The History of Life on Earth

Chapter 25

Objectives

• Define radiometric dating, serial endosymbiosis, Pangaea, snowball Earth, exaptation, heterochrony, and paedomorphosis
• Describe the contributions made by Oparin, Haldane, Miller, and Urey toward understanding the origin of organic molecules
• Explain why RNA, not DNA, was likely the first genetic material
• Describe and suggest evidence for the major events in the history of life on Earth from Earth’s origin to 2 billion years ago

• Briefly describe the Cambrian explosion
• Explain how continental drift led to Australia’s unique flora and fauna
• Describe the mass extinctions that ended the Permian and Cretaceous periods
• Explain the function of Hox genes
Changing Life on a Changing Earth

• Life is a continuum extending from the earliest organisms to the great variety of species that exist today
• Geological events that alter environments change the course of biological evolution
• Conversely, life changes the planet that it inhabits

The Origin of Life

• Conditions on early Earth made the origin of life possible
  – Most biologists now think that it is at least a credible hypothesis that chemical and physical processes on early Earth produced very simple cells through a sequence of stages
According to one hypothetical scenario there were four main stages in this process:
  - abiotic synthesis of small organic molecules
  - joining of these small molecules into macromolecules
  - packaging of molecules into “protobionts”
  - origin of self-replicating molecules

Synthesis of Organic Compounds on Early Earth

- Earth formed about 4.6 billion years ago along with the rest of the solar system
- Earth’s early atmosphere contained water vapor and many chemicals released by volcanic eruptions
  - Laboratory experiments simulating an early Earth atmosphere have produced organic molecules from inorganic precursors, but the existence of such an atmosphere on early Earth is certain

Miller and Urey set up a closed system in their laboratory to simulate conditions thought to have existed on early Earth. A warmed flask of water simulated the primeval sea. The strongly reducing “atmosphere” in the system consisted of H₂, methane (CH₄), ammonia (NH₃), and water vapor. Sparks were discharged in the synthetic atmosphere to mimic lightning. A condenser cooled the atmosphere, raining water and any dissolved compounds into the miniature sea.

As material circulated through the apparatus, Miller and Urey periodically collected samples for analysis. They identified a variety of organic molecules, including amino acids such as alanine and glutamic acid that are common in the proteins of organisms. They also found many other amino acids and complex, oily hydrocarbons.

Organic molecules, a first step in the origin of life, can form in a strongly reducing atmosphere.
Instead of forming in the atmosphere, the first organic compounds on Earth may have been synthesized near submerged volcanoes and deep-sea vents.
Extraterrestrial Sources of Organic Compounds

- Some of the organic compounds from which the first life on Earth arose may have come from space
  - Carbon compounds have been found in some of the meteorites that have landed on Earth

Looking Outside Earth for Clues About the Origin of Life

- The possibility that life is not restricted to Earth is becoming more accessible to scientific testing

Abiotic Synthesis of Polymers
Protobionts

• Protobionts are aggregates of abiotically produced molecules surrounded by a membrane or membrane-like structure
  – Small organic molecules polymerize when they are concentrated on hot sand, clay, or rock
  – Protobionts form spontaneously from abiotically produced organic compounds
    • For example, small membrane-bounded droplets called liposomes can form when lipids or other organic molecules are added to water

The “RNA World” and the Dawn of Natural Selection

• The first genetic material was probably RNA, not DNA
• RNA molecules called ribozymes have been found to catalyze many different reactions, including:
  – Self-splicing
  – Making complementary copies of short stretches of their own sequence or other short pieces of RNA
Early protobionts with self-replicating, catalytic RNA would have been more effective at using resources and would have increased in number through natural selection.

The Fossil Record

- The fossil record chronicles life on Earth
  - Careful study of fossils opens a window into the lives of organisms that existed long ago and provides information about the evolution of life over billions of years.
How Rocks and Fossils Are Dated

- Sedimentary strata reveal the relative ages of fossils
  - Index fossils are similar fossils found in the same strata in different locations
    - Allow strata at one location to be correlated with strata at another location
  - The absolute ages of fossils can be determined by radiometric dating
The magnetism of rocks can also provide dating information
- Magnetic reversals of the north and south magnetic poles have occurred repeatedly in the past
  - Leave their record on rocks throughout the world

The Origin of New Groups of Organisms
- Fossil sequences detail the origins of new groups of organisms
  - Mammals belong to the group of animals called tetrapods
    - The evolution of unique mammalian features through gradual modifications can be traced from ancestral synapsids through the present

![Diagram showing the evolution of synapsids and mammals](image-url)
The Geologic Record

• By studying rocks and fossils at many different sites geologists have established a geologic record of Earth's history
• The geologic record is divided into:
  – Three eons: the Archaean, the Proterozoic, and the Phanerozoic
    • Many eras and periods
  – Many of these time periods mark major changes in the composition of fossil species

• The analogy of a clock can be used to place major events in the Earth's history in the context of the geological record
The Early History of Life

- The oldest known fossils are stromatolites
  - These are rocklike structures composed of many layers of bacteria and sediment which date back 3.5 billion years ago
- Prokaryotes were Earth’s sole inhabitants from 3.5 to about 2 billion years ago
- As prokaryotes evolved, they exploited and changed young Earth
Photosynthesis and the Oxygen Revolution

• The earliest types of photosynthesis did not produce oxygen
  – These systems were probably similar in structure and function to cyclic photophosphorylation in modern plants
• Oxygenic photosynthesis probably evolved about 3.5 billion years ago in cyanobacteria
  – The evidence for this is the first appearance of bands of iron oxide in ancient sea beds dating from this time period

• When oxygen began to accumulate in the atmosphere about 2.7 billion years ago it posed a challenge for life
  – It provided an opportunity to gain abundant energy from light
  – It provided organisms an opportunity to exploit new ecosystems
The Origins of Eukaryotes

- The oldest fossils of eukaryotic cells date back 2.1 billion years
  - Among the most fundamental questions in biology is how complex eukaryotic cells evolved from much simpler prokaryotic cells
  - Eukaryotic cells arose from symbioses and genetic exchanges between prokaryotes
    - The theory of endosymbiosis proposes that mitochondria and plastids were formerly small prokaryotes living within larger host cells
      - The prokaryotic ancestors of mitochondria and plastids probably gained entry to the host cell as undigested prey or internal parasites

- In the process of becoming more interdependent the host and endosymbionts would have become a single organism
  - The evidence supporting an endosymbiotic origin of mitochondria and plastids includes similarities in inner membrane structures and functions
  - Both have their own circular DNA
Eukaryotic Cells as Genetic Chimeras

- Additional endosymbiotic events and horizontal gene transfers may have contributed to the large genomes and complex cellular structures of eukaryotic cells
  - Some investigators have speculated that eukaryotic flagella and cilia evolved from symbiotic bacteria, based on symbiotic relationships between some bacteria and protozoans

The Origin of Multicellularity

- Multicellularity evolved several times in eukaryotes
- After the first eukaryotes evolved a great range of unicellular forms evolved
  - Multicellular forms evolved also

The Earliest Multicellular Eukaryotes

- Molecular clocks date the common ancestor of multicellular eukaryotes to 1.5 billion years
  - The oldest known fossils of eukaryotes are of relatively small algae that lived about 1.2 billion years ago
- Larger organisms do not appear in the fossil record until several hundred million years later
  - Chinese paleontologists recently described 570-million-year-old fossils that are probably animal embryos
The Colonial Connection

- The first multicellular organisms were colonies
  - Collections of autonomously replicating cells
- Some cells in the colonies became specialized for different functions
  - The first cellular specializations had already appeared in the prokaryotic world

The “Cambrian Explosion”

- Most of the major phyla of animals appear suddenly in the fossil record that was laid down during the first 20 million years of the Cambrian period
Fossils of two animal phyla, Cnidaria and Porifera, are somewhat older, dating from the late Proterozoic. Molecular evidence suggests that many animal phyla originated and began to diverge much earlier, between 1 billion and 700 million years ago.

Colonization of Land by Plants, Fungi, and Animals

- Plants, fungi, and animals colonized land about 500 million years ago.
- Symbiotic relationships between plants and fungi are common today and date from this time.
Continental Drift

- Earth’s continents are not fixed
  - They drift across our planet’s surface on great plates of crust that float on the hot underlying mantle
  - Often, these plates slide along the boundary of other plates pulling apart or pushing against each other
- Many important geological processes occur at plate boundaries or at weak points in the plates themselves
• The formation of the supercontinent Pangaea during the late Paleozoic era and its breakup during the Mesozoic era explain many biogeographic puzzles.

Mass Extinctions

• The fossil record chronicles a number of occasions when global environmental changes were so rapid and disruptive that a majority of species were swept away
  – Two major mass extinctions, the Permian and the Cretaceous have received the most attention
  – The Permian extinction claimed about 96% of marine animal species and 8 out of 27 orders of insects and is thought to have been caused by enormous volcanic eruptions.
The Cretaceous extinction doomed many marine and terrestrial organisms, most notably the dinosaurs and is thought to have been caused by the impact of a large meteor.
• Much remains to be learned about the causes of mass extinctions but it is clear that they provided life with unparalleled opportunities for adaptive radiations into newly vacated ecological niches.
Adaptive Radiation

- Adaptive radiation is the evolution of diversely adapted species from a common ancestor upon introduction to new environmental opportunities.

Worldwide Adaptive Radiations

- Mammals underwent an adaptive radiation after the extinction of terrestrial dinosaurs:
  - The disappearance of dinosaurs (except birds) allowed for the expansion of mammals in diversity and size.
- Other notable radiations include photosynthetic prokaryotes, large predators in the Cambrian, land plants, insects, and tetrapods.
Regional Adaptive Radiations

• Adaptive radiations can occur when organisms colonize new environments with little competition
  – The Hawaiian archipelago is one of the world’s great showcases of adaptive radiation

Studying the Genetics of Speciation

• The explosion of genomics is enabling researchers to identify specific genes involved in some cases of speciation
Evolution of the Genes That Control Development

• Genes that program development control the rate, timing, and spatial pattern of changes in an organism’s form as it develops into an adult

Changes in Rate and Timing

• Heterochrony is an evolutionary change in the rate or timing of developmental events
  – It can have a significant impact on body shape
• Allometric growth is the proportioning that helps give a body its specific form
  – Different allometric patterns contribute to the contrasting shapes of human and chimpanzee skulls
• Heterochrony can alter the timing of reproductive development relative to the development of nonreproductive organs.
  – In paedomorphosis the rate of reproductive development accelerates compared to somatic development.
  • The sexually mature species may retain body features that were juvenile structures in an ancestral species.

Changes in Spatial Pattern

• Substantial evolutionary change can also result from alterations in genes that control the placement and organization of body parts.
• Homeotic genes determine such basic features as where a pair of wings and a pair of legs will develop on a bird or how a flower’s parts are arranged.
• The products of one class of homeotic genes called *Hox* genes provide positional information in the development of fins in fish and limbs in tetrapods.
• The evolution of vertebrates from invertebrate animals was associated with alterations in \textit{Hox} genes

Changes in Genes
• New morphological forms likely come from gene duplication events that produce new developmental genes
  – A possible mechanism for the evolution of six-legged insects from a many-legged crustacean ancestor has been demonstrated in lab experiments
    • Specific changes in the \textit{Ubx} gene have been identified that can "turn off" leg development
Changes in Gene Regulation

- Changes in the form of organisms may be caused more often by changes in the regulation of developmental genes instead of changes in their sequence.
  - For example, three-spine sticklebacks in lakes have fewer spines than their marine relatives.
    - The gene sequence remains the same, but the regulation of gene expression is different in the two groups of fish.

Results

Hypothesis A: Differences in sequence
Result: No
The 262 amino acids of the Pitx1 protein are identical.

Hypothesis B: Differences in expression
Marine stickleback embryo: expression in ventral spine and mouth regions
Lake stickleback embryo: expression only in mouth regions

Red arrows indicate regions of Pitx1 expression.
Evolution Is Not Goal Oriented

- Evolution is like tinkering—it is a process in which new forms arise by the slight modification of existing forms

Evolutionary Novelties

- Most novel biological structures evolve in many stages from previously existing structures
- Structures that are co-opted for a different purpose than its original role are known as exaptations
  - Some complex structures, such as the eye have had similar functions during all stages of their evolution
Evolutionary Trends

- The fossil record often shows apparent trends in evolution that may arise because of adaptation to a changing environment
  - According to the species selection model trends may result when species with certain characteristics endure longer and speciate more often than those with other characteristics
  - The appearance of an evolutionary trend does not imply that there is some intrinsic drive toward a particular phenotype