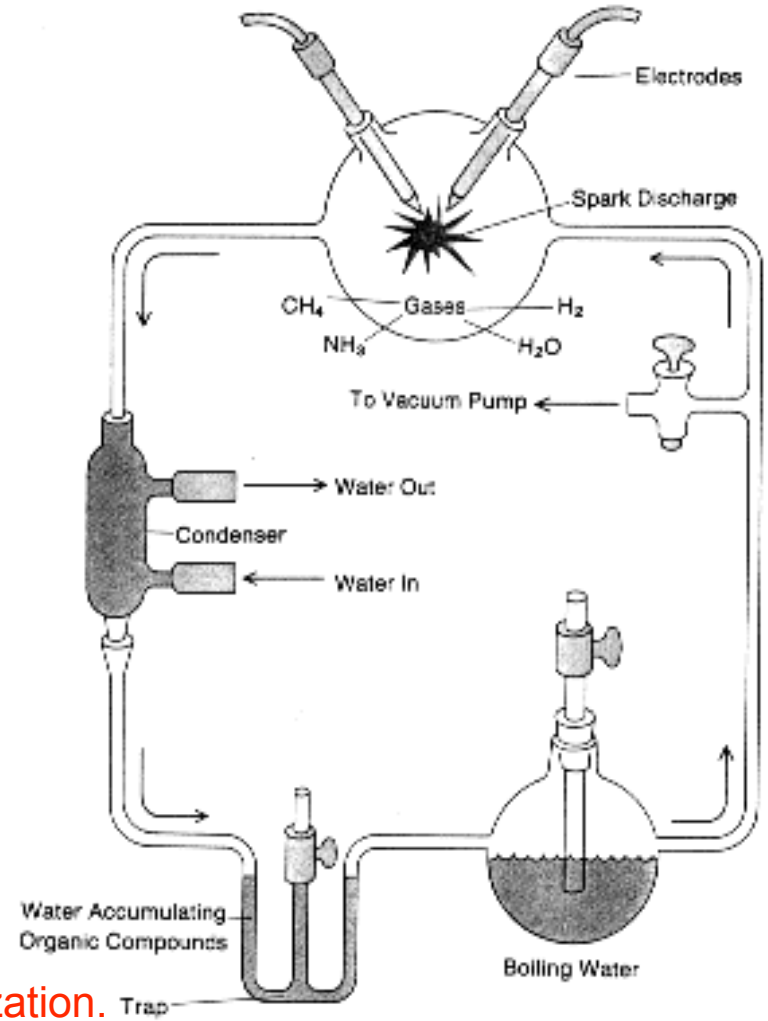
Important Steps in Creation of Life from Inanimate Matter

- Creation of small organic molecules in a nonoxidizing atmosphere via lightening strokes, UV light, etc.
- Dissolving of small organic molecules in primitive oceans to form Haldane's warm and dilute primordial soup. Contribution of phosphates, etc., from rocks.
- Synthesis of ATP, GTP, CTP, UTP, and their deoxy counterparts dATP, dGTP, dCTP, dTTP, as the precursors to nucleic acids. Mostly ATP.
- Polymerization by nonbiological means of amino acids into proteins and of nucleoside triphosphates into nucleic acids (RNA and DNA). Primary difficulty is to remove water in the joints: In ocean, water, water everywhere.
  - monomer: H-M-OH
  - polymer: H-M_1-M_2…-M_n-OH

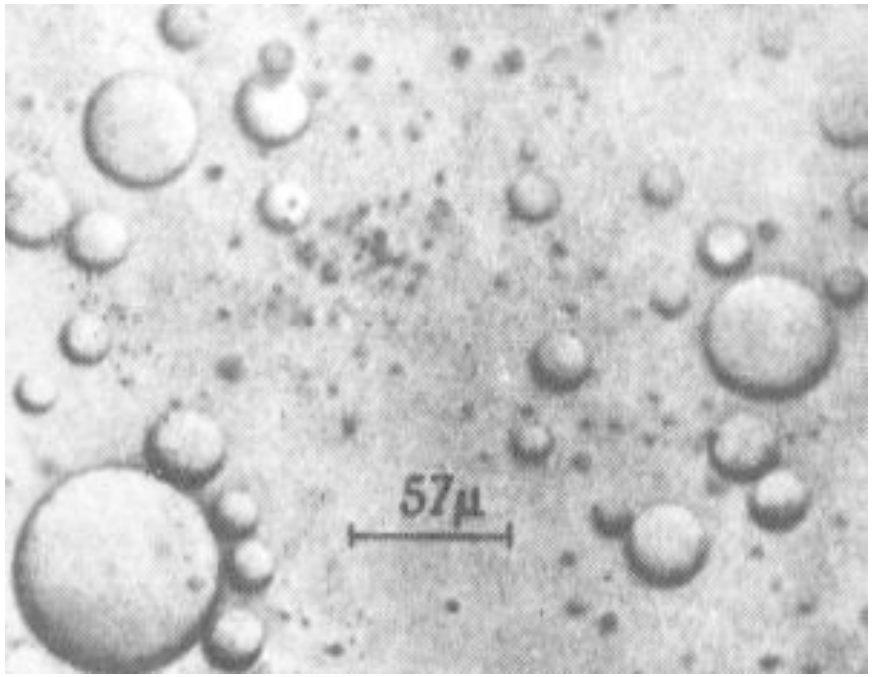
    H-M_1-…-M_{n-1}-OH + H-M_n-OH →

    H-M_1-…-M_n-OH + H-O-H Drives de-polymerization.

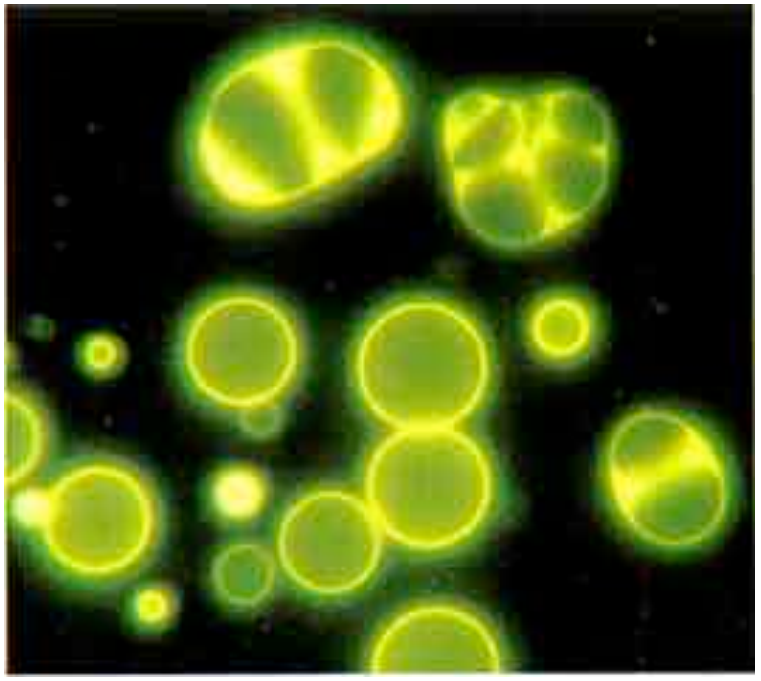
Miller-Urey (1953)Experiments



Organics in Water Will Form Concentrated Droplets if They Contain Lipids (Oils)



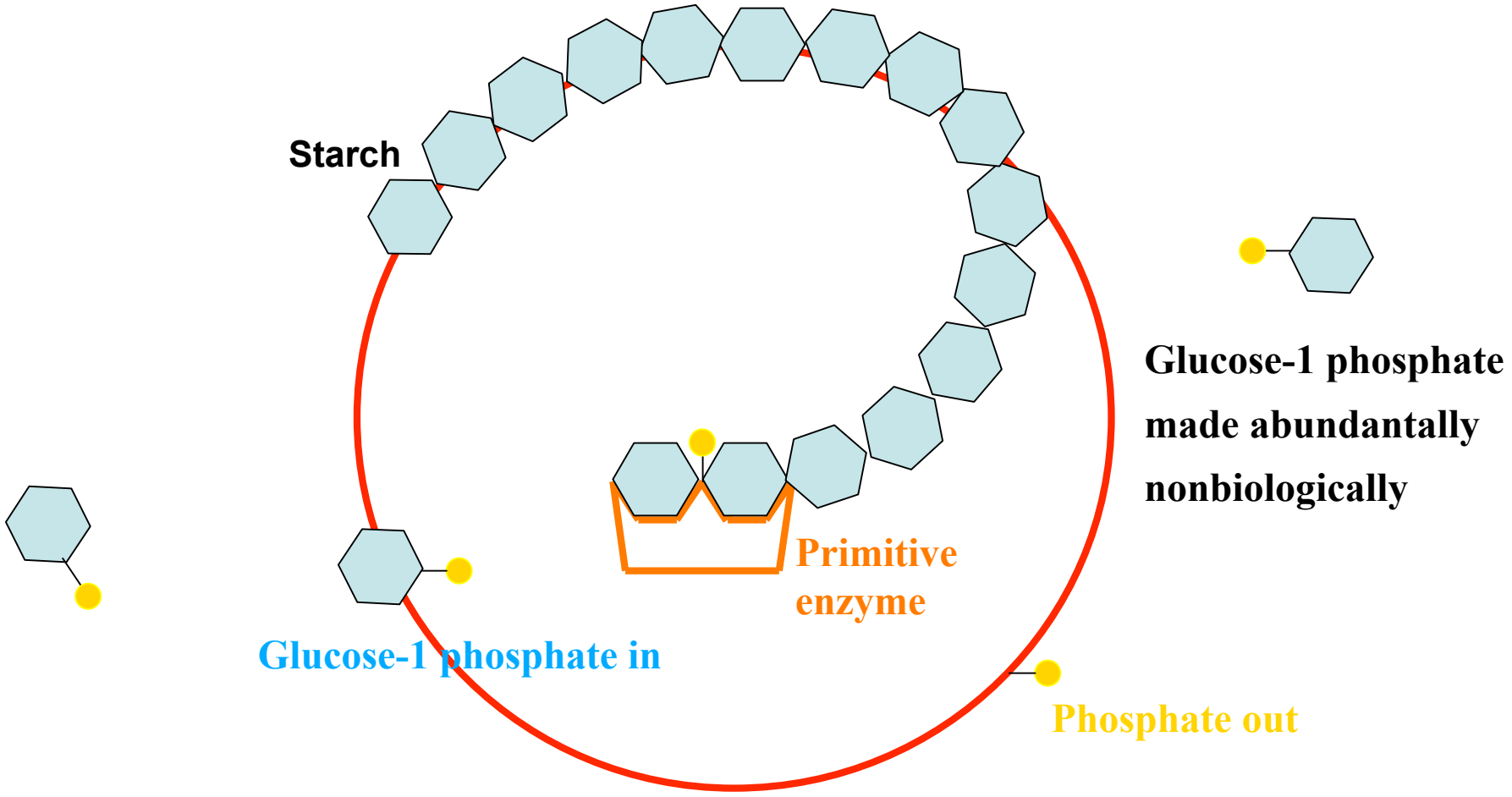
Coacervates



Vesicles

Think chicken soup

Advantage for Polymerization Reactions in Protocells



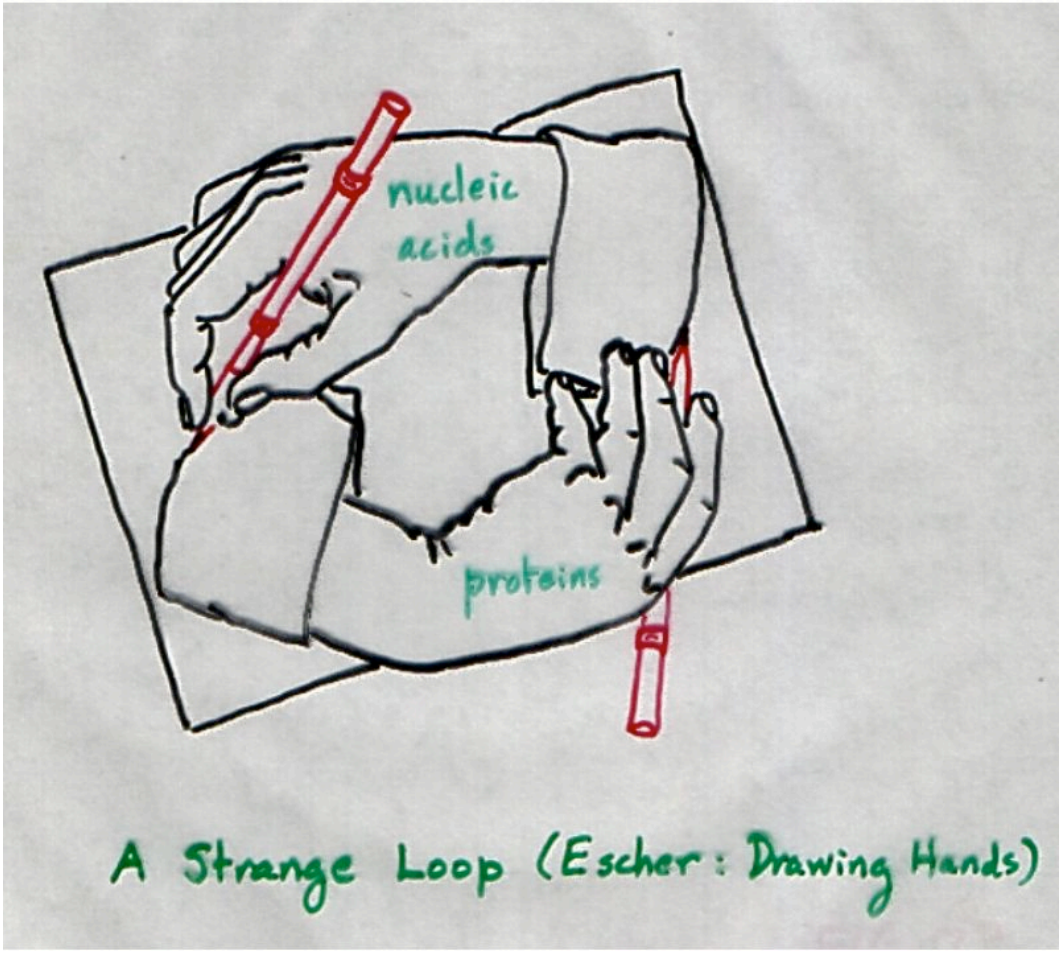
Stiff wall has survival value in rough seas.

Chicken or Egg?

Need proteins to perform polymerization reactions in presence of water; need nucleic acids to remember how to make proteins.

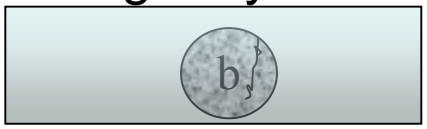
Which came first, proteins or nucleic acids?

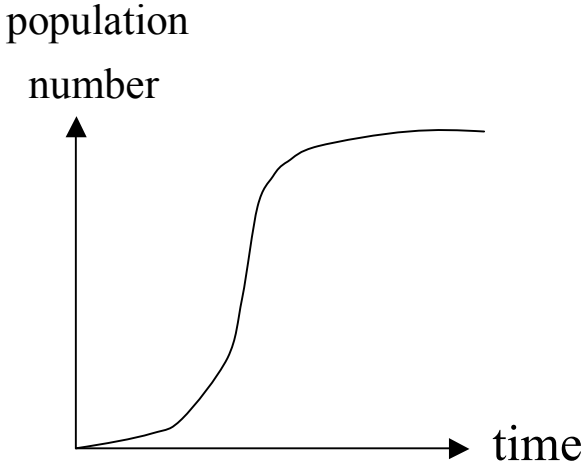
Many researchers feel that answer might be RNA, which is capable of self-polymerization. Was there once a RNA world? Ideas of Carl Woese & Leslie Orgel.



A Plausible History of Life on Earth (A Theory)

- First living organism 3.5 billion yr ago: primitive bacterium which absorbed and restructured small organic molecules produced nonbiologically in its environment. Too simple even to ferment.





- Explosive growth in numbers from lack of competition led to exhaustion of ATP. Early demise of countless billions, but also step-by-step, from back-to-front, a fermentation cycle to produce ATP from glucose.
- When free glucose also ran out, resultant biological stress selected for evolution of a biological mechanism to produce glucose from more abundant natural resources: CO_2 + (H_2S or H_2O) + sunlight. Photosynthesis, with H_2O, a waste product is O_2.
- Gradual increase in atmospheric oxygen (which precipitated out soluble iron in oceans as red beds of rust 2 billion yr ago) led to selective advantage if organisms could exploit this reactive gas in ATP production from glucose: Respiration.
- Consumers (bacteria) now could survive by scavenging organic matter released upon deaths of producers (blue-green algae).

Faint Early Sun and Snowball Earth

- Early Sun fainter than it is today.
- Earth would be considerably colder in distant past except for methane gas in atmosphere that provided a strong greenhouse effect.
- Transition of atmosphere to oxidizing one 2.3 billion yr ago chemically removed methane and, combined perhaps with a fortuitous drift of continents to equator of Earth, triggered runaway global glaciation -- “Snowball Earth.” (Ice reflects sunlight.)
- Without weathering of rocks to bury carbonates in deep ocean trenches, however, continued outgassing of CO_2 from volcanoes led, over hundred million yr, to build-up of this greenhouse gas, triggering a catastrophic warming and melting of glaciers -- “Hothouse Earth.”
- Driver for evolution to eukaryotic cells?

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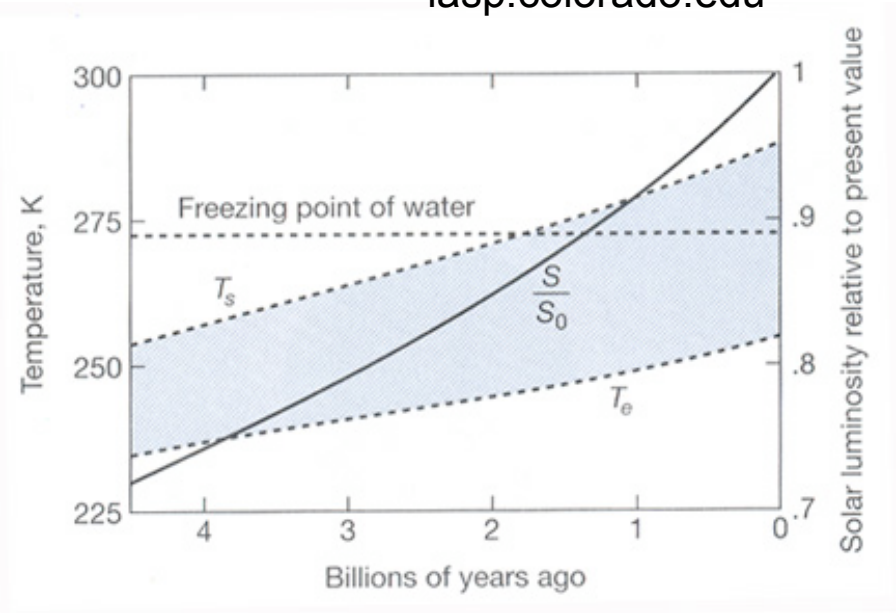
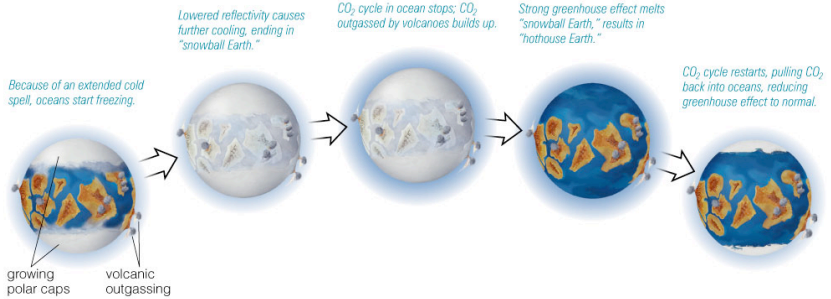




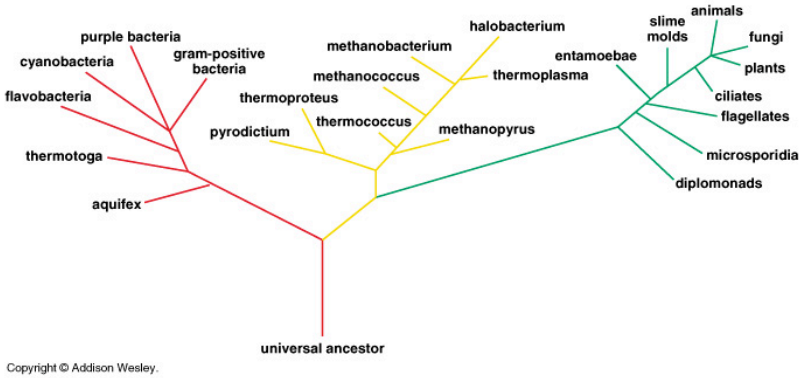
Stromatolites Radioactively Dated to 3.5 Billion Yr Ago as Fossil Record of Early Unicellular Organisms

Living mats of bacterial growth.

Stromaltolites = “beds of stone”

Extremophiles and Archaea

- A major surprise of the past three decades is the discovery of the existence of life under extreme environments – near cracks on the ocean floor, in boiling hot sulfur springs, and at a few km depths in the interior of the solid Earth. These organisms derive their ultimate source of energy and nutrients from below, the deep earth, rather than from above, sunlight.
- "Extremophiles," the generic name given such organisms, give rise to the hope that life may exist under extraterrestrial conditions much more harsh than believed possible previously.
- Many of the single-celled organisms that belong to the category of "extremophile" form a branch of life, archaea, distinct from the bacteria/blue-green algae and eukarya. The relationship between these three branches is complex, with recent research indicating considerable mixing of genetic material among the different groups.
- Nevertheless, because many of the classic arguments given earlier for a single origin of life still holds, consensus holds that a "last universal common ancestor" (LUCA) existed which gave rise to all these lifeforms. But it is an open question whether LUCA originated near the surface or the deep bowels of the Earth (or more fancifully, from extraterrestrial material brought here via meteorites).



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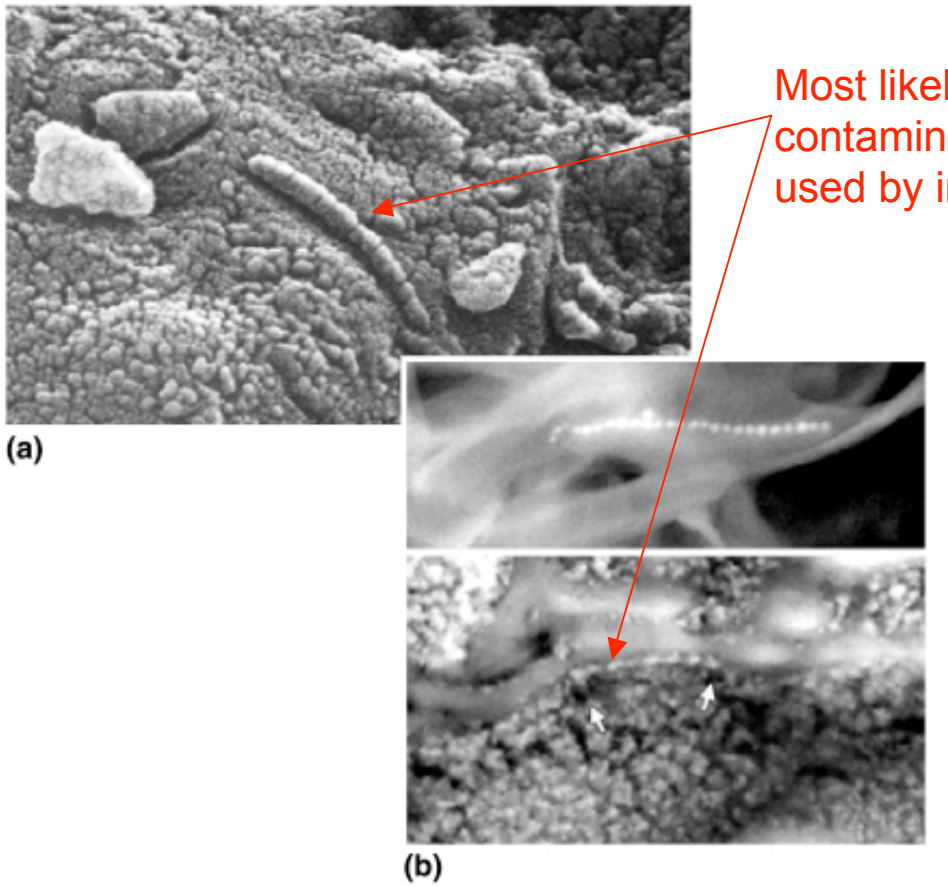
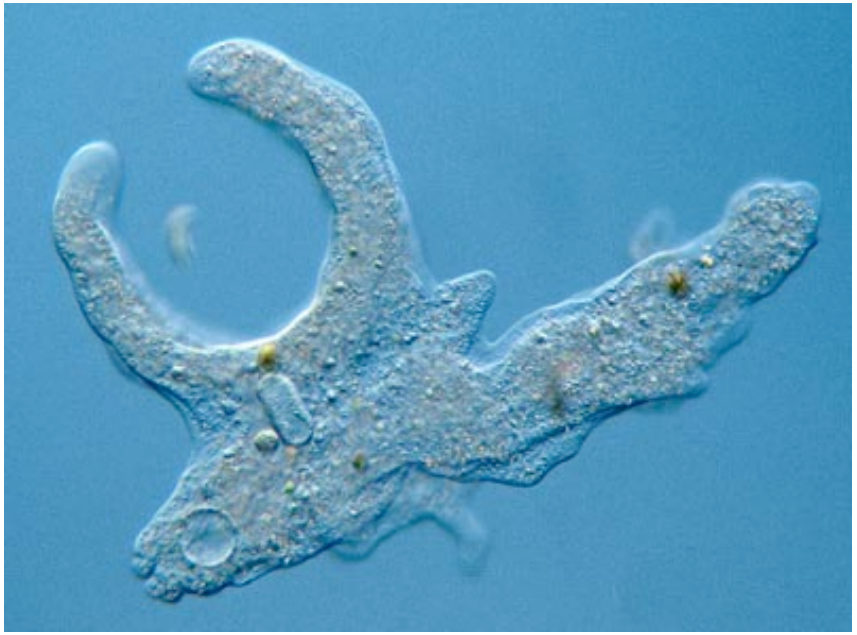
Martian Meteorite: LUCA?

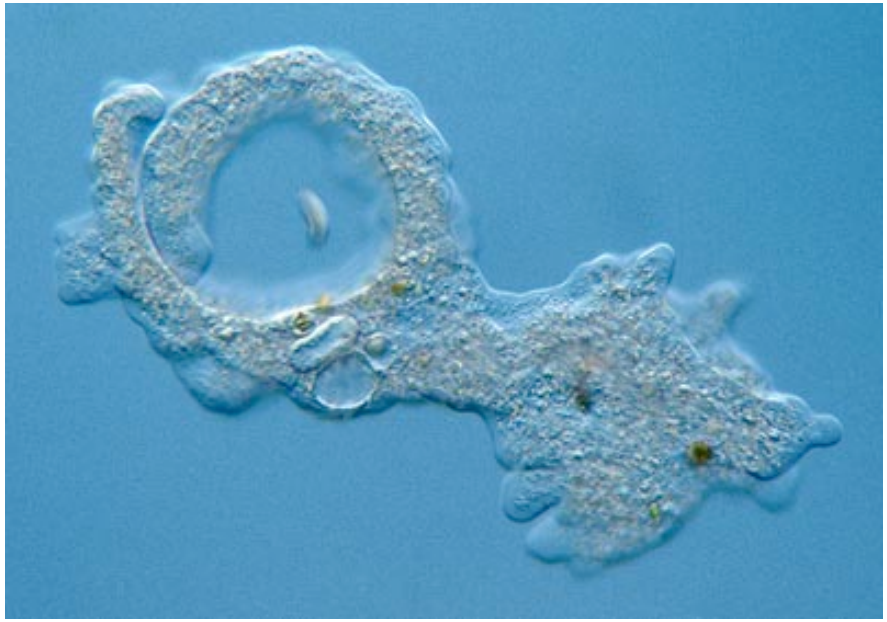


Most likely product of contamination from machine used by investigators?

If Martian meteorite really did supply LUCA, then we are all Martians!

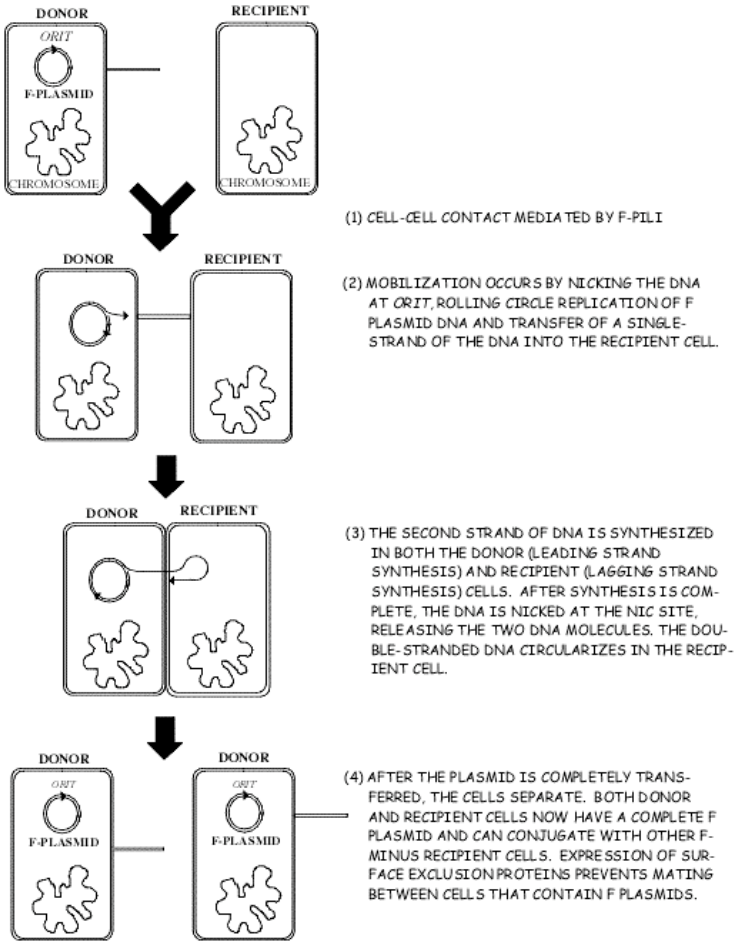
Amoeba Engulfing a Ciliate





The selection for cells with sufficient DNA to "remember" growing list of metabolic chains led to large size. Large scavenging cells can efficiently acquire nutrients by engulfing whole small cells. In one such episode, diner found dinner indigestible. If small ingested bacterium divided slowly and did not kill its host, host may produce daughter cells which contained examples of ingested bacterium. Later generations entered into a symbiotic relationship, whereby small bacterium took over duty of ATP production. Lynn Margulis has proposed symbiosis for the origin of mitochondria. Similar origin for chloroplasts from eating indigestible blue-green algae?

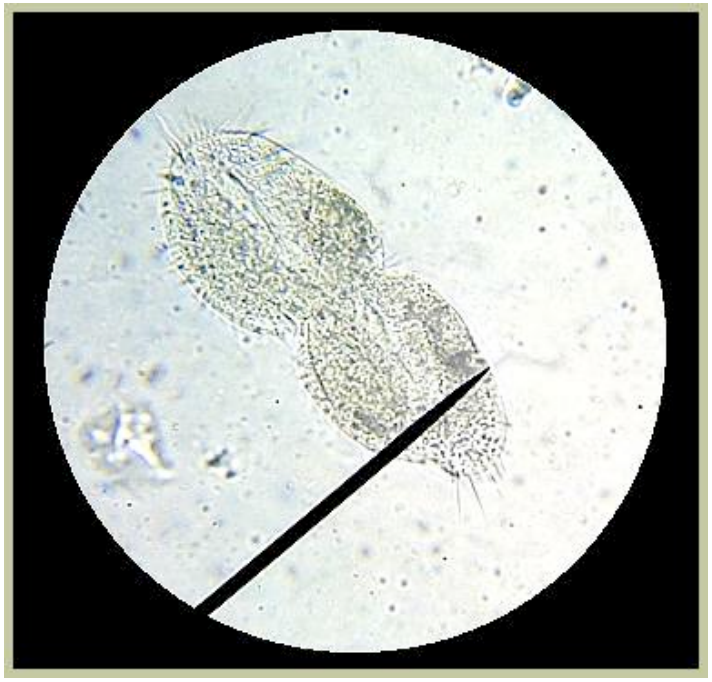
Conjugation: Bacterial Sex



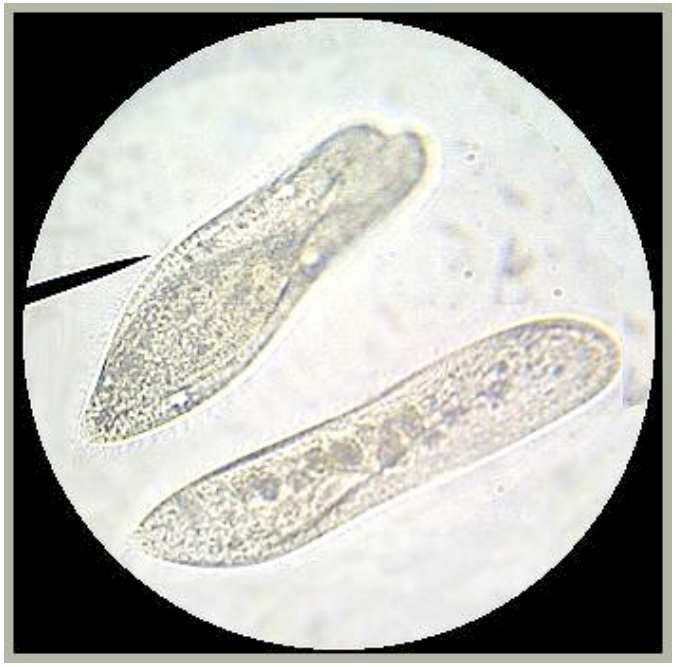
Such fusion processes may have been much more common in the past before cells developed sophisticated defense mechanisms against random mergers. The existence of smaller functional units (nucleus, mitochondria, chloroplasts, etc.) enclosed by membranes has many selective advantages. The appearance of eukaryotes, paving the way to multicellular organisms, was one of the most important events in the tree of life.

Paramecia
Dividing and Conjugating

Eukaryotes such as paramecia are capable of fairly sophisticated sex. Occasionally, two mating paramecia can fuse and form a doublet animal. These doublets have two sets of chromosomes and can reproduce by fission to give other doublets. Doublets can also revert back to singlets. Origin of diploid and haploid states and advanced sex?



Dividing paramecium

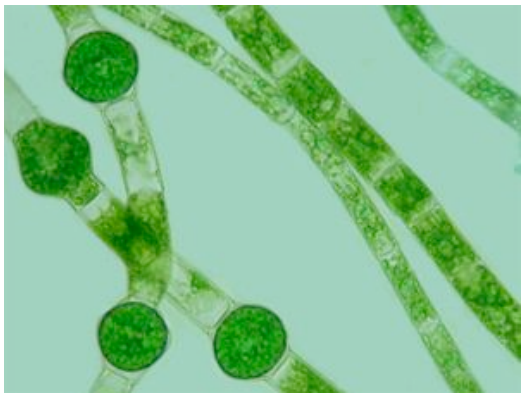


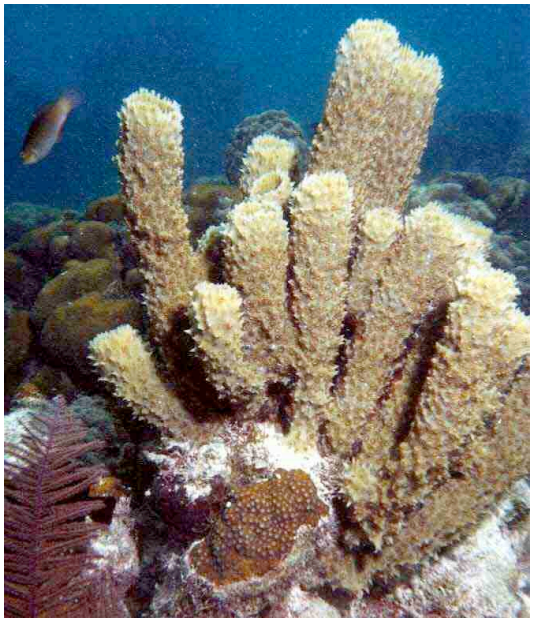
Doublet & singlet

Photo Credit: Ron DeAngelis

The Emergence of Multicellular Organisms Among Eukarya

- When there are predatory cells about, it pays to be as large as possible so that you cannot be engulfed. But there exists limits on how large a single cell can grow and still function efficiently. Solution: band together in colonies (filamentous green algae, sponges, etc.). Not directed!
- Advanced multicelluar organisms show more cell differentiation. Hallmark of higher organisms is ability of its cells to specialize to form tissues, different tissues to act collectively as organs, and different organs to coordinate activities to give the entire specimen.





Cell Differentiation & Complex Organisms

- *Fertilization* of egg by sperm produces an *embryo*.
- In the further development of a complex organism, the embryo produces different kinds of cells (such as *embryonic stem cells*), which divide and *differentiate into more specialized forms*.
- Different cells combine to form *tissues*, different tissues combine to form *organs*, different organs combine to form *organ systems*, different organ systems combine to form the *organism*.
- Through natural selection, *populations* of different organisms come *under environmental stress*, *adapt or become extinct, and evolve into new species*.

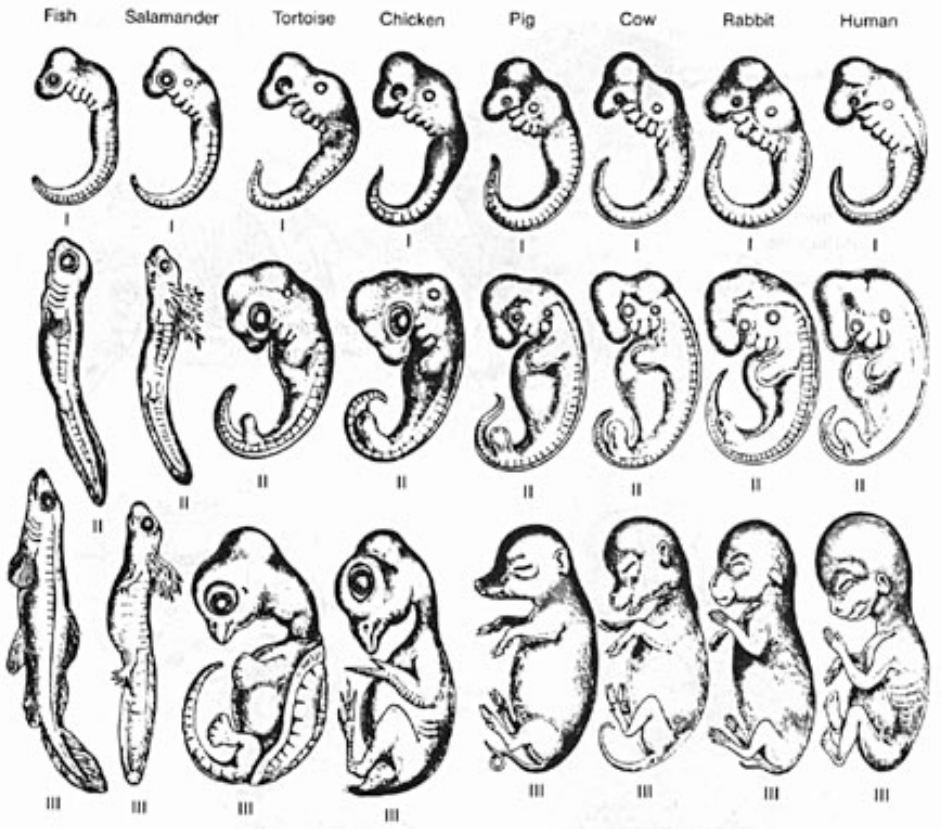
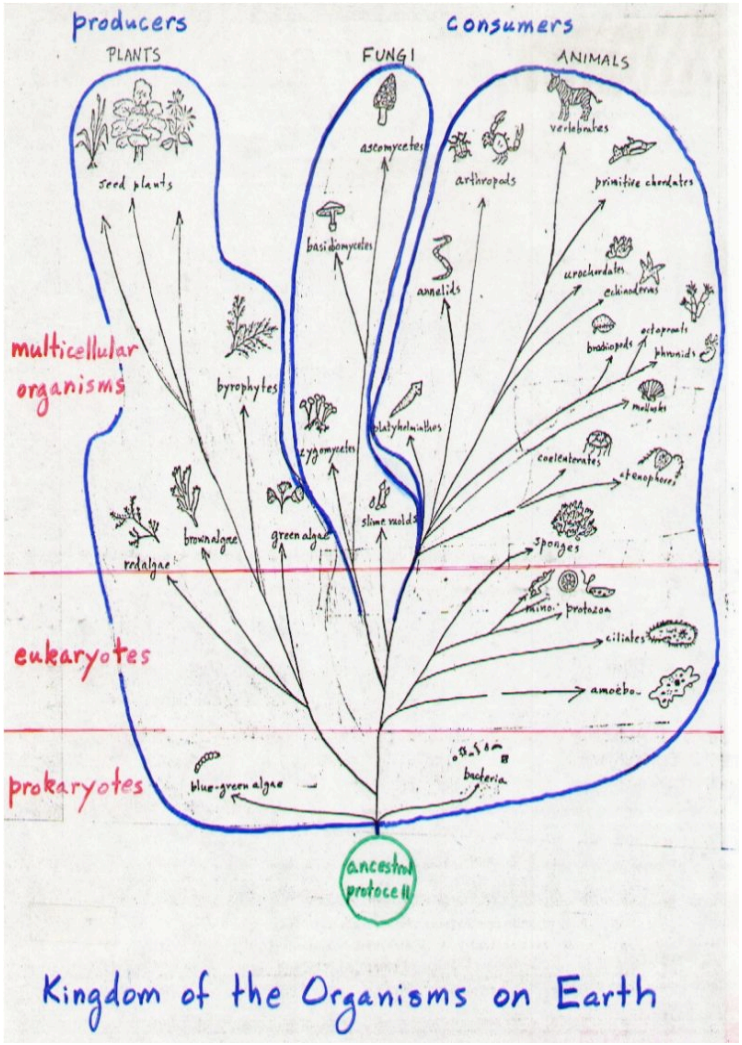


Figure 3–10

A series of embryos of different vertebrates at comparable stages of development. The earlier the stage of development, the more strikingly similar are the different groups. Note that each of the embryos begins with a similar number of gill arches (pouches below the head) and a similar vertebral column. In later stages of development, these and other structures are modified to yield the various different forms. (The embryos in the different groups have been scaled to the same approximate size so that comparisons can be made between them.) (From Romanes, adapted from Haeckel.)

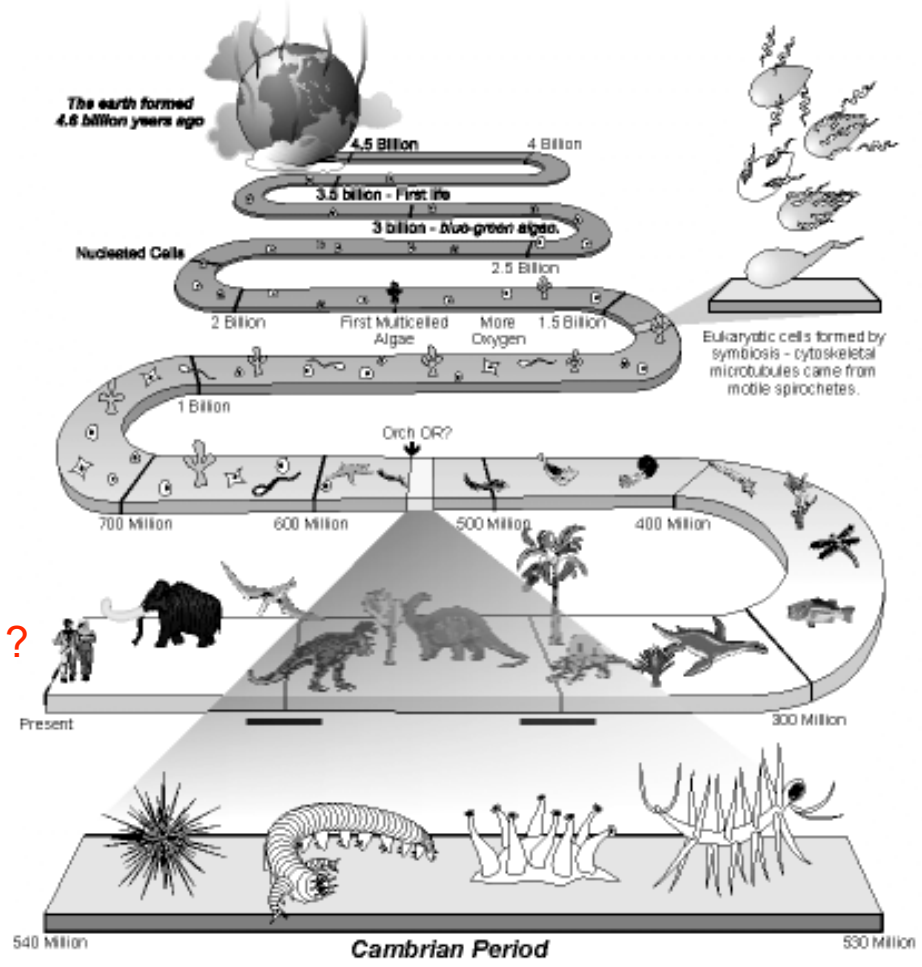
Charles Darwin: “The Origin of Species” and the Tree of Life

“It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with many worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us. These laws, taken in the largest sense, being Growth and Reproduction; Inheritance, which is almost implied by Reproduction; Variability, from the direct and indirect external conditions of life, and from use and disuse; a Ratio of Increase so high as to lead to a Struggle for Life; and as a consequence to natural selection, entailing a Divergence of Character and the Extinction of less improved forms. Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows. There is grandeur in this view of life, with its several powers having been originally breathed into a few forms, or into one; and that while this earth has gone cycling according to the fixed laws of gravity, from so simple a beginning, endless forms, most beautiful and wonderful, have been, and are being, evolved.”



History of Life on Earth

When you leave class today, look around at the life teeming on campus. Realize then that not only are you related to all the types of humans around you, but you are connected also to the squirrel in the tree, to the tree itself, as well as to the grass on the ground and the insects flitting in the air. An origin of life from inanimate matter even gives you a common bond with the air, rocks, and waters of Earth. And the atoms in everything came from the big bang and the stars. What a glorious thing indeed is life on Earth! Please help to preserve it.



Is the emergence of human intelligence good or bad for the future of life on Earth?