EVOLUTION

Descent with Modification
(Chapter 22)

YOU MUST KNOW…

- How Lamarck's view of the mechanism of evolution differed from Darwin's.
- Several examples of evidence for evolution and how they each support how organisms have changed over time.
- The difference between structures that are homologous and those that are analogous, and how this relates to evolution.
- The role of adaptations, variation, time, reproductive success, and heritability in evolution.

The Darwinian revolution challenged traditional views of a young Earth inhabited by unchanging species (22.1)

- Historical Setting
  - **Carolus Linnaeus** (1707-1778): Grouped similar species into increasingly general categories, reflecting what he considered the pattern of their creation.
    - Developed **taxonomy**, the branch of biology dedicated to the naming and classification of all forms of life.
    - Developed **binomial nomenclature**, a two-part naming system that includes the organism's genus and species.
  - **Georges Cuvier** (1769-1832): French geologist opposed to the idea of evolution.
    - Advocated the principle that events in the past occurred suddenly, as with catastrophes, and by different mechanisms than those occurring today. This explained boundaries between strata and location of different species.
  - **Charles Lyell** (1797-1875): English geologist and friend of Charles Darwin
    - Developed the idea that the geologic processes that have shaped the planet have been uniform over a long period of time and not by a series of catastrophes occurring over a short period of time.
    - *Importance*: ***The Earth must be very old***. An old Earth has time for evolution; a very young Earth does not. Lyell gave Darwin the gift of time.
    - Lyell's *Principles of Geology* was studied by Darwin during his journeys.
  - **Jean-Baptiste de Lamarck** (1744-1829): Developed an early theory of evolution based on two principles:

- **Use and disuse** is the idea that parts of the body that are used extensively become larger and stronger, while those that are not used deteriorate.
- **Inheritance of acquired characteristics** assumes that characteristics acquired during an organism's lifetime could be passed on to the next generation. *Example*: A weightlifter's child could be born with a more muscular anatomy.
- *Importance*: Lamarck recognized that species evolve and the match of organisms to their environment occurs through gradual evolutionary change. His explanatory mechanism, however, was flawed.

Descent with modification by natural selection explains the adaptations of organisms and the unity and diversity of life (22.2)

- Charles Darwin's voyage on the HMS Beagle from 1831 to 1836 was the impetus for the development of his theory of evolution by natural selection.
- Darwin's mechanism for evolution was natural selection. Recall that Lamarck's mechanism was the inheritance of acquired characteristics.
- Natural selection explains how adaptations arise.
    - Adaptations are heritable characteristics that enhance organisms' ability to survive and reproduce in specific environments. Example: Desert foxes have large ears, which radiate heat. Arctic foxes have small ears, which conserve body heat.
- Darwin's theory of natural selection involves these important points:
    - Individuals in a population vary in their traits, many of which are heritable.
    - A population can produce far more offspring than can survive. With more individuals than the environment can support, competition is inevitable.
    - Individuals with inherited traits that are better suited to the local environment are more likely to survive and reproduce than individuals less well-suited. This is sometimes phrased as "differential reproductive success."
    - Evolution occurs as the unequal reproductive success of individuals ultimately leading to adaptations to their environment. Over time, natural selection can increase the match between organisms and their environment.
- If an environment changes, or if individuals move to new environment, natural selection may result in adaptation to these new conditions, sometimes giving rise to new species in the process.

TIP FROM THE READERS

When explaining evolution, avoid any language that makes it sound like a species "needs" a feature and so it evolves. Don't write "survival of the fittest" but instead describe how selection favors a feature that results in leaving more offspring. Evolution is not goal oriented.

- **Artificial selection** is the process by which species are modified by humans. *Example*: Selective breeding for milk or meat production; development of dog breeds.
- *Individuals do not evolve.* ***Populations*** *evolve*.

Evolution is supported by an overwhelming amount of scientific evidence (22.3)

- Evidence for Evolution
  - **Direct Observations of Evolutionary Change**
    - Insect populations can rapidly become resistant to pesticides such as DDT.
    - Evolution of drug-resistant viruses and antibiotic-resistant bacteria.
  - **Homology and Convergent Evolution**
    - **Homology**: Characteristics in related species can have an underlying similarity even though they have very different functions. *Similarity resulting from common ancestry is known as homology*.
    - **Homologous structures** are anatomical signs of evolution. *Examples*: Forelimbs of mammals that are now used for a variety of purposes, such as flying in bats or swimming in whales, but were present and used in a common ancestor for walking. (See Figure 22.15 in your book.)
    - **Embryonic homologies**: Comparison of early stages of animal development reveals many anatomical homologies in embryos that are not visible in adult organisms. *Examples*: All vertebrate embryos have a post-anal tail and pharyngeal pouches.
    - **Vestigial organs** are structures of marginal, if any, importance to the organism. They are remnants of structures that served important functions in the organisms' ancestors. *Example*: Remnants of the pelvis and leg bones are found in some snakes.
    - **Molecular homologies** are shared characteristics on the molecular level. Examples: All life-forms use the same genetic language of DNA and RNA. Amino acid sequences coding for hemoglobin in primate species shows great similarity, thus indicating a common ancestor.
    - **Convergent evolution** explains why distantly related species can resemble one another. Convergent evolution has taken place when two organisms developed similarities as they adapted to similar environmental challenges – not because they evolved from a common ancestor. The likenesses that result from convergent evolution are considered **analogous** rather than homologous. Think of it like this: Similar problems have similar solutions. Here are some examples:
      - The torpedo shapes of a penguin, dolphin, and shark are the solution to movement through an aqueous environment.
      - Sugar gliders (marsupial mammals) and flying squirrels (eutherian mammals) occupy similar niches in their respective habitats.
  - **The Fossil Record**: *Fossils provide evidence for the theory of evolution*.

        - Fossils are remains or traces of organisms from the past. They are found in sedimentary rock. **Paleontology** is the study of fossils.
        - Fossils show that evolutionary changes have occurred over time and the origin of major new groups of organisms.
        - Darwin's theory of evolution through natural selection explains the succession of forms in the fossil record. Transitional fossils have been found that link ancient organisms to modern species, just as Darwin's theory predicts.
    - **Biogeography**: The geographic distribution of species.
        - Species in a discrete geographic area tend to be more closely related to each other than to species in distant geographic areas. *Example*: In South America, desert animals are more closely related to local animals in other habitats than they are to the desert animals of Asia. This reflects evolution, not creation.
        - **Continental drift** and the break-up of *Pangaea* can explain the similarity of species on continents that are distant today.
        - **Endemic species** are found at certain geographic location and nowhere else. *Example*: Marine iguanas are endemic to the Galápagos.

ORGANIZE YOUR THOUGHTS

1. Evolution is change in species over time.
2. There is overproduction of offspring, which leads to competition for resources.
3. Heritable variations exist within a population.
4. These variations can result in differential reproductive success.
5. Over generations, this can result in changes in the genetic composition of the population.

And remember… Individuals do not evolve! ***Populations*** *evolve.*

The Evolution of Populations
(Chapter 23)

YOU MUST KNOW…

- How mutation and sexual reproduction each produce genetic variation.
- The conditions for Hardy-Weinberg equilibrium.
- How to use the Hardy-Weinberg equation to calculate allele frequencies to test whether a population is evolving. (LO 1.4)
- What effects genetic drift, migration or selection may have on a population, and analyze data to justify your predictions. (LO 1.6-1.8)

Genetic variation makes evolution possible (23.1)

- Phenotypic variation reflects genetic variation. As you look at your classmates, their phenotypic variation may be caused by the either-or differences of a single gene or the range of variation typical of multiple genes. How many students have attached versus free ear lobes (an either-or difference as the results of one gene); what is the range of height in your class (multiple genes yielding variation along a continuum)?
- **Mutations** are the only source of *new* genes and new alleles.
    - Only mutations in cell lines that produce gametes can be passed to offspring.
- **Point mutations** are changes in one nucleotide base in a gene. They can have significant impact on phenotype, as in sickle-cell disease.
- **Chromosomal mutations** delete, disrupt, duplicate, or rearrange many loci at once. They are usually harmful but not always. Gene duplications (often from mistakes in crossing over) can result in an expanded genome with new genes that may accumulate mutations over generations and take on new functions.
- However, **most of the genetic variations** within a population are due to the sexual recombination of alleles that already exist in a population.
- Sexual reproduction shuffles existing alleles and deals them at random to produce individual genotypes. Recall that there are *three mechanisms* for this shuffling of alleles:
    - **Crossing over** during prophase I of meiosis.
    - **Independent assortment** of chromosomes during meiosis (2^{23} different combinations possible in the formation of human gametes!)
    - **Fertilization** (2^{23} x 2^{23} different possible combinations for human sperm and egg)

The Hardy-Weinberg equation can be used to test whether a population is evolving (23.2)

- **Population genetics** is the study of how populations change genetically over time.
- **Population**: A group of individuals of the same species that live in the same area and interbreed, producing fertile offspring.

- **Gene pool**: All of the alleles at all loci in all the members of a population.
- In diploid species, each individual has two alleles for a particular gene, and the individual may be either heterozygous or homozygous.
- If all members of a population are homozygous for the same allele, the allele is said to be **fixed**. Only one allele exists at that particular locus in the population. For example, the fruit fly is heterozygous for 1,920 of its 13,700 genes - the remaining 11,780 are fixed. It follows that the greater the number of fixed alleles, the lower the species' genetic diversity.

> **ORGANIZE YOUR THOUGHTS**
>
> **Five Conditions for Hardy-Weinberg Equilibrium**
>
> 1. No change in allelic frequency due to mutation.
> 2. Random mating.
> 3. No natural selection.
> 4. The population size must be extremely large. (No genetic drift.)
> 5. No gene flow. (Emigration, immigration, transfer of pollen, etc.)

- The **Hardy-Weinberg principle** is used to describe a population that is not evolving. It states that the frequencies of alleles and genes in a population's gene pool will remain constant over the course of generations unless they are acted upon by forces *other* than Mendelian segregation and the recombination of alleles. The population is at **Hardy-Weinberg equilibrium**.
- However, it is unlikely that all the conditions for Hardy-Weinberg equilibrium will be met. Allele frequencies change. Populations evolve. This can be tested by applying the **Hardy-Weinberg equation**.
- Note that the dominant phenotype includes both p^2 and $2pq$. For example, if brown eyes are dominant a person with brown eyes could be homozygous (p^2) or heterozygous ($2pq$). Because the dominant phenotype includes two possible genotypes (and two mathematical variables in p and q), we must look to the recessive phenotype to determine q. The recessive phenotype, blue eyes in our example, is q^2 and every individual with blue eyes has the same genotype (bb), which is not the case with brown eyes. It is therefore possible to take the square root of the frequency of the recessive phenotype in the population to find q. For example, if 36% of the population has blue eyes, or $q^2 = 0.36$, then $q = 0.6$ and $p = 0.4$. Here is the rule to remember: *Always find q first*!

Natural selection, genetic drift, and gene flow can alter allele frequencies in a population (23.3)

- Let's back up before we go on. In nature, is it likely that all the conditions for HW equilibrium will be met? NO! Therefore, populations are evolving, which means their allelic frequencies are changing. This concept will look at specific factors that will alter allelic frequency. Note that each of them represents an exception to one of the five conditions for HW equilibrium listed earlier.

- Mutations can alter gene frequency but are rare.
- **The three major factors** that alter allele frequencies and bring about most evolutionary change are *natural selection*, *genetic drift*, and *gene flow*.
  - **Natural selection** results in alleles being passed to the next generation in proportions different from their relative frequencies in the present generation. Individuals with variations that are better suited to their environment tend to produce more offspring than those with variations that are less suited.
  - **Genetic drift** is the unpredictable fluctuation in allele frequencies from one generation to the next. The smaller the population, the greater the chance is for genetic drift. This is a *random*, *nonadaptive* change in allele frequencies. Genetic drift can lead to a loss of genetic diversity, even causing some genes to become fixed in the new population. Two examples follow.
    - **Founder effect**: A few individuals become isolated from a larger population and establish a new population whose gene pool is not reflective of the source population.
    - **Bottleneck effect**: A sudden change in the environment (for example, an earthquake, flood, or fire) drastically reduces the size of a population. The few survivors that pass through the restrictive bottleneck may have a gene pool that no longer reflects the original population's gene pool. *Example*: The population of California condors was reduced to nine individuals. This represents a bottlenecking effect.
- **Gene flow** occurs when a population gains or loses alleles by genetic additions or subtractions from the population. This results from the movement of fertile individuals or gametes. *Gene flow tends to reduce the genetic differences between populations*, thus making populations more similar.

Natural selection is the only mechanism that consistently causes adaptive evolution (23.4)

- **Relative fitness** refers to the contribution an organism makes to the gene pool of the next generation relative to the contributions of other members. Fitness does *not* indicate strength or size. It is measured only by reproductive success.
- Natural selection acts more directly on the phenotype and indirectly on the genotype and can alter the frequency distribution of heritable traits in three ways (Figure 23.13).
  - **Directional selection** *Example*: Large black bears survived periods of extreme cold better than smaller ones and so became more common during glacial periods.
  - **Disruptive selection** *Example*: A population has individuals with either large beaks or small beaks but few with intermediate beak size. Apparently the intermediate beak size is not efficient in cracking either the large or small seeds that are common.
  - **Stabilizing selection** *Example*: Birth weights of most humans lie in a narrow range, as those babies who are very large or very small have higher mortality.
- **Sexual selection** is a form of natural selection in which individuals with certain inherited characteristics are more likely than other individuals to obtain mates. It can result in **sexual**

dimorphism, a difference between the two sexes in secondary sexual characteristics such as differences in size, color, ornamentation, and behavior.

- **How is genetic variation preserved in a population?**
  - **Diploidy**: Because most eukaryotes are diploid, they are capable of hiding genetic variation (recessive alleles) from selection.
  - **Heterozygote advantage**: Individuals who are heterozygous at a certain locus have an advantage for survival. *Example*: In sickle-cell disease, individuals homozygous for normal hemoglobin are more susceptible to malaria, whereas homozygous recessive individuals suffer from the complications of sickle-cell disease. Heterozygotes benefit from protection from malaria and do not have sickle-cell disease, so the mutant allele remains relatively common.
- **Why natural selection cannot produce perfect organisms**:
  - Selection can only edit existing variations.
  - Evolution is limited by historical constraints.
  - Adaptations are often compromises.
  - Chance, natural selection, and the environment interact.

The Origin of Species
(Chapter 24)

YOU MUST KNOW…

- The biological concept of species.
- Prezygotic and postzygotic barriers that maintain reproductive isolation in natural populations.
- A description of similar species that are maintained separate by each type of isolating barrier.
- How allopatric and sympatric speciation are similar and different.
- How a change in chromosome number can lead to sympatric speciation.
- Why speciation rates are often rapid in situations when adaptive radiation occurs or during times of ecological stress.
- The connection between a change in gene frequency, a change in the environment, natural selection or genetic drift and speciation. (LO 1.24)
- How punctuated equilibrium and gradualism describe two different tempos of speciation.

The biological species concept emphasizes reproductive isolation (24.1)

- **Speciation** is the process by which new species arise.
- **Microevolution** is change in the genetic makeup of a population from generation to generation. It refers to adaptations that are confined to a single gene pool.
- **Macroevolution** refers to the broad pattern of evolutionary change above the species level, such as the appearance of feathers and other such novelties, used to define higher taxa.
- The **biological species concept** defines a species as a group of populations whose members have the potential to interbreed in nature and produce viable, fertile offspring but are unable to produce viable, fertile offspring with members of other groups.
- **Reproductive isolation** is defined as the existence of biological barriers that impede members of two species from producing viable, fertile hybrids.
- **Prezygotic and postzygotic** are two types of barriers that prevent members of different species from producing offspring that can also successfully reproduce. Examples of prezygotic barriers, those that prevent mating or hinder fertilization if mating has occurred, include the following:
    - **Habitat isolation**: Two species can live in the same geographic area but not in the same habitat; this will prevent them from mating because they will not encounter each other.
    - **Behavioral isolation**: Some species use certain signals or types of behavior to attract mates, and these signals are unique to their species. Members of other species do not respond to the signals; thus, mating does not occur.

- **Temporal isolation**: Species may breed at different times of day, different seasons, or different years, and this can prevent them from mating.
- **Mechanical isolation**: Species may be anatomically incompatible.
- **Gametic isolation**: Even if the gametes of two species do meet, they might be unable to fuse to form a zygote.

Examples of postzygotic barriers, those that prevent a hybrid zygote from developing into a fertile adult, include the following:

- **Reduced hybrid viability**: When a zygote is formed, genetic incompatibility may cause development to cease.
- **Reduced hybrid fertility**: Even if the two species produce a viable offspring, reproductive isolation is still occurring if the offspring is sterile and can't reproduce.
- **Hybrid breakdown**: Sometimes two species mate and produce viable, fertile hybrids; however, when the hybrids mate, their offspring are weak or sterile.

Speciation can take place with or without geographic separation (24.2)

- In **allopatric speciation** a population forms a new species because it is geographically isolated from the parent population. When the population is geographically isolated gene flow is interrupted, resulting in reproductive isolation.
    - Some **geologic events or processes** that can fragment a population, resulting in geographic isolation of new populations, include the emergence of a mountain range, the formation of a land bridge, or evaporation in a large lake that produces several small lakes.
    - Small, newly isolated populations undergo allopatric speciation more frequently because they are more likely to have their gene pools significantly altered. Speciation is confirmed when individuals from the new population are unable to mate successfully with individuals from the parent population.
- A second type of speciation is **sympatric speciation**, in which a small part of a population forms a new species without being geographically separated from the parent population. It can result from part of the population switching to a new habitat; switching to a different resource such as food; or an accident during cell division, resulting in extra sets of chromosomes (polyploidy).
    - An example of a mechanism that can lead to sympatric speciation in plants is the formation of **polyploid** plants through nondisjunction in meiosis. For example, these plants may have a $4n$ chromosome number instead of the normal $2n$ number. They cannot breed with diploid members and produce fertile offspring. Although the formation of new species due to the formation of polyploids is rare in animals, it is very common in plants (80% of plant species were involved in a polyploidy event).
- **Adaptive radiation** occurs when many new species arise from a single common ancestor. In adaptive radiations the new species fill different ecological niches in their communities. Catastrophes such as volcanoes, landslides, or mass extinctions open new niches.

Speciation can occur rapidly or slowly and can result from changes in few or many genes (24.4)

- **Gradualism** proposes that species descended from a common ancestor and gradually diverge more and more in morphology as they acquire unique adaptations.
- **Punctuated equilibrium** is a term used to describe periods of apparent stasis punctuated by sudden change observed in the fossil record.

The History of Life on Earth
(Chapter 25)

YOU MUST KNOW…

- A scientific hypothesis about the origin of life on Earth.
- The age of the Earth and when prokaryotic and eukaryotic life emerged.
- Characteristics of the early planet and its atmosphere.
- How Miller and Urey tested the Oparin-Haldane hypothesis and what they learned.
- Methods used to date fossils and rocks and how fossil evidence contributes tour understanding of changes in life on Earth.
- Evidence for endosymbiosis.
- How continental drift can explain the current distribution of species (biogeography).
- How extinction events open habitats that may result in adaptive radiation.

Conditions on early Earth made the origin of life possible (25.1)

- The current hypothesis about how life arose consists of four main stages:
  - Abiotic (nonliving) synthesis of small organic molecules, such as amino acids and nitrogenous bases.
  - The joining of these small molecules into macromolecules, such as proteins and nucleic acids.
  - The packaging of these molecules into **protocells**, membrane-enclosed droplets, whose internal chemistry differed from that of the external environment.
  - The origin of self-replicating molecules that made inheritance possible.
- Earth was formed about **4.6 billion years ago**, and life on Earth emerged about **3.8 billion years ago**. For the first three-quarters of Earth's history, all of its living organisms were microscopic and primarily unicellular.
- Hypothetical early conditions of Earth have been simulated in laboratories, and organic molecules have been produced.
  - **Oparin** and **Haldane** hypothesized that the early atmosphere, thick with water vapor, nitrogen, carbon dioxide, methane, ammonia, hydrogen, and hydrogen sulfide, provided with energy from lightning and UV radiation, could have formed organic compounds, a primitive "soup" from which life arose.
  - **Miller** and **Urey** tested this hypothesis and produced a variety of amino acids. Miller-Urey-type experiments show that the abiotic synthesis of organic molecules is possible under various assumptions about the composition of the early atmosphere.

- It is hypothesized that **self-replicating RNA** (not DNA) was the **first genetic material**. RNA, which plays a central role in protein synthesis, can also carry out a number of enzyme-like catalytic functions. These RNA catalysts are called **ribozymes**.

The fossil record documents the history of life (25.2)

- The **fossil record** is the sequence in which fossils appear in the layers of sedimentary rock that constitute Earth's surface. **Paleontologists** study the fossil record. Fossils, which may be remains of dead organisms or impressions they left behind, are most often found in sedimentary rock formed from layers of minerals settling out of water. The fossil record is incomplete because it favors organisms that existed for a long time, were relatively abundant and widespread, and had shells or hard bony skeletons.
- Rocks and fossils are dated several ways:
    - **Relative dating** uses the order of rock strata to determine the relative age of fossils. The oldest fossils are deposited in the lower strata.
    - **Radiometric dating** uses the decay of radioactive isotopes to determine the age of the rocks or fossils. It is based on the rate of decay, or **half-life** of the isotope. The half-life is the time necessary for 50% of the parent isotope to decay. For example, the half-life of radioactive carbon-14 is 5,730 years (the common isotope carbon-12 is not radioactive). Living organisms accumulate both carbon-12 and carbon-14 in a known ratio. Once the organism dies no more carbon is obtained, but the carbon-14 decays into nitrogen-14. Measuring the carbon-14-to-carbon-12 ratio in a fossil can reveal its age. For example, if the fossil ratio of carbon-14 to carbon-12 is one-eighth the ratio of present-day individuals, the fossil is about 17,190 years old (5780 x 3 half-lives).

Key events in life's history include the origins of single-celled and multicelled organisms and the colonization of land (25.3)

- The earliest living organisms were **prokaryotes**.
- About 2.7 billion years ago, **oxygen** began to accumulate in Earth's atmosphere as a result of photosynthesis. The rise of oxygen doomed many prokaryotic groups, but others evolved in the new oxygen-rich environment, including the evolution of groups capable of cellular respiration.
- **Eukaryotes** appeared about 2.1 billion years ago.
    - The **endosymbiotic hypothesis** proposes that mitochondria and plastids (chloroplasts) were formerly small prokaryotes that began living within larger cells.
    - **Evidence** for this hypothesis includes the following:
        - Both organelles have enzymes and transport systems homologous to those found in the plasma membranes of living prokaryotes.
        - Both replicate by a splitting process similar to prokaryotes.
        - Both contain a single, circular DNA molecule, not associated with histone proteins.
        - Both have their own ribosomes, which can translate their DNA into proteins.

- **Multicellular eukaryotes** evolved about 1.2 billion years ago.
- The **colonization of land** occurred about 500 million years ago, when **plants, fungi, and animals** began to appear on Earth.

The rise and fall of groups of organisms reflect differences in speciation and extinction rates (25.4)

- **Continental drift** is the movement of Earth's continents on great plates that float on the hot, underlying mantle. The San Andreas Fault marks where two plates are sliding past each other. Where plates have collided, mountains are uplifted.
    - Continental drift can help explain the disjunct geographic distribution of certain species, such as a fossil freshwater reptile found in both Brazil in South America and Ghana in west Africa, today widely separated by ocean.
    - Continental drift can explain why no eutherian (placental) mammals are indigenous to Australia.
- **Mass extinctions**, loss of large numbers of species in a short period, have resulted from global environmental changes that have caused the rate of extinction to increase dramatically.
    - By removing large numbers of species, a mass extinction can drastically alter a complex ecological community. Evolutionary lineages can disappear. *Example*: The dinosaurs were lost in a mass extinction 65 million years ago. Mass extinctions cause many ecological niches to be vacated. After mass extinctions those niches can be filled by the evolution of new species in an adaptive radiation.
    - Mass extinctions open niches that new species may occupy. For examples, the rise of mammals occurred following the loss of dinosaurs. This is an example of adaptive radiation.
- **Adaptive radiations** are periods of evolutionary change in which groups of organisms form many new species whose adaptations allow them to fill different ecological niches. After each of the five major extinctions as adaptive radiation occurred. Adaptive radiations also occur after major evolutionary innovations, such as seeds in plants or feathers in birds, or newly colonized areas where new species face little competition. *Example*: The Galápagos finch species are the result of an adaptive radiation due to the creation of new niches when volcanic action formed new land.

Major changes in body form can result from changes in the sequences and regulation of developmental genes (25.5)

- **Evo-devo** is a field of study in which evolutionary biology and developmental biology converge. (Evo = from evolution, Devo = from development) This field is illuminating how slight genetic divergences can be magnified into major morphological differences between species.
- Evolutionary novelty can arise when structures that originally played one role gradually acquire a different one. Structures that evolve in one context but become co-opted for another function

are sometimes called **exaptations**. For example, it is possible that feathers of modern birds were co-opted for flight after functioning in some other capacity, such as thermoregulation.

- **Heterochrony** is an evolutionary change in the rate or timing of developmental events. Changing relative rates of growth even slightly can change the adult form of organisms substantially, thus contributing to the potential for evolutionary change. The increased rate in growth of bat finger bones provide the underlying support for bat wings, whereas the decreased rate of growth in leg and pelvic bones in whales led to the loss of hind limbs.
- **Homeotic genes** are master regulatory genes that determine the location and organization of body parts. Homeotic genes affect where a pair of wings will develop or how a flower's parts are arranged.
- ***Hox*** genes are one class of homeotic genes. Changes in *Hox* genes and in the genes that regulate them can have a profound effect on morphology, thus contributing to the potential for evolutionary change. An example is seen in the variable expression of a *Hox* gene in a snake limb bud and a chicken leg bud, resulting in no legs in the snake and a skeletal extension in the chicken.

Evolution is not goal oriented (25.6)

- Evolution is like tinkering – a process in which new forms arise by the slight modification of existing forms. Even large changes, like the ones that produced the first mammals, can result from the modification of existing structures or existing developmental genes.

Phylogeny and the Tree of Life
(Chapter 26)

YOU MUST KNOW…

- The taxonomic categories and how they indicate relatedness.
- How systematics is used to develop phylogenetic trees.
- How to construct a phylogenetic tree that represents processes of biological evolution. (LO 1.13)
- The three domains of life, including their similarities and their differences.
- The significance of widely conserved processes across the three domains.

CONNECT WITH THE CURRICULUM FRAMEWORK

This chapter is a rich source of possible questions. Note these specific objectives, and be sure you can do each of these tasks.

- The student is able to pose scientific questions about a group of organisms whose relatedness is described by a phylogenetic tree or cladogram in order to (1) identify shared characteristics, (2) make inferences about the evolutionary history of the group, and (3) identify character data that could extend or improve the phylogenetic tree. (LO 1.17)
- The student is able to evaluate evidence provided by a data set in conjunction with a phylogenetic tree or a simple cladogram to determine evolutionary history and speciation. (LO 1.18)
- The student is able to create a phylogenetic tree or simple cladogram that correctly represents evolutionary history and speciation from a provided data set. (LO 1.19)

Phylogenies show evolutionary relationships (26.1)

- **Phylogeny** is the evolutionary history of a species or a group of related species. It is constructed by using evidence from systematics, a discipline that focuses on classifying organisms and their evolutionary relationships. Its tools include fossils, morphology, genes, and molecular evidence.
- **Taxonomy** is an ordered division of organisms into categories based on a set of characteristics used to assess similarities and differences.
- **Binomial nomenclature** uses a two-part naming system that consists of the **genus** to which the species belongs as well as the organisms' **species** within the genus, such as *Canis familiaris*, the scientific name of the common dog. This system was developed by **Carolus Linnaeus**.

- The hierarchical classification of organisms consists of the following levels, beginning with the most general or inclusive: **domain, kingdom, phylum, class, order, family, genus**, and **species**. Each categorization at any level is called a **taxon**.
- Systematists use branching diagrams called **phylogenetic trees** to depict hypotheses about evolutionary relationships. The branches of such trees reflect the hierarchical classifications of groups nested within more inclusive groups. (See Figure 26.4)
- Notice on Figure 26.4 that two branch points are numbered. Each number represents a *common ancestor* of the two branches.
- The basics of how to read a phylogenetic tree are given in Figure 26.5.

Phylogenies are inferred from morphological and molecular data (26.2)

- **Homologous structures** are similarities due to shared ancestry, such as the bones of a whale's flipper and a tiger's front limb.
- **Convergent evolution** has taken place when two organisms developed similarities as they adapted to similar environmental challenges – not because they evolved from a common ancestor. *Example*: The streamlined bodies of a tuna and a dolphin show convergent evolution.
- The likenesses that result from convergent evolution are considered **analogous** rather than homologous. They do not indicate relatedness but rather similar solutions to similar problems. *Example*: The wing of a butterfly is analogous to the wing of a bat. Both are adaptations for flight.
- **Molecular systematics** uses DNA and other molecular data to determine evolutionary relationships. The more alike the DNA sequences of two organisms, the more closely related they are evolutionarily.

Shared characters are used to construct phylogenetic trees (26.3)

- A **cladogram** depicts patterns of shared characteristics among taxa and forms the basis of a **phylogenetic tree**.
- A **clade**, within a tree, is defined as a group of species that includes an ancestral species and all its descendants. Clades are monophyletic.
- **Shared derived characters** are used to construct cladograms. They are evolutionary novelties unique to a particular clade. For example, hair is a shared derived character of mammals.
- A **shared ancestral characteristic** is one that originated in an ancestor of the taxon. For example, all mammals have backbones, but a backbone does not distinguish a mammal from other vertebrates because all vertebrates have a backbone.
- Study Figure 26.10 to understand why a clade is *monophyletic* , and what is meant by paraphyletic and polyphyletic groupings. Each cladogram is a hypothesis about the evolutionary relatedness of the organisms included. The goal of taxonomy is to understand the lines of descent from ancestral forms well enough to produce monophyletic cladograms. This means the cladogram reflects the common ancestor and all of its descendants. Many times, however, scientists lack the data to make a monophyletic cladogram, resulting in paraphyletic or

polyphyletic groupings. As data become available, the cladograms are improved until, hopefully, a monophyletic cladogram can be formed.

- The terms *monophyletic*, *paraphyletic*, and *polyphyletic* are not in the Curriculum Framework, but questions about these ideas are common. The terms help to organize your learning and will be ones your college professors will expect you to know.

An organism's evolutionary history is documented in its genome (26.4)

- The rate of evolution of DNA sequences varies from one part of the genome to another; therefore, comparing these different sequences helps us to investigate relationships between groups of organisms that diverged a long time ago.
    - DNA that codes for ribosomal RNA changes relatively *slowly* and is useful for investigating relationships between taxa that diverged hundreds of millions of years ago.
    - DNA that codes for mitochondrial DNA (mtDNA) evolves *rapidly* and can be used to explore recent evolutionary events.

Molecular clocks help track evolutionary time (26.5)

- **Molecular clocks** are methods used to measure the absolute time of evolutionary change based on the observation that some genes and other regions of the genome appear to evolve at constant rates. The underlying assumption for molecular clocks is that the number of nucleotide substitutions in related genes is proportional to the time that has elapsed since the genes branched from their common ancestor.

New information continues to revise our understanding of the tree of life (26.6)

- Taxonomy is in flux! When your authors were in high school, we were taught that there were two kingdoms, plants and animals; then in our college courses, we were introduced to five kingdoms: Monera, Protista, Plantae, Fungi, and Animalia.
- Now biologists have adopted a **three-domain system**, which consists of the domains Bacteria, Archaea, and Eukarya. This system arose from the finding that there are two distinct lineages of prokaryotes.
- The domains Bacteria and Archaea contain *prokaryotic* organisms, and Eukarya contains *eukaryotic* organisms. As we gain more tools for analysis, earlier ideas about evolutionary relatedness are changed, and so taxonomy, too, continues to evolve.