Chapter 15

Tracing Evolutionary History

PowerPoint Lectures for

***Biology: Concepts & Connections*, Sixth Edition**

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Lecture by Joan Sharp

Introduction: *On the Wings of Eagles, Bats, and Pterosaurs*

- Wings have evolved from vertebrate forelimbs in three groups of land vertebrates: pterosaurs, bats, and birds
- The separate origins of these three wings can be seen in their differences
  - Different bones support each wing
  - The flight surfaces of each wing differ

Introduction: *On the Wings of Eagles, Bats, and Pterosaurs*

- All three wings evolved from the same ancestral tetrapod limb by natural selection
- Major changes over evolutionary time (like the origin of wings) represent **macroevolution**

EARLY EARTH AND THE ORIGIN OF LIFE

15.1 Conditions on early Earth made the origin of life possible

- **A recipe for life**

Raw materials

+

Suitable environment

+

Energy sources

15.1 Conditions on early Earth made the origin of life possible

- The possible composition of Earth's early atmosphere
  - H_2O vapor and compounds released from volcanic eruptions, including N_2 and its oxides, CO_2, CH_4, NH_3, H_2, and H_2S
- As the Earth cooled, water vapor condensed into oceans, and most of the hydrogen escaped into space

15.1 Conditions on early Earth made the origin of life possible

- Many energy sources existed on the early Earth
  - Intense volcanic activity, lightning, and UV radiation

15.1 Conditions on early Earth made the origin of life possible

- Earth formed 4.6 billion years ago
- By 3.5 billion years ago, photosynthetic bacteria formed sandy stromatolite mats
- The first living things were much simpler and arose much earlier


CENTIMETRE
INCH

15.1 Conditions on early Earth made the origin of life possible

Chemical conditions → Abiotic synthesis of monomers ← Physical conditions

Stage 1 Abiotic synthesis of monomers

↓

Stage 2 Formation of polymers

↓

Stage 3 Packaging of polymers into *protobionts*

↓

Stage 4 Self-replication

15.2 TALKING ABOUT SCIENCE: Stanley Miller's experiments showed that the abiotic synthesis of organic molecules is possible

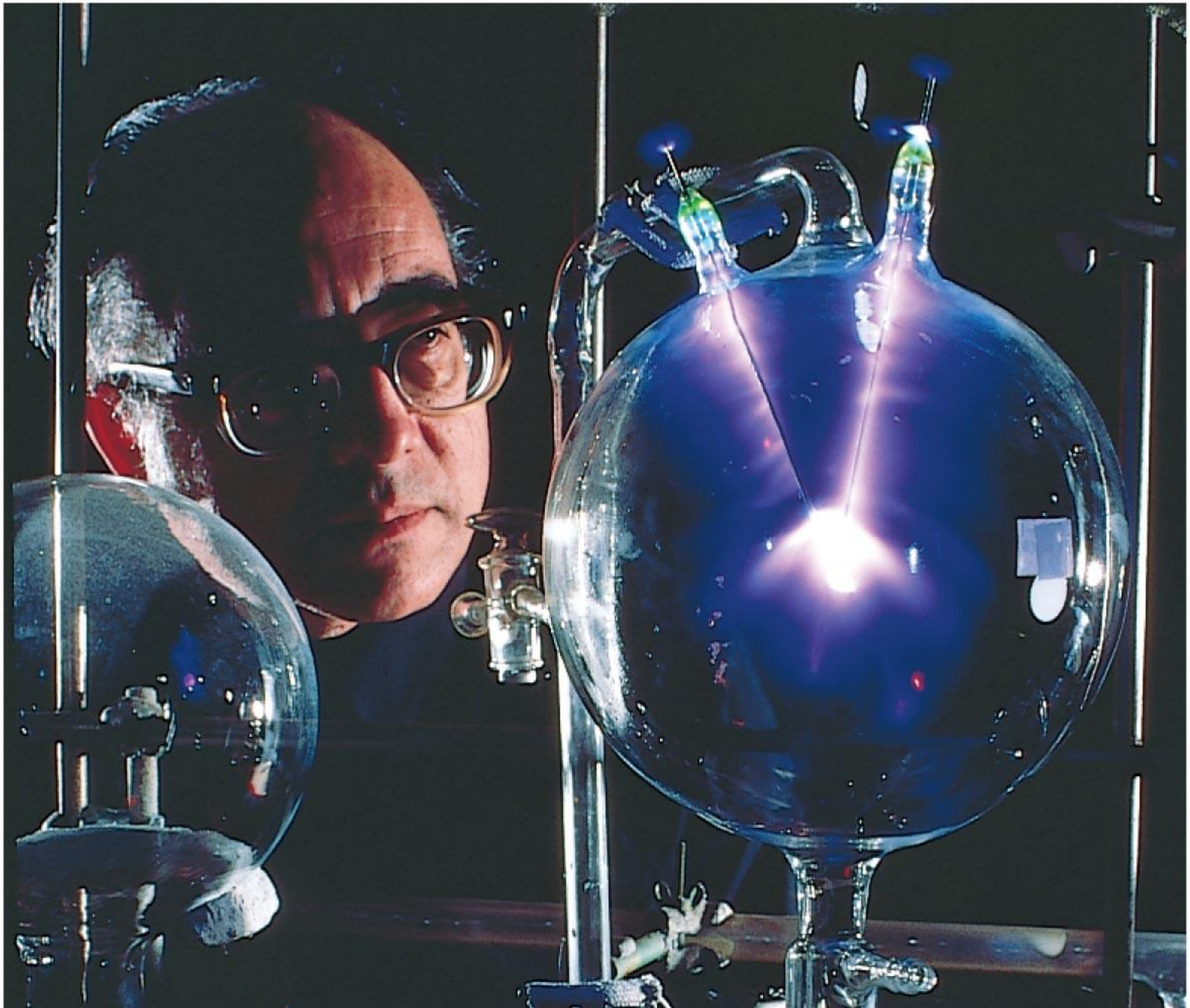
- In the 1920s, two scientists—the Russian A. I. Oparin and the British J. B. S. Haldane—independently proposed that organic molecules could have formed on the early Earth
- Modern atmosphere is rich in O_2, which oxidizes and disrupts chemical bonds
- The early Earth likely had a reducing atmosphere

15.2 TALKING ABOUT SCIENCE: Stanley Miller's experiments showed that the abiotic synthesis of organic molecules is possible

- In 1953, graduate student Stanley Miller tested the Oparin-Haldane hypothesis
  - Miller set up an airtight apparatus with gases circulating past an electrical discharge, to simulate conditions on the early Earth
  - He also set up a control with no electrical discharge
    - Why?

PLAY Video: Hydrothermal Vent

PLAY Video: Tubeworms



15.2 TALKING ABOUT SCIENCE: Stanley Miller's experiments showed that the abiotic synthesis of organic molecules is possible

- After a week, Miller's setup produced abundant amino acids and other organic molecules
  - Similar experiments used other atmospheres and other energy sources, with similar results
  - Miller-Urey experiments demonstrate that **Stage 1, abiotic synthesis of organic molecules**, was possible on the early Earth

15.2 TALKING ABOUT SCIENCE: Stanley Miller's experiments showed that the abiotic synthesis of organic molecules is possible

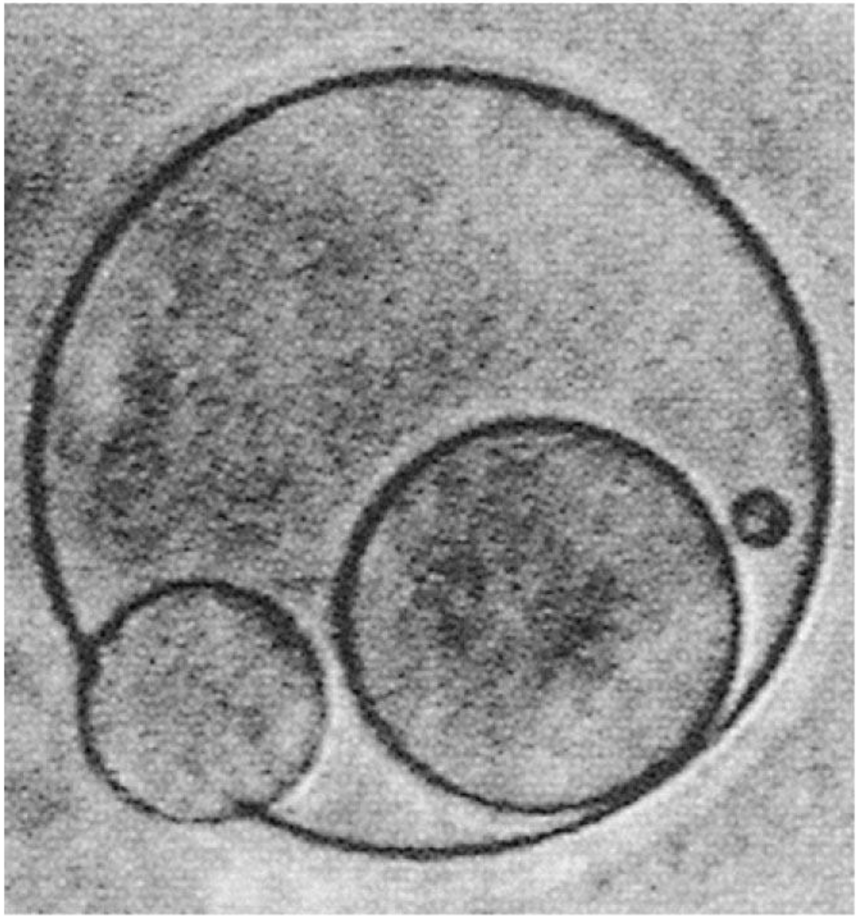
- **An alternative hypothesis**
  - Submerged volcanoes and deep-sea hydrothermal vents may have provided the chemical resources for the first life

15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

- **Stage 2: The formation of polymers**
  - Monomers could have combined to form organic polymers
  - Same energy sources
  - Clay as substratum for polymerization?

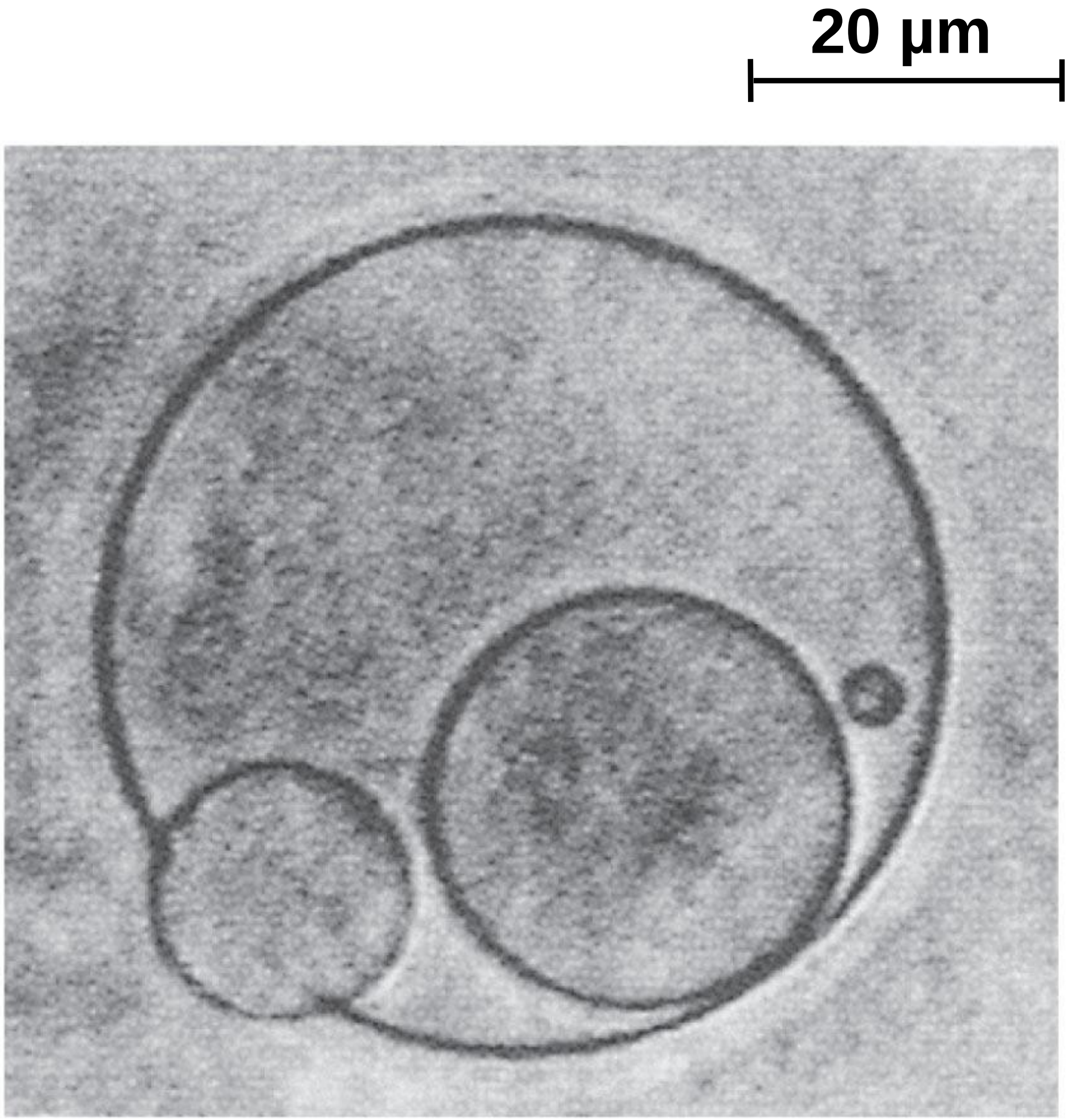
15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

- **Stage 2: Packaging of polymers into protobionts**
  - Polymers could have aggregated into complex, organized, cell-like structures

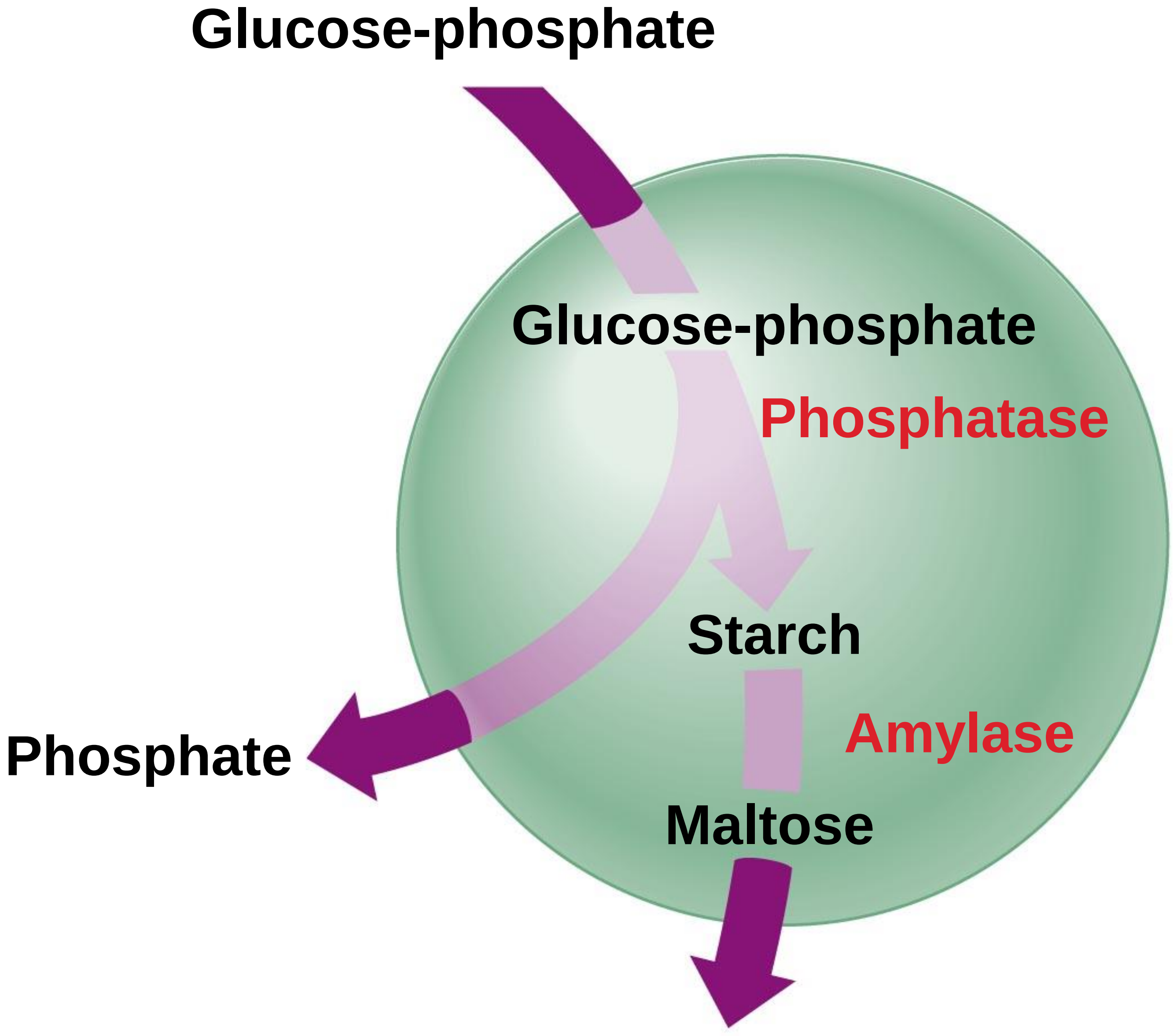


15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

- **What characteristics do cells and protobionts share?**
  - Structural organization
  - Simple reproduction
  - Simple metabolism
  - Simple homeostasis



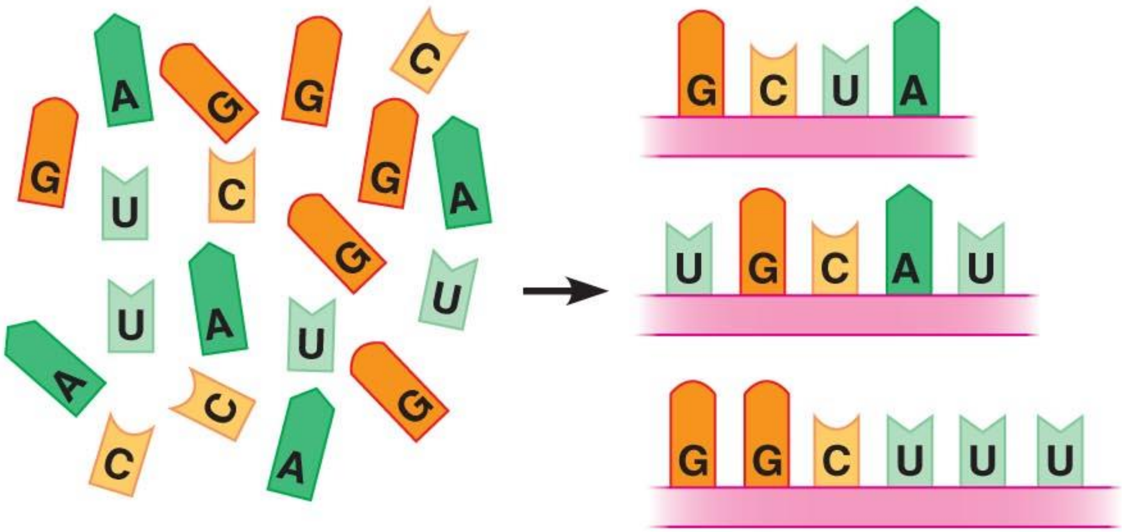
(a) Simple reproduction by liposomes



(b) Simple metabolism

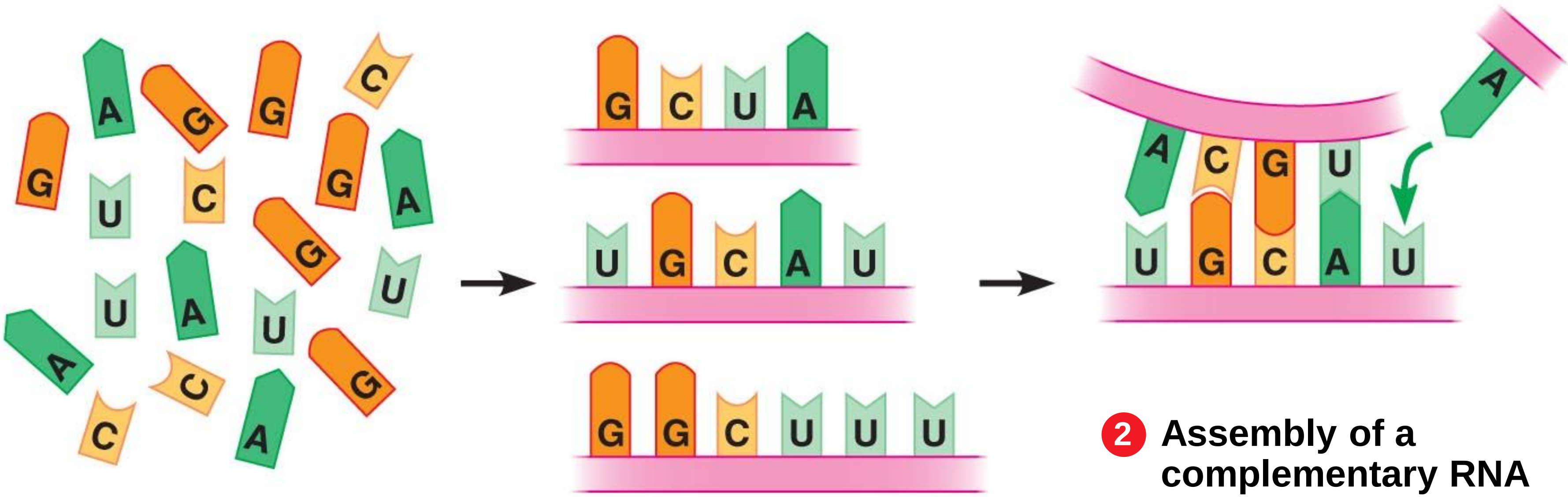
15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

- **Which came first?**
  - Life requires the maintenance of a complex, stable, internal environment
    - What provides this in modern cells?
  - Life requires accurate self replication
    - What provides this in modern cells?



Monomers

1 Formation of short RNA polymers: simple “genes”



Monomers

1 Formation of short RNA polymers: simple "genes"

2 Assembly of a complementary RNA chain, the first step in replication of the original "gene"

15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

- **Stage 4: Self-replication**
  - RNA may have served both as the first genetic material *and* as the first enzymes
  - The first genes may have been short strands of RNA that replicated without protein support
  - RNA catalysts or **ribozymes** may have assisted in this process.

RNA world!

15.3 The formation of polymers, membranes, and self-replicating molecules represent stages in the origin of the first cells

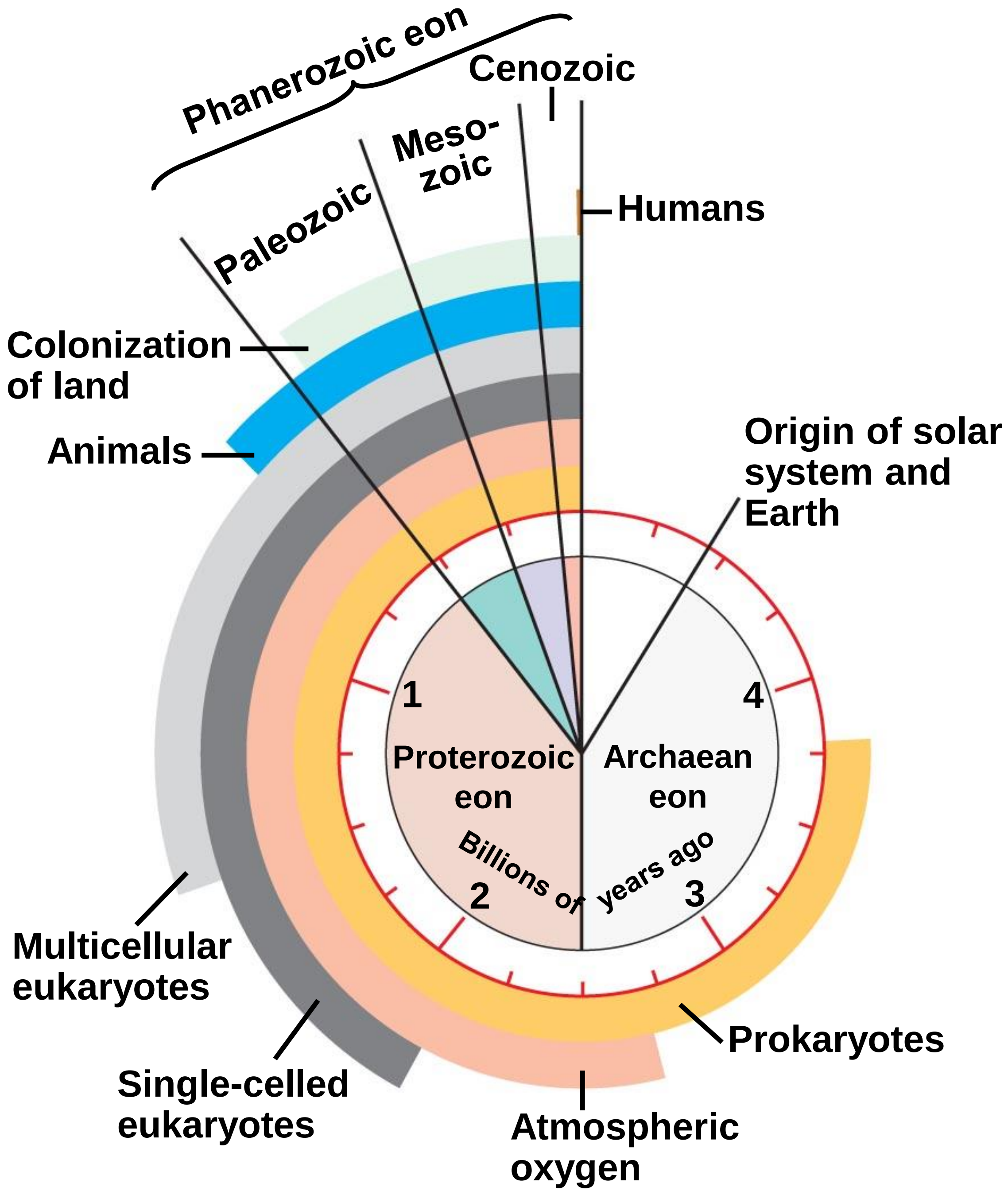
- A variety of protobionts existed on the early Earth
- Some of these protobionts contained self-replicating RNA molecules

How could natural selection have acted on these protobionts?

MAJOR EVENTS IN THE HISTORY OF LIFE

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life's history

- Three eons
  - Archaean and Proterozoic lasted 4 billion years
  - Phanerozoic is the last ½ billion years
    - Divided into Paleozoic era, Mesozoic era, Cenozoic era


Phanerozoic eon
Cenozoic
Meso-
zoic
Paleozoic
Humans
Colonization
of land
Animals
Origin of solar
system and
Earth
1
4
Proterozoic
eon
Archaean
eon
Billions of years ago
2
3
Multicellular
eukaryotes
Single-celled
eukaryotes
Prokaryotes
Atmospheric
oxygen

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life's history

- Prokaryotes lived alone on Earth for 1.5 billion years
  - They created our atmosphere and transformed Earth's biosphere
- Virtually all metabolic pathways evolved within prokaryotes
  - Atmospheric oxygen appeared 2.7 billion years ago due to prokaryotic photosynthesis
  - Cellular respiration arose in prokaryotes, using oxygen to harvest energy from organic molecules

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life's history

- The eukaryotic cell probably originated as a community of prokaryotes, when small prokaryotes capable of aerobic respiration or photosynthesis began living in larger cells
  - Oldest fossils of eukaryotes are 2.1 billion years old

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life's history

- Multicellular forms arose about 1.5 billion years ago
  - The descendents of these forms include a variety of algae, plants, fungi, animals
- The oldest known fossils of multicellular organisms were small algae, living 1.2 billion years ago

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life’s history

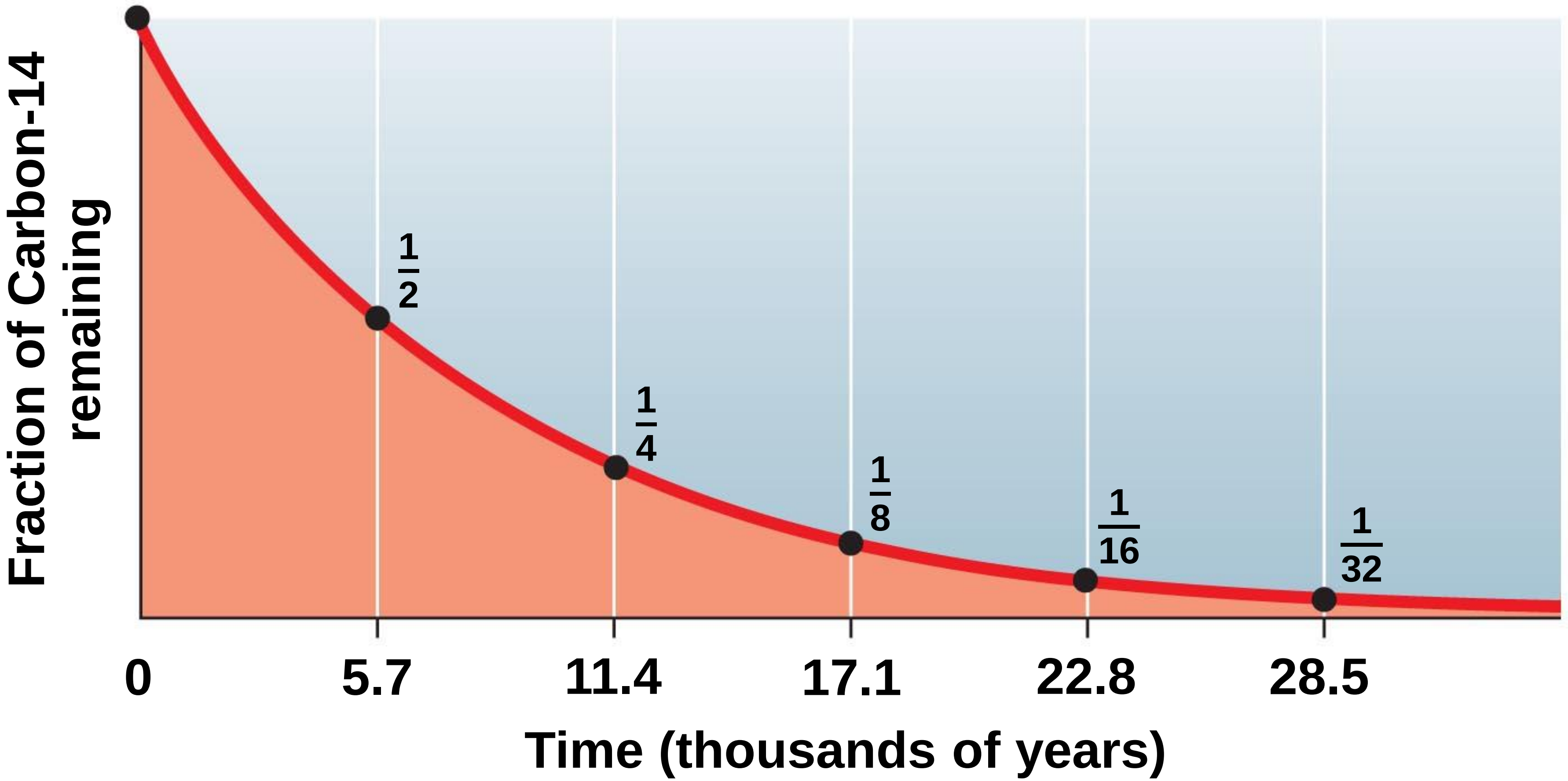
- The diversity of animal forms increased suddenly and dramatically about 535–525 million years ago in the Cambrian explosion
- Fungi and plants colonized land together 500 million years ago
  - Roots of most plants have fungal associates that exchange water and minerals for nutrients

15.4 The origins of single-celled and multicelled organisms and the colonization of land are key events in life’s history

- Arthropods and tetrapods are the most widespread and diverse land animals
- Human lineage diverged from apes 7–6 million years ago
  - Our species originated 160,000 years ago

15.5 The actual ages of rocks and fossils mark geologic time

- **Radiometric dating** measures the decay of radioactive isotopes
- "Young" fossils may contain isotopes of elements that accumulated when the organisms were alive
  - Carbon-14 can date fossils up to 75,000 years old
- Potassium-40, with a half-life of 1.3 billion years, can be used to date volcanic rocks that are hundreds of millions of years old
  - A fossil's age can be inferred from the ages of the rock layers above and below the strata in which the fossil is found



Fraction of Carbon-14 remaining
1/2
1/4
1/8
1/16
1/32
0
5.7
11.4
17.1
22.8
28.5
Time (thousands of years)

15.6 The fossil record documents the history of life

- The fossil record documents the main events in the history of life
- The **geologic record** is defined by major transitions in life on Earth

PLAY Animation: The Geologic Record

TABLE 15.6 THE GEOLOGIC RECORD

Relative Duration of Eons	Era	Period	Epoch	Age (Millions of Years Ago)	Some Important Events in the History of Life
Phanerozoic	Cenozoic	Neogene	Holocene		Historical time
				0.01	
			Pleistocene		Ice ages; humans appear
				1.8	
			Pliocene		Origin of genus *Homo*
				5.3	
			Miocene		Continued radiation of mammals and angiosperms; apelike ancestors of humans appear
				23	
		Paleogene	Oligocene		Origins of many primate groups, including apes
				33.9	
			Eocene		Angiosperm dominance increases; continued radiation of most present-day mammalian orders
				55.8	
			Paleocene		Major radiation of mammals, birds, and pollinating insects
				65.5	
	Mesozoic	Cretaceous			Flowering plants appear; many groups of organisms, including most dinosaurs, become extinct at end of period
				145.5	
		Jurassic			Gymnosperms continue as dominant plants; dinosaurs abundant and diverse
				199.6	
		Triassic			Cone-bearing plants dominate landscape; origin and radiation of dinosaurs; origin of mammals
				251	
	Paleozoic	Permian			Radiation of reptiles; origin of most present-day groups of insects; extinction of many marine and terrestrial organisms at end of period
				299	
		Carboniferous			Extensive forests of vascular plants; first seed plants; origin of reptiles; amphibians dominant
				359.2	
		Devonian			Diversification of bony fishes; first tetrapods and insects
				416	
		Silurian			Diversification of early vascular plants
				443.7	
		Ordovician			Marine algae abundant; colonization of land by fungi, plants, and animals
				488.3	
		Cambrian			Sudden increase in diversity of many animal phyla
				542	
Proterozoic		Ediacaran			Diverse algae and soft-bodied invertebrate animals
				635	
				2,100	Oldest fossils of eukaryotic cells
				2,500	
Archaean				2,700	Concentration of atmospheric oxygen increases
				3,500	Oldest fossils of cells (prokaryotes)
				3,800	Oldest known rocks on Earth's surface
				Approx. 4,600	Origin of Earth

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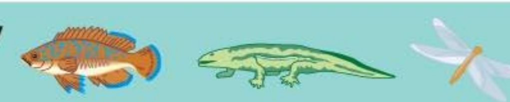
		Devonian			Diversification of bony fishes; first tetrapods and insects 
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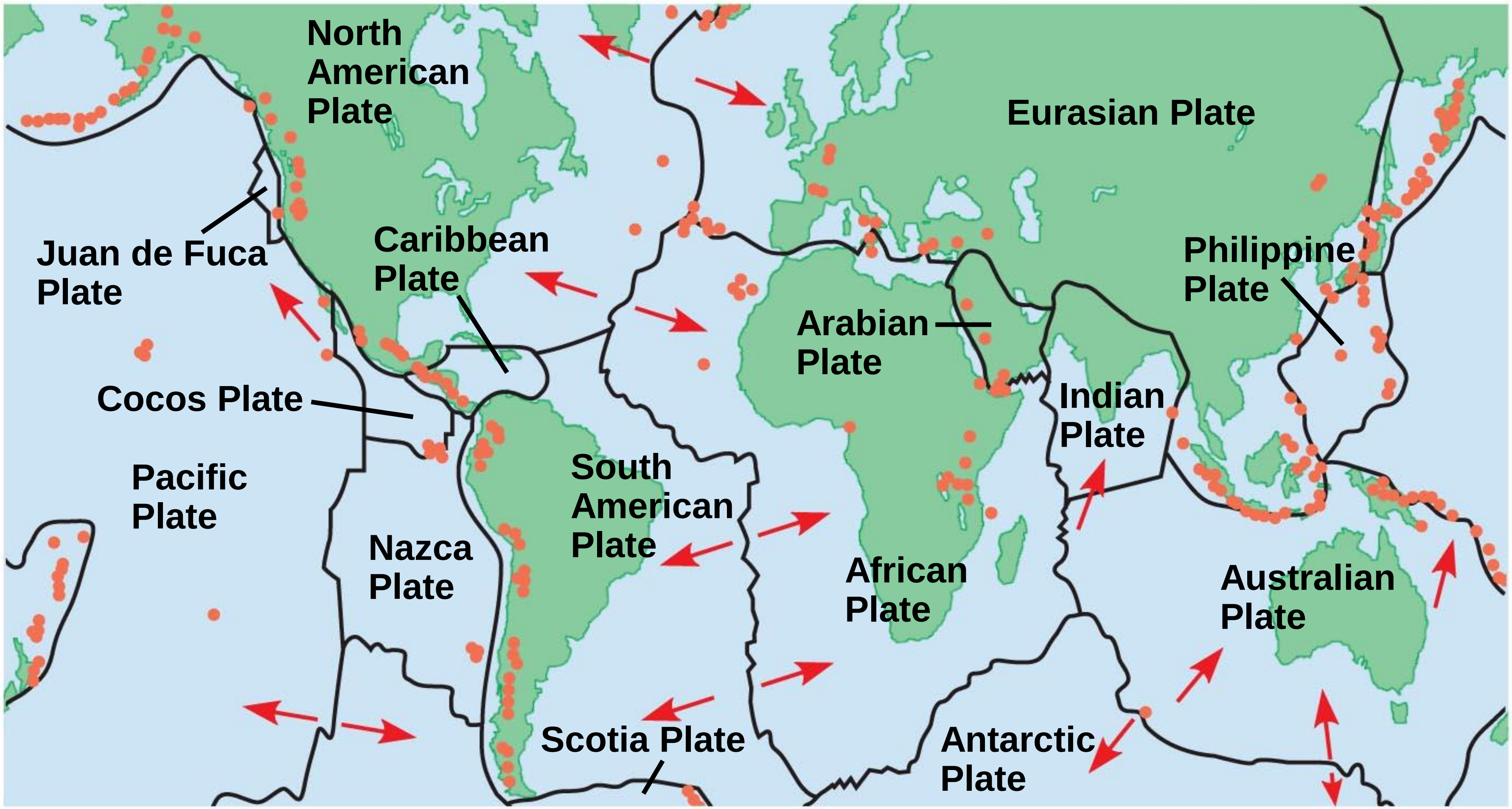
MECHANISMS OF MACROEVOLUTION

15.7 Continental drift has played a major role in macroevolution

- **Continental drift** is the slow, continuous movement of Earth's crustal plates on the hot mantle
  - Crustal plates carrying continents and seafloors float on a liquid mantle
- Important geologic processes occur at plate boundaries
  - Sliding plates are earthquake zones
  - Colliding plates form mountains

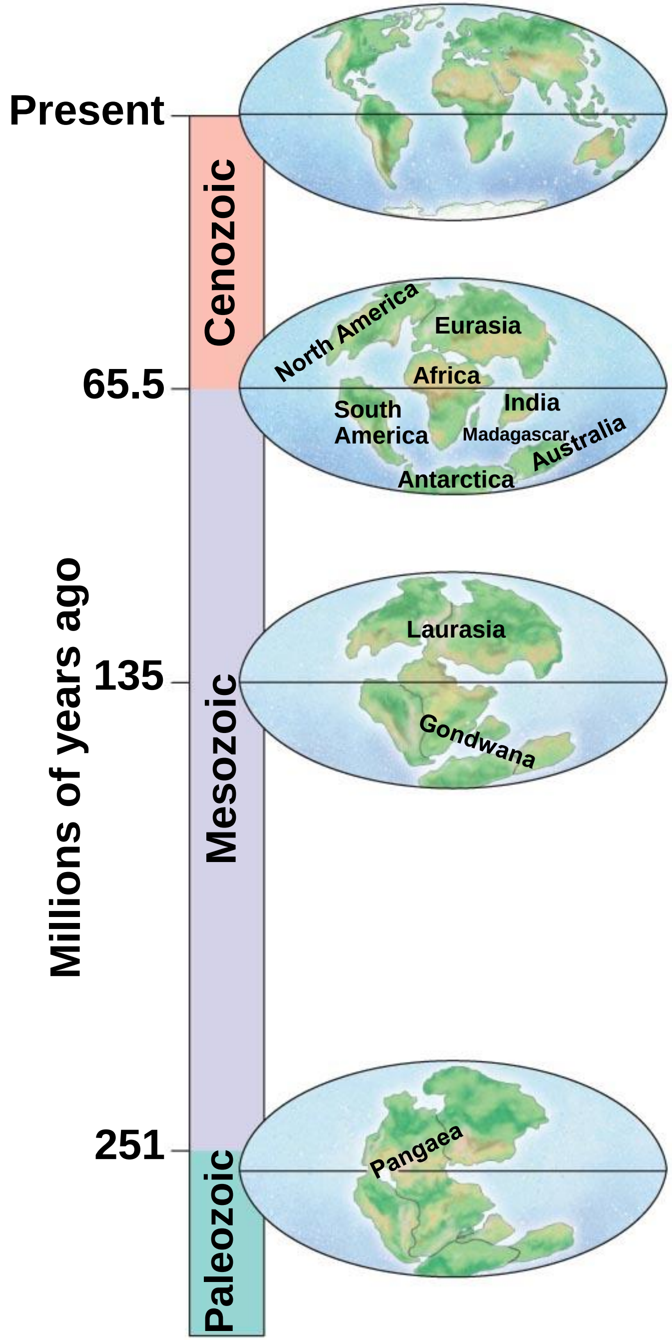
PLAY Video: Lava Flow

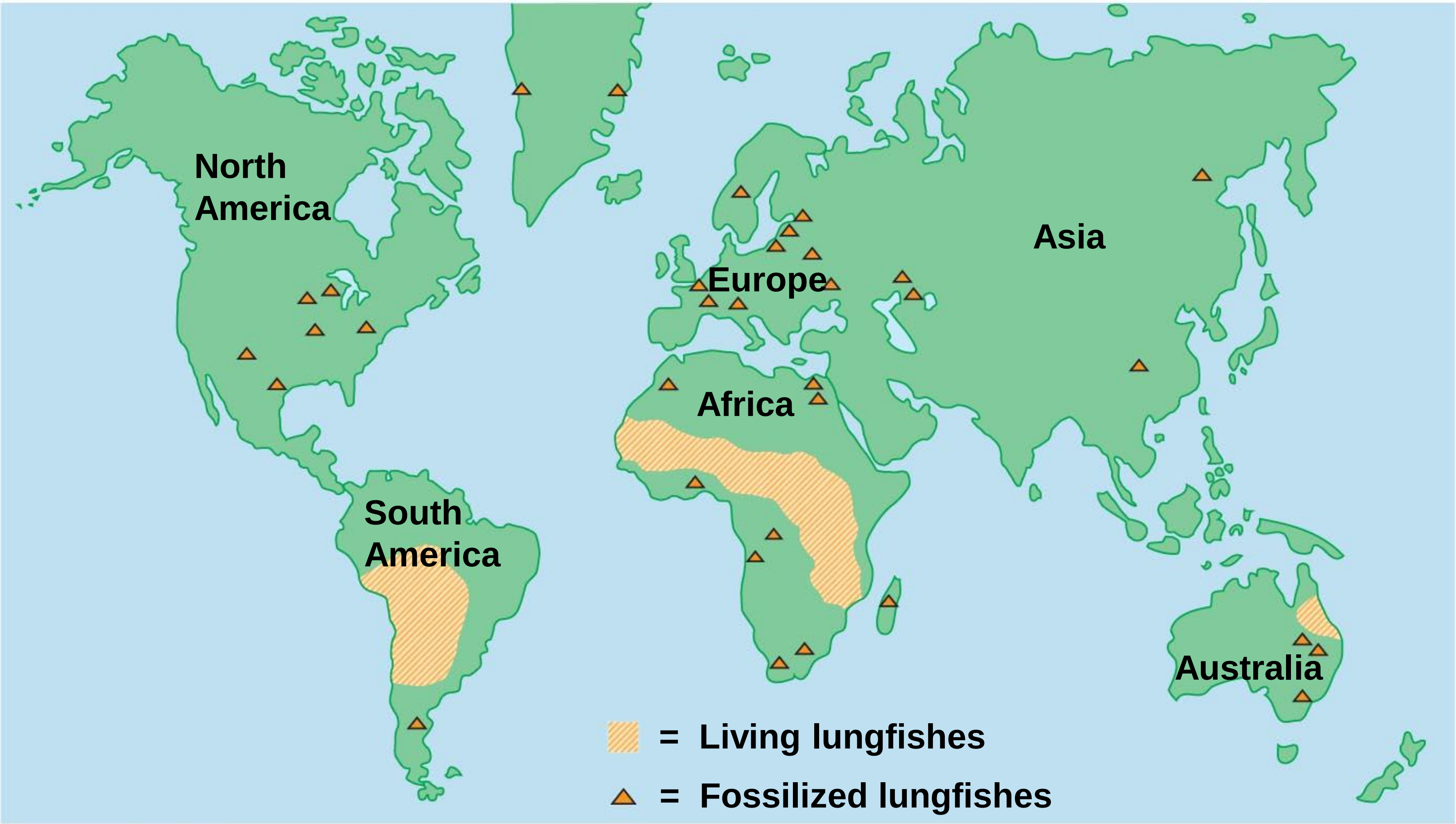

North American Plate
Eurasian Plate
Juan de Fuca Plate
Caribbean Plate
Philippine Plate
Arabian Plate
Cocos Plate
Indian Plate
Pacific Plate
South American Plate
Nazca Plate
African Plate
Australian Plate
Scotia Plate
Antarctic Plate

15.7 Continental drift has played a major role in macroevolution

- The supercontinent **Pangaea**, which formed 250 million years ago, altered habitats and triggered the greatest mass extinction in Earth's history
  - Its breakup led to the modern arrangement of continents
  - Australia's marsupials became isolated when the continents separated, and placental mammals arose on other continents
  - India's collision with Eurasia 55 million years ago led to the formation of the Himalayas

PLAY Video: Volcanic Eruption


Present
65.5
135
251
Millions of years ago
Cenozoic
Mesozoic
Paleozoic
North America
Eurasia
Africa
South America
India
Madagascar
Australia
Antarctica
Laurasia
Gondwana
Pangaea


North America
Europe
Asia
Africa
South America
Australia
= Living lungfishes
= Fossilized lungfishes

15.8 CONNECTION: The effects of continental drift may imperil human life

- Volcanoes and earthquakes result from the movements of crustal plates
  - The boundaries of plates are hotspots of volcanic and earthquake activity
  - An undersea earthquake caused the 2004 tsunami, when a fault in the Indian Ocean ruptured


San Andreas Fault
North American Plate
San Francisco
Santa Cruz
Pacific Plate
Los Angeles
California

15.9 Mass extinctions destroy large numbers of species

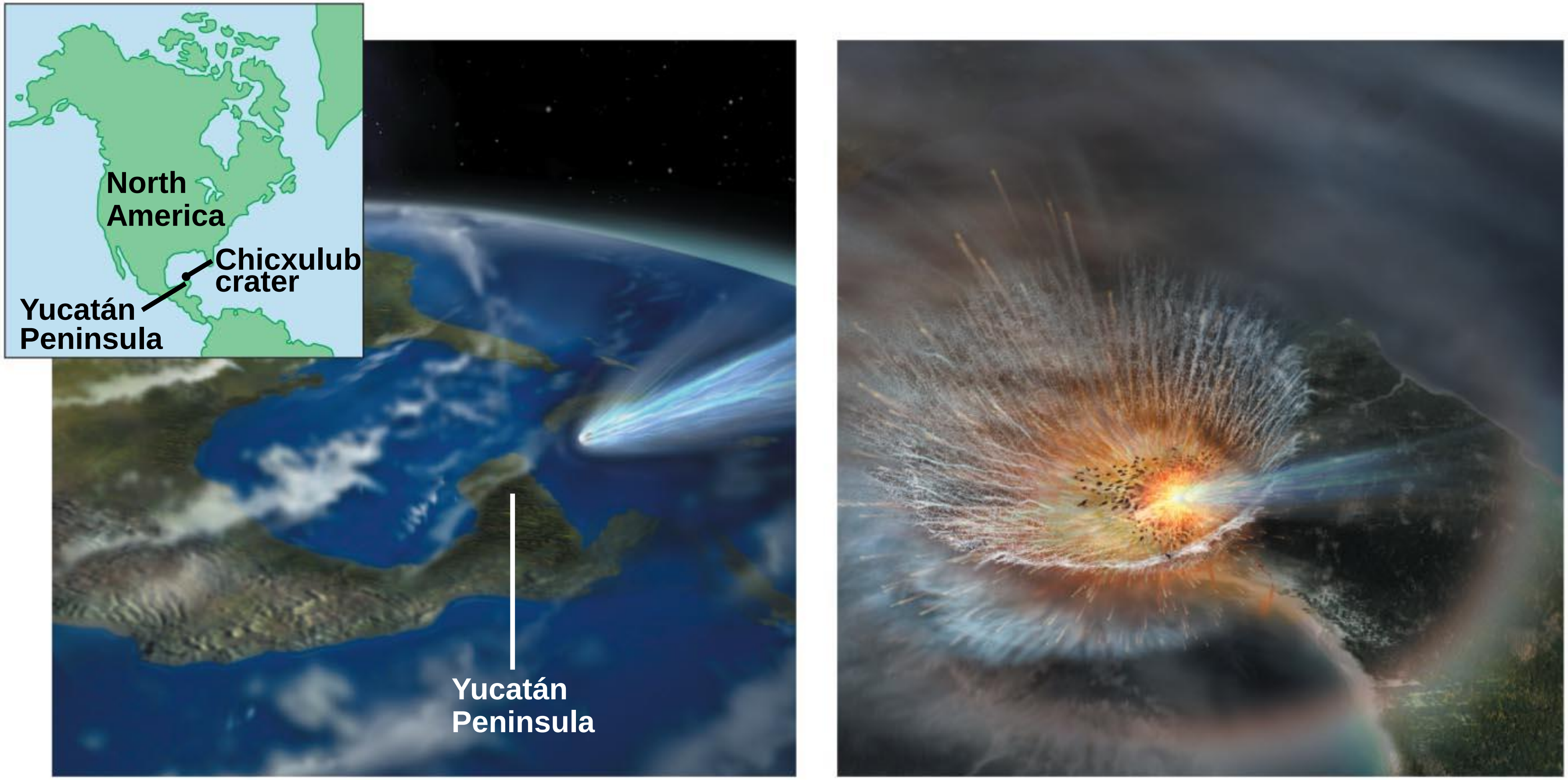
- Extinction is the fate of all species and most lineages
- The history of life on Earth reflects a steady background extinction rate with episodes of mass extinction
- Over the last 600 million years, five mass extinctions have occurred in which 50% or more of the Earth's species went extinct

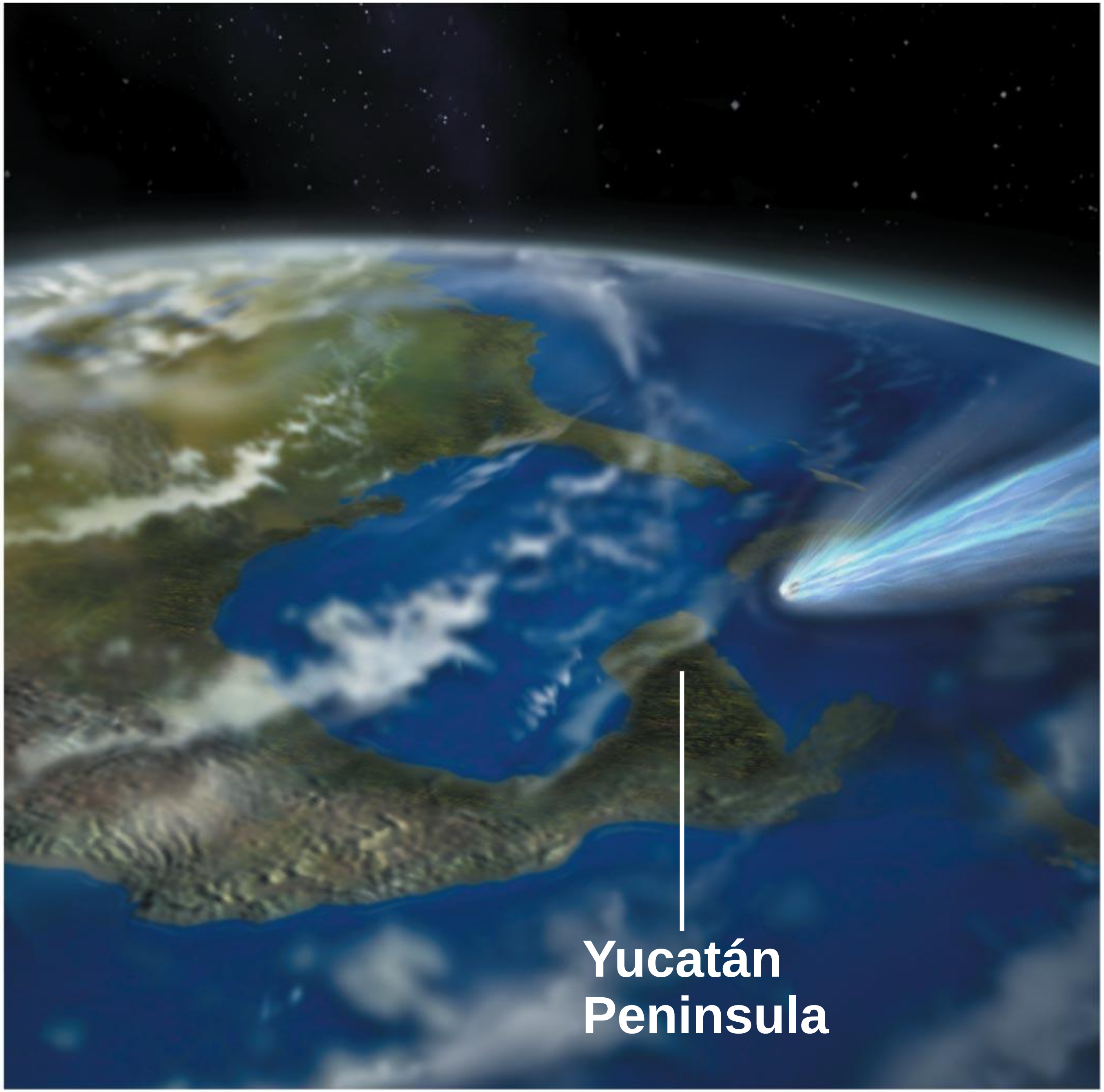
15.9 Mass extinctions destroy large numbers of species

- **Permian extinction**
  - 96% of shallow water marine species died in the Permian extinction
  - Possible cause?
    - Extreme vulcanism in Siberia released CO_2, warmed global climate, slowed mixing of ocean water, and reduced O_2 availability in the ocean

15.9 Mass extinctions destroy large numbers of species

- **Cretaceous extinction**
  - 50% of marine species and many terrestrial lineages went extinct 65 million years ago
    - All dinosaurs (except birds) went extinct
  - Likely cause was a large asteroid that struck the Earth, blocking light and disrupting the global climate


North
America
Chicxulub
crater
Yucatán
Peninsula
Yucatán
Peninsula

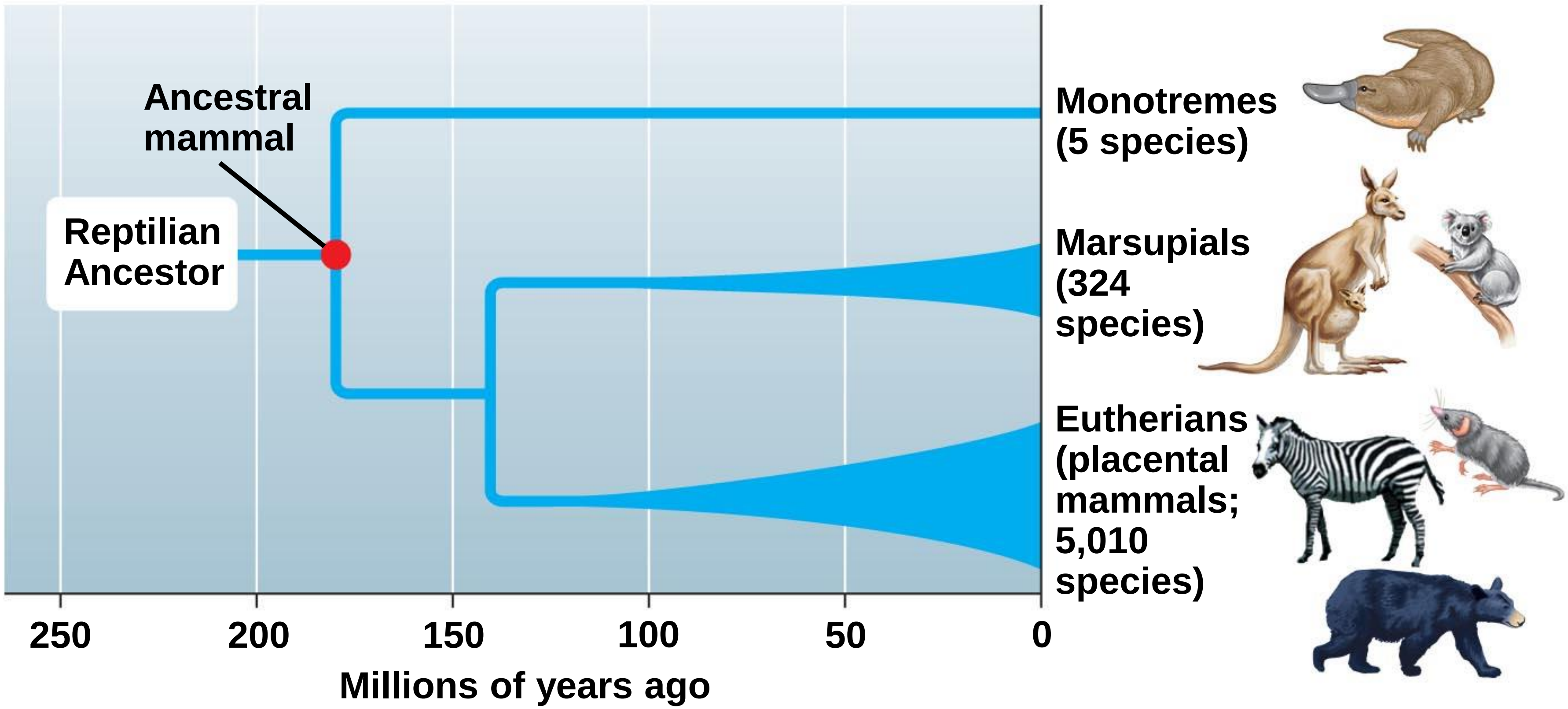

Yucatán
Peninsula

15.9 Mass extinctions destroy large numbers of species

- It took 100 million years for the number of marine families to recover after Permian mass extinction
- Is a 6th extinction under way?
  - The current extinction rate is 100–1,000 times the normal background rate
  - It may take life on Earth millions of years to recover

15.10 EVOLUTION CONNECTION: Adaptive radiations have increased the diversity of life

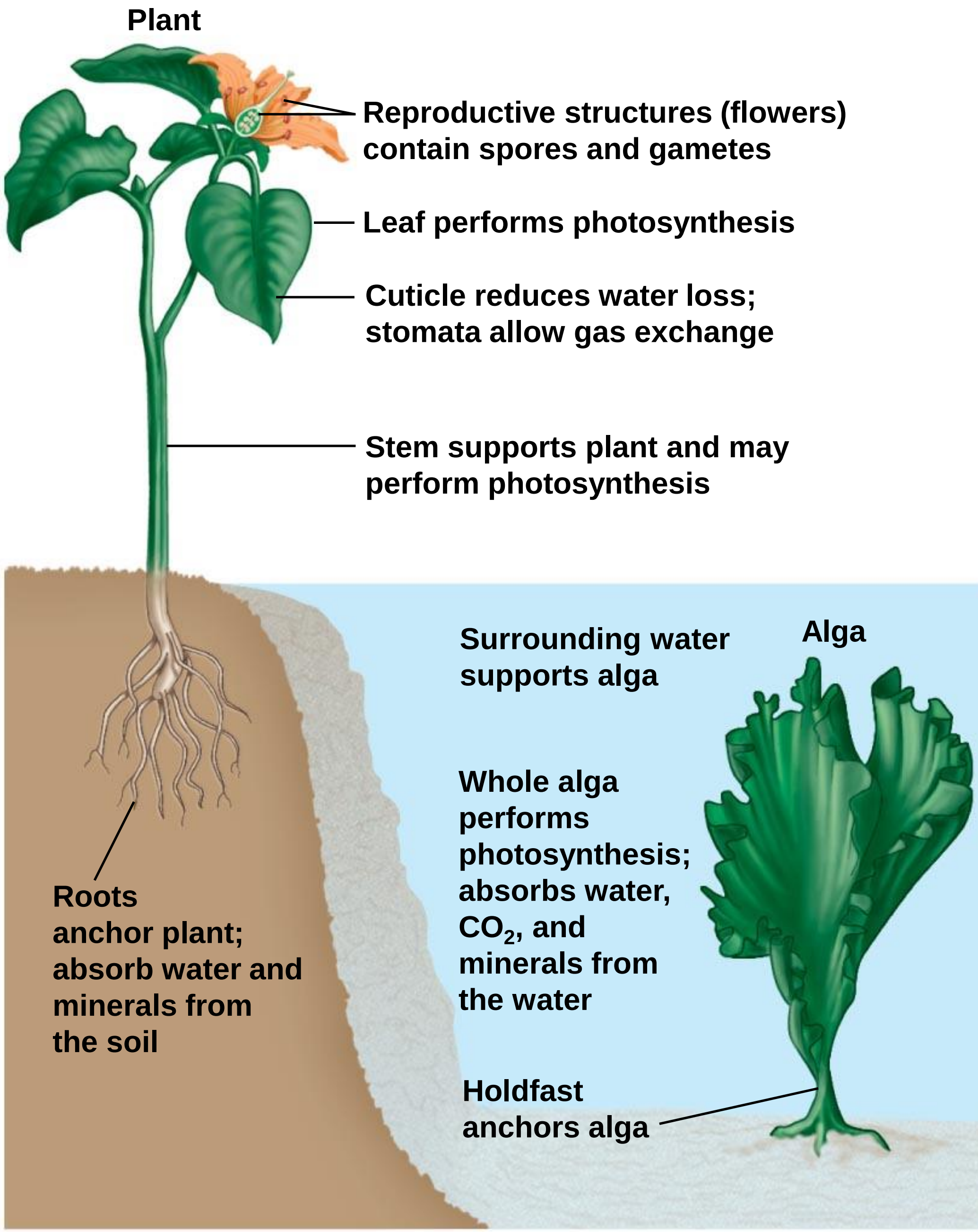
- **Adaptive radiation:** a group of organisms forms new species, whose adaptations allow them to fill new habitats or roles in their communities
- A rebound in diversity follows mass extinctions as survivors become adapted to vacant ecological niches
  - Mammals underwent a dramatic adaptive radiation after the extinction of nonavian dinosaurs 65 million years ago



Ancestral
mammal
Reptilian
Ancestor
Monotremes
(5 species)
Marsupials
(324
species)
Eutherians
(placental
mammals;
5,010
species)
250
200
150
100
50
0
Millions of years ago

15.10 EVOLUTION CONNECTION: Adaptive radiations have increased the diversity of life

- Adaptive radiations may follow the evolution of new adaptations, such as wings
  - Radiations of land plants were associated with many novel features, including waxy coat, vascular tissue, seeds, and flowers


Plant
Reproductive structures (flowers) contain spores and gametes
Leaf performs photosynthesis
Cuticle reduces water loss; stomata allow gas exchange
Stem supports plant and may perform photosynthesis
Surrounding water supports alga
Alga
Whole alga performs photosynthesis; absorbs water, CO_2, and minerals from the water
Roots anchor plant; absorb water and minerals from the soil
Holdfast anchors alga

15.11 Genes that control development play a major role in evolution

- "**Evo-devo**" is a field that combines evolutionary and developmental biology
- Slight genetic changes can lead to major morphological differences between species
  - Changes in genes that alter the timing, rate, and spatial pattern of growth alter the adult form of an organism
- Many developmental genes have been conserved throughout evolutionary history
  - Changes in these genes have led to the huge diversity in body forms

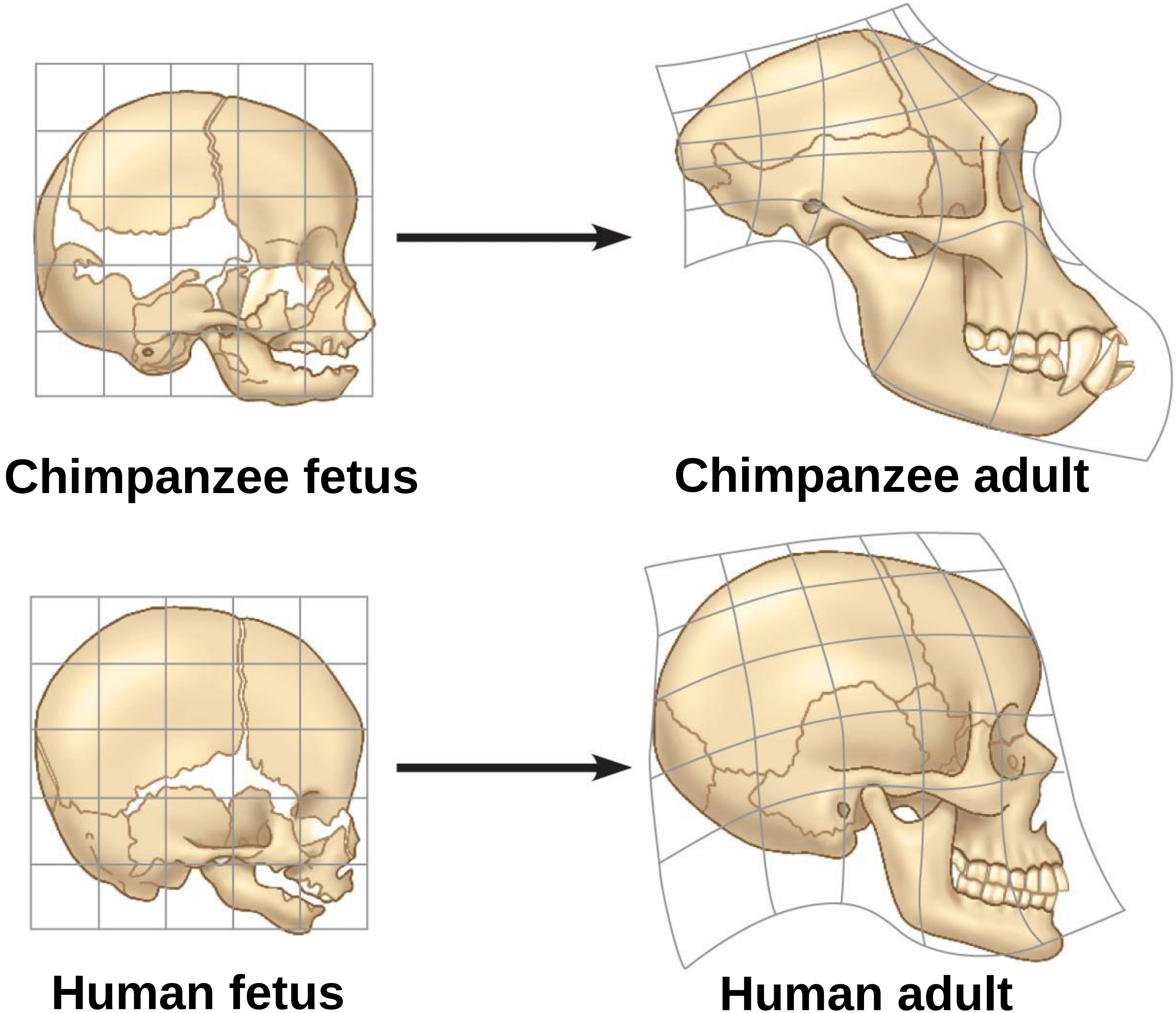
PLAY

Animation: Allometric Growth


Gills

15.11 Genes that control development play a major role in evolution

- Human development is **paedomorphic**, retaining juvenile traits into adulthood
  - Adult chimps have massive, projecting jaws; large teeth; and a low forehead with a small braincase
  - Human adults—and both human and chimpanzee fetuses—lack these features
  - Humans and chimpanzees are more alike as fetuses than as adults
- The human brain continues to grow at the fetal rate for the first year of life

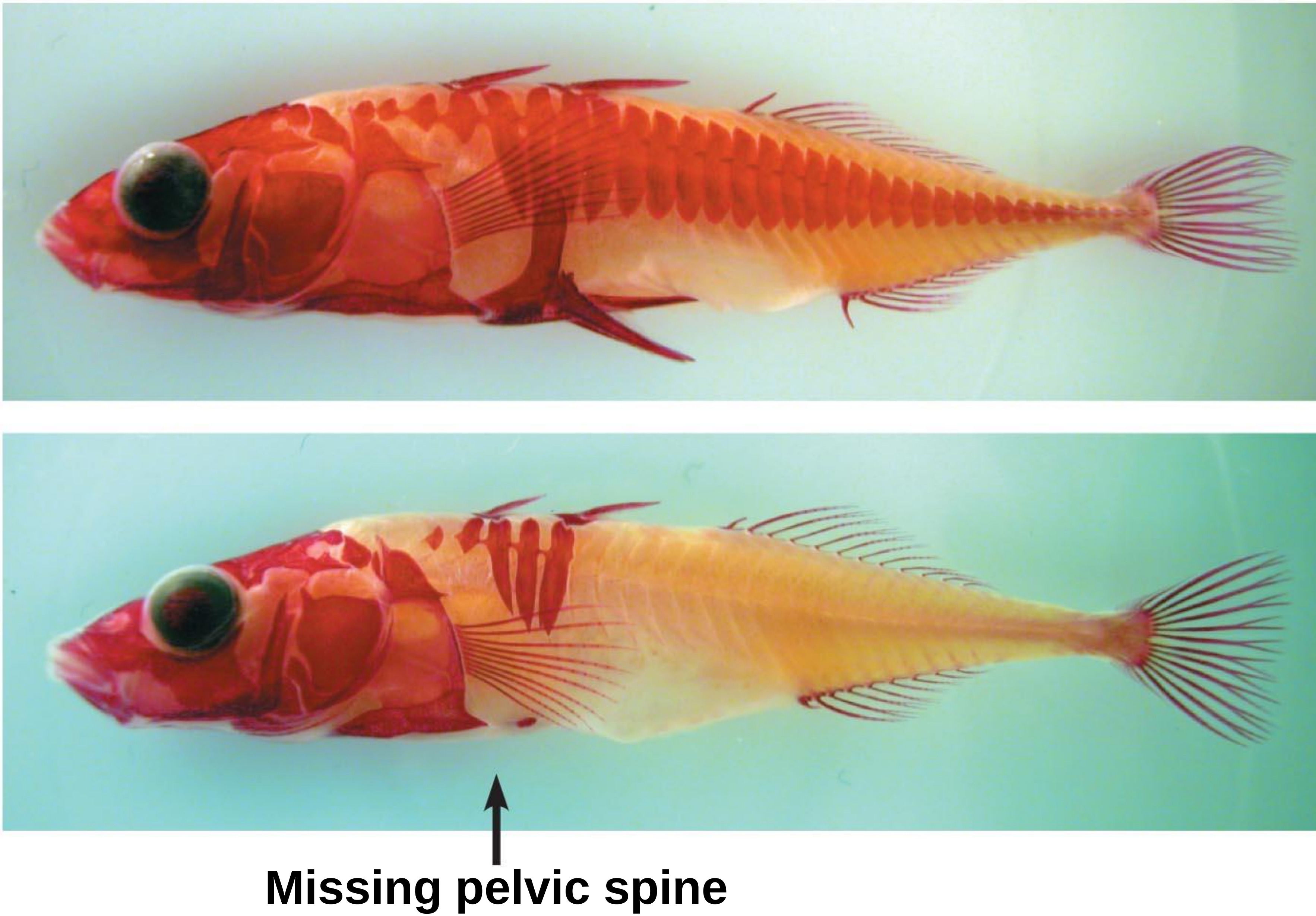

Chimpanzee fetus
Chimpanzee adult
Human fetus
Human adult

15.11 Genes that control development play a major role in evolution

- **Homeotic genes** are master control genes that determine basic features, such as where pairs of wings or legs develop on a fruit fly
- Developing fish and tetrapod limbs express certain homeotic genes
  - A second region of expression in the developing tetrapod limb produces the extra skeletal elements that form feet, turning fins into walking legs

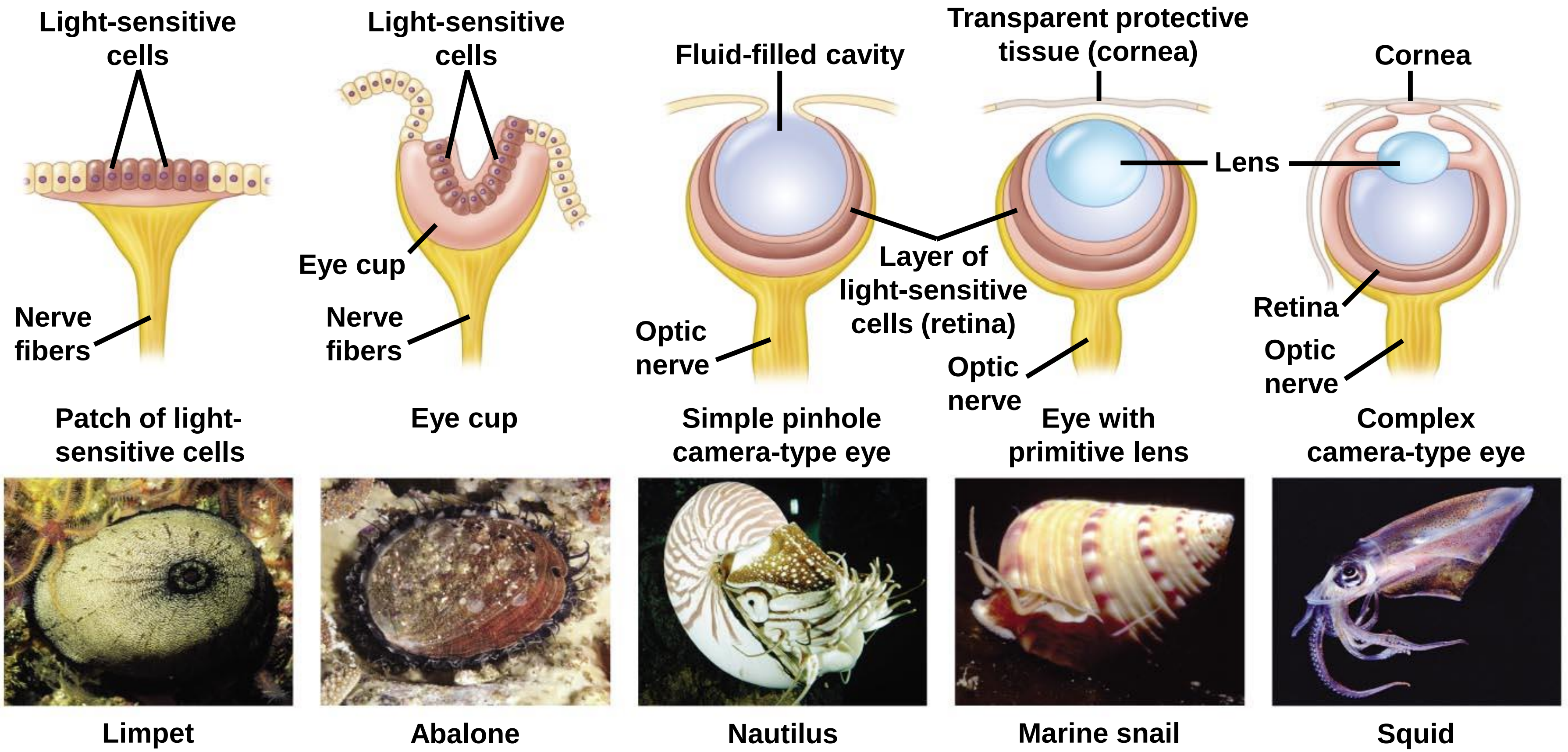
15.11 Genes that control development play a major role in evolution

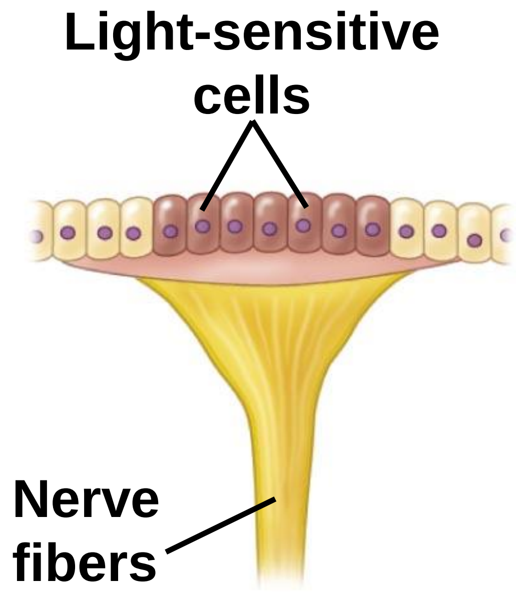
- Duplication of developmental genes can be important in the formation of new morphological features
- A fruit fly has a single cluster of homeotic genes; a mouse has four
  - Two duplications of these gene clusters in evolution from invertebrates into vertebrates
  - Mutations in these duplicated genes may have led to the origin of novel vertebrate characteristics, including backbone, jaws, and limbs


Missing pelvic spine

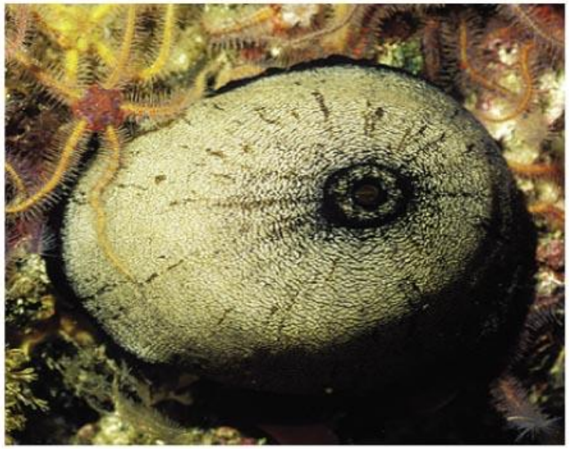
15.12 Evolutionary novelties may arise in several ways

- In the evolution of an eye or any other complex structure, behavior, or biochemical pathway, each step must bring a selective advantage to the organism possessing it and must increase the organism's fitness
  - Mollusc eyes evolved from an ancestral patch of photoreceptor cells through series of incremental modifications that were adaptive at each stage
  - A range of complexity can be seen in the eyes of living molluscs
  - Cephalopod eyes are as complex as vertebrate eyes, but arose separately

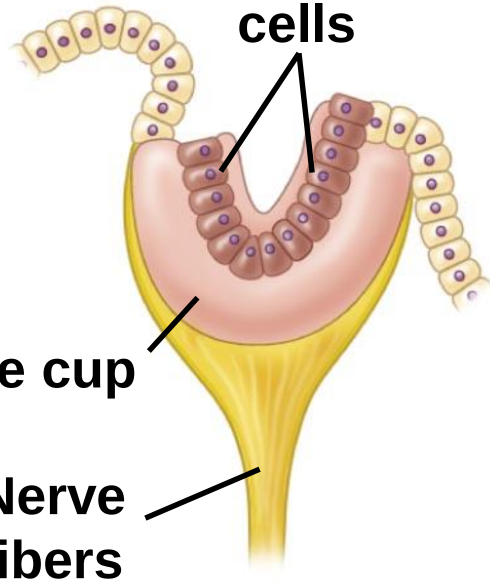

Light-sensitive cells
Nerve fibers
Patch of light-sensitive cells
Light-sensitive cells
Eye cup
Nerve fibers
Eye cup
Fluid-filled cavity
Optic nerve
Simple pinhole camera-type eye
Layer of light-sensitive cells (retina)
Transparent protective tissue (cornea)
Lens
Optic nerve
Eye with primitive lens
Cornea
Retina
Optic nerve
Complex camera-type eye
Limpet
Abalone
Nautilus
Marine snail
Squid



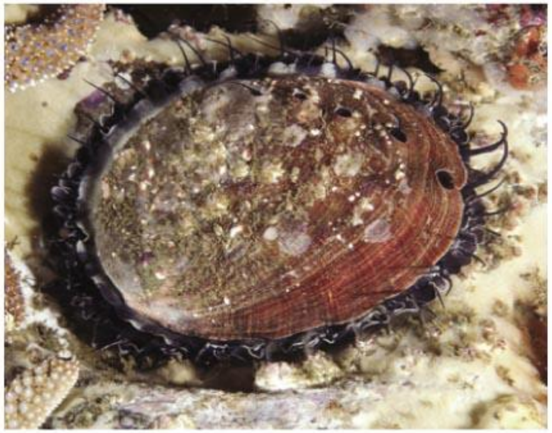
Patch of light-sensitive cells



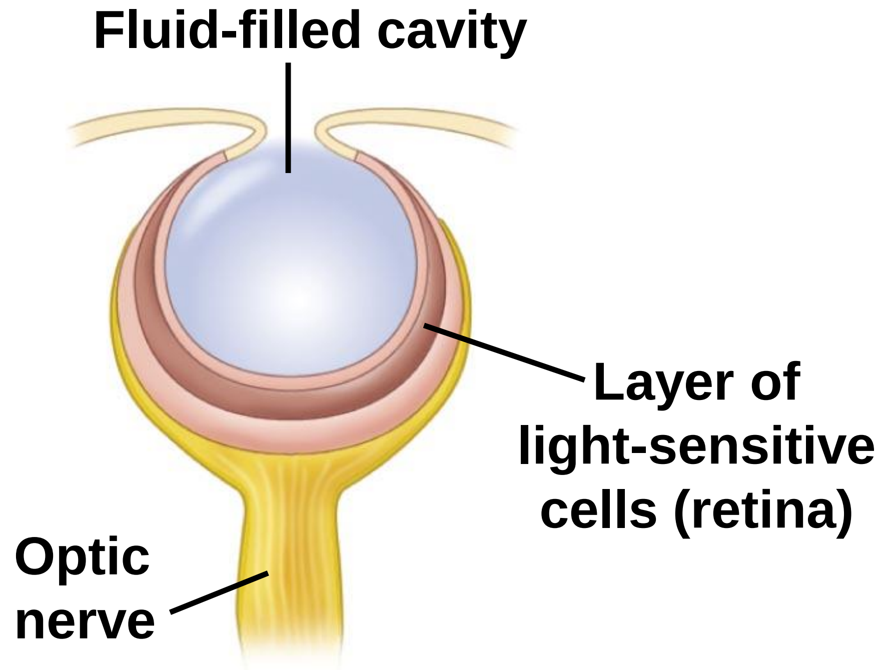
Limpet



Eye cup

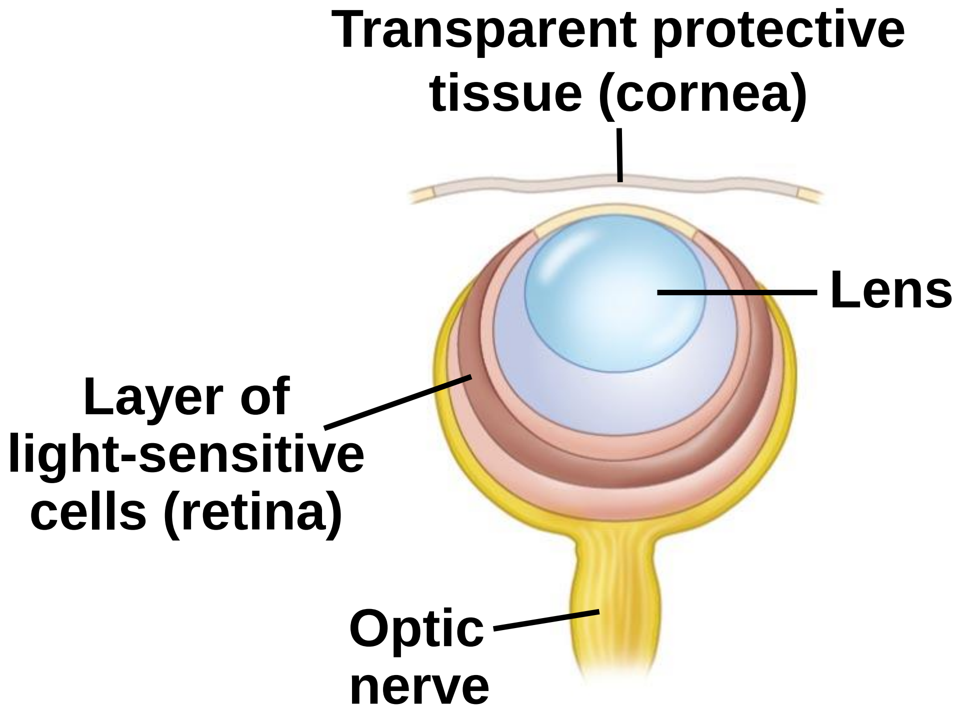


Abalone



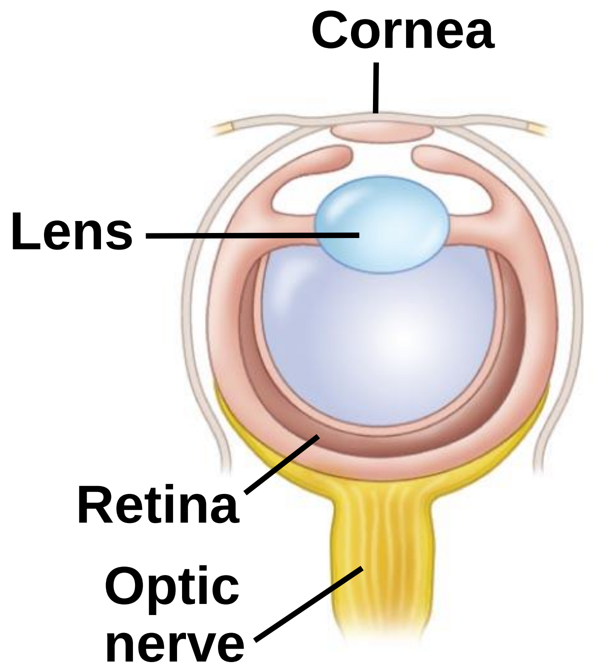
Simple pinhole camera-type eye

Nautilus



Eye with primitive lens

Marine snail



Complex camera-type eye

Squid

15.12 Evolutionary novelties may arise in several ways

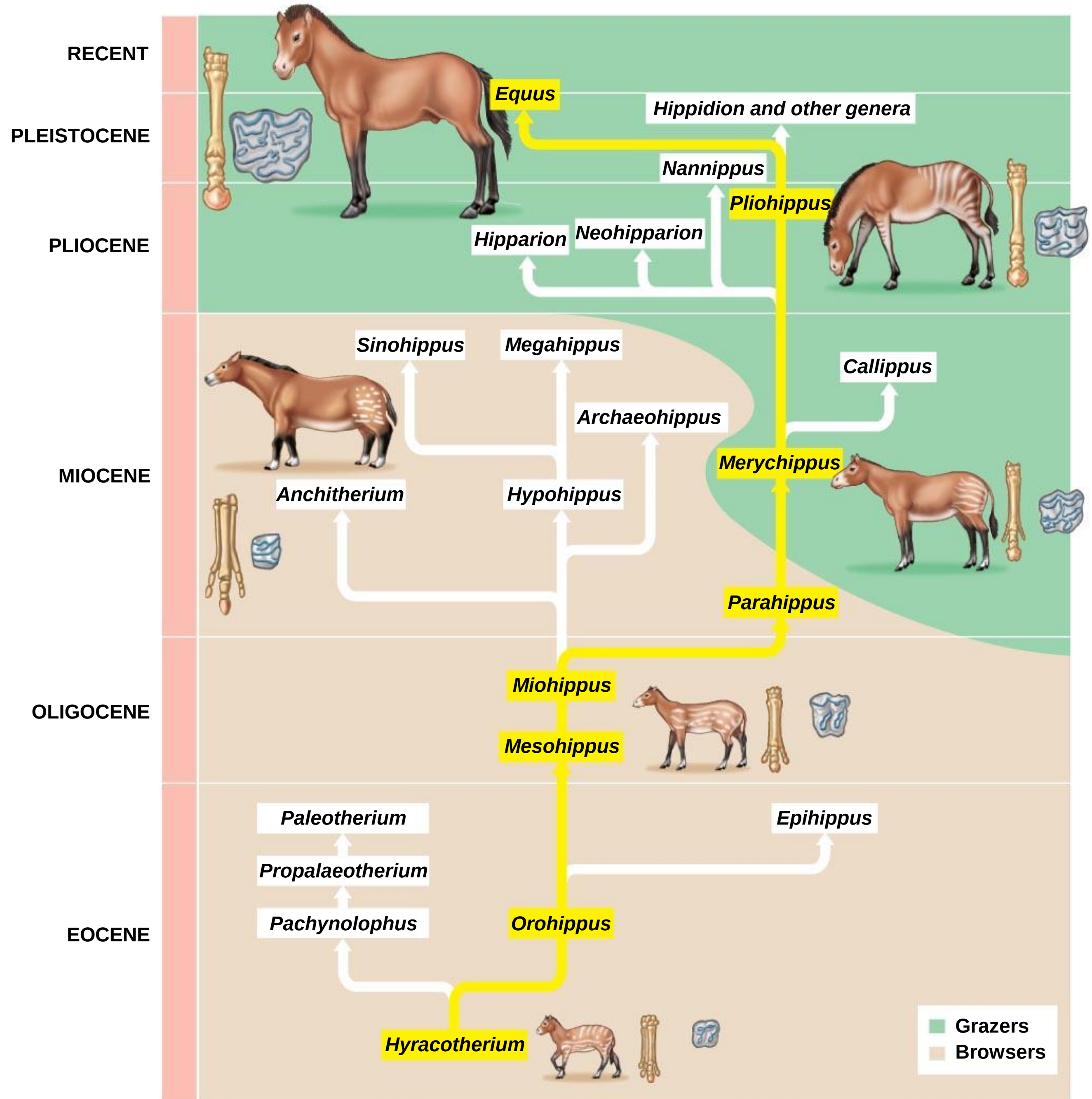
- Other novel structures result from *exaptation*, the gradual adaptation of existing structures to new functions
- Natural selection does not anticipate the novel use; each intermediate stage must be adaptive and functional
  - The modification of the vertebrate forelimb into a wing in pterosaurs, bats, and birds provides a familiar example

15.13 Evolutionary trends do not mean that evolution is goal directed

- *Species selection* is the unequal speciation or unequal survival of species on a branching evolutionary tree
  - Species that generate many new species may drive major evolutionary change
- Natural selection can also lead to macroevolutionary trends, such as evolutionary arms races between predators and prey
  - Predators and prey act on each other as significant agents of natural selection
  - Over time, predators evolve better weaponry while prey evolve better defenses

15.13 Evolutionary trends do not mean that evolution is goal directed

- Evolution is not goal directed
- Natural selection results from the interactions between organisms and their environment
- If the environment changes, apparent evolutionary trends may cease or reverse


RECENT
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
Equus
Hippidion and other genera
Nannippus
Pliohippus
Hipparion
Neohipparion
Sinohippus
Megahippus
Callippus
Archaeohippus
Merychippus
Anchitherium
Hypohippus
Parahippus
Miohippus
Mesohippus
Paleotherium
Epihippus
Propalaeotherium
Pachynolophus
Orohippus
Hyracotherium
Grazers
Browsers

PHYLOGENY AND THE TREE OF LIFE

15.14 Phylogenies are based on homologies in fossils and living organisms

- **Phylogeny** is the evolutionary history of a species or group of species
- Hypotheses about phylogenetic relationships can be developed from various lines of evidence
  - The fossil record provides information about the timing of evolutionary divergences
  - Homologous morphological traits, behaviors, and molecular sequences also provide evidence of common ancestry

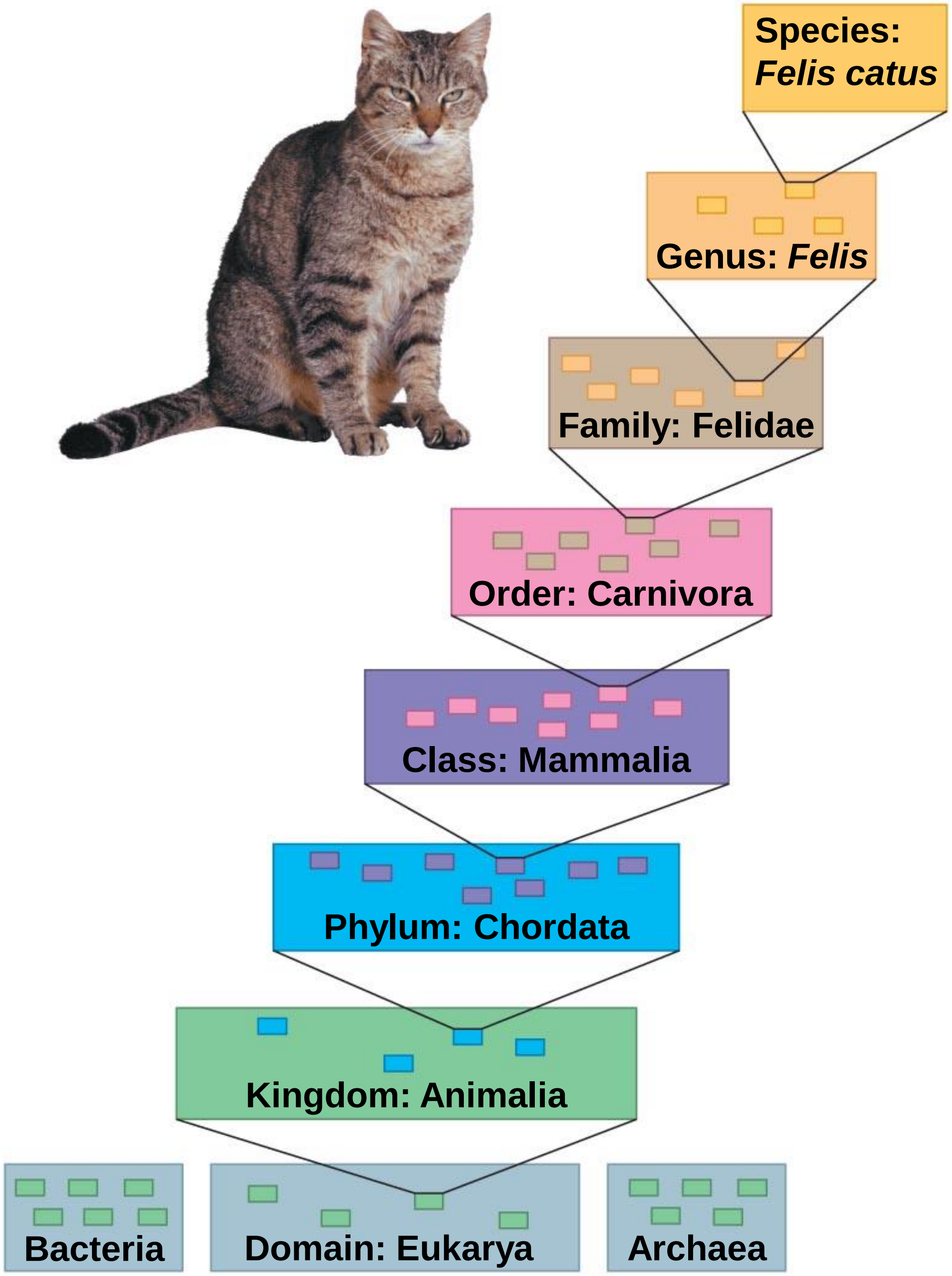
15.14 Phylogenies are based on homologies in fossils and living organisms

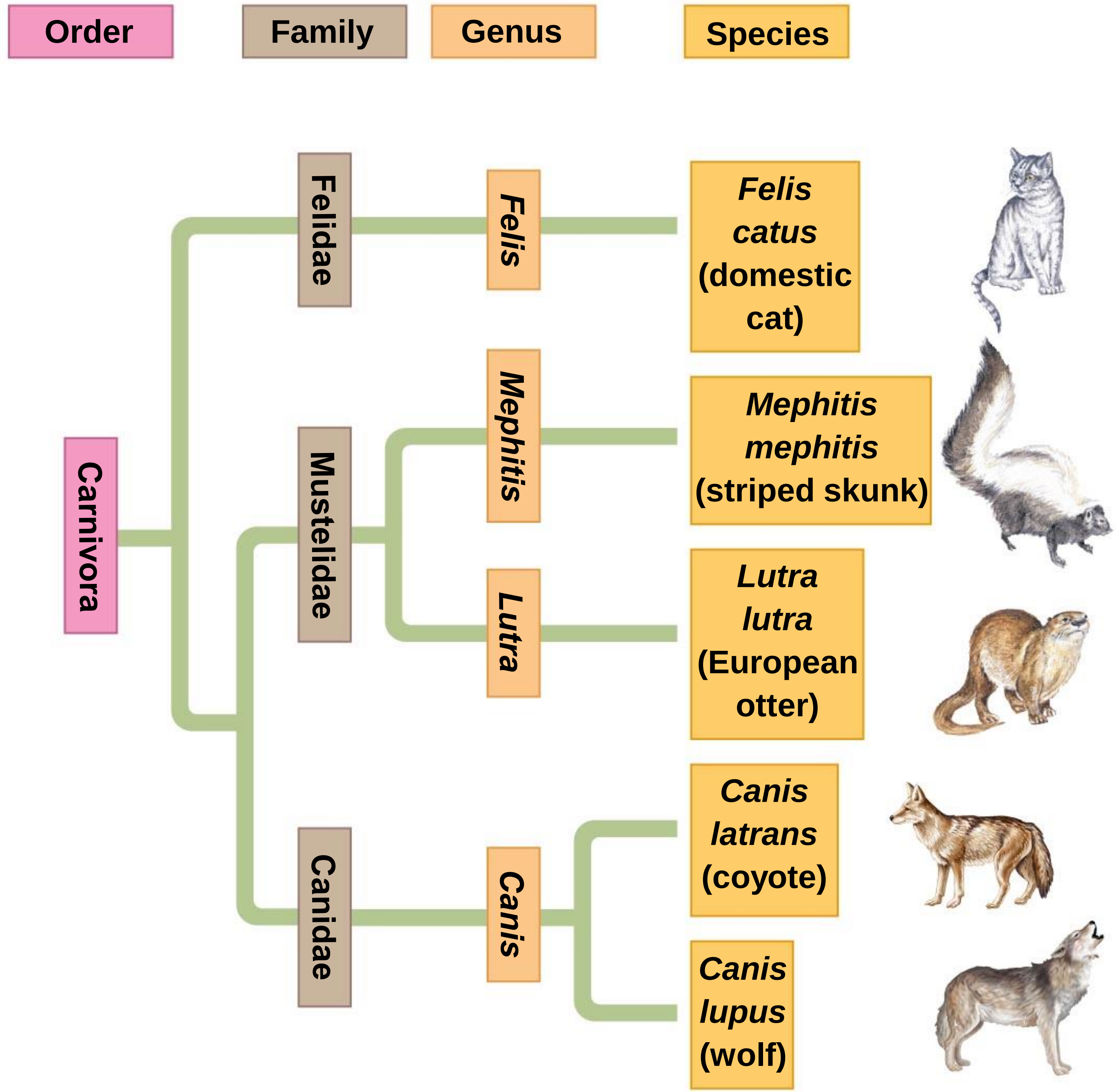
- Analogous similarities result from **convergent evolution** in similar environments
  - These similarities do not provide information about evolutionary relationships

15.15 Systematics connects classification with evolutionary history

- **Systematics** classifies organisms and determines their evolutionary relationship
- Taxonomists assign each **species** a **binomial** consisting of a **genus** and species name
- Genera are grouped into progressively larger categories.
- Each taxonomic unit is a **taxon**

PLAY Animation: Classification Schemes


Species:
Felis catus
Genus: *Felis*
Family: Felidae
Order: Carnivora
Class: Mammalia
Phylum: Chordata
Kingdom: Animalia
Bacteria
Domain: Eukarya
Archaea



Order
Family
Genus
Species
Carnivora
Felidae
Mustelidae
Canidae
Felis
Mephitis
Lutra
Canis
Felis catus (domestic cat)
Mephitis mephitis (striped skunk)
Lutra lutra (European otter)
Canis latrans (coyote)
Canis lupus (wolf)

15.16 Shared characters are used to construct phylogenetic trees

- A **phylogenetic tree** is a hypothesis of evolutionary relationships within a group
- **Cladistics** uses **shared derived characters** to group organisms into **clades**, including an ancestral species and all its descendents
  - An inclusive clade is **monophyletic**
- **Shared ancestral characters** were present in ancestral groups

15.16 Shared characters are used to construct phylogenetic trees

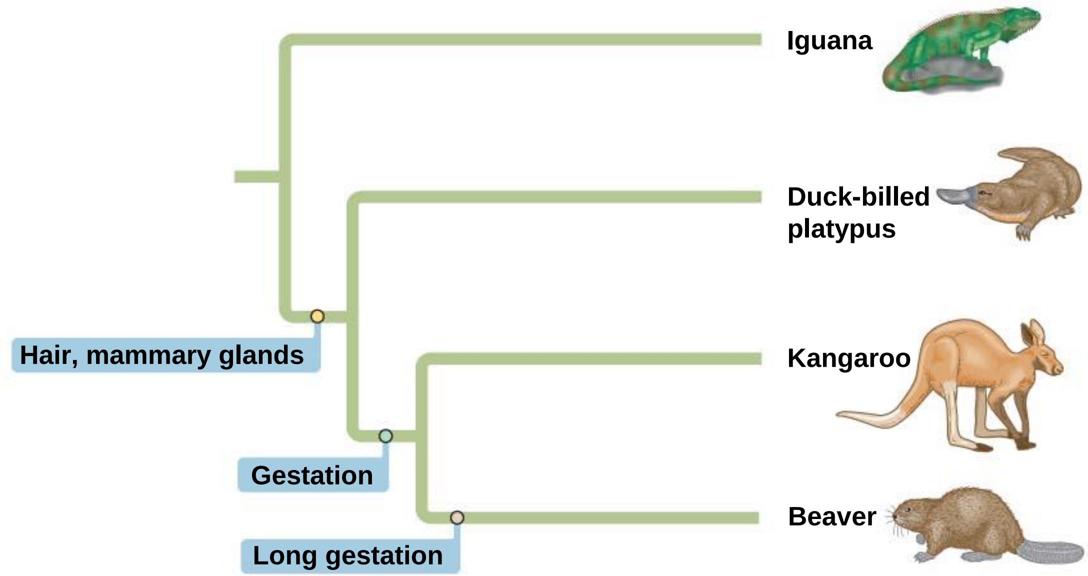
- An important step in cladistics is the comparison of the **ingroup** (the taxa whose phylogeny is being investigated) and the **outgroup** (a taxon that diverged before the lineage leading to the members of the ingroup)
  - The tree is constructed from a series of branch points, represented by the emergence of a lineage with a new set of derived traits
  - The simplest (most **parsimonious**) hypothesis is the most likely phylogenetic tree

PLAY Animation: Geologic Record

TAXA

CHARACTERS	Iguana	Duck-billed platypus	Kangaroo	Beaver
Long gestation	0	0	0	1
Gestation	0	0	1	1
Hair, mammary glands	0	1	1	1

Character Table

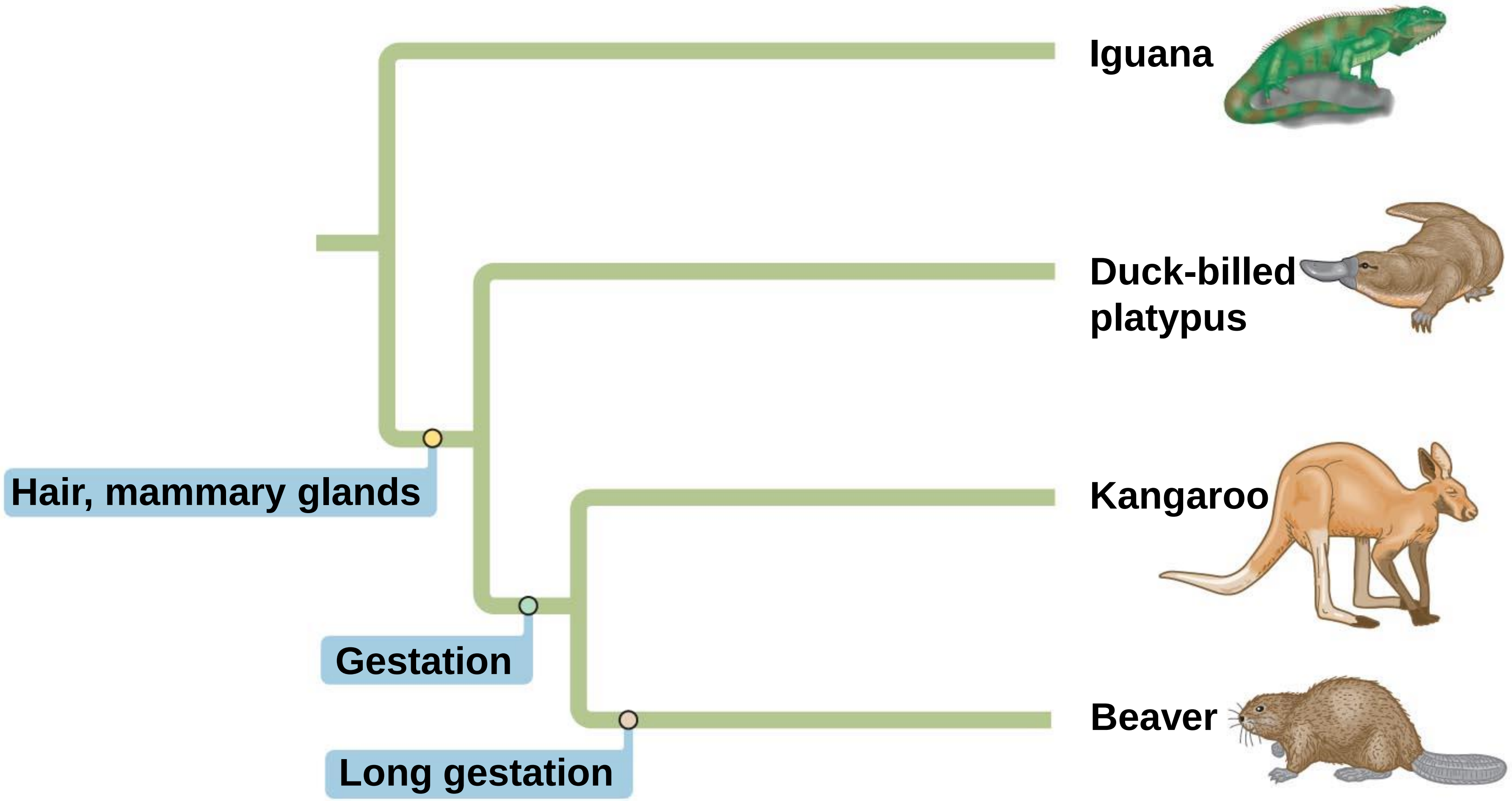


Phylogenetic Tree

TAXA

CHARACTERS	Iguana	Duck-billed platypus	Kangaroo	Beaver
Long gestation	0	0	0	1
Gestation	0	0	1	1
Hair, mammary glands	0	1	1	1

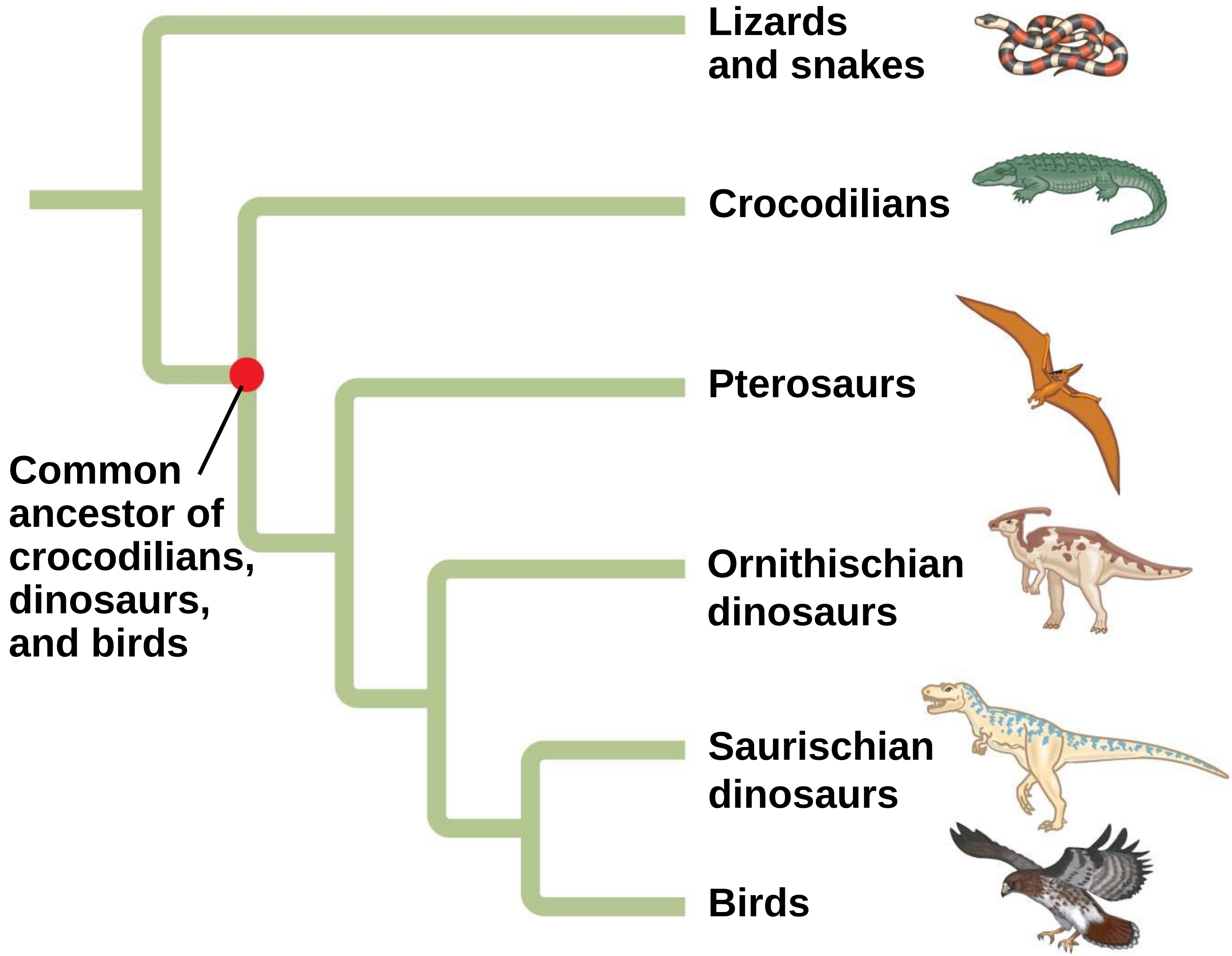
Character Table

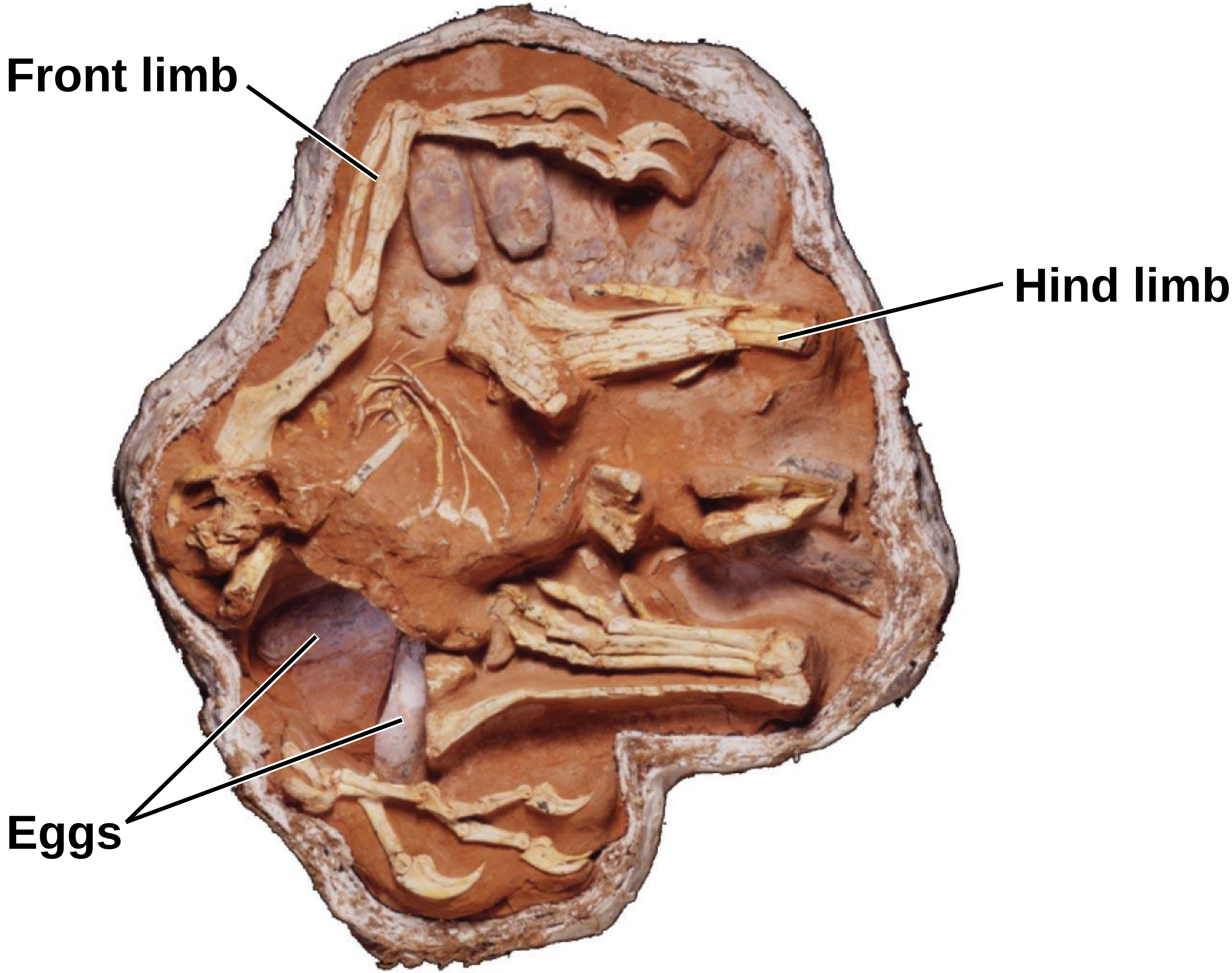


Phylogenetic Tree

15.16 Shared characters are used to construct phylogenetic trees

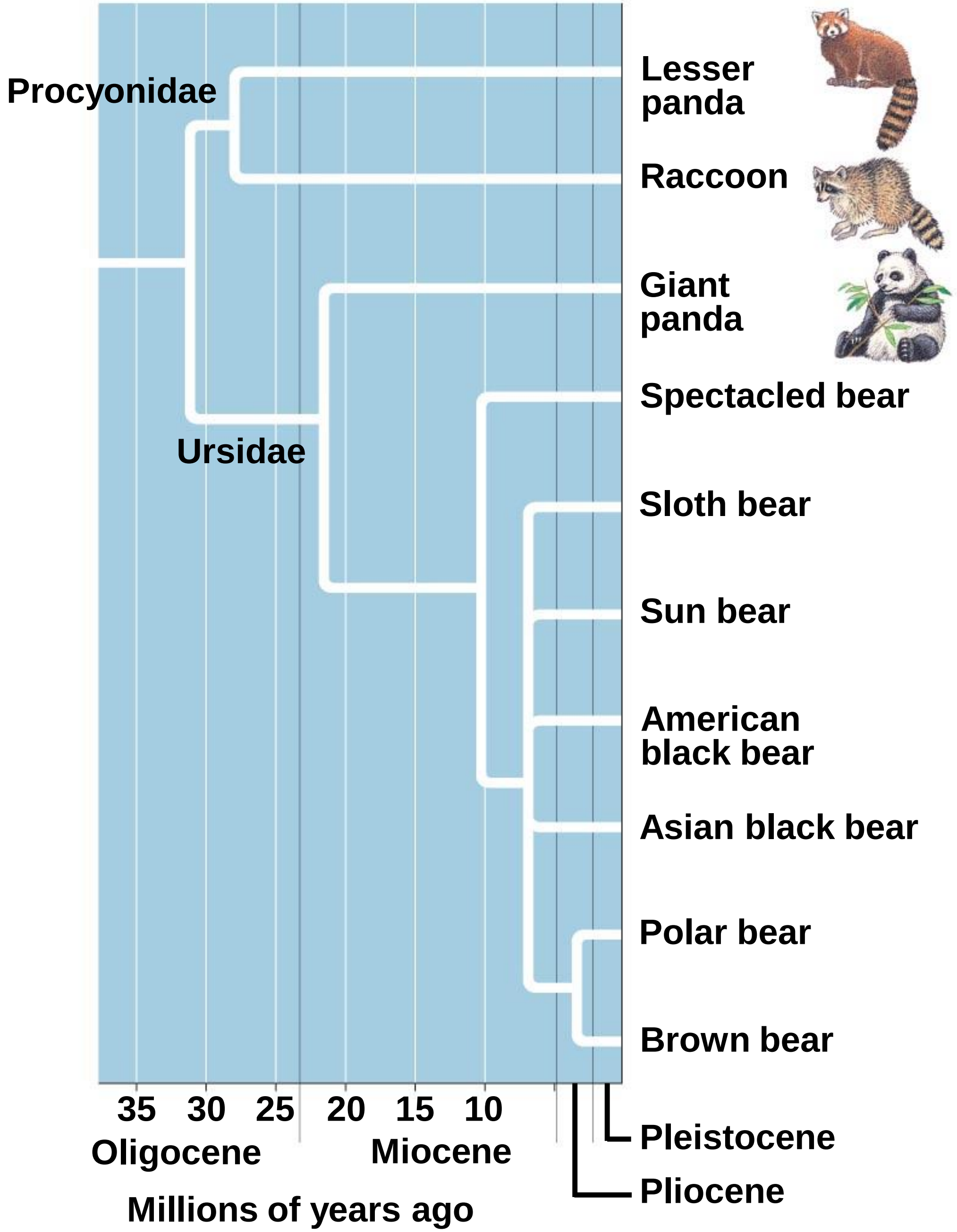
- The phylogenetic tree of reptiles shows that crocodilians are the closest living relatives of birds
  - They share numerous features, including four-chambered hearts, singing to defend territories, and parental care of eggs within nests
  - These traits were likely present in the common ancestor of birds and crocodiles


Lizards
and snakes
Crocodilians
Pterosaurs
Ornithischian
dinosaurs
Saurischian
dinosaurs
Birds
Common
ancestor of
crocodilians,
dinosaurs,
and birds


Front limb
Hind limb
Eggs

15.17 An organism's evolutionary history is documented in its genome

- **Molecular systematics** compares nucleic acids or other molecules to infer relatedness of taxa
  - Scientists have sequenced more than 100 billion bases of nucleotides from thousands of species
- The more recently two species have branched from a common ancestor, the more similar their DNA sequences should be
- The longer two species have been on separate evolutionary paths, the more their DNA should have diverged


Procyonidae
Lesser panda
Raccoon
Giant panda
Spectacled bear
Ursidae
Sloth bear
Sun bear
American black bear
Asian black bear
Polar bear
Brown bear
35
30
25
20
15
10
Oligocene
Miocene
Pliocene
Pleistocene
Millions of years ago

15.17 An organism's evolutionary history is documented in its genome

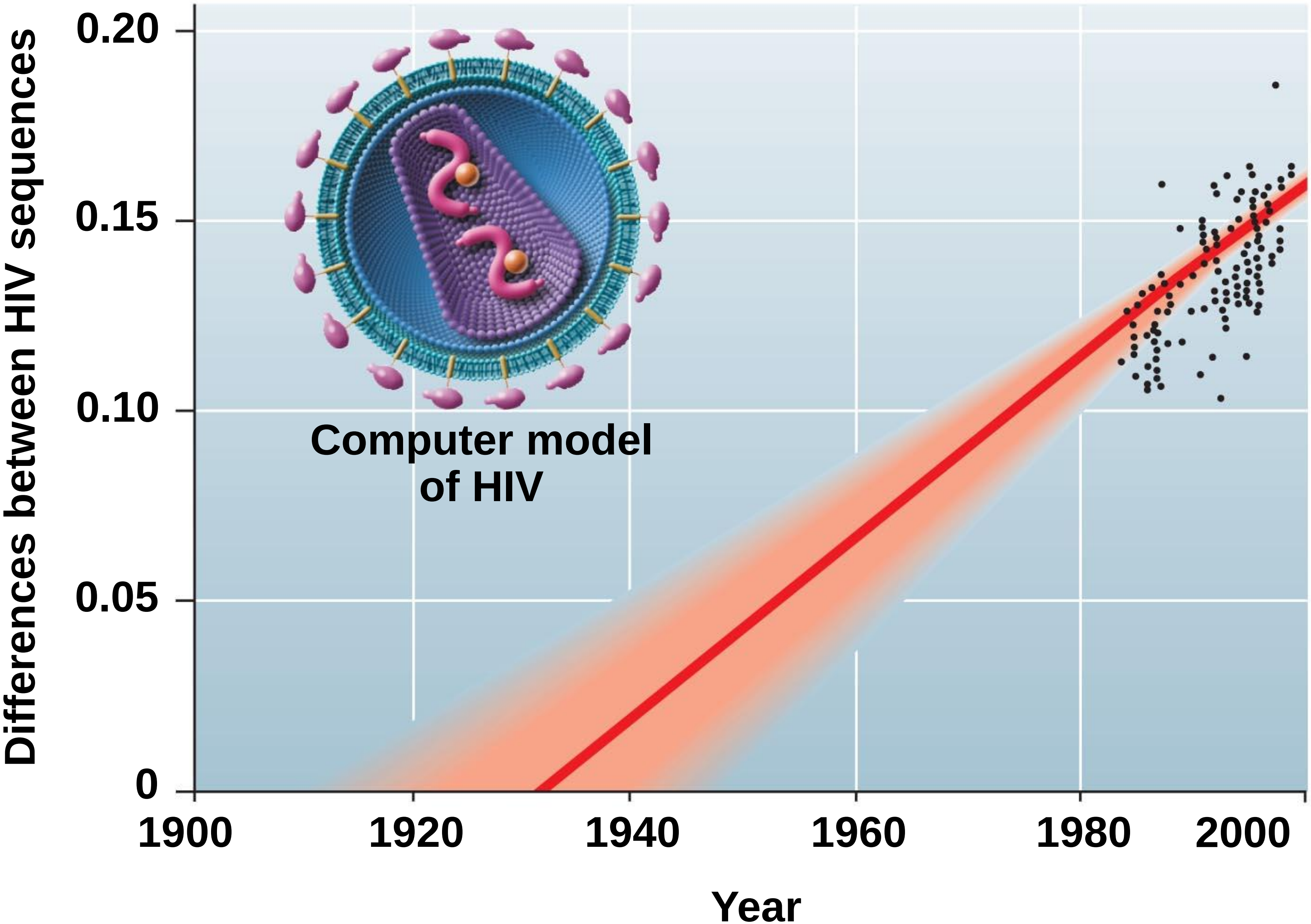
- Different genes evolve at different rates
  - DNA coding for conservative sequences (like rRNA genes) is useful for investigating relationships between taxa that diverged hundreds of millions of years ago
    - This comparison has shown that animals are more closely related to fungi than to plants
  - mtDNA evolves rapidly and has been used to study the relationships between different groups of Native Americans, who have diverged since they crossed the Bering Land Bridge 13,000 years ago

15.17 An organism's evolutionary history is documented in its genome

- Homologous genes have been found in organisms separated by huge evolutionary distances
  - 50% of human genes are homologous with the genes of yeast
- Gene duplication has increased the number of genes in many genomes
  - The number of genes has not increased at the same rate as the complexity of organisms
  - Humans have only four times as many genes as yeast

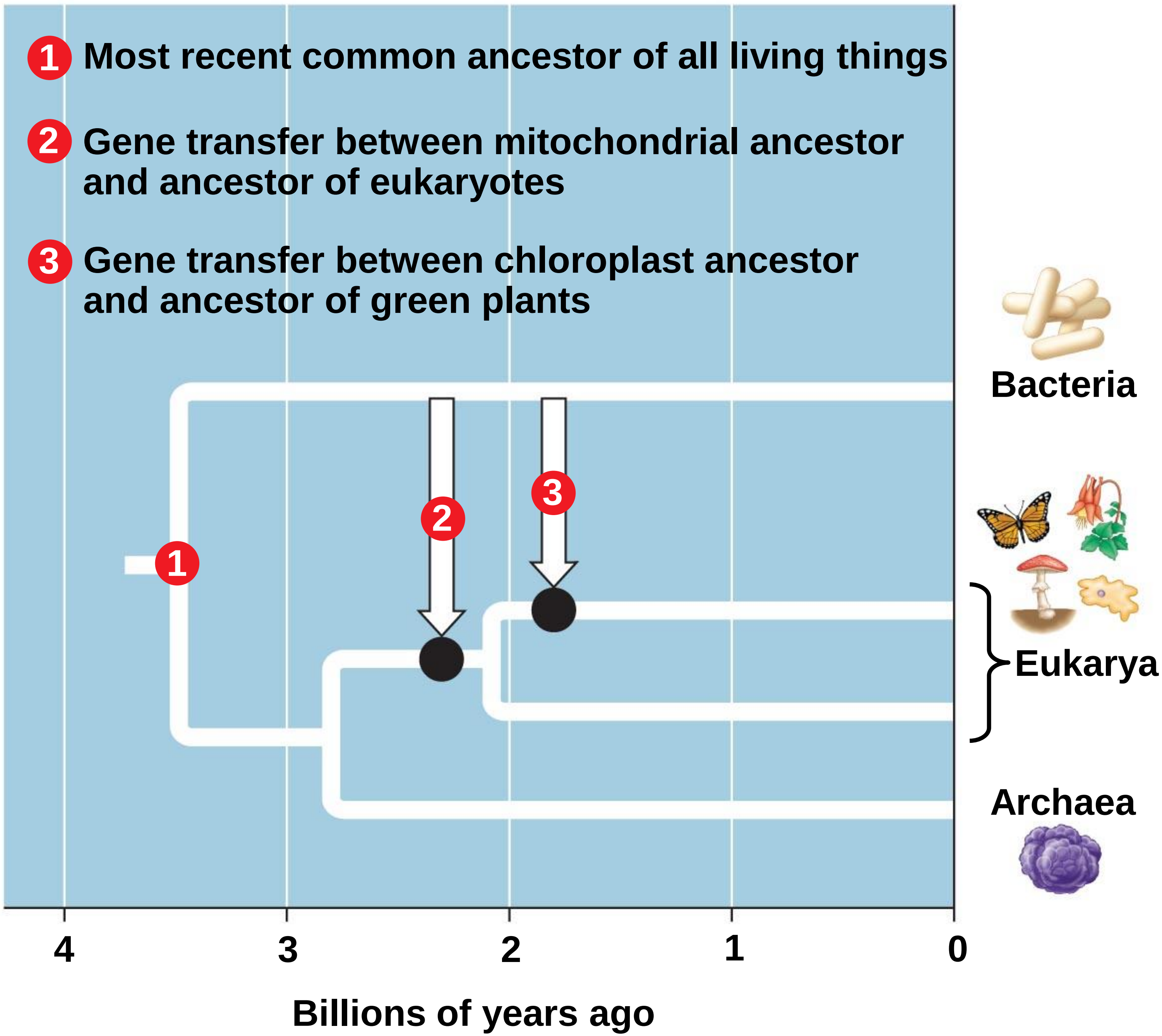
15.18 Molecular clocks help track evolutionary time

- Some regions of the genome appear to accumulate changes at constant rates
- **Molecular clocks** can be calibrated in real time by graphing the number of nucleotide differences against the dates of evolutionary branch points known from the fossil record
  - Molecular clocks are used to estimate dates of divergences without a good fossil record
  - For example, a molecular clock has been used to estimate the date that HIV jumped from apes to humans

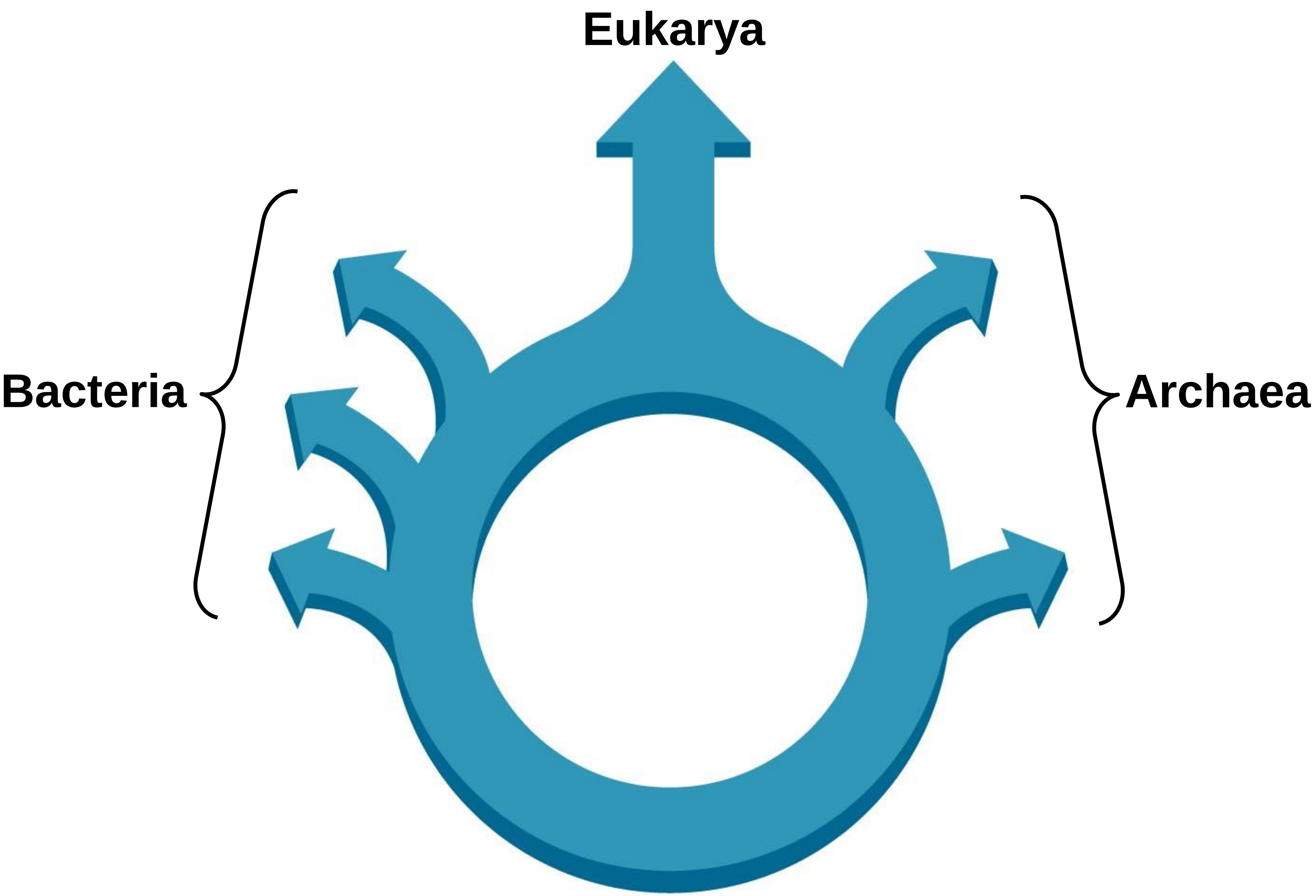

Differences between HIV sequences
0.20
0.15
0.10
0.05
0
Computer model
of HIV
1900
1920
1940
1960
1980
2000
Year

15.19 Constructing the tree of life is a work in progress

- An evolutionary tree for living things has been developed, using rRNA genes
  - Life is divided into **three domains:** the prokaryotic domains Bacteria and Archaea and the eukaryote domain Eukarya (including the kingdoms Fungi, Plantae, and Animalia)
- Molecular and cellular evidence indicates that Bacteria and Archaea diverged very early in the evolutionary history of life
  - The first major split was divergence of Bacteria from other two lineages, followed by the divergence of the Archaea and Eukarya

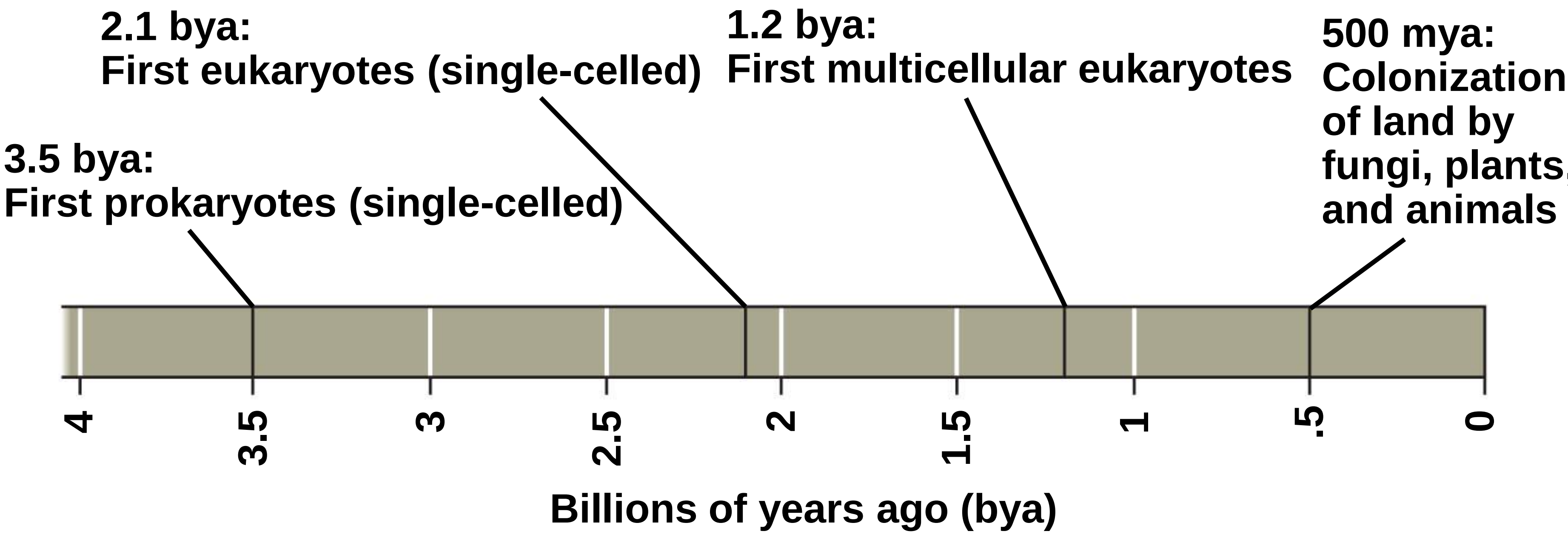


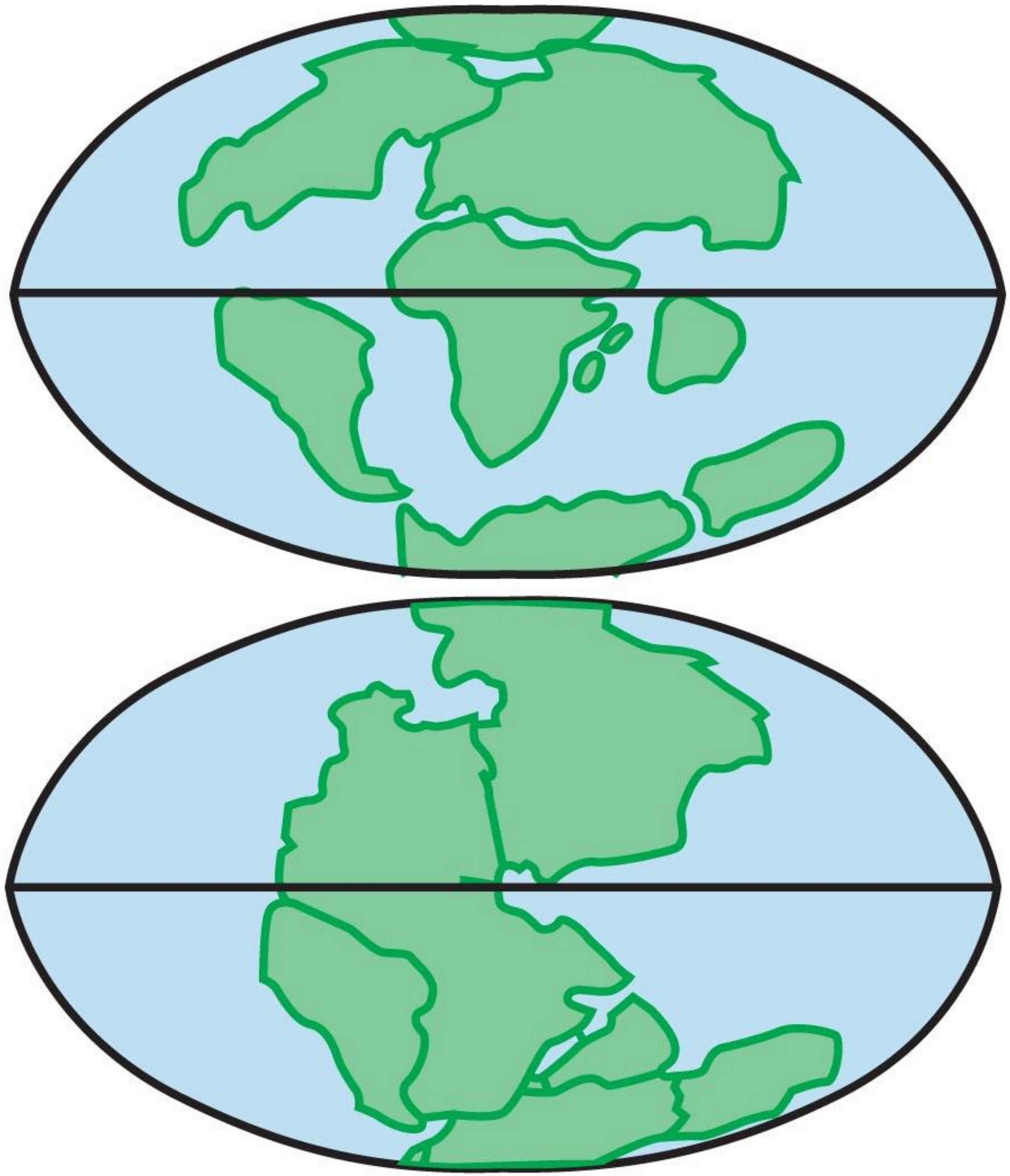
1 Most recent common ancestor of all living things
2 Gene transfer between mitochondrial ancestor and ancestor of eukaryotes
3 Gene transfer between chloroplast ancestor and ancestor of green plants
Bacteria
Eukarya
Archaea
1
2
3
4
3
2
1
0
Billions of years ago

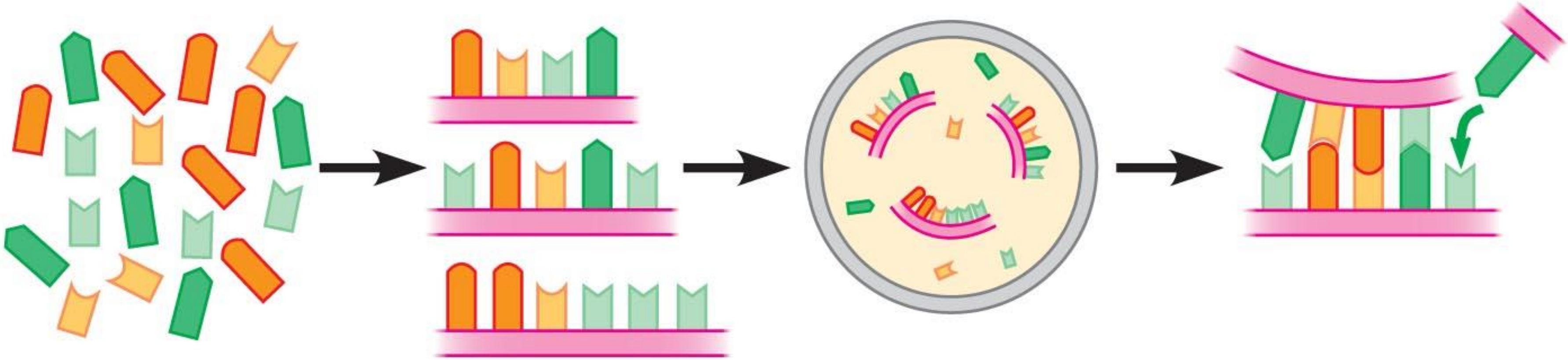

Eukarya
Bacteria
Archaea

15.19 Constructing the tree of life is a work in progress

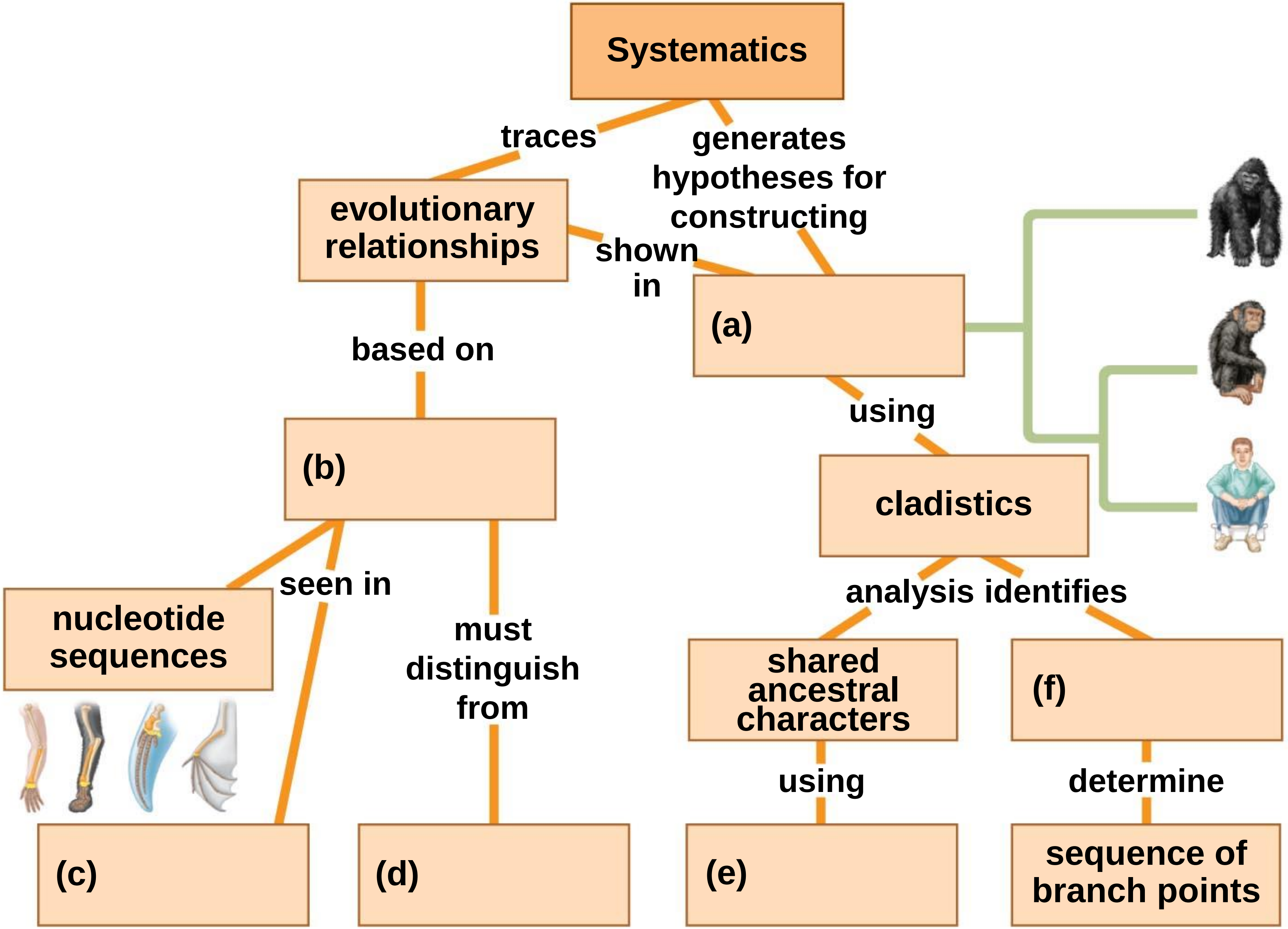
- There have been two major episodes of **horizontal gene transfer** over time, with transfer of genes between genomes by plasmid exchange, viral infection, and fusion of organisms:
  1. Gene transfer between a mitochondrial ancestor and the ancestor of eukaryotes,
  2. Gene transfer between a chloroplast ancestor and the ancestor of green plants
- We are the descendents of Bacteria *and* Archaea


2.1 bya:
First eukaryotes (single-celled)
1.2 bya:
First multicellular eukaryotes
500 mya:
Colonization of land by fungi, plants, and animals
3.5 bya:
First prokaryotes (single-celled)
4
3.5
3
2.5
2
1.5
1
.5
0
Billions of years ago (bya)

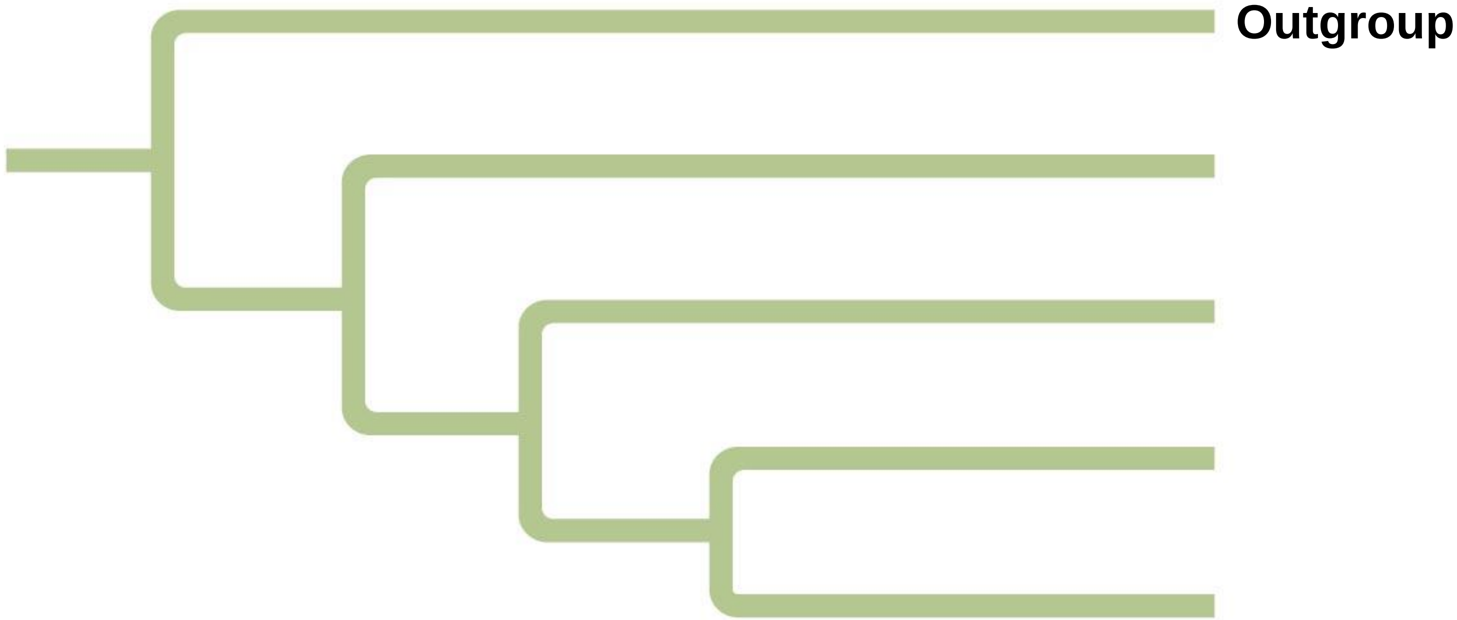




(a) (b) (c) (d)


Systematics
traces
generates hypotheses for constructing
evolutionary relationships
shown in
(a)
based on
using
(b)
cladistics
seen in
nucleotide sequences
must distinguish from
analysis identifies
shared ancestral characters
(f)
using
determine
(c)
(d)
(e)
sequence of branch points

Trait	*Velociraptor*	*Coelophysis*	*Archaeopteryx*	*Allosaurus*
Hollow bones	1	1	1	1
Three-fingered hand	1	0	1	1
Half-moon-shaped wristbone	1	0	1	0
Reversed first toe	0	0	1	0



You should now be able to

1. Compare the structure of the wings of pterosaurs, birds, and bats and explain how the wings are based upon a similar pattern
2. Describe the four stages that might have produced the first cells on Earth
3. Describe the experiments of Dr. Stanley Miller and their significance in understanding how life might have first evolved on Earth
4. Describe the significance of protobionts and ribozymes in the origin of the first cells

You should now be able to

5. Explain how and why mass extinctions and adaptive radiations may occur
6. Explain how genes that program development are important in the evolution of life
7. Define an exaptation, with a suitable example
8. Distinguish between homologous and analogous structures and describe examples of each; describe the process of convergent evolution

You should now be able to

9. Describe the goals of phylogenetic systematics; define the terms clade, monophyletic groups, shared derived characters, shared ancestral characters, ingroup, outgroup, phylogenetic tree, and parsimony
10. Explain how molecular comparisons are used as a tool in systematics, and explain why some studies compare ribosomal RNA (rRNA) genes and other studies compare mitochondrial DNA (mtDNA)