Life evolution

Planets and Astrobiology, Academic Year 2019-2020
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Life evolution

Essential for understanding how multicellular and intelligent life may emerge in extrasolar planetary systems

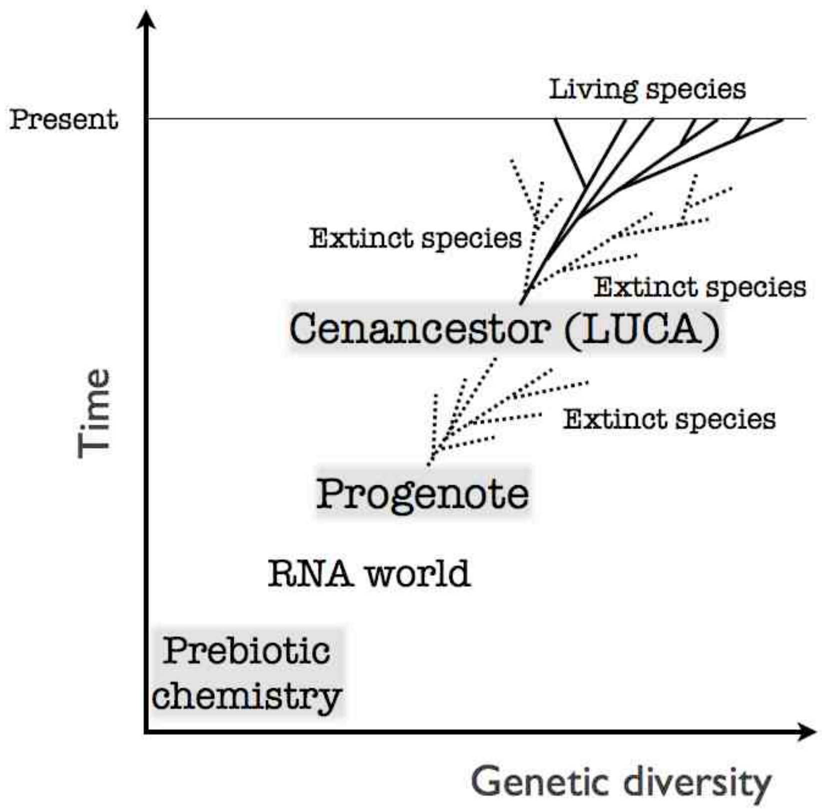
Theoretical scenario set up by the Darwinian theory of evolution
Involve both chance and necessity (i.e. random and deterministic ingredients)

Darwinism has been succesfully tested in terrestrial life

Life evolution

General considerations

- There is no 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 co-evolution of life and its environment should be considered together
- Evolution of the biosphere

Theoretical framework: mechanisms of life evolution

- Natural selection (deterministic ingredient)
  - 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 (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

Experimental methods for studies of life evolution

Mainly based on:

- 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

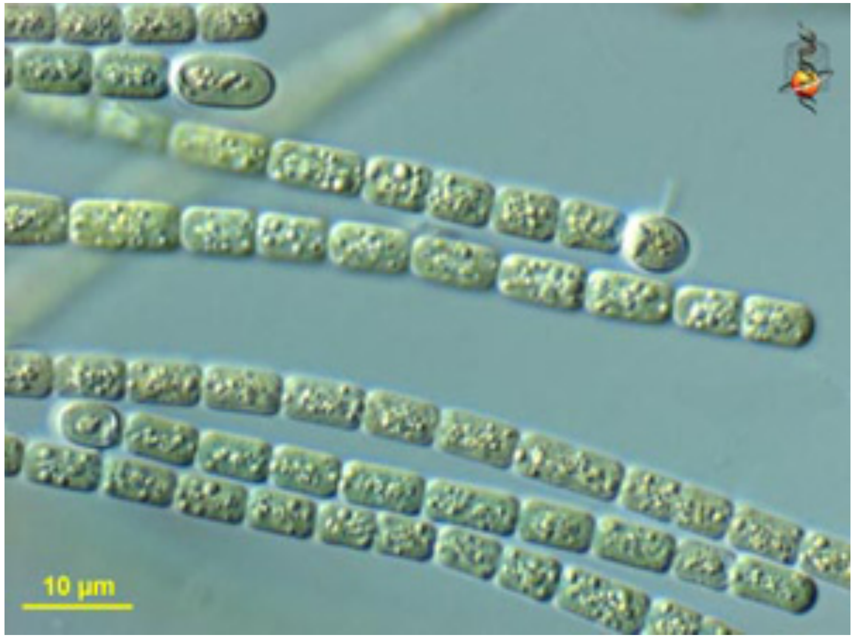
- Phylogenetic analysis
  - Provides evidence of the evolution at the molecular level
  - Relative (but not absolute) dating can be obtained

Important steps in the evolution of terrestrial life

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

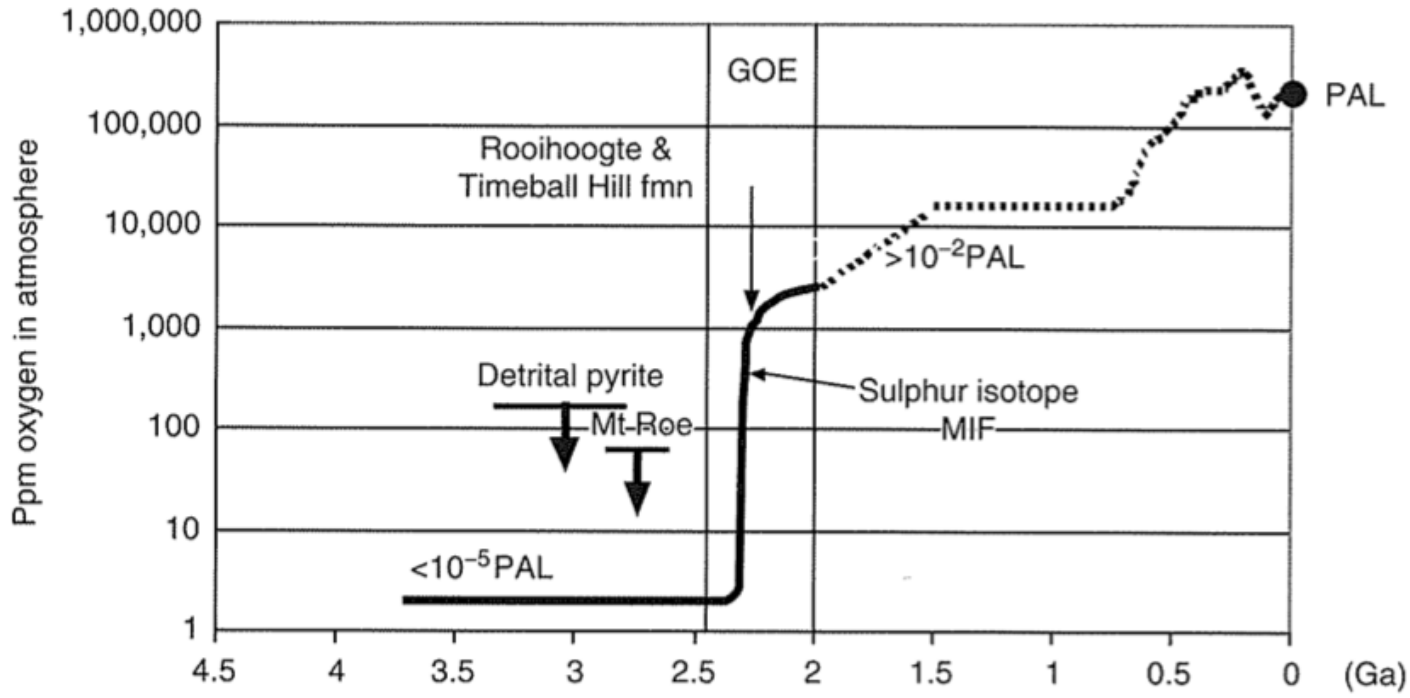
Development of photosynthesis

- 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



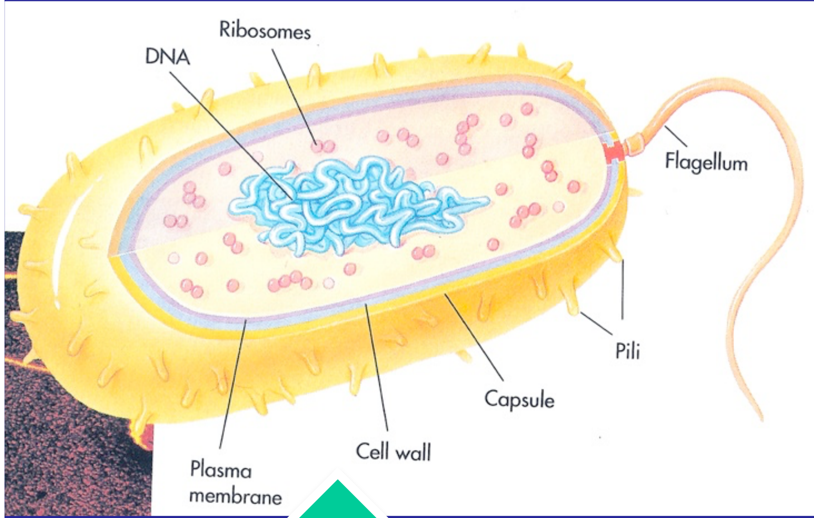
The "great oxidation event"

- 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



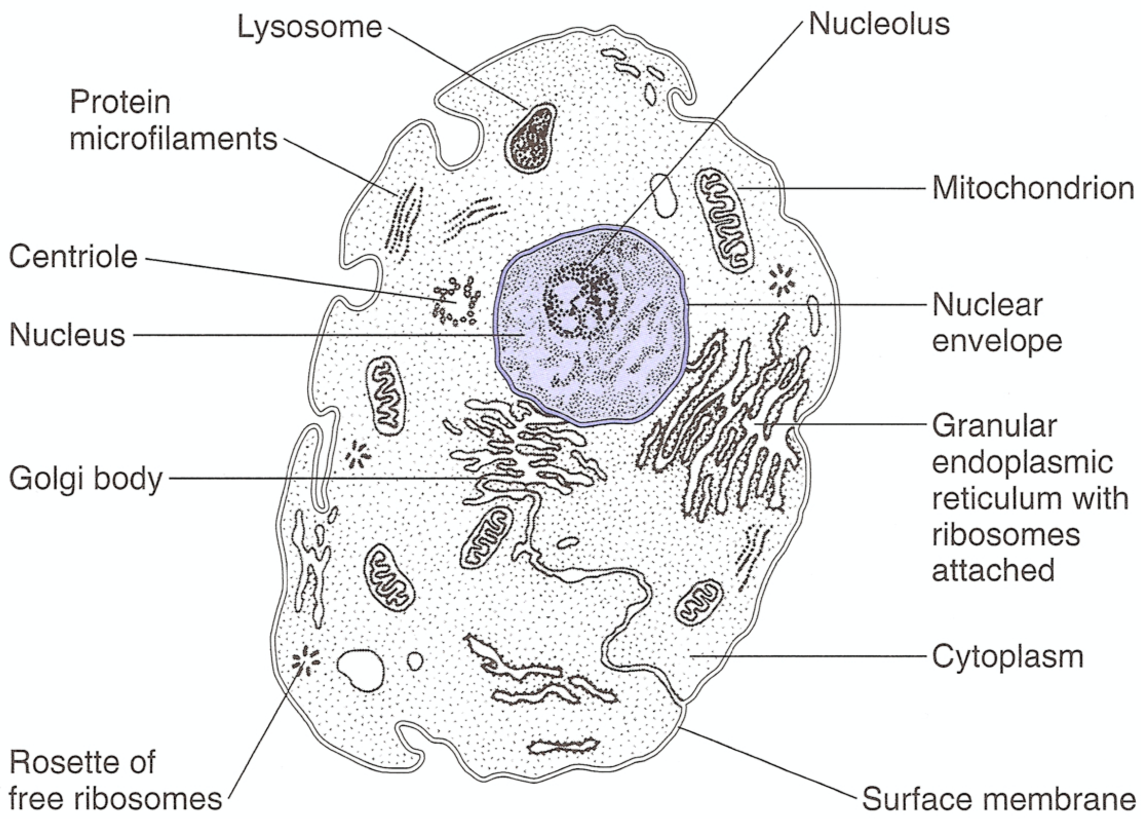
Emergence of eukaryotic cells

- From <u>prokaryotic</u> (archaea and bacteria) to <u>eukaryotic</u> 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



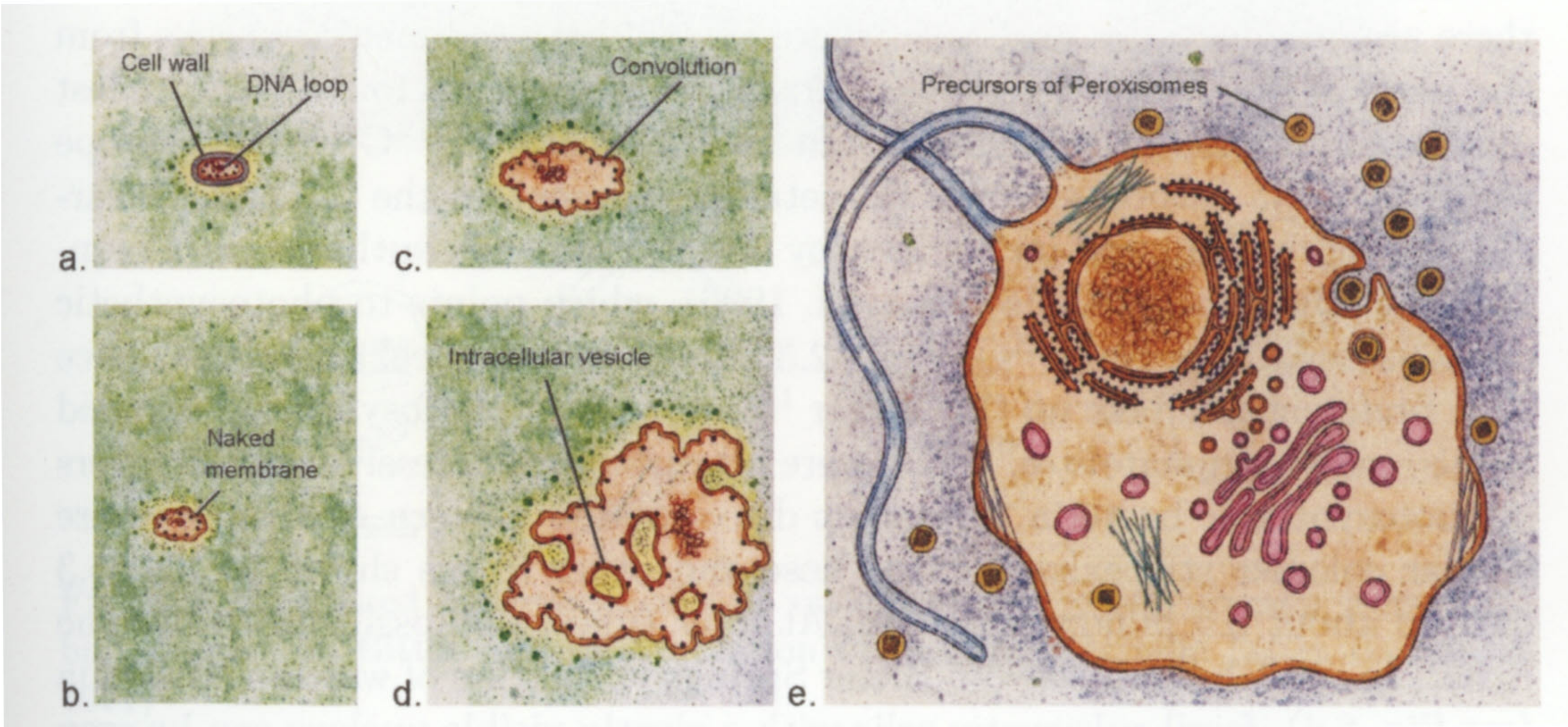
Emergence of eukaryotic cells

– 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)



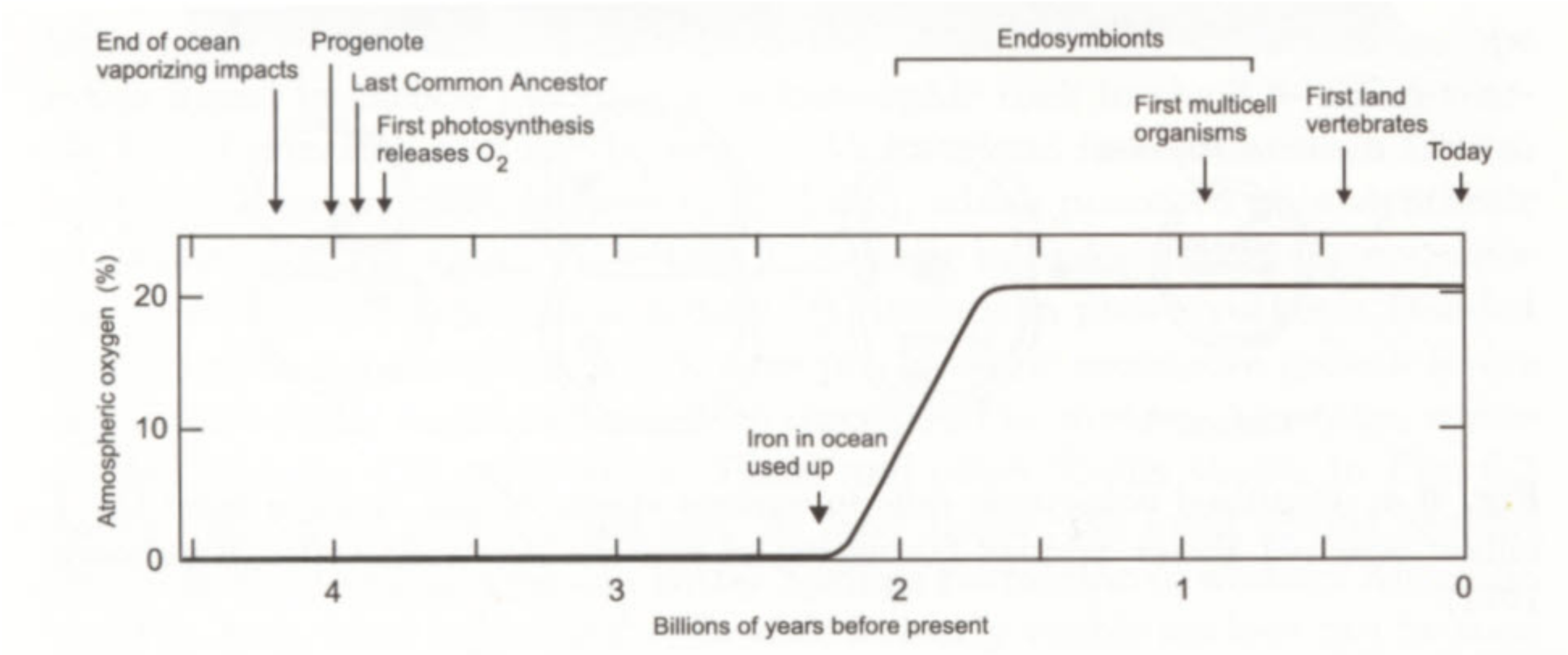
Appearance of multicellular organisms

- 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

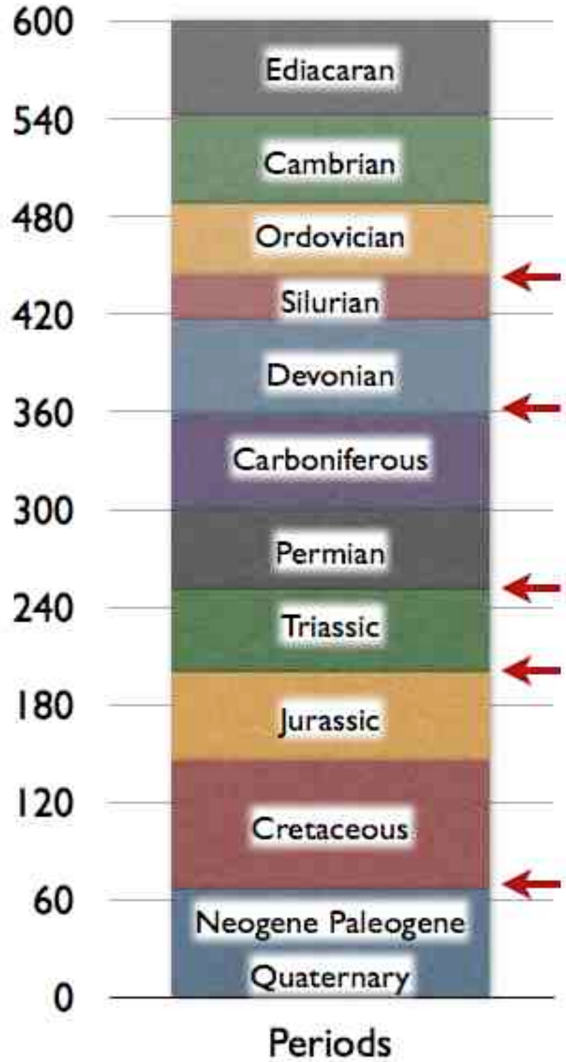


Evolution of macroscopic organisms

- 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
- 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

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

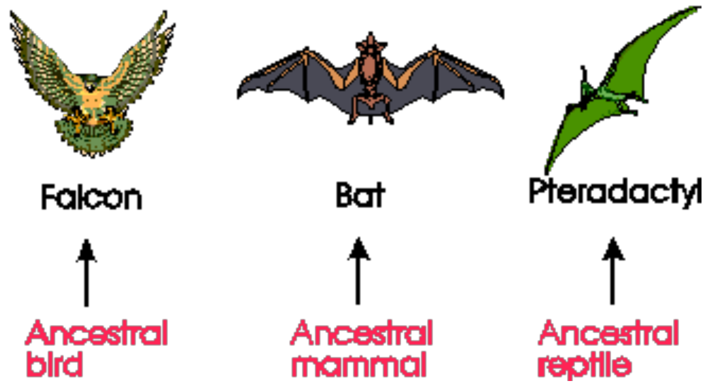
Darwin deduced his theory of evolution, based on natural selection, without a knowledge of the molecular structures or the processes involved in the modification and accumulation of genetic information

Natural selection is a universal concept that can be applied to any form of life, not just the terrestrial one, as long as there are ways to store and transmit the genetic information and accumulate variations

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 multicellular 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

- On the basis of the above considerations, which are universal, we expect evolution to yield a prevalence of microscopic life also in exoplanets