Life evolution

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Life evolution

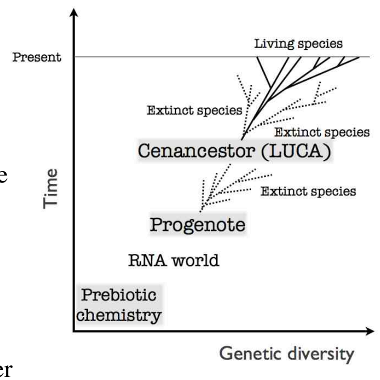
General considerations

- There is no clear distinction between the last stages of "life origin" and the first stages of "life evolution"
- The present-time living species are a small fraction of the total number of (extinct) species appeared in the course of evolution

After abiogenesis, life spreads on the planet and starts to influence the environment and its physical conditions

-The <u>co-evolution of life and its environment</u> should be considered together

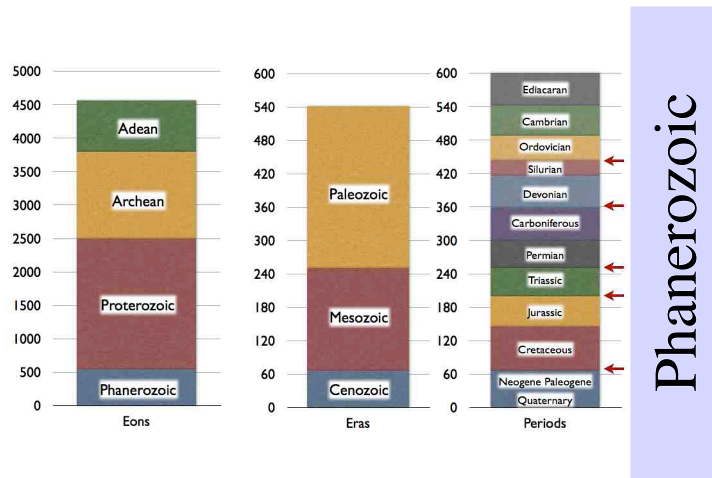
-Evolution of the <u>biosphere</u>



Methods of life-evolution studies

- Analysis of geological strata that include traces of past life
  - The strata can be dated accurately by means of radiodating techniques
  - The geochemical study of the strata provides the following possibilities:
    - finding traces of past biological activity even in the absence of macroscopic fossil records
    - deducing the physico/chemical conditions of the environment that hosted the ancient forms of life
- Phylogenetic analysis
  - Provides evidence of the evolution at the molecular level
  - Relative (but not absolute) dating can be obtained

Geological time scale

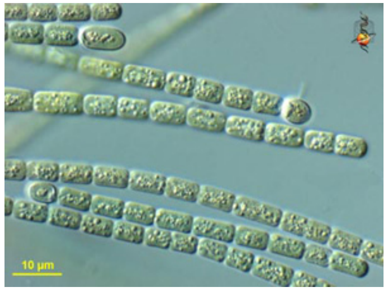


Important steps in the evolution of terrestrial life

after the emergence of fully-developed cells
with DNA-proteins machinery enclosed in biological membranes

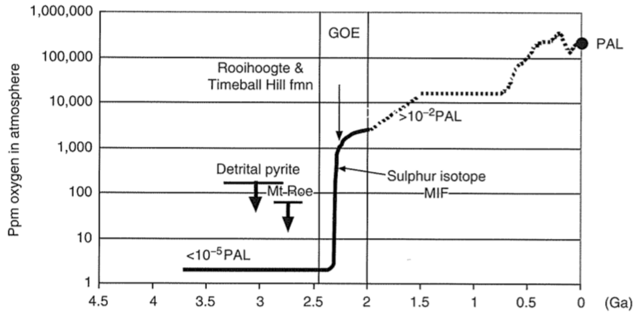
Development of photosynthesis

- Photosynthesis
  - Energy source not limited in time and available on all the planet surface
  - Greater possibility of life expansion
- First photosynthetic systems already present around the mid archean
  - Mostly anoxygenic systems
    - in bacteria, but not in archaea
  - Green bacteria, purple bacteria (sulfur and non-sulfur types)
- Oxygenic photosynthesis was surely present at 2.9 Ga, perhaps even much earlier
  - Cyanobacteria



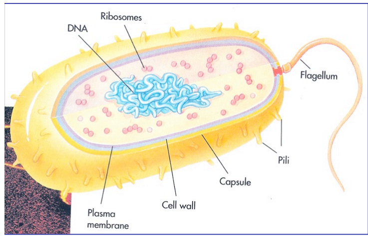
The "great oxidation event"

- The oxygen produced by photosynthesis is initially consumed by oxidation of the minerals present on the Earth surface
  - For a long period of time the level of atmospheric oxygen does not increase
- Between 2.5 and 2.0 Ga there is a sudden rise of the atmospheric oxygen
  - From ~1% PAL (Present Atmospheric Level), to ~10% circa 1.5 Ga

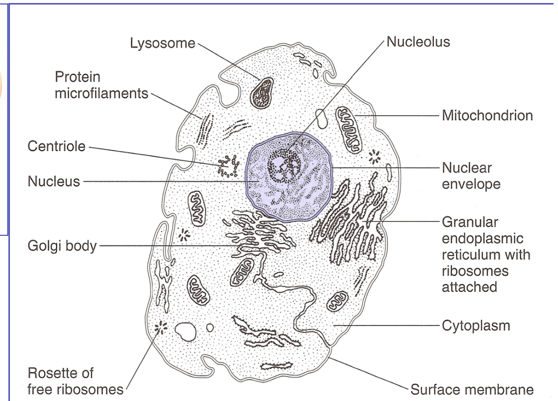


Emergence of eukaryotic cells

- From prokaryotic (archaea and bacteria) to eukaryotic cells
  - Eukaryotic cells have a much higher level of internal organization, featuring organelles with specific functional properties
- The oldest robust evidence of eukaryotes are dated at ~ 2.6-2.7 Ga
  - Likely to be present even before



Typical sizes
prokaryotes: 1 – 5 µm
eukaryotes: 10 – 100 µm



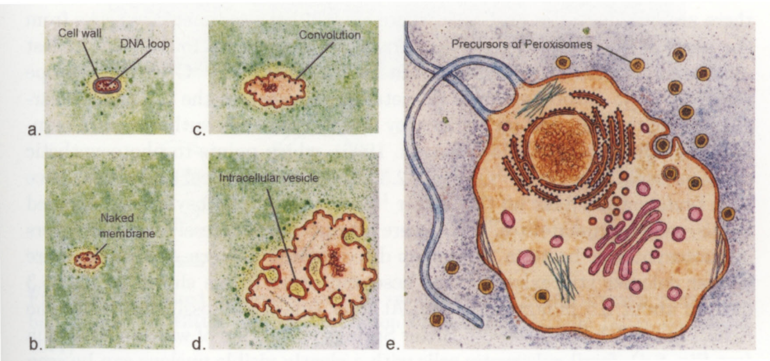
Emergence of eukaryotic cells

- The organelles are reminiscent of bacteria and their presence is interpreted as the result of a phenomenon of endosymbiosis

  Examples:

  chloroplasts reminiscent of <u>cyanobacteria</u> (photosynthesis)

  mitochondria reminiscent of <u>purple bacteria</u> (ATP production)

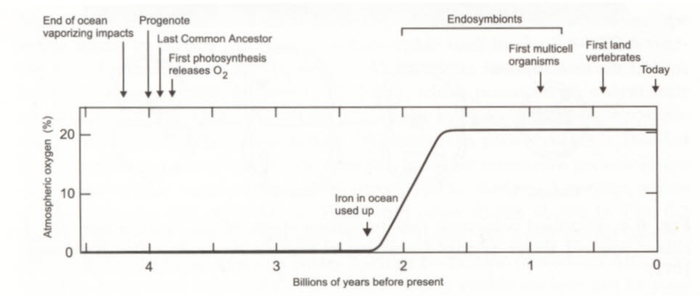


Appearance of multicellular organisms

- Multicellular organisms are characterized by a coordinated network of cells that, despite sharing the same DNA, are highly specialized and carry out different functions
  - Multicellular life possibly emerged as a response to environmental conditions
  - Unicellular organisms are not able to exploit all the potential resources offered by the environment
- Multicellular life emerged several times on Earth
  - Animals, plants and most fungi have emerged through independent evolutionary pathways

Appearance of multicellular organisms

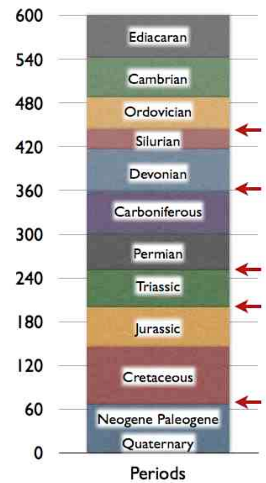
- Multicellular life appears only after the emergence of eukaryotic cells
  - Prokaryotic cells only give rise to unicellular organisms
- Multicellular organisms probably appear around 1.0-0.8 Ga
- The increase of the oxygen level must have played an important role in the development of eukaryotes and multicellular organisms
  - *<u>Oxygen metabolism is more efficient than anaerobic metabolism</u>*



Evolution of macroscopic organisms

- Macroscopic organisms appear at ~ 0.6 Ga (Ediacaran)
  - About 3 billon years after the origin of life

- The Cambrian period features a fast development of all present-day species
  - Starting at 540 Ma ("Cambrian explosion")
- Major extinctions appear in the geological record (red arrows)
  - At intervals of the order of 10^8 years, but without a defined frequency
  - Extinctions lie at the border between geological periods



Last steps of life evolution

- Emergence of the homeothermy
  - –Most animals and plants are *poikilotherms*, i.e. they have little control of their internal temperature and are extremely sensitive to variations of ambient conditions
  - –Part of the animal kingdom developed the *homeothermy*, i.e. the capability of stabilizing the internal temperature in presence of (moderate) variations of ambient conditions
- Brain development
  - –Neural connections in the animal kingdom gradually developed functions of central control and brains
  - –Brains are extremely sensitive to temperature variations and are only present in homeotherms
- Self-conscious organisms
  - –A few millon years ago, about 3.5 billon years after the origin of life, self-conscious organisms emerged
  - –To our knowledge, this transition has occurred only once on Earth

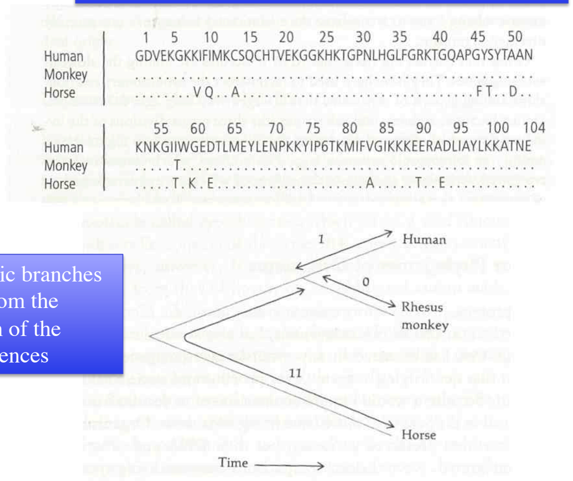
The mechanisms of evolution

- Natural selection
  - Individuals of a given species with genes best suited to adapt to a specific environmental change have better chances to transmit their genes to the following generations
  - The accumulation of the modified genetic pool in the course of generations leads to the origin of new species
  - At variance with non-scientific teleological interpretations, Darwinian evolution works *a posteriori*, favouring the most suitable variations for a given function that already exists
- Genetic variation
  - The capability of accumulating variations in the genetic pool is one of the key ingredients of evolution

    Variations of the genetic pool can be obtained through vertical and horizontal gene transfer; also mutations can provide a source of genetic variability, even though they tend to be destructive

Molecular evolutionary studies confirm results obtained from classic phenotype studies

Aminoacid sequence of one protein (cytochrome-c) present in humans, rhesus monkeys , and horses



Phylogenetic branches obtained from the comparison of the above sequences

Evolution of life in the Universe

Lessons learned from the evolution of terrestrial life

Open questions

Universality of the phenomenon of life evolution

Time scales

Probability of occurrence of the different stages of evolution

Natural selection as a universal phenomenon

The existence of the mechanism of natural selection is independent of the exact way in which the genetic information is coded and transmitted

Darwin deduced his theory of evolution, based on natural selection, without a knowledge of the molecular structures or the processes involved in the modification and accumulation of genetic information

Natural selection is a universal phenomenon that can occur in life different from the terrestrial one, as long as there are ways to store and transmit the genetic information accumulating variations

"Chance and necessity" in biological evolution

Jacques Monod (1970)

Evolution results from a combination of casual <u>and</u> deterministic processes

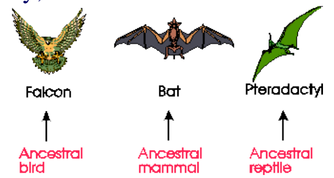
Genetic variations, via exchanges or mutations, occur in a random fashion and represent the <u>*chance*</u>

Natural selection filters those genetic variations that increase the adaptation to environmental pressure. Natural selection represents the <u>*necessity*</u>

Evolutionary convergence

- Independently evolved similarities present in unrelated species
  - Similarities developed as a result of similar environmental pressure
  - Many examples are known, demonstrated by the comparison of morphological and genetic features

A classic example is the development of wings, that took place several times, in independent way, in the course of evolution



- Evolutionary convergence is an example of the deterministic aspects of evolution
  - Similar developments (e.g. wings) can be expected also in life outside Earth, as a result of similar environmental pressure (e.g. need to fly)

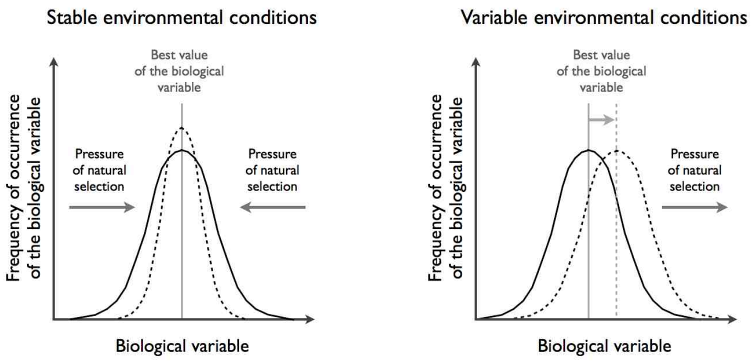
Time scales and probability of evolutionary steps

- The time scales of evolution of *terrestrial* life represent a significant fraction of cosmological time scales
  - About 2.5 billon years for the development of multicellular life
  - About 3.5 billon years for the development of a technological civilization

Open questions

- How universal are the time scales of terrestrial evolution?
  - Which conditions would make these time scales shorter or longer in other planets?
- What is the probability of occurrence of each evolutionary step?
  - Which conditions are required for the occurrence of the different steps of evolution?
- Answering these questions is fundamental to understand whether multicellular life or technological civilizations can be present in exoplanets

Rate of evolution and environmental changes



The rate of evolution is expected to correlate with the rate of variability of the environmental conditions

Planets with a relatively high variability of ambient conditions (in space and time) may trigger a faster biological evolution

Probability of occurrence of the different stages of life evolution

A possible way to cast light on the probability of occurrence of a given evolutionary step is to study the frequency of occurrence of the same step in the course of terrestrial evolution

- The appearance of multicellular organisms is one the few fundamental steps that has taken place several times (animals, plants and fungi)
  - The same step of evolution is likely to occur also in other worlds
- However, some important steps, like the appearance of self-consciousness, seem to have taken place only once
  - It is hard to assess which is the probability of occurrence of this important step of evolution

Frequency of macroscopic life in the Universe

The vast majority of terrestrial organisms is microscopic (unicellular) and has a relatively low level of internal organization (prokaryotes)

- Possible reasons:
  - Microscopic life requires less evolutionary steps and shorter time scales of evolution
  - Simple organisms have a larger flexibility of evolutionary adaptation

    Short time scales of reproduction
  - Microscopic organisms require less environmental resources
- Since the above reasons are universal, we expect evolution to yield a <u>prevalence of microscopic life</u> also in other worlds