Astrobiology
Lecture 12

Life evolution

Trieste University, Academic Year 2021-2022
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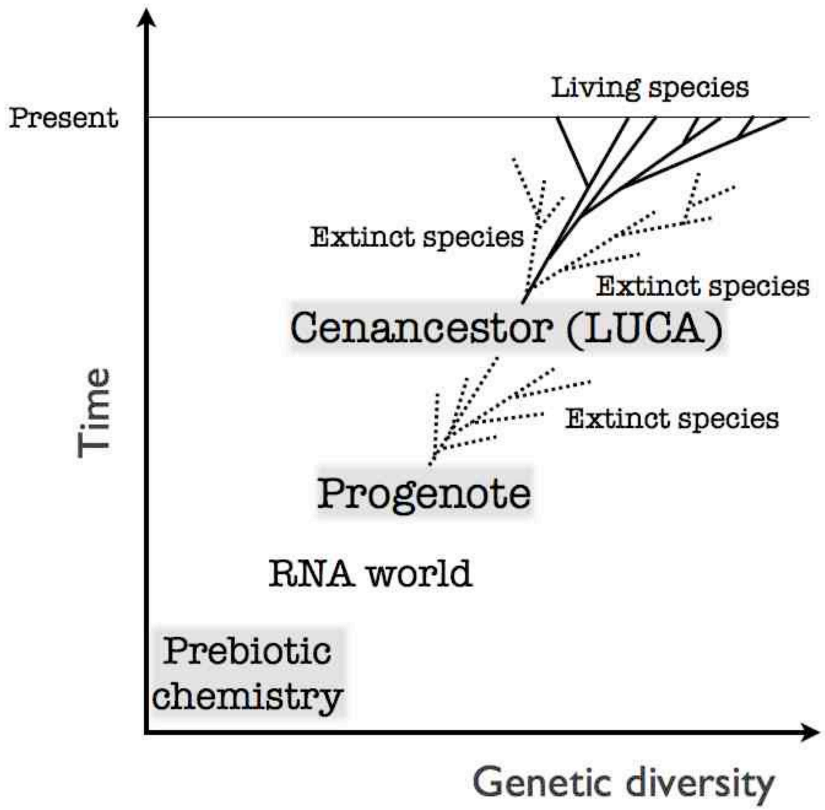
Life evolution

Understanding the evolution of terrestrial life is essential for understanding if multicellular and intelligent life may develop outside Earth



General considerations

- There is no clearcut distinction between the last stages of "life origin" and the first stages of "life evolution"
- Present-day species are a small fraction of the total number of (extinct) species appeared in the course of evolution

Life and the biosphere

After the abiogenesis, life spreads on the planet

Every environmental niche with resources and habitable conditions is colonized

Once life is widespread, the biosphere begins to influence significantly the chemical and physical conditions of the planet

- The co-evolution of life and its environment should be considered together
- Evolution of the biosphere

Life evolution

Theoretical framework: Darwinian theory of evolution

Involve both chance and necessity

(i.e. random and deterministic ingredients)

Darwinism has been succesfully tested in terrestrial life

At variance with non-scientific, teleological interpretations,

Darwinian evolution works *a posteriori*

Mechanisms of life evolution

- Genetic variation (random ingredient)
  - 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
- Natural selection (deterministic ingredient)
  - Individuals 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

Experimental methods for studies of life evolution

- Analysis of geological strata that include traces of past life
  - The strata can be dated accurately by means of radiodating techniques
  - From the geochemical study of the strata we can:

    find traces of past biological activity even in the absence of macroscopic fossil records

    deduce the physico/chemical conditions of the environment that hosted the fossil forms of life

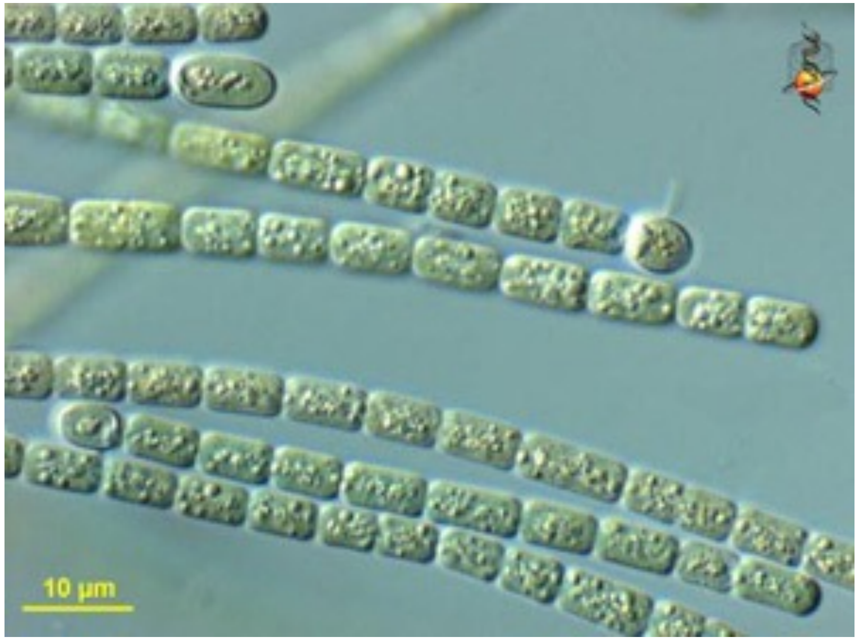
- Phylogenetic analysis
  - Provides evidence of the evolution at the molecular level
  - Only relative dating can be obtained (not absolute)

Important steps in the evolution of terrestrial life

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

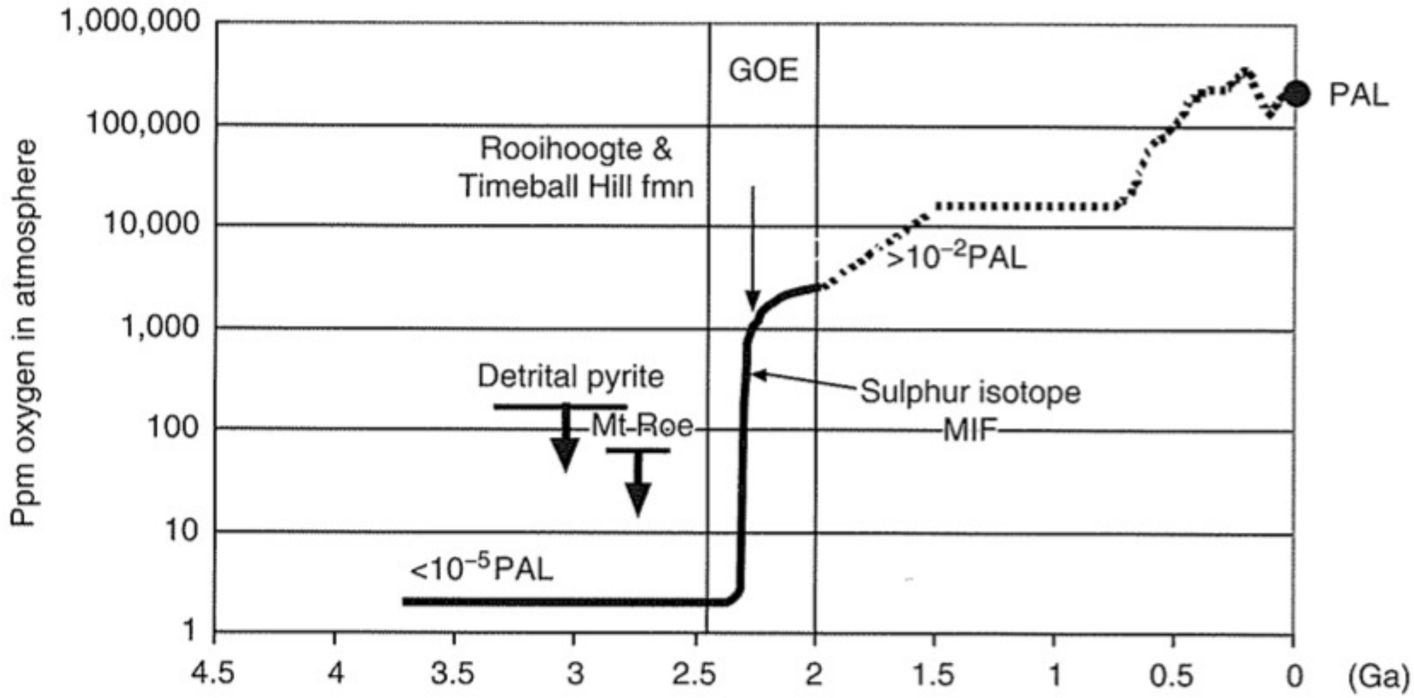
Development of photosynthesis

- 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 carry out oxygenic photosynthesis, up to the present time



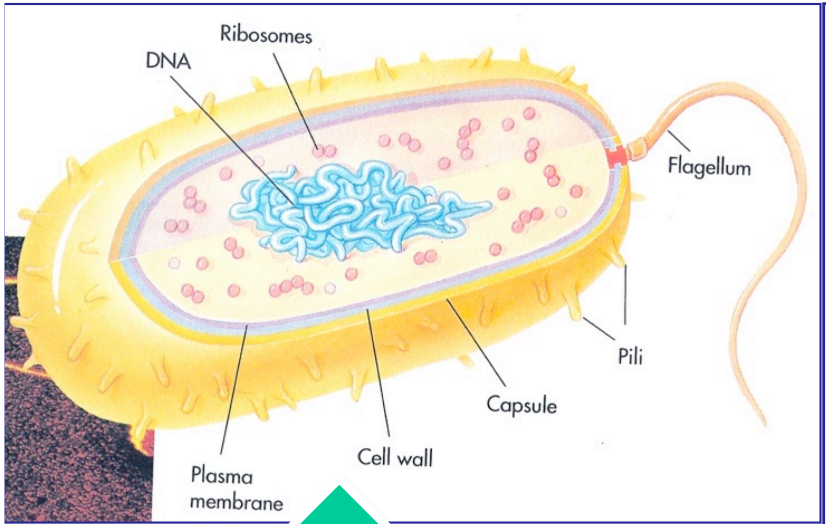
The “great oxidation event”

- 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



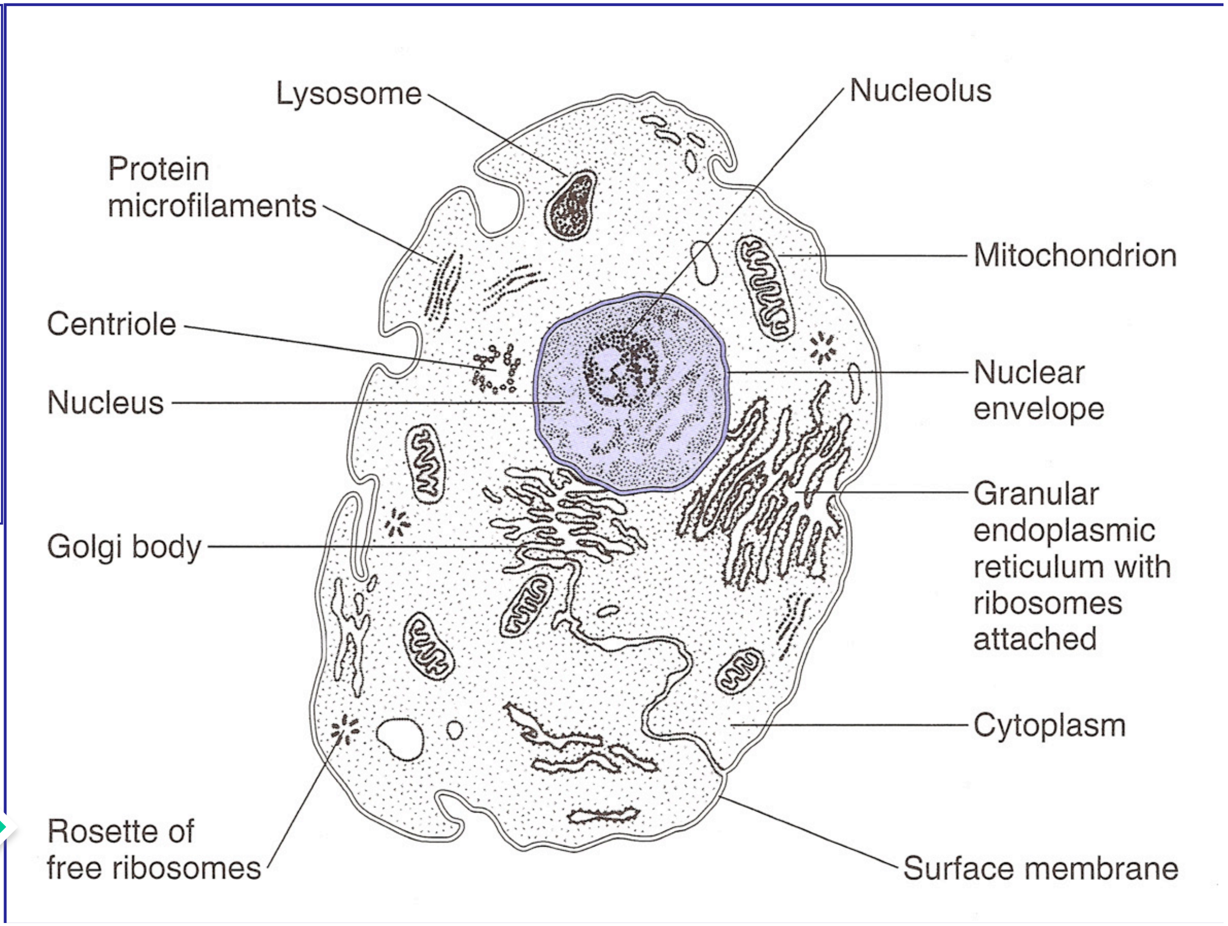
Emergence of eukaryotic cells

- 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



prokaryotes: 1 – 5 μm

eukaryotes: 10 – 100 μm



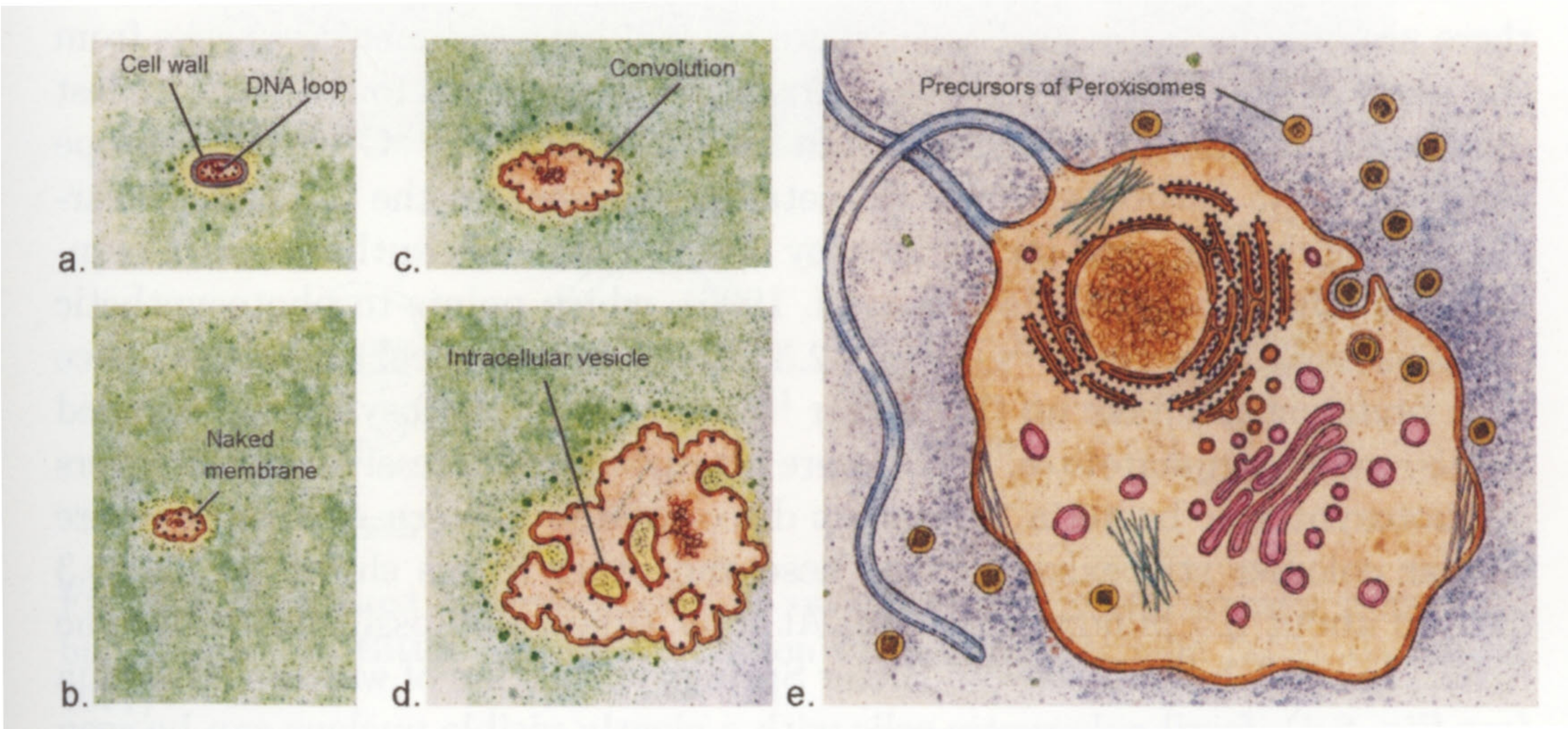
Emergence of eukaryotic cells

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

Examples:

chloroplasts reminiscent of cyanobacteria (photosynthesis)

mitochondria reminiscent of purple bacteria (ATP production)



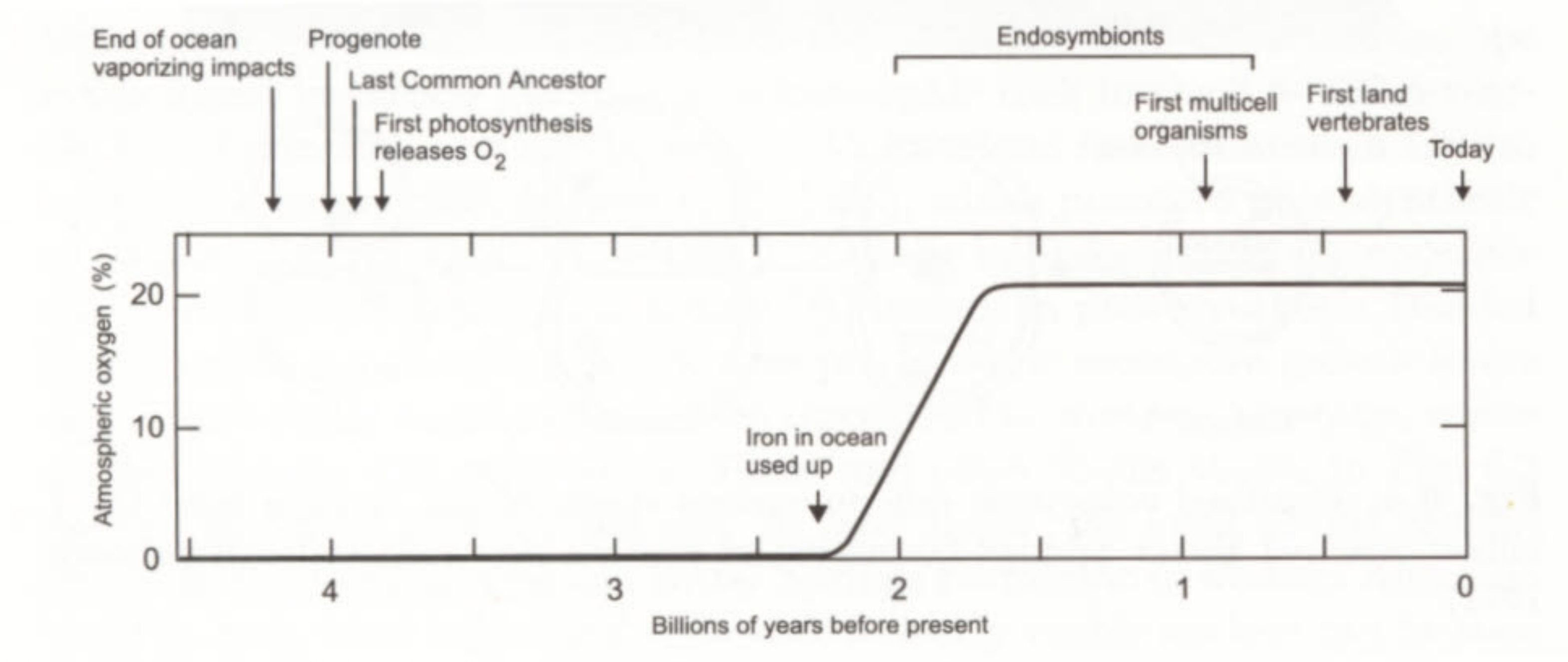
Appearance of multicellular organisms

- Multicellular organisms are characterized by a coordinated network of cells that, despite sharing the same genetic information, are highly specialized and carry out different functions
  - Multicellular life probably 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
  - Oxygen metabolism is more efficient than anaerobic metabolism

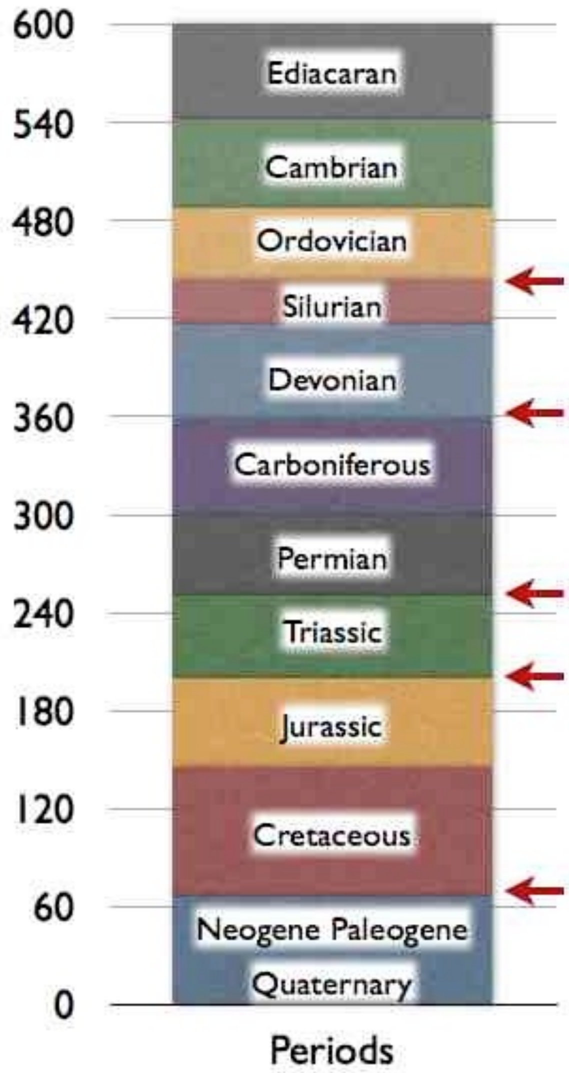


Evolution of macroscopic organisms

- 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
  - Homeothermy might have been a precondition for the emergence of brains

Last steps of life evolution

- Self-consciousness

  –Self-conscious organisms emerged only a few millon years ago, about 3.5 billon years after the origin of life

  –To our knowledge, this transition has occurred only once on Earth

  –On Earth, the appearance of self-consciousness required several steps, including oxygenic metabolism, complex cellular organization (eukaryotes), multicellularity, neural networks, homeothermy, brains

Evolution of life in the Universe

Some lessons learned from the evolution of terrestrial life

Universality of the phenomenon of life evolution

Evolutionary convergence

Frequency of multicellular life

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 organized

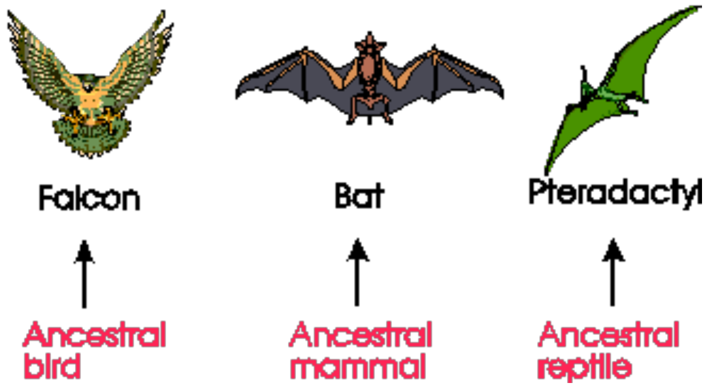
Darwin deduced his theory of evolution, based on natural selection, without a knowledge of the molecular structures or the processes involved in the modification and accumulation of genetic information

Natural selection is a universal concept that can be applied to any form of life, not just the terrestrial one, as long as genetic variations can accumulate in the course of subsequent generations

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
  - Implies that 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)

Frequency of unicellular life in the Universe

In spite of the growth of complexity in the course of evolution, 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
    - Evolution does not go backwards when the organism is complex
  - Microscopic organisms require less environmental resources

Frequency of multicellular life in the Universe

The number of multicellular species on Earth is miuch smaller than that of unicellular ones

- Possible reasons:
  - Multicellular life requires more evolutionary steps to emerge
  - Mulitcellular, macroscopi organisms have a lower flexibility of evolutionary adaptation
    - Longer time scales of reproduction
    - Evolution does not go backwards when the organism is complex
  - Macroscopic organisms require more environmental resources

Frequency of different types of life in the Universe

- Based on the above considerations, which are universal, we expect evolution to yield a prevalence of microscopic life also outside Earth

- Advanced forms of life evolution are expected to be more rare

  This is true, in particular, for the appearance of brains, which requires a large number of evolutionary steps