Chapter 12

Evolutionary Theory

12.1 Lesson 12.1: Darwin and The Theory of Evolution

Lesson Objectives

- Identify important ideas Darwin developed during the voyage of the *Beagle*, and give examples of his observations that supported those ideas.
- Recognize that scientific theories and discoveries are seldom the work of just one individual.
- Describe prevailing beliefs before Darwin about the origin of species and the age of the earth.
- Evaluate Lamarck's hypothesis about how species changed.
- Analyze the impact of Lyell's *Principles of Geology* on Darwin's work.
- Evaluate the influence of Malthus' ideas about human population on Darwin's thinking.
- Discuss the relationship between Alfred Russel Wallace and Charles Darwin.
- Describe the general ideas of Darwin's Theory of Evolution.
- Use Darwin's reasoning to explain natural selection as the mechanism of evolution.
- Explain how natural selection results in adaptation to environment.
- Recognize the importance of variation to species survival.
- Relate the idea of differential survival to the concept of natural selection.
- Interpret the expression "descent with modification."
- Discuss the concept of "common ancestry."
- Show how Darwin's theory provides a scientific explanation for the fossil record.
- Interpret Darwin's theory as an example of the general principle that the present arises from the materials and forms of the past.

Introduction

Charles Darwin's **Theory of Evolution** represents a giant leap in human understanding. It explains and unifies all of biology – thousands of years of natural history from before Darwin's time, as well as the 150 years of genetics, molecular biology, and even ecology since Darwin published the theory. It directs our responses to disease and our practice of agriculture. It enlightens conservation biology. It has the potential to guide our future decisions about biotechnology. Apart from science, the Theory of Evolution has dramatically changed how we think about ourselves and how we relate to the world. Because the theory has influenced so many aspects of human life, it is crucial that you understand it thoroughly.

The "Theory of Evolution" contains two major ideas:

The first is evolution itself.

1. Present life has arisen gradually from past life forms. The millions of species of plants, animals, and microorganisms that live on Earth today are related by descent from common ancestors.

The second describes how evolution happens.

1. **Natural selection** explains how the diversity of life has arisen through time.

The main goal of this lesson will be to clarify these ideas. The lesson will begin by exploring Darwin's experiences. The ideas of others who influenced Darwin's thinking will also be presented. Finally, the content and significance of the theory itself will be analyzed.

The Voyage of the Beagle

Captained by a 26-year-old Royal Navyman and carrying a 22-year-old "gentleman's companion" who collected beetles competitively, His Majesty's Ship *Beagle* set sail on one of the shortest days of the year 1831 to chart South American coastal waters. Alarmed by the suicides of his own uncle and the previous *Beagle* commander, Captain Robert FitzRoy had sought a social and educational equal to accompany him at dinner and in scientific endeavors throughout the anticipated two-year voyage. Charles Darwin, financed by his wealthy father, assumed the unpaid positions of the ship's naturalist and captain's friend.

Darwin resisted his family's hopes that he become a doctor or clergyman. During the two years before he dropped out of medical studies, he was repulsed by the brutality of surgery but fascinated by natural history – field observations of plants, animals, rocks, and fossils. He observed marine mammals on the English coast, and learned taxidermy from a freed slave whose talk of rain forests ignited curiosity in Darwin. After his disappointed father switched him to a school of theology, Darwin again gravitated toward natural history,

Figure 12.1: The HMS *Beagle* carried 22-year-old Charles Darwin as an unpaid naturalist and "gentleman companion" for the ship's captain. (17)

becoming a protégée of botanist John Steven Henslow in order to learn the popular pastime of competitive beetle collecting. He managed to pass his theology exams, but his interests continued to reflect his passion for natural history, including William Paley's "argument for divine design in nature." He had just postponed entry into the clergy in order to study geology – mapping rock layers in Wales – when he received the invitation to join FitzRoy on the *Beagle*.

Planned to last two years, the voyage shown in **Figures** 12.1 and 12.2, stretched to five years. Darwin spent over 3 years of this time on land, carefully observing rock formations and collecting animals, plants, and fossils (**Figure** 12.4). Throughout the journey, he used his observations to develop a series of ideas which later became the foundation for his theory of evolution by natural selection (**Figure** 12.5). A few of his ideas, observations, and experiences follow.

Rock and Fossil Formations

During the voyage of the *Beagle*, Darwin made a number of geological observations that helped form his theory. Rock and fossil formations that he observed suggested that continents and oceans had changed dramatically over time.

- Darwin found rocks at a continental divide, 13,000 feet *above* sea level, which contained fossil seashells.
- A river in Argentina rose gradually through a series of plateaus, which Darwin and FitzRoy interpreted as ancient beaches.
- After experiencing a volcanic eruption and an earthquake in Chile, Darwin found a

Figure 12.2: The *Beagle*s voyage continued for nearly five years, although original plans called for only two. Darwin spent over three years of that time on land, collecting plants, animals, and fossils, and developing his ideas about evolution and natural selection. (27)

bed of newly dead mussels, which the quake had lifted nine feet above the sea.

- A petrified forest embedded in sandstone at 7,000 feet had been a sunken coastal woodland, buried in sand and then uplifted into mountains.
- Near Lima, Darwin recognized coral atolls as the result of sinking volcanoes, with coral adding layer after layer to keep the living reef close to the sunlit surface, as shown in **Figure** 12.3.

Tropical Rain Forests and Many New Plant, Animal, and Fossil Species

During the voyage of the *Beagle,* Darwin made a number of observations of plants, animals, and fossils that helped him form his theory. Observations of tropical rain forests and many new plant, animal, and fossil species encouraged Darwin to reconsider the source of the vast diversity of life.

- In Brazil, Darwin collected great numbers of insects – especially beetles!
- Inland from Montevideo, Darwin dug up the hippopotamus-like skull of an extinct giant capybara.

Figure 12.3: Darwin explained coral atolls in terms of slowly sinking volcanoes. Evidence for slow geologic change contributed a great deal to his thinking about slow changes in life. (7)

- After collecting his first marsupial in Australia, Darwin exclaimed that some people might think "'Surely two distinct Creators must have been [at] work."

Figure 12.4: Marine Iguanas (left) and Blue-footed Boobies (right) were among the tremendous variety of new and very different plants and animals Darwin identified during the voyage of the *Beagle*. He developed his ideas about evolution and natural selection to explain the remarkable similarities and differences he had observed. (6)

Native Cultures Raised Questions

During the voyage of the *Beagle*, observations of native cultures led Darwin to question the relationship between humans and animals and the development of civilizations.

- Disgusted by the enslavement of blacks in Brazil, Darwin argued with FitzRoy so fiercely that the captain temporarily banished him from dining.
- At the tip of South America, Darwin wrote "I could not have believed how wide was the difference between savage and civilized man: it is greater than between a wild and domesticated animal."

- Darwin described New Zealand Maoris as savage, in contrast to missionary-influenced Tahitians.
- Jemmy Buttons, a South American native who had "been civilized" in England, chose to stay in South America rather than continue with the *Beagle* - to the great dismay of the Englishmen convinced of their civilization's superiority.

Figure 12.5: Darwin's encounters with native cultures influenced his thinking as much as his discoveries of fossils and new species. This painting was taken from original pictorial records of the *Beagle* voyage. (23)

Sedimentary Rocks Implied Gradual Changes

Darwin also made a number of observations that implied gradual changes in both the Earth and in living organisms, as opposed to catastrophic changes, including:

- Many inland sediments had clearly been deposited by quiet tides rather than catastrophic floods.
- Gauchos, cowboys of Argentina, helped Darwin find and excavate fossils of gigantic extinct mammals, including armadillos and one of the largest mammals of all time, the ground sloth *Megatherium* (**Figure** 12.6). Darwin recorded that these sediments bore no trace of a Biblical flood.

Figure 12.6: Darwin found two separate fossils of one of the largest mammals of all time, a giant ground sloth, *Megatherium.* He noted that they were found in sediments which had been deposited slowly over long periods of time, rather than suddenly as by a catastrophic flood. (31)

Life on Island Chains

The distribution of life on island chains challenged the dogma of the unchangability of species. The Galapagos Islands are arguably where Darwin made his most influential observations. The Galapagos Islands are a group of 16 volcanic islands near the equator about 600 miles from the west coast of South America. Darwin was able to spend months on foot exploring the islands.

- Darwin noted that locals could distinguish each island's variation of Galapagos tortoise, shown in **Figure** 12.7. Surprisingly, he did not collect their shells, despite dining on the giant reptiles during the voyage.
- A series of birds now known as the Galapagos (or Darwin's) finches were also specific to certain islands. Darwin failed to label the locations in which he had collected these rather drab-looking birds, but fortunately, FitzRoy and the ship's surgeon were more careful with their collections.
- Darwin interpreted the different Galapagos mockingbirds as varieties, but wrote that if varieties were a step on the way to new species, "such facts (would) undermine the stability of Species."

Figure 12.7: Like many seamen, Darwin and the crew of the *Beagle* dined on Galapagos tortoise, a convenient animal to carry live on long voyages. However, locals living on the islands claimed the tortoises varied according to the islands from which they came, and this idea later played an important role in Darwin's thinking about the origins of species. (20)

Throughout the trip, Darwin shown in **Figure** 12.8, sent his mentor, Henslow, collections of plants, animals, insects, and fossils – many of which were previously unknown. While Darwin traveled, Henslow promoted his work by sharing his geological writings and fossils with renowned naturalists. By the time the *Beagle* returned to England in October of 1836, Darwin himself had been accepted as an established naturalist. His father set up investment accounts to fund his son's career as a "gentleman scientist." At that time, governments and universities did not fund scientific research, so only independently wealthy individuals could afford to practice pure science. This position gave Darwin the contacts, resources, and freedom he needed to develop his ideas into the theory of evolution by natural selection.

Figure 12.8: Darwin's writings on geology and the collections of plants, animals, and fossils he sent back to England established his reputation as a naturalist even before he returned from his voyage. After his return, his father supported him as a "gentleman scientist," allowing him to further develop the ideas inspired by his *Beagle* travels. (3)

Standing on the Shoulders of Giants

Science, like evolution, builds on the past. Darwin's theory was a product not only of his own intellect, but also of the times in which he lived and the ideas of earlier great thinkers. Some of these ideas colored Darwin's perspective during his five years on the *Beagle;* many contributed to his thinking after the voyage. Not until 23 years after he returned to England did Darwin crystallize his thoughts and evidence sufficiently to publish his theory.

Before Darwin, most people believed that all species were created at the same time and remained unchanged throughout history. History, they thought, reached back just 6,000 years.

One of the first scientists to explore change in species was Jean Baptiste Lamarck. Lamarck believed that organisms improve traits through increased use, and then pass the improved feature on to their offspring. According to this idea of **inheritance of acquired characteristics**, giraffes have long necks because early giraffes stretched their necks to reach tall trees and then passed the longer necks on to their calves, as shown in **Figure** 12.9. This attempt to explain adaptation was popular during the 19th century, and undoubtedly influenced Darwin's thinking. Although Lamarck advanced the proposal that species change, evidence does not support inheritance of acquired characteristics. You can weight-train for years, but unless your children train as hard as you did, their muscles will never match yours! We will look later at Darwin's explanation for giraffes' necks.

Much as Lamarck questioned the dogma that species do not change, Charles Lyell challenged the belief that the earth was young. In *Principles of Geology,* he recorded detailed observations of rocks and fossils, and used present patterns and processes as keys to past events. He concluded that many small changes over long periods of time built today's landscapes, and that the earth must be far older than most people believed. Captain FitzRoy gave Darwin a copy of *Principles of Geology* just before the *Beagle* left England, and Darwin "saw through [Lyell's] eyes" during the voyage. Darwin's theory that present species developed gradually over long periods of time reflects Lyell's influence.

The idea that natural laws, rather than miracles, govern life as well as geology grew during the early 19th century. Charles Babbage wrote that God had the power to make laws, which in time produce species. His close friend, John Herschel, called for a search for natural laws underlying the "mystery of mysteries" of how species formed. Later, Darwin cited Herschel as "one of our greatest philosophers" and then said he intended "to throw some light on the origin of species — that mystery of mysteries."

Darwin's idea that individuals in a population compete for resources came from reading Thomas Malthus. Malthus described a human "struggle for existence" due to exponential population growth and limited food. Darwin thought that animal and plant populations might have similarly limited resources. If so, offspring suited to their environment would be more likely to survive, while those less "fit" would perish.

Breeders of pigeons, dogs, and cattle inspired Darwin's ideas about selection. By choosing

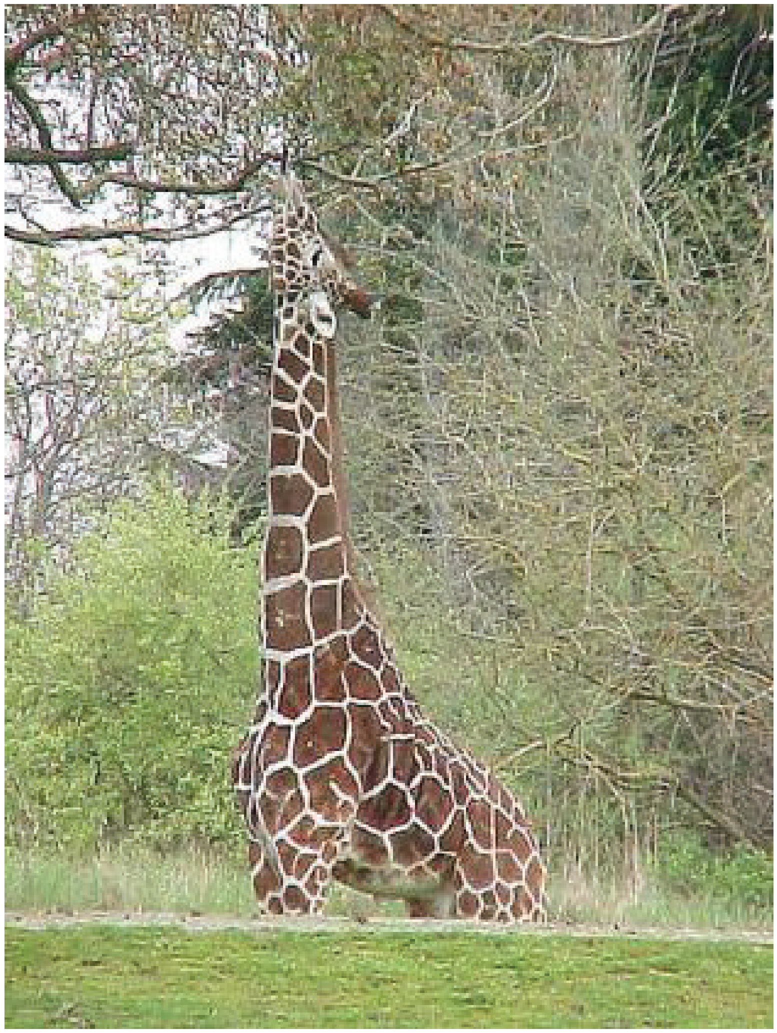

Figure 12.9: According to Lamarck's idea, inheritance of acquired characteristics, giraffes have long necks because earlier giraffes stretched their necks to reach tall trees, and then passed their lengthened necks down to their calves. Evidence does not support this hypothesis, but many credit Lamarck for advancing the idea that species develop and change. (33)

which animals reproduced, breeders could achieve remarkable changes and diversity in a relatively short time. Variations in traits were clearly abundant and heritable. Darwin referred to selective breeding as **artificial selection**. His observations of how artificial selection worked helped him to develop his concept of **natural selection** (**Figure** 12.10).

Figure 12.10: The way in which animal breeding artificially selects desirable variations influenced Darwin's ideas of natural selection. The English Carrier Pigeon (left), the English Fantail (center), and the Fiary Swallow (right) have all "descended" from the common rock pigeon (*Columbia livia*), with the help of human breeders. (24)

One of the last individuals to influence Darwin's theory was Alfred Russel Wallace, a naturalist whose work in Malaysia led him to conclusions similar to Darwin's. In 1858 - over 20 years since the *Beagle* returned to England - Wallace sent Darwin a paper which described concepts nearly identical to Darwin's ideas about evolution and natural selection. Lyell helped arrange a joint presentation to the Linnean society two weeks later. Darwin, shocked by the sudden competition, worked quickly to complete his book by the following year. Although both naturalists had independently come to the same conclusions, the extensive evidence and careful logic Darwin presented in *The Origin of the Species* earned him the greater share of recognition for the theory of evolution by natural selection.

Standing on the shoulders of the giants who went before him, Darwin was able to see past the countless details of his beloved work in natural history to formulate a unifying theory to explain the diversity of life.

Darwin's Theory of Evolution

Darwin lived in an increasingly scientific society which had begun to accept the idea that universal "laws" governed processes in nature - perhaps including life itself. Like Lamarck, Darwin understood that species change. With Lyell, he saw that the history of Earth and its life covered a vast amount of time. From his observations of animal breeding, he recognized that even within species, individuals showed variation in traits, and that the variations could be passed to offspring. Recalling Malthus, he knew that populations could produce far more offspring than the environment could support. He predicted that individuals with traits which suited the environment would survive and reproduce to pass their favorable traits to offspring, as shown in **Figure** 12.11. Those whose traits were less suited to the environment would die. Just as humans select for breeding those cattle which produce more milk, he reasoned, nature (the limited environment) selects individuals which use resources most efficiently. Thus, he called his explanation of how species change *natural selection.*

Darwin defined natural selection as the ”principle by which each slight variation [of a trait], if useful, is preserved,” and he later regretted that he had not named it “natural preservation.” Today it is often defined as the process by which a certain trait becomes more common within a population. Let’s look once more at the parts of this process, and then we will consider its consequences.

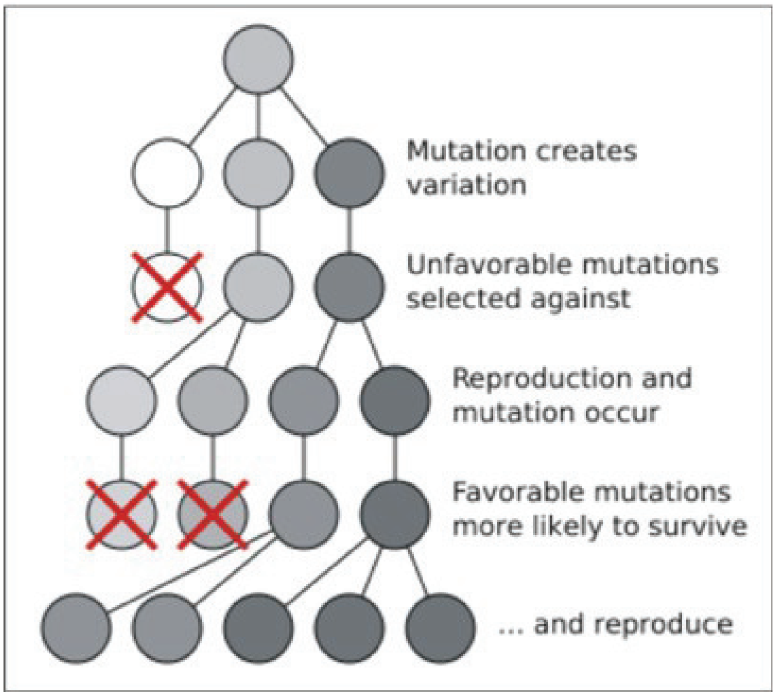

Figure 12.11: Natural selection involves heritable variation, overproduction of offspring, preferential survival of individuals having variations favorable for the environment, and reproduction by survivors. This diagram shows two selection events, with reproduction after each one. (26)

By chance, heritable variations exist within a species.

Darwin did not know that genes made of DNA determine traits. Much later, scientists learned that mutations in DNA can change genes and produce variations in traits. However, his observations of animal breeding and his detailed studies of barnacles and orchids convinced him that small, heritable variations in traits were common among individuals within a species. Darwin probably recognized that sexual reproduction increased variety in offspring. He expressed considerable concern that his own health problems might be heritable, especially when his beloved daughter Annie grew ill and died. He believed that his marriage to his cousin may have contributed to his children's weaknesses.

Species produce more offspring than can survive.

Malthus argued that human populations grow exponentially if unchecked, but that disease, starvation, or war will limit population growth eventually. High birth rates and high death rates were characteristic of human history. Darwin himself had ten children; three died before maturity. Darwin reasoned that all species had the capacity to grow. However, his observations showed that most populations remained stable due to environmental limits. He concluded that many offspring must die. The phrases ***overproduction of offspring*** and ***struggle for existence*** summarize this idea.

Offspring with favorable variations are more likely to survive to reproduce.

Although heritable variations appeared to be random, death, Darwin reasoned, was not. Offspring which, *by chance*, had variations which "fit" or adapted them to their environment would have a greater chance to survive to maturity and a greater chance to reproduce. Offspring without such adaptations were more likely to die. Thus, well-adapted individuals produce more offspring. ***Differential survival and reproduction*** is a cornerstone of natural selection.

Gradually, individuals with favorable variations make up more of the population.

Can an individual organism evolve? No. Though an individual organism can be better adapted to its environment, it still must mate with others of its species, so by definition, it is not a new species. It is just an individual with a better chance of survival in its environment. It is the accumulation of many adaptations that, over many generations, results in a new species.

Through chance variation, overproduction of offspring, and differential survival and reproduction, the proportion of individuals with a favorable trait (or favorable phenotype) will increase. The result is a population of individuals adapted to their environment. It is the variation within a species that increases the likelihood that at least some members of a species will be adapted to their environment and survive under changed conditions.

It is important to note that natural selection is *not* directed or intentional. It depends on chance variations - due to genetic variations - and can work only with the "raw material" of existing species. Occasionally, variations which have no particular adaptive logic may survive. However, the limits set by resources and environment usually mean an increase in traits which help survival or reproduction, and the loss of traits which harm them. Gradually, ***species change***. Eventually, changes accumulate and a new species is formed.

Let's compare natural selection to inheritance of acquired characteristics (Lamarck's idea mentioned above). How would Darwin's mechanism explain the long necks of giraffes?

1. ***Heritable variation***: In the past, some giraffes had short necks, and some had long necks.
2. ***Overproduction of offspring***: Giraffes produced more young than the trees in their environment could support.
3. ***Differential survival and reproduction***: Because the long-necked giraffes could feed from taller trees, they were more likely to survive and produce more offspring. Short-necked giraffes were more likely to starve before they could reproduce.
4. ***Species change***: The long-necked giraffes passed their long necks on to their calves, so that each generation, the population contained more long-necked giraffes.

Recall that Lamarck believed that giraffes could stretch their necks to reach tall trees, and pass their stretched necks on to offspring. If this were true, evolution would reward effort toward a goal. Darwin showed that evolution is not goal-directed. Instead, the environment reinforces variations which occur by chance.

Lyell studied the geology which surrounded him and saw that the environment had changed many times over a vast amount of time. Darwin studied the life across continents and saw, in addition to tremendous variation, that species had changed – in response to the changes in their environment – over that vast amount of time. Both proved, with careful observations and well-reasoned inferences, that the present arises from the past. Limited to our brief lifespans, we see today's species as fixed. Darwin taught us how to see the relationships between them; to see that they developed from earlier, distinctly different species; to see that all of them - all of *us* - share common ancestors (**Figure** 12.12). The cartoons which showed Darwin as an ape (an example is shown in the next lesson) did a great disservice to his theory of evolution. Far too many people limit their understanding of evolution to the simple phrase that "we came from apes." We humans share common ancestors not only with the great apes, but with ALL of life – blue whales, gazelles, redwood trees, saguaros, fireflies, mosquitoes, puffballs, amebas, and bacteria. As Darwin said in closing the *Origin*, "There is grandeur in this view of life."

Darwin delighted in the great diversity of life, but also saw unity within that diversity. He saw striking patterns in the similarities and differences. Seeking an explanation for those patterns, he developed the concept of natural selection. Natural selection explains how today's organisms could be related – through "descent with modification" from common ancestors. Natural selection explains the story told by the fossil record – the long history of life on Earth. Natural selection is a scientific answer (if only partial) to the old questions: Who are we? How did we come to be?

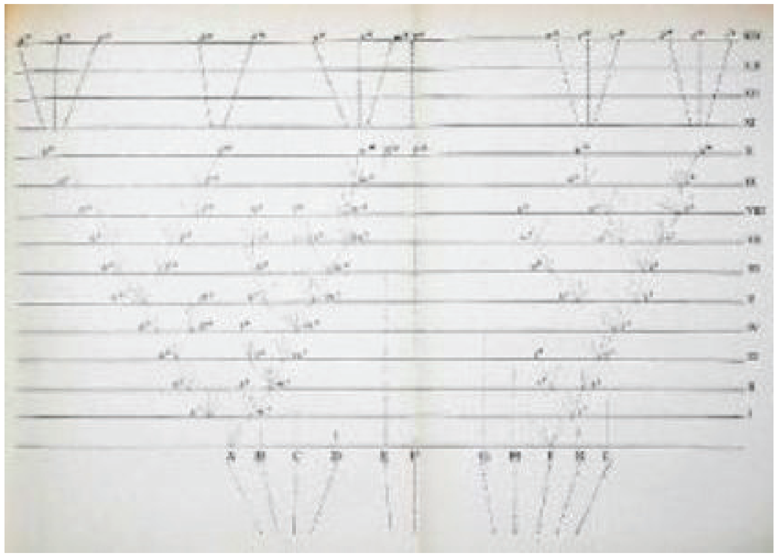

Figure 12.12: A sketch from Darwin's *Origin of Species,* this "Tree of Life" depicts his ideas of how today's species (top row, XIV) have descended with modification from common ancestors. The theory implies that all species living today have a universal common ancestor – that we humans are related to all of Earth's plants, animals, and microorganisms. (34)

In the light of natural selection, it is easy to see that variation – differences among individuals within a population – increases the chance that at least some individuals will survive if the environment changes. Here is a strong argument against cloning humans: if we were all genetically identical – if variation (or genetic variation) did not exist – a virus which previously could kill just some of us would either kill all of us, or none of us. Throughout the long history of life, variation has provided insurance that inevitable changes in the environmental will not mean the extinction of a species. Similarly, the diversity of species ensures that environmental change will not mean the extinction of life. Life has evolved (or, the Earth's changing environment has selected) variation and diversity because they ensure survival. Causes of mutation may have pre-existed, but in a sense, life has embraced them. And sexual reproduction has evolved to add further to variation and diversity (as discussed in the *Cell Division and Reproduction* chapter).

Adaptations are logical because the environment imposes limits on organisms, selecting against those who do not "fit." Adaptations arise through gradual accumulation of chance variations, so they cannot be predicted, despite the fact that they appear to be goal-directed or intentional. Adaptations relate to every aspect of life: food, water, oxygen, nutrients, shelter, growth, response, reproduction, movement, behavior, ability to learn. Adaptations connect organisms to the resources in their environments. You are born with your adaptations; they are not changes you make to fit yourself into an environment. If the environment changes, the adaptive value of some of your inherited characteristics may also change. Our human appetites for salt and fat, for example, may remain from our past, when fat and salt were rare in our environment; now that they are easily available, we consume more than is good for us. Biologist E.O. Wilson believes adaptations reach every aspect of human life - that social, political, and even religious behaviors are rooted in our genes. Of course, we can learn – and learning allows us to adapt within our lifetimes to environmental change. The ability to learn is itself an adaptation – perhaps our greatest gift. But more and more, we are discovering that much of our behavior – including learning - is genetically programmed – a gift from our ancestors similar to vision and hearing, or breathing and digestion.

Darwin's theory can be summarized in two statements All living species share common ancestors, and

Natural selection explains how species change.

In this lesson, we have explored Darwin's reasoning. In the next lesson, we will consider the abundant evidence which supports his ideas.

Lesson Summary

- The Theory of Evolution has changed how we see ourselves and how we relate to our world.
- The theory has two basic ideas: the common ancestry of all life, and natural selection.

- Darwin studied medicine and theology, but he first worked as ship's naturalist on the HMS *Beagle*.
- During the 5-year voyage, Darwin spent over 3 years on land exploring new rocks, fossils, and species.
- From his observations, Darwin developed new ideas which later formed the foundation of his theory.

1. Rock and fossil formations suggested that continents and oceans had changed dramatically.
2. Tropical rain forests encouraged Darwin to reconsider the source of the vast diversity of life.
3. Native cultures raised questions about the relationship between humans and animals.
4. Sedimentary rocks implied gradual, as opposed to catastrophic, changes in the earth and in life.
5. The distribution of life on island chains challenged the dogma of the immutability of species.

- After he returned, his reputation as a naturalist and his father's financial support allowed him to become a "gentleman scientist," free to analyze his collections, formulate his theory, and write about both.

- Like all scientific theories, Darwin's was a product of both his own work and the work of other scientists.
- Before Darwin, most people believed that all species were created and unchanging about 6000 years ago.
- Jean-Baptiste Lamarck proposed that acquired characteristics could be inherited. Evidence did not support his mechanism for change, but Darwin shared his ideas of change in species.
- Charles Lyell wrote that present rock formations have developed through gradual changes over long periods of time. Darwin applied his ideas to present life forms.
- Observations of animal breeding helped Darwin appreciate the importance of heritable variations.
- Malthus' work showed that populations produce more offspring than the environment can support.
- Charles Babbage and John Herschel believed that natural laws governed the origin of species.
- Alfred Russel Wallace formulated a theory very similar to Darwin's. Although they collaborated on a joint paper, Darwin's clear and forceful *Origin of Species* earned him greater credit.

- The two general ideas of Darwin's Theory are evolution and natural selection.
- The concept of natural selection includes these observations and conclusions:

1. By chance, heritable variations exist within a species.
2. Species produce more offspring than can survive.
3. Offspring with favorable variations are more likely to survive to reproduce.
4. Gradually, individuals with favorable variations make up more of the population.

- Variation among individuals within species ensures that some will survive environmental change.
- Because some variations help survival in a specific habitat more than others, individuals having those variations are more likely to survive and reproduce.
- This differential survival and reproduction results in a population which is adapted to its environment.
- The result of natural selection is gradual change in species, and when enough changes have accumulated, new species form. This is "descent with modification."
- The idea that natural selection has led to the origin of all species, together with evidence from the fossil record, means that all existing species are related by "common ancestry."
- Evolution by natural selection explains the history of life as recorded in the fossil record.
- Common ancestry explains the similarities, and natural selection in the face of environmental change explains the differences among present-day species.
- Like Lyell's Principles of Geology, Darwin's Theory of Evolution supports the general principle that the present arises from the materials and forms of the past.

Review Questions

1. State 3 of the 5 ideas Darwin developed during the Voyage of the Beagle. For each idea, give and example of a specific observation he made which supports the idea.
2. Compare and contrast Darwin's position as a "gentleman scientist" with today's professional scientists.
3. What does the expression "standing on the shoulders of giants" say about Darwin and his Theory of Evolution? Support your interpretation with at least three specific examples.
4. Explain the importance of Lyell's Principles of Geology to Darwin's work.
5. Discuss the influence of animal breeding on Darwin's thinking.
6. Clarify the relationship between Darwin and Alfred Russel Wallace.
7. Summarize in your own words the two basic ideas which make up Darwin's Theory of Evolution.
8. Compare and contrast Lamarck's and Darwin's ideas using the evolution of the human brain as an example.
9. Why is it incorrect to say that evolution means organisms adapt to environmental change?
10. Why is it not correct to say that evolution means "we came from monkeys?"

Further Reading / Supplemental Links

- http://www.aboutdarwin.com/voyage/voyage03.html
- http://darwin-online.org.uk/
- http://www.ucmp.berkeley.edu/history/evolution.html
- http://www.pbs.org/wgbh/evolution/
- http://www.literature.org/authors/darwin-charles/the-origin-of-species/
- http://www.life.umd.edu/emeritus/reveal/pbio/darwin/darwindex.html

Vocabulary

adaptation A characteristic which helps an organism survive in a specific habitat.

artificial selection Animal or plant breeding; artificially choosing which individuals will reproduce according to desirable traits.

inheritance of acquired characteristics The idea that organisms can increase the size or improve the function of a characteristic through use, and then pass the improved trait on to offspring.

law A statement which reliably describes a certain set of observations in nature; usually testable.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

theory An explanation which ties together or unifies a large group of observations.

Points to Consider

- How might the Theory of Evolution help us to understand and fight disease?
- What other aspects of medicine could benefit from an understanding of evolution?
- How can evolution and natural selection improve conservation of species and their environments?
- How would you put into words the ways in which evolution has changed the way we look at ourselves?
- How do you think it has altered the way we relate to other species? To the Earth?
- Consider the human brain. If Lamarck's hypothesis about inheritance of acquired characteristics were true, how would your knowledge compare to your parents?

12.2 Lesson 12.2: Evidence for Evolution

Lesson Objectives

- Clarify the significance of a scientific theory.
- Recognize that Darwin supported his theory with a great deal of evidence, and that many kinds of evidence since his time have further strengthened the theory of evolution.
- Describe how Darwin used the fossil record to support descent from common ancestors.
- Compare and contrast homologous structures and analogous structures as evidence for evolution.
- Give examples of evidence from embryology which supports common ancestry.
- Explain how vestigial structures support evolution by natural selection.
- Discuss the molecular similarities found in all species of organisms.
- Describe how evolution explains the remarkable molecular similarities among diverse species.
- Analyze the relationship between Darwin's Theory of Evolution and more recent discoveries such as Mendel's work in genetics and the molecular biology of DNA and protein.
- Relate the distribution of plants and animals to changes in geography and climate.
- Explain how biogeography supports the theory of evolution by natural selection.
- Summarize the explanation given by both Darwin and Wallace for the distribution of few, closely related species across island chains.

Introduction

You are probably aware that the concept of evolution still generates controversy today, despite its wide acceptance. In *The Origin of the Species*, Darwin mentioned humans only once, predicting, "Light will be thrown on the origin of man and his history." Nevertheless, some people immediately distorted its far-reaching message about the unity of life into near-sighted shorthand: humans "came from" monkeys (**Figure** 12.13).

Figure 12.13: In Darwin's time and today, many people incorrectly believe that evolution means "humans come from monkeys." This interpretation does not do justice to Darwin's theory, which holds that all species share common ancestry. (16)

In the last lesson, you learned that evolution relates all of life – not just humans and monkeys. In this lesson, you will learn that biological evolution, like all scientific theories, is much more than just an opinion or **hypothesis**, it is based on evidence.

In science, a **theory** is an explanation which ties together or unifies a large group of observations. Scientists accept theories if they have a great deal of supporting evidence. In *The Origin of the Species,* Darwin took the time to compile massive amounts of fossil and biological evidence to support his ideas of natural selection and descent from common ancestors. He clearly and effectively compared animal breeding (artificial selection), which was familiar to most people, and natural selection. Because Darwin provided so much evidence and used careful logic, most scientists readily accepted natural selection as a mechanism for change in species. Since Darwin's time, additional fossil and biological data and new fields of biology such as genetics, molecular biology, and biogeography have dramatically confirmed evolution as a unifying theory – so much so that eminent biologist Theodosius Dobzhansky wrote that "Nothing in biology makes sense except in the light of evolution."

In this lesson, you can explore and evaluate for yourself the many kinds of evidence which support the theory of evolution by natural selection. You will also have the opportunity to appreciate the power of evolution to explain observations in every branch of biology.

The Fossil Record: Structural Changes Through Time

Few would argue that dinosaurs roamed Earth in the past, but no longer exist. The **fossil record** is a revealing window into species that lived long ago. **Paleontologists** have carefully analyzed the preserved remains and traces of animals, plants, and even microorganisms to reconstruct the history of life on Earth (see the *History of Life* chapter for more detail). **Relative** (rock layer position) and **absolute (radioisotope) dating** techniques allow geologists to sequence the **fossils** chronologically and provide a time scale. Geology also reveals the environmental conditions of past species.

For many reasons, the fossil record is not complete. Most organisms decomposed or were eaten by scavengers after death. Many species lacked hard parts, which are much more likely to fossilize. Some rocks and the fossils they contained have eroded and disappeared. Moreover, much of evolution happens in the small populations that survive changes in environmental conditions, so the chance that intermediates will fossilize is low. Nevertheless, the current record includes billions of fossils – over 300 million from Los Angeles' LaBrea Tar Pits alone, and an estimated 800 billion in South Africa's Beaufort Formation. Analysts have identified 250,000 species among these remains.

Although the fossil record is far more detailed today than in Darwin's time, Darwin was able to use it as powerful evidence for natural selection and common descent. Throughout geological history, species that appear in an early rock layer disappear in a more recent layer. Darwin argued that a species' appearance recorded its origin, and that its disappearance showed extinction. Moreover, he noted remarkable similarities among structures in differing species, supporting common ancestry. Finally, he could often correlate environmental conditions with structures, supporting his idea that natural selection led to adaptations which improved survival within certain habitats.

As an example, let's analyze a relatively complete set of fossils which record the evolution of the modern horse. **Figure** 12.14 sequences five species which show major evolutionary changes. The oldest fossil shows a fox-sized animal with slender legs and nearly vertical digits: *Hyracotherium* bit and chewed soft leaves in wooded marshlands. Geology and paleontology suggest that the climate gradually dried, and grasslands slowly replaced the marshes. *Mesohippus* was taller, with fewer, stronger digits – better able to spot and run from predators, and thus more likely to survive and reproduce in the new grasslands. *Merychippus* was taller

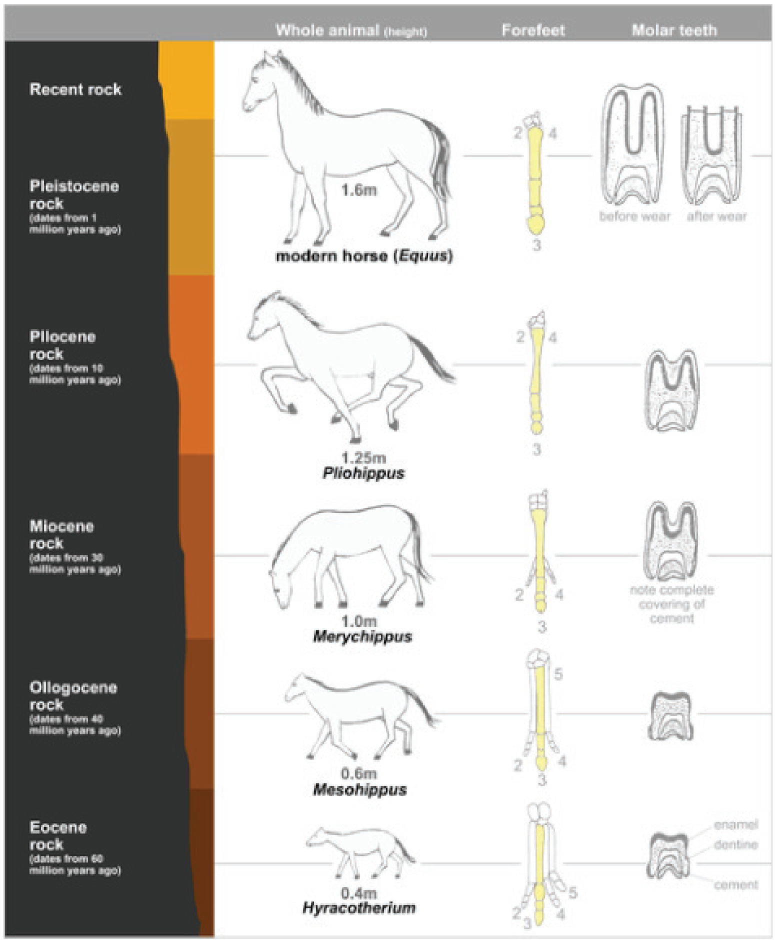

Figure 12.14: The fossil record for relatives of the modern horse is unusually complete, allowing us to select a few which show major change over time. These changes can be correlated with environmental changes, supporting the ideas of evolution and natural selection. However, the linear arrangement is misleading; addition of all known fossils would show a branching, bushy path of descent and common ancestry. (2)

still, and kept only one, enlarged digit – a hoof to run fast on the hard ground. By *Pliohippus* time, molar teeth had widened and elongated to grind the tough grasses. These fossils show gradual structural changes which correspond to changes in the environment. They appear to show a smooth, linear path directed toward the "goal" of the modern horse, but this is deceiving. These five fossils are merely "snapshots" of a bushy family tree containing as many as 12 genera and several hundred species. Some transitions are smooth progressions; others are abrupt. Together, they support natural selection and descent with modification from common ancestors.

Comparative Anatomy and Embryology

The evidence Darwin presented in *The Origin of Species* included not only fossils but also detailed comparisons of living species at all life stages. Naturalists in Darwin's time were experts in **comparative anatomy** – the study of the similarities and differences in organisms' structures (body parts). At different times during his life, Darwin studied the comparative anatomy of closely related species of marine mammals, barnacles, orchids, insectivorous plants, and earthworms.

Species which share many similarities are closely related by a relatively recent common ancestor. For example, all orchids share parallel-veined leaves, two-sided flowers with a "lip," and small seeds (**Figures A and B** 12.15). Species which share fewer similarities, sharing only basic features, are related by relatively distant ancestor. The sundew, one of the insectivorous plants Darwin studied, shares leaves and petals with orchids, but the leaves are wide with branching veins and the flowers are radially symmetrical rather than two-sided (**Figure C** 12.15). The many species of orchids, then, share a recent common ancestor, but they also share a more distant ancestor with the sundew.

Homologous and Analogous Structures

Similarities can show two different kinds of relationships, both of which support evolution and natural selection.

(1) Similarities shared by closely related species (species who share many characteristics) are **homologous**, because the species have descended from a common ancestor which had that trait. Homologous structures may or may not serve the same function. **Figure** 12.16 shows the forelimbs of mammals, considered homologous because all mammals show the same basic pattern: a single proximal bone joins a pair of more distal bones, which connect to bones of the wrist, "hand," and digits. With this basic pattern, bats build wings for their lives in the air, whales form fins for their lives in the sea, and horses, as we have seen, construct long, hoofed legs for speed on land. Therefore, homologous structures support common ancestry.

(2) Similarities shared by distantly related species may have evolved separately because they live in similar habitats. These structures are **analogous** because they serve similar functions,

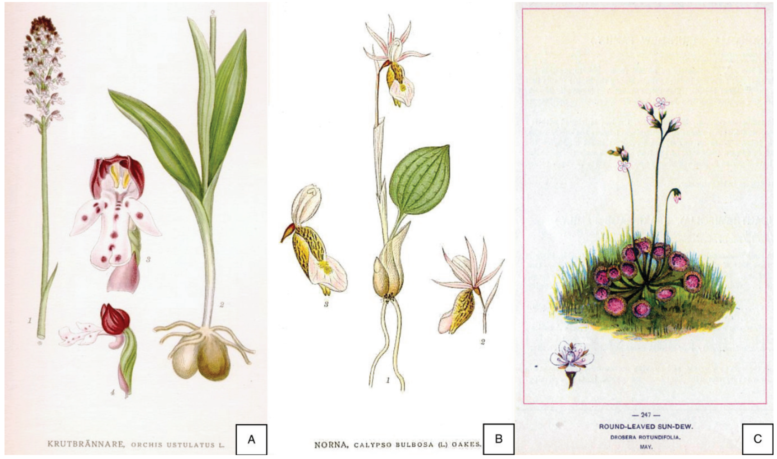

Figure 12.15: Darwin's Theory of Evolution explains both the similarities and the differences among living things. All flowering plants share leaves, petals, stamens, and pistil, but orchids have parallel-veined leaves and flowers with lips and fused stamens and pistil, while sundews have leaves with branching veins and flowers with equal petals and separate stamens and pistil. The two species of orchid (A and B) share a recent common ancestor, whereas all three species share a more distant common ancestor. (14)

but evolved independently. **Figure** 12.17 compares the wings of bats, bird, and pterosaurs. Bats evolved wings as mammals, pterosaurs as dinosaurs, and birds from a separate line of reptiles. Their wings are analogous structures, each of which evolved independently, but all of which suit a lifestyle in the air. Note that although the wings are analogous, their bones are homologous: all three share a common but more distant vertebrate ancestor, in which the basic forelimb pattern evolved. Because analogous structures are independent adaptations to a common environment, they support natural selection.

Embryology

Embryology is a branch of comparative anatomy which studies the development of vertebrate animals before birth or hatching. Like adults, embryos show similarities which can support common ancestry. For example, all vertebrate embryos have gill slits and tails, shown in **Figure** 12.18. The "gill slits" are not gills, however. They connect the throat to the outside early in development, but in many species, later close; only in fish and larval amphibians do they contribute to the development of gills. In mammals, the tissue between the first gill slits forms part of the lower jaw and the bones of the inner ear. The embryonic tail does not develop into a tail in all species; in humans, it is reduced during development to the coccyx, or tailbone. Similar structures during development support common ancestry.

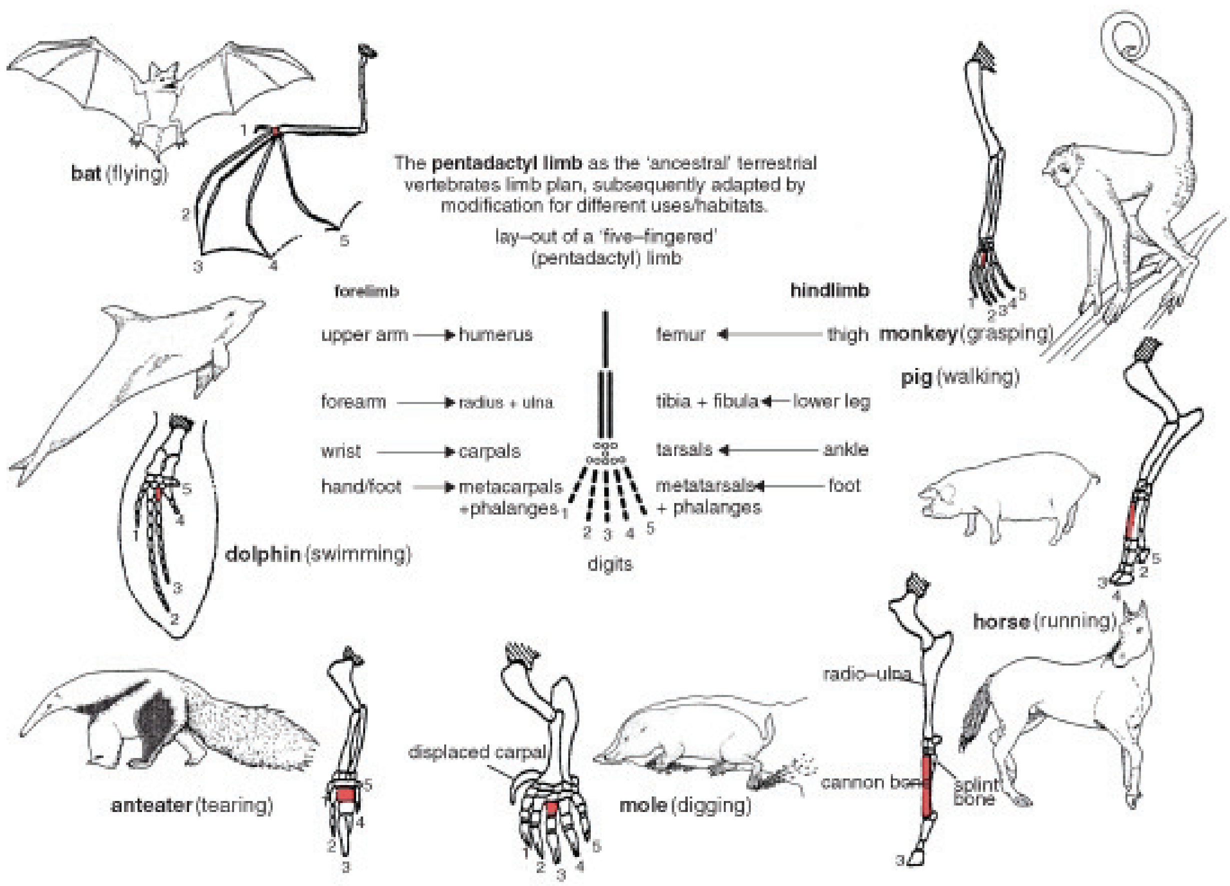

Figure 12.16: **Homologous structures** are similarities throughout a group of closely related species. The similar bone patterns in bat's wings, dolphin's flippers, and horse's legs support their descent from a common mammalian ancestor. (13)

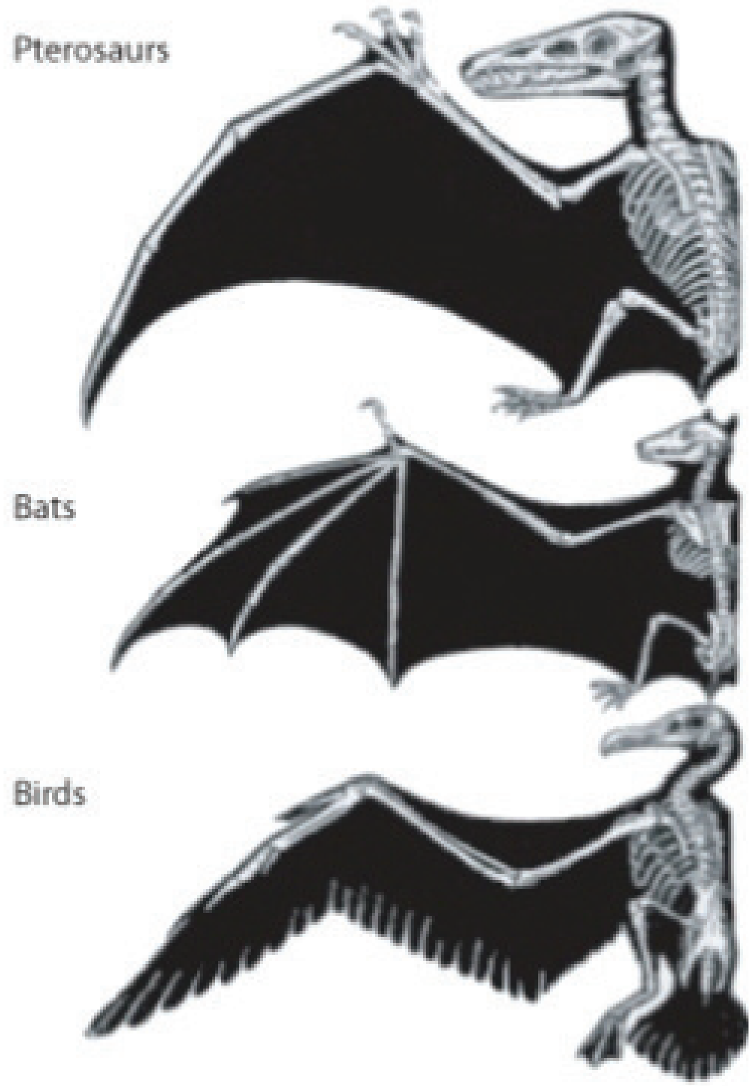

Figure 12.17: The wings of pterosaurs, bats, and birds illustrate both homologous and analogous structures. Similarities in the patterns of bones are due to descent from a common vertebrate (reptilian) ancestor, so they are homologous. However, the wings of each evolved independently, in response to similar environments, so they are analogous, and provide evidence for natural selection. (5)

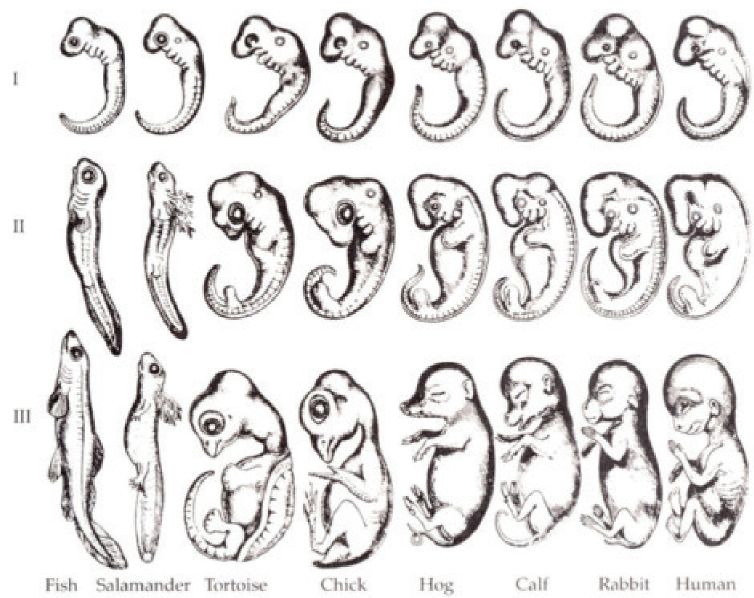

Figure 12.18: **Comparative embryology** reveals homologies which form during development but may later disappear. All vertebrate embryos develop tails, though adult humans retain only the coccyx. All vertebrate embryos show gill slits, though these develop into gill openings only in fish and larval amphibians. In humans, gills slits form the lower jaw and Eustachian tube. Many scientists consider developmental homologies evidence for ancestry, although some embryologists believe that these particular drawings exaggerate the similarities. (8)

Vestigial Structures

Structures which are reduced and perhaps even nonfunctional, such as the human tail and the human appendix, are considered **vestigial structures**. The tail, of course, functions for balance in many mammals, and the human appendix may have served digestive functions in herbivorous ancestors. Whales, which evolved from land mammals, do not have legs or hair as adults; both begin to develop in embryos, but then recede. Vestigial leg bones remain, buried deep in their bodies, shown in **Figure A** 12.19.

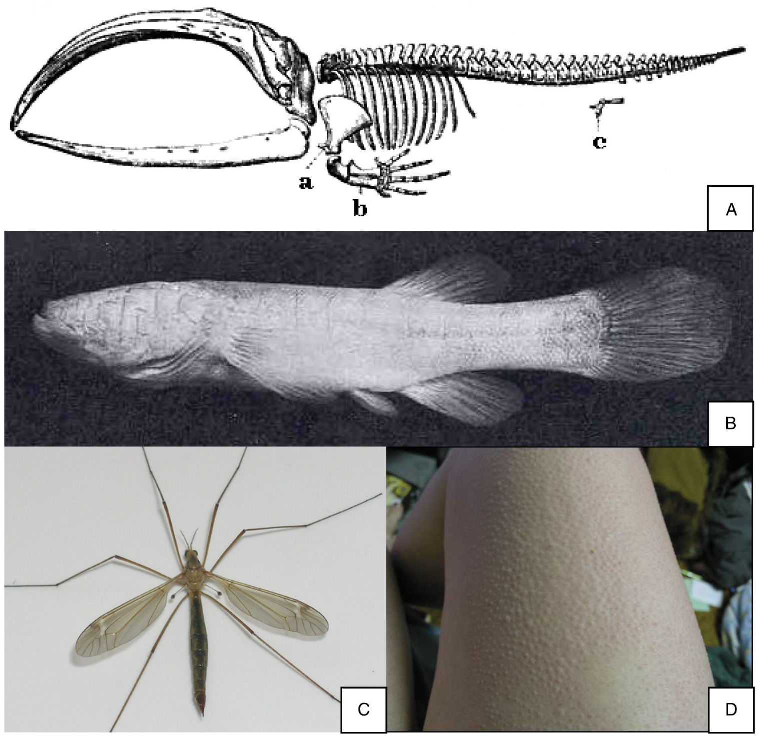

Figure 12.19: Vestigial structures show evolutionary reduction or loss of unneeded structures which were useful to ancestors. A: Whales retain remnants of their mammalian ancestors' leg bones (c). B: Cavefish lack the eyes and pigments important to their relatives who live in lighted habitats. C: True flies have reduced insects' second pairs of wings to balancing knobs. D: We still show the reflex which raises hairs for insulation in cold air in our furry relatives, but all we have to show for our follicle's efforts are goosebumps. (21)

True flies have reduced the second pair of wings found in most insects to halteres for balance shown in **Figure B** 12.19. Cavefish lose both eyes and pigment, because both would require energy to build and are useless in the lightless habitat they have adopted shown in **Figure C** 12.19. You are probably very familiar with a fine example of a vestigial behavior: goosebumps raise the sparse hairs on your arms even though they are no longer sufficiently dense to insulate you from the cold by trapping warm air next to your skin; in most mammals, this reflex is still quite functional shown in **Figure D** 12.19. Most vestigial structures are homologous to similar, functioning structures in closely related species, and as such, support both common ancestry and (incomplete!) natural selection.

Molecular Biology

Did you know that your genes may be 50% the same as those of a banana?

Unknown in Darwin's time, the "comparative anatomy" of the molecules which make up life has added an even more convincing set of homologies to the evidence for evolution. All living organisms have genes made of DNA. The order of nucleotides – As, Ts, Cs, and Gs - in each gene codes for a protein, which does the work or builds the structures of life. Proteins govern the traits chosen (or not) in natural selection. For all organisms, a single Genetic Code translates the sequence of nucleotides in a gene into a corresponding chain of 20 amino acids. By itself, the universality of DNA genes and their code for proteins is strong evidence for common ancestry. Yet there is more.

If we compare the sequence of nucleotides in the DNA of one organism to the sequence in another, we see remarkable similarities. For example, human DNA sequences are 98-99% the same as those of chimpanzees, and 50% the same as a banana's! These similarities reflect similar metabolism. All organisms have genes for DNA replication, protein synthesis, and processes such as cellular respiration. Although metabolic processes do not leave fossils, similar DNA sequences among existing organisms provide excellent evidence for common ancestry.

The *differences* in DNA sequences are even more intriguing. Many are single base substitutions resulting from mutations accumulated through time. Assuming mutations occur randomly, the number of differences in bases between any two species measures the time elapsed since two organisms shared a common ancestor. This type of "molecular clock" has confirmed traditional classification based on anatomy. Most scientists consider it sufficiently powerful to clarify or correct our understanding of evolutionary history. For example, human DNA differs 1.2% from chimpanzees, 1.6% from gorillas, and 6.6% from baboons; we can infer from this data that humans and chimpanzees share a relatively recent common ancestor, and that the common ancestor we share with gorillas lived much longer ago. **Figure** 12.20 shows a **cladogram** depicting hypothetical evolutionary relationships constructed with this data. Similarities and differences in the sequences of amino acids in proteins support common ancestry in the same way, because they are determined by DNA.

Heritability and variation in traits are essential parts of Darwin's theory of evolution by natural selection. Since he published *The Origin of the Species,* rediscovery of Mendel's identification of genes and how they are inherited has confirmed Darwin's ideas. Molecular biology has clarified the nature of genes and the sources of variation. Comparative analysis of DNA and proteins continues to give us an exquisitely detailed view of patterns of variation, common ancestry, and how evolution works.

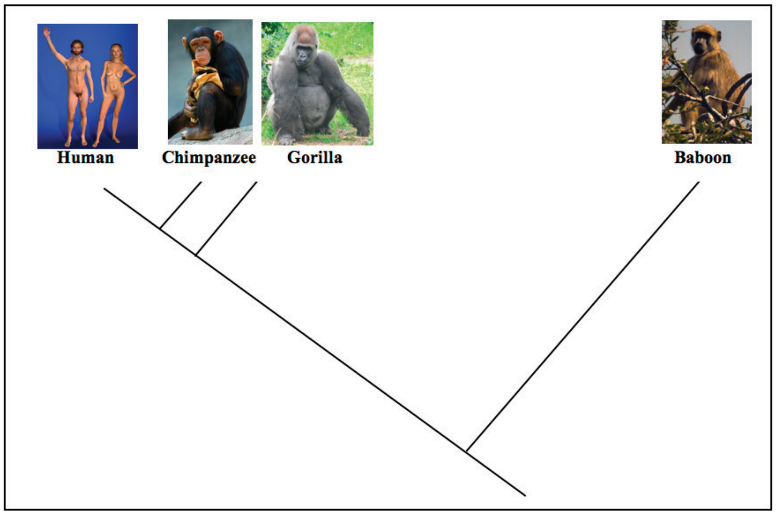

Figure 12.20: Cladograms use comparison data to construct diagrams showing evolutionary relationships. This cladogram uses comparisons of DNA nucleotide sequences to reveal patterns of descent from common ancestors. Molecular biology has supported and extended our understanding of evolutionary relationships based on traditional anatomy. (29)

Biogeography

Australia, Africa, and South America occupy the same latitude, at least in part, and therefore have roughly the same climate. If plants and animals were distributed only according to their adaptations to habitat, we would expect the same species to occupy similar regions of these continents. However, the short-tailed monkeys, elephants, and lions in Africa differ significantly from the long-tailed monkeys, llamas, and jaguars of South America, and even more from the koalas, kangaroos, and Tasmanian devils of Australia. **Biogeography** studies the distribution of plants and animals and the processes that influence their distribution – including evolution and natural selection. Only geologic change and evolution can explain the distributions of many species, so biogeography is another kind of evidence for the theory of evolution.

Alfred Russel Wallace, who developed his own ideas of evolution and natural selection at the same time as Darwin, explained the distributions of many species in terms of changes in geography (such as formation of land bridges) and environment (for example, glaciations) and corresponding evolution of species. **Figure** 12.21 shows the six biogeographical regions he identified: Nearctic, Neotropical, Palaearctic, Ethiopian, Oriental, and Australian.

Let's consider just the camel family as an example, shown in **Figure** 12.22 of how biogeography explains the distribution of species. Fossils suggest that camel ancestors originated in North America. Distant fossils show structural similarities which suggest that their descendants migrated across the Bering land bridge to Asia and across the Isthmus of Panama into South America. These two isolated populations evolved in different directions due to

Figure 12.21: Alfred Russel Wallace identified six major biogeographic regions: Nearctic, Neotropical, Palaearctic, Ethiopian, Oriental, and Australian Regions. Wallace explained the distributions of many animals and plants as a result of changes in geography and evolution. (1)

differences in chance variations and habitat. Today's descendants are llamas and guanacos in South America, and camels in Asia. Asian camels continued to migrate west into Africa, giving rise to two species – the dromedary in Africa, and the Bactrian in eastern Asia.

The distribution of some older fossils shows an opposite pattern; for example, fossils of a single species of fern, *Glossopteris*, have been found in South America, Africa, India, Antarctica, and Australia (**Figure** 12.23). Putting together many such distributions and a great deal of geologic data, Alfred Wegener showed that the continents were long ago united as Gondwanaland, and have since drifted apart. His theory of **continental drift** and its modern form, **plate tectonics**, help to further explain patterns of evolutionary descent in space and time.

Island Biogeography

Island biogeography studies archipelagos (oceanic island chains) as isolated sites for evolution. Both Darwin and Wallace used examples from isolated oceanic islands, such as the Galapagos and Hawaii, in their arguments for evolution and natural selection. Until humans arrived, terrestrial mammals and amphibians were completely absent on these islands. Darwin and Wallace showed that the animals and plants which were present had blown or drifted from one of the continents, or had descended – with modifications which suited the new habitats – from one of the original colonists. Terrestrial mammals and amphibians, having no powers of dispersal across oceans (until humans came along), were understandably absent.

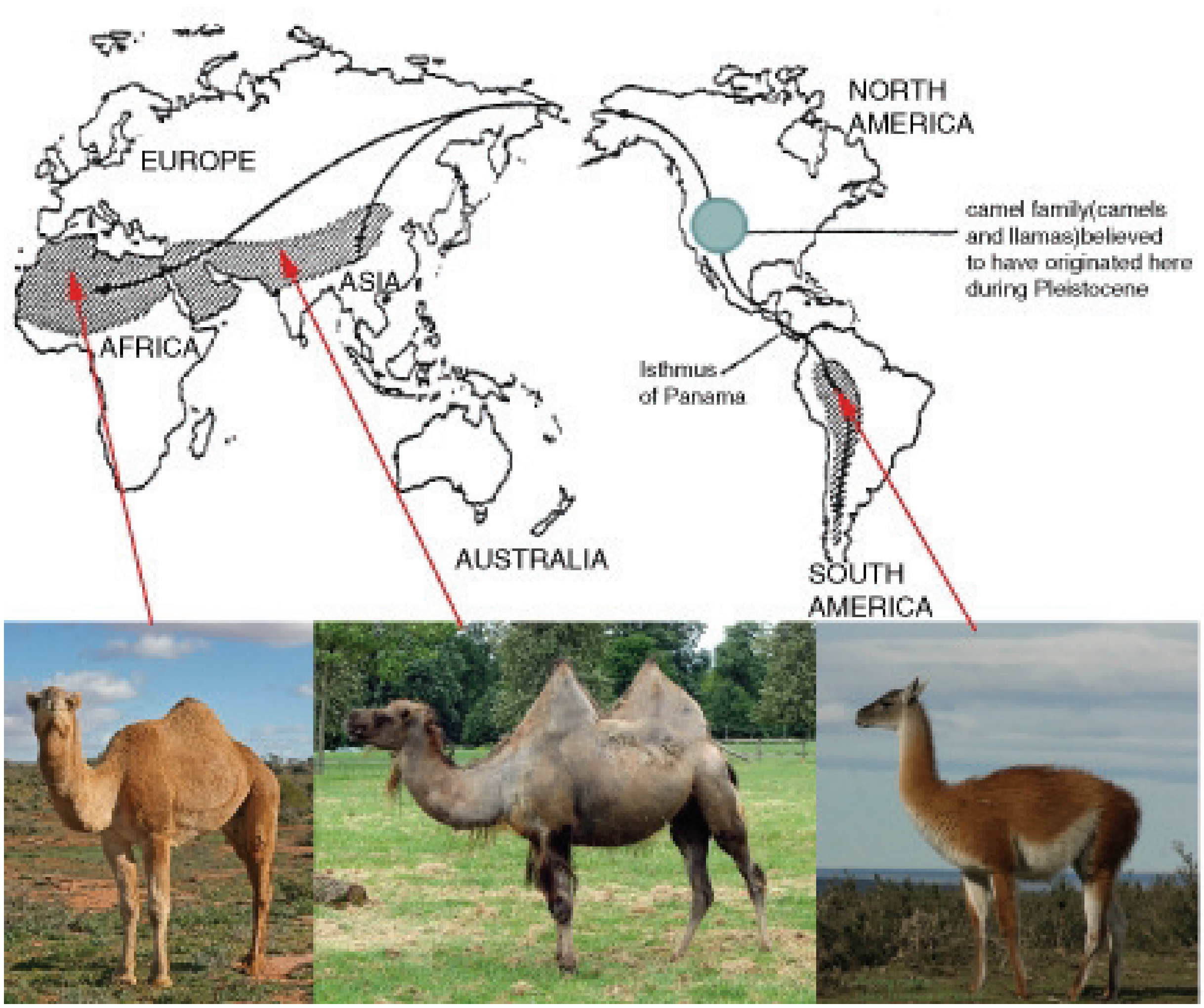

Figure 12.22: Biogeography explains the distribution of camel-like animals as a result of geographical changes and independent evolution. Today, the descendants of early camel ancestors are the dromedary in Africa, the Bactrian camel in Asia (center), and the guanaco (right) and llamas of South America. (15)

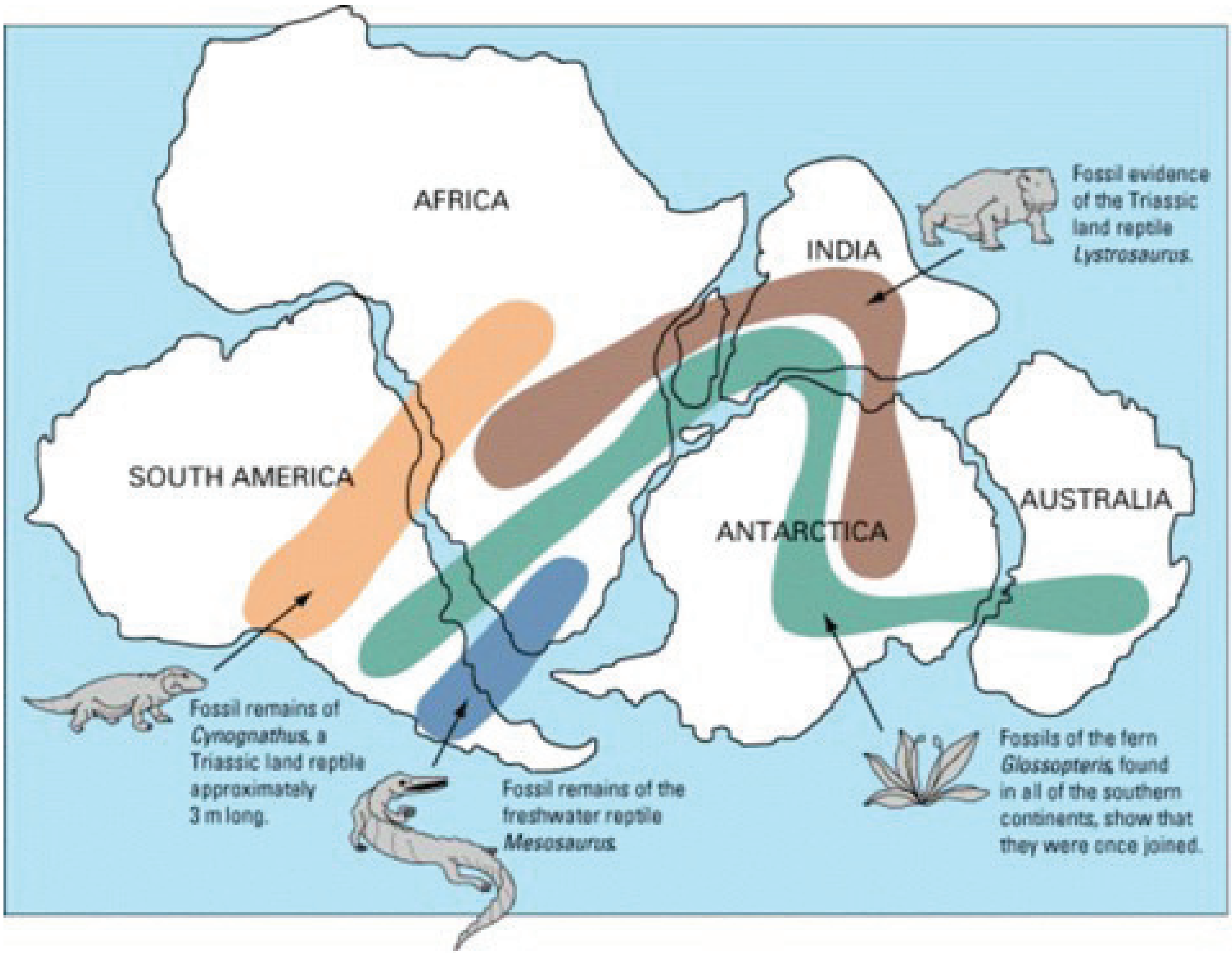

Figure 12.23: The locations of fossils such as Glossopteris on widely separated continents form contiguous patterns if the continents are joined. These patterns led to the theory of plate tectonics. Gondwanaland, a supercontinent of long ago, played an important part in evolution, natural selection and the history of life. (18)

Darwin's Finches

Only long after returning from his voyage did Darwin, with help from ornithologist John Gould, realize that the Galapagos birds he had collected but dismissed as uninteresting blackbirds, grosbeaks, finches, and a wren, were actually all closely related descendants of a single ancestral finch which had relatives on the South American mainland. Careful analysis showed that each of the 12 new species was confined and adapted to a specific habitat on a specific island. The finches, now known as "Darwin's finches" (**Figure A** 12.24), clearly support both descent with modification and natural selection. Hawaiian honeycreepers (**Figure B** 12.24) are a more colorful but also more endangered example of the same evolutionary process of **adaptive radiation**. Bills ranging from thick and heavy (finch-like) for seed-eaters to long and curved for probing flowers illustrate the variations by which descendants of a single, original finch-like colonizer adapted to multiple ecological niches on the islands. Unfortunately, human destruction of habitat and introductions of rodents, the mongoose, and the mosquito which carries avian malaria have caused the extinction of 15 honeycreeper species, and still threaten the species which remain.

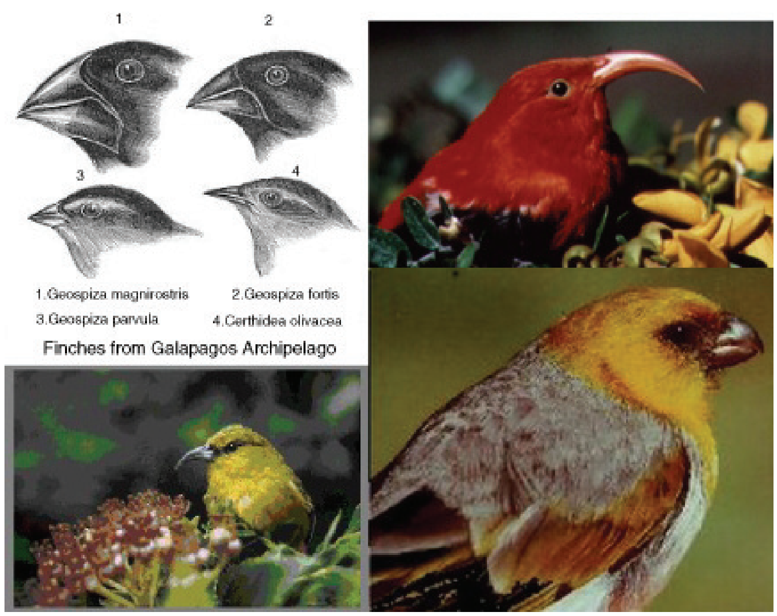

Figure 12.24: Darwin's finches (above) on the Galapagos and honeycreepers (right) on Hawaii show the adaptive radiation of single finch ancestors which first colonized the islands. Each species show descent with modification, and the variety of bill shapes show adaptation to a specific niche. Many similar examples from island biogeography support evolution and natural selection. Honeycreepers are the finch-like palila (top right), the flower-probing I'iwi (center), and another nectar feeder, the amakihi (bottom). (12)

Scientific Evidence

Altogether, the fossil record, homologies, analogies, vestigial structures, molecular uniformity and diversity, and biogeography provide powerful scientific evidence for the descent of today's species from common ancestors. Some details of natural selection have been and are still being modified. However, the remarkable biological discoveries of the 150 years since Darwin published *The Origin of the Species* have dramatically strengthened support for his theory. Moreover, Darwin's theory continues to enlighten new discoveries. Perhaps we could paraphrase Dobzhansky: Everything in biology makes sense in the light of evolution. The only piece still missing from the evidence puzzle is direct observation of the process itself. Darwin thought that humans could never witness evolution in action because of the vast time periods required. For once, however, he was mistaken; evolution in action is the subject of the next lesson.

Lesson Summary

- Evolution is not "just a theory" as a scientific theory, it explains and unifies the entire field of biology and has a great deal of evidence supporting it.
- The evidence includes the comparisons and observations Darwin included in his *Origin,* and new knowledge from genetics and molecular biology, added since the Origin was published.

- Darwin used the fossils known in his time as evidence for his ideas, and today's record is even more convincing.
- Often, fossil species first appear in older rocks, and disappear in younger rocks, providing evidence that species change.
- Changes in climate indicated by geology correlate with changes in fossil species and their adaptations, supporting the idea of natural selection.
- The fossil record for horses shows gradual changes which correspond to changes in the environment.

- Many basic similarities in comparative anatomy support recent common ancestry.
- Similarities in structure for closely related species are homologous.
- Similarities in structure among distantly related species are analogous if they evolved independently in similar environments. They provide good evidence for natural selection.
- Examples of evidence from embryology which supports common ancestry include the tail and gill slits present in all early vertebrate embryos.
- Vestigial structures are reduced and perhaps even nonfunctional, but homologous to fully developed and functional similar structures are in a closely related species; these support the idea of natural selection.

- Cavefish without sight or pigment and humans with goose bumps illustrate the concept of vestigiality.

- The universality of DNA for genes, amino acids to build protein enzymes and the Genetic Code is strong evidence for common ancestry.
- Similarities in metabolic pathways such as DNA replication and transcription and cellular respiration are further evidence for common ancestry.
- Within these similarities are differences in the sequence of As, Ts, Cs, and Gs due to the accumulation of mutations.
- Comparison of DNA sequences supports descent with modification and can be used to clarify evolutionary relationships.
- A Cladogram is a tree-like diagram showing evolutionary relationships which can be construction from one or a number of kinds of comparison data; DNA sequence comparisons are often used.
- Darwin's Theory of Evolution is strongly supported and also helps to explain many more recent discoveries, such Mendel's work in genetics and the molecular biology of DNA and protein.

- Changes in geographic features such as land bridges explain puzzling fossil species distributions.
- Older fossil distributions suggest that the continents have joined and separated during Earth's history.
- Plate tectonics explain the distant locations of closely related species as the result of continental drifting.
- Both Darwin and Wallace proposed that oceanic island chain species often descended from a single colonizing mainland species and adapted to open niches through natural selection.
- Galapagos finches (Darwin's finches) and Hawaiian honeycreepers each fill many different ecological niches as the result of adaptive radiation from a single colonizing finch-like ancestor.

Review Questions

1. Why is it wrong to say that the Theory of Evolution is "just a theory"?
2. How did Darwin use the fossil record to support descent from common ancestors and natural selection?
3. Summarize how the fossil record for ancestors and relatives of the horse supports the relationship between evolution and changing environments.
4. Compare and contrast homologous and analogous structures as evidence for evolution.
5. Give two examples of evidence from embryology which support common ancestry.
6. Use an example to show how vestigial structures support evolution by natural selection.

7. List the molecular similarities found in all species of organisms, which support common ancestry.
8. Interpret the following cladogram in terms of evolutionary relationships and the DNA data which could have been used to construct it.
9. Relate the distribution of plants and animals to changes in geography and climate, using at least one specific example.
10. Use a specific example to illustrate the explanation given by both Darwin and Wallace for the distribution of few, closely related species across island chains.

Further Reading / Supplemental Links

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- Jonathan Weiner, The Beak of the Finch: A Story of Evolution in Our Time (Alfred A. Knopf, 1994).

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Vocabulary

absolute (radioisotope) dating A technique for dating fossils based on exponential decay of a radioactive isotope incorporated into the rock at the time of its formation or the fossil at the time of the organism's death.

adaptive radiation A pattern of speciation which involves the relatively rapid evolution from a single species to several species to fill a diversity of available ecological niches.

analogous traits Similar structures with identical functions shared by distantly related species; analogous traits result from natural selection in similar environments, but they evolve independently.

biogeography The study of patterns of distribution of species on continents and islands.

cladogram A tree-like diagram showing evolutionary relationships according to a given set of data, such as molecular data.

comparative anatomy The study of the similarities and differences in organisms' structures.

comparative embryology The study of the similarities during the embryological development of vertebrate animals; reveals homologies which form during development but may later disappear.

embryology A branch of comparative anatomy which studies the development of vertebrate animals before birth or hatching.

fossil The mineralized remains of an animal, plant, or other organism.

fossil record An arrangement of all known fossils according to their position in time, using rock layer and radiometric dating.

homologous structures Structures which descended (evolved) from the same structure within a common ancestor; may or may not serve the same function.

homology Similarity which has resulted from shared ancestry.

hypothesis A proposed, testable answer to a question or explanation of an observation.

island biogeography The study of archipelagos (oceanic island chains) as isolated sites for evolution.

paleontology The study of fossils to explore the history of life.

relative dating A technique for aging fossils based on comparing their positions within rock layers; fossils in lower layers are usually older than fossils in upper layers.

theory An explanation which ties together or unifies a large group of observations.

vestigial structure Structures which are reduced and perhaps even nonfunctional in one species but homologous to functional structures in a closely related species.

Points to Consider

- Which type of evidence for evolution is most convincing to you?
- Evidence confirms that evolution is a powerful theory. What other examples of theories have you encountered in your study of science? How would you compare their importance to the importance of evolution?
- In this lesson, we have used the terms hypothesis, law, and theory. How would you explain the differences between these scientific ideas?

12.3 Lesson 12.3: Evolution Continues Today - Can We Control It?

Lesson Objectives

- Recognize that the process of evolution by natural selection continues to change our world and our selves, both despite and because of our best efforts to control it.
- Understand that we have added direct observation of natural selection to the evidence for evolution.
- Evaluate the importance of artificial selection to human life.
- Discuss our use of hybridization to improve yield and adapt crops to many climates.
- Explain how cloning contradicts the principles of natural selection.
- Compare genetic engineering to traditional methods of breeding and domestication.
- Use the concept of natural selection to explain the resistance of bacteria to antibiotics and insects to pesticides.
- Explain why an individual bacterium cannot *on its own* change from sensitive to resistant towards antibiotics.
- Assess the severity of the problem of antibiotic resistance.
- Recognize that viral epidemics occur when chance viral mutations adapt the virus to new hosts.
- Describe the evidence for natural selection among Darwin's finches documented by the Grants.

Introduction

Much of the immediate success of Darwin's book was due to his careful comparison of his new idea of natural selection to the well-known breeding of animals. Darwin was especially interested in pigeons, and his observations of their many varieties inspired his own early thinking. Humans have relied on **artificial selection** ever since we first put seeds in the ground some ten thousand years ago. Today, our continuing efforts to develop crops and animals for food, work, and companions have expanded beyond breeding to include genetic engineering. Dismay about our effects on the environment is encouraging us to see ourselves more as a part of nature than above it; perhaps we will eventually abandon Darwin's term "artificial selection" in favor of **coevolution**. Evolution by natural selection is not just an explanation of the history of life. The process of Darwin's theory clearly continues, changing our world and ourselves - both despite and because of our best efforts to control it. And we have reached beyond Darwin's wildest expectations; we now have direct observations of **natural selection** to add to the overwhelming evidence for evolution.

Artificial Selection - or Coevolution?

The range of variations induced in relatively short periods of time by animal breeders convinced Darwin that natural selection across **geologic time** could have produced the great diversity of present life. Domestication of animals has resulted in the remarkable variety of dogs (**Figure** 12.25) from wolves, as well as cattle, horses, llamas, camels, and a few evolutionary dead-ends, such as the donkey.

Figure 12.25: Selective breeding has led to dramatic differences among breeds in a relatively short time, yet dogs are still able to interbreed with wolves - the wild species from which they originated. Darwin used his observations of artificial selection, as he called it, to derive and promote his theory of evolution by natural selection. (11)

However, artificial selection has resulted in the achievement that extends far beyond our immediate, intentional goals. Our initial cultivation of plants such as corn (**Figure** 12.26) played a role in the eventual development of human civilization.

Since Darwin's time, selective breeding and **hybridization** – mixing of separate species - has become even more sophisticated. We have further hybridized high-yield hybrids with local varieties throughout the world, intentionally adapting them to local climates and pests. Unfortunately, our widespread destruction of habitat is eroding the species and genetic diversity which provides the raw material for such efforts. Moreover, against our intent, our hybrids sometimes interbreed with natural varieties in the wild, leading to what some call **genetic pollution**. An example is a tiger, thought to be pure Bengal but actually a Bengal-Siberian hybrid, released in India to demonstrate the survival abilities of captive-raised tigers. The tiger did survive – to pollute the genetically pure Bengal population in a national park with northern-adapted Siberian genes (**Figure** 12.27).

The new field of biotechnology has dramatically changed our quest to improve upon natural selection. Ironically, one new development intentionally undermines the very foundation of Darwin's theory. As the first mammal to be **cloned**, a sheep name Dolly showed breeders of animals from farms to racetracks that they could copy "ideal" individuals without the bothersome variation which accompanies sexual reproduction (**Figure** 12.28). Many people hope that future decisions about cloning will consider Darwin's lessons about the value of variation in unpredictable, changing environments.

Figure 12.26: Over time, selective breeding has modified teosinte's few fruitcases (left) into modern corn's rows of exposed kernels (right). Cultivation of crops such as corn and wheat gave early humans the freedom to develop civilizations. (19)

Figure 12.27: The natural genes which adapted the Indian Bengal tiger (*Panthera tigris tigris*, left) and the Russian Siberian tiger (*Panthera tigris altaica*, right) to their unique habitats were mixed or "polluted" when a captive hybrid was released into a national park in India. The "escape" of non-native genes into a wild population is *genetic pollution*. (4)

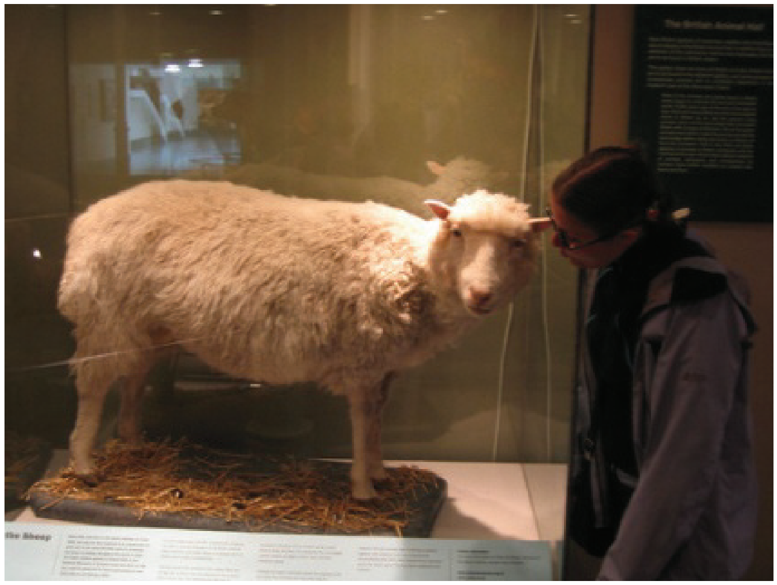

Figure 12.28: Dolly, the first cloned mammal, is preserved for public display after six years of public life. Cloning can copy animals we believe are superior, but it denies the importance of variation to survival of species – a point made clear in Darwin's ideas about natural selection. (9)

Another contribution of biotechnology is **genetic engineering**, the transfer of a gene from one organism to another. First, we inserted the human gene for insulin into bacteria, which – as bacteria use the same universal Genetic Code as we use – read the DNA and produced the human protein for use by diabetics. Many more cost-saving and designer medical advances have followed, including

- production of clotting factors for hemophiliacs
- vaccines for devastating diseases such as hepatitis B
- a breast cancer "designer drug," herceptin
- the potential for cheap, effective vaccines in fruits such as bananas

We have extended genetic engineering to agriculture, improving range, nutrition, resistance to disease, and other aspects of life. **Transgenic** animals - which possess genes from another species - now produce vaccines and hormones, serve in scientific research, and entertain us as pets (**Figure** 12.29). However, as for traditional agriculture, fears surround potential cross-pollination and interbreeding with wild populations. Modified genes have been found in plants up to 21 km (13 miles) away from their source. If such transfers spread resistance to herbicides or pesticides to wild populations, they will have defeated their intended purpose.

In his book, *The Botany of Desire*, Michael Pollan questions our feelings of superiority over our domesticated plants and animals. Discussing our domestication of the apple for its sugar,

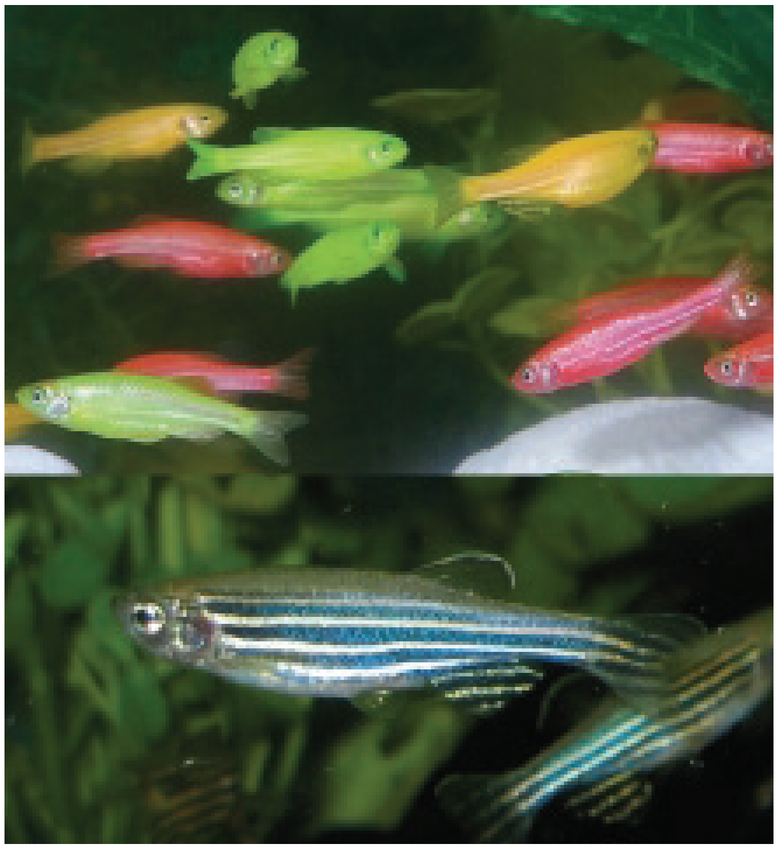

Figure 12.29: Genetic engineering has influenced our practices of medicine, research, agriculture, and animal husbandry – and recently the pet world. Zebra fish (natural species lower right) have received genes from jellyfish (green and yellow) or a coral (red) so that they glow. Originally "designed" for research, they are now bred for aquarists. Did we choose them, or did they choose us? (10)

the tulip for its beauty, marijuana for its psychogenic effects, and the potato for its food value, Pollan takes the plants' view of the evolving relationships. Could it not be that, as we have selected and modified these plants, they have also selected us for our powers to ensure their survival and reproduction – and changed us in the process? Are domestication of animals, cultivation of plants, and selective breeding actually forms of coevolution? Pollan's delightful yet sobering treatise may reflect a growing realization that we humans are as much a part of nature as any other species. Yes, we can influence evolution in a number of ways. However, we remain subject to natural selection, and every choice we make has effects on evolution – including our own. As we have already seen, and will see again in the next topic, our choices often have unintended effects.

Evolution of Resistance

In almost unprecedented actions during May 2007, United States government agencies put a US citizen on a no-fly list, urged border agents to detain him, failed to detect his re-entry into the US, and eventually ordered him into involuntary isolation, urging individuals who had flown with him on several international flights to be tested for XDR-TB. Why were such drastic measures needed? What is XDR-TB, and how did it originate? The answers show evolution in action today - in a way that all of us need to understand for our own well-being.

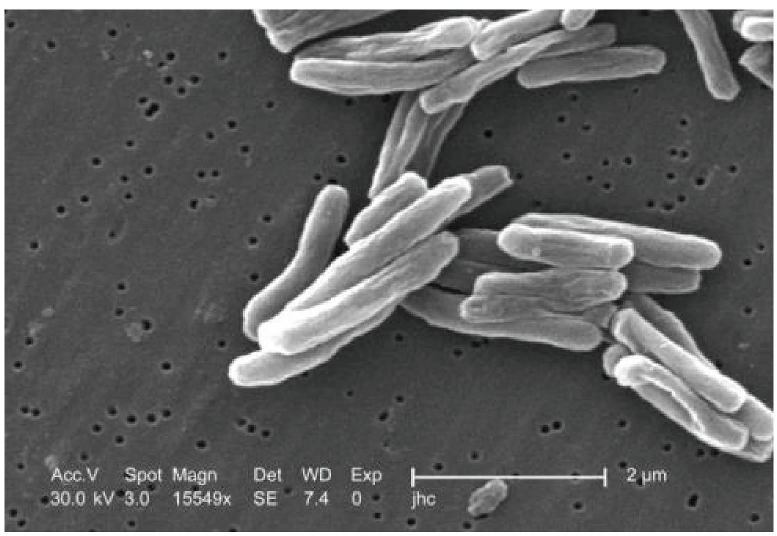

Figure 12.30: An electron microphotograph reveals the rod-shaped cells of the bacterium which causes tuberculosis (TB). We cannot, however, distinguish the antibiotic-resistant varieties by appearance; only chemical analysis can discover which patients are infected with XDR-TB. Natural selection, however, can distinguish the resistant varieties from those which are sensitive to antibiotics. Or would that be considered artificial selection, because we are (albeit inadvertently) choosing which bacteria survive? (32)

Tuberculosis (TB) has infected and killed humans since at least 4000 BCE. Today, over onethird of the world's population has been exposed to the bacterium which causes tuberculosis (**Figure** 12.30), but 90% of those carry the microorganism without symptoms. In the past, the 10% who did develop the characteristic lung infection had a 50% chance of dying. The advent of antibiotics in the mid-20th century dramatically improved survival, although the slow-growing bacteria required treatments of 6-12 months rather than days. Just 40 years later, in the 1990s, a new strain appeared with a mortality rate comparable to lung cancer – up to 80%. MDR-TB, or multi-drug resistant TB, is not treatable by two of the most effective anti-TB antibiotics. Then, about the year 2000, a second, more menacing strain emerged. XDR-TB, or extensively drug-resistant TB, is not treatable by either the two major drugs or the less-effective "second line" drugs now used to treat MDR-TB. Late in 2006, an epidemic of XDR-TB developed in South Africa. Currently there are no available drugs that can effectively treat this strain of TB.

Clearly these strains of TB are new, and changing rapidly. The evolution of resistance is a growing problem for many disease-causing bacteria and also for parasites, viruses, fungi, and cancer cells. The "miracle" of drug treatment which appeared to protect humans from disease may be short-lived. How does resistance happen? How can we prevent it?

First, recognize that resistance describes the bacterium (or other microorganism) – not the human. Bacteria multiply much more rapidly than humans, and therefore can evolve much more rapidly. Consider a population of bacteria infecting an individual with tuberculosis. Like all populations, individuals within that population show variation. **Mutations** add more variation. By chance, mutation may change the chemistry of one or a few bacteria so that they are not affected by a particular antibiotic. If the infected human begins to take antibiotics, they change the environment for the bacteria, killing most of them. However, the few bacteria which by chance have genes for resistance will survive this change in environment - and reproduce offspring which also carry the genes. More and more of the bacterial population will be resistant to antibiotics, because the antibiotics select for resistance. The bacteria are merely evolving in response to changes in their habitats! If the resistant bacteria are transmitted to another human "habitat," their population continues to expand, and if the new "habitat" takes different drugs, natural selection may result in multi-drug resistance (**Figure** 12.31).

How widespread is the problem? *Staphylococcus aureus* bacteria first showed resistance to penicillin just four years after the drug was put into use; today, some strains have shown resistance to nearly all antibiotics. These are now known as one of several "superbugs." The Human Immunodeficiency Virus (HIV) has become resistant to several antiviral drugs, and cancer cells within an individual often evolve resistance to chemotherapy drugs. Pesticide resistance is evolving in a similar manner; U.S. crop losses to insect pests have increased from 7% in the 1940s to more than 13% in the 1980s, despite the use of more types of pesticides in the 1980s.

What can we do about this particular instance of evolution which we have unwittingly encouraged? In general, we should reduce the use of antibiotics where possible and safe in order to lessen the selective pressure on bacteria. Here are some practices to keep in mind:

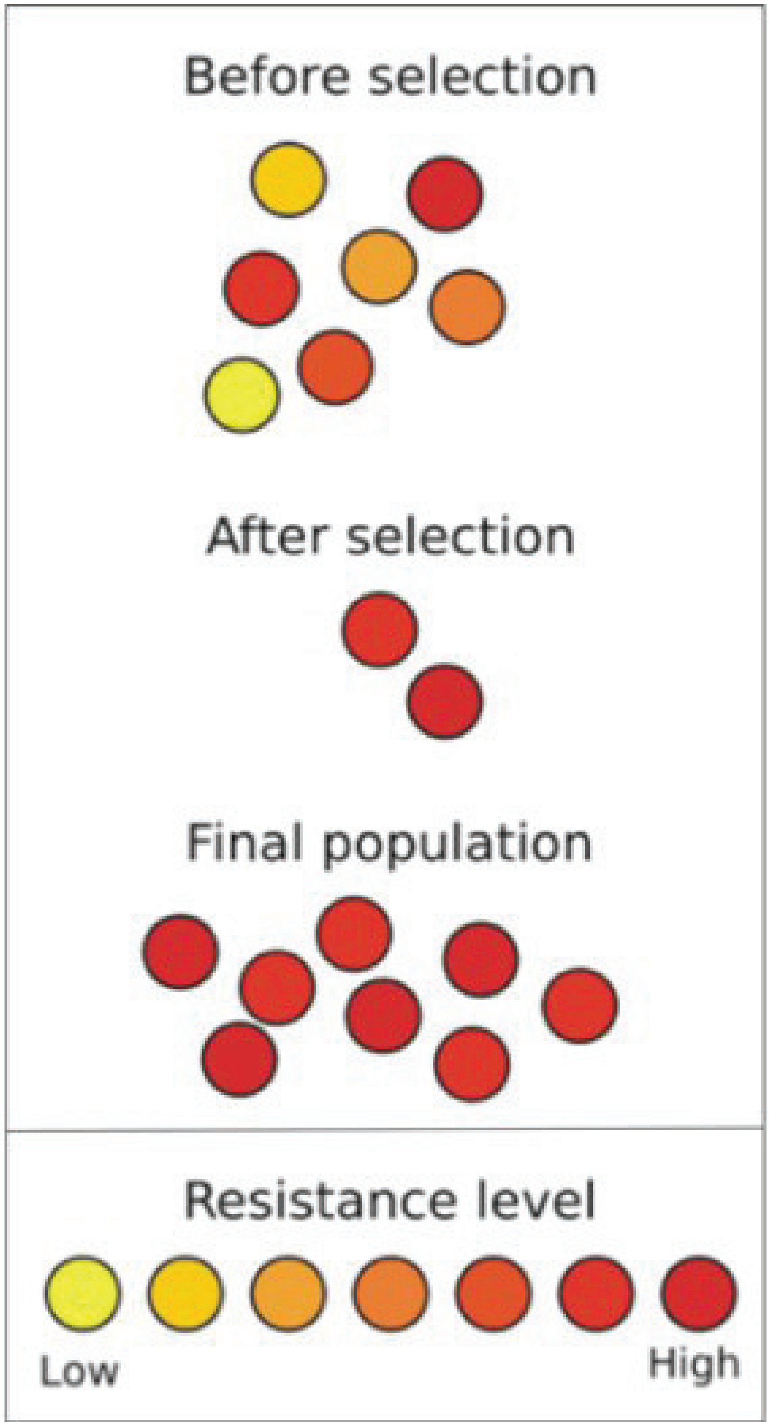

Figure 12.31: The development of resistance to antibiotics is a classic example of natural selection. *Before selection*, a number of heritable variations in level of resistance exist within the population (see legend at bottom). *After selection* by antibiotics, only those bacteria resistant to antibiotics survive. Only these resistant bacteria reproduce, so that the *final population* contains a greater proportion of resistant bacteria. (25)

1. Don’t take antibiotics for viral infections such as colds and flu; they act only on bacteria.
2. When antibiotics are appropriate, take them exactly as prescribed, and complete the entire course.
3. Never take antibiotics which are left over from an earlier illness or prescribed for someone else.
4. Consider purchasing meats and other animal products from animals not treated with antibiotics.
5. Consider purchasing organic produce, which is not treated with pesticides.
6. Resist the use of pesticides in your own gardens.

We have unintentionally sped up the evolution of microorganisms, but at the same time, their development of resistance has given us a window into the process which underlies all changes in life, natural selection.

Evolution Continues, and We “Catch it in the Act”

Much more passively and with a clear understanding of our lack of control, humans have watched viruses rapidly evolve through mutation to cause frightening worldwide epidemics, or **pandemics** - from the 1918 “Spanish flu” through Severe Acute Respiratory Syndrome (SARS) and West Nile virus, to the widely anticipated “avian flu” caused by a highly pathogenic viral subtype of influenza A (**Figure** 12.32), known as H5N1, and the 2009 ”swine flu” caused by the H1N1 influenza virus. Figure 8 shows the increase in human infections and deaths from H5N1. Mutations have adapted it for life in birds and in humans, and for transmission from bird to bird and bird to human. If a future mutation adapts it for effective transmission from human to human, a serious epidemic could result. If, as some argue, influenza pandemics occur in cycles, we are overdue for a dramatic demonstration of evolution and natural selection.

Peppered moths (**Figure** 12.33) are mostly white with black specks – a color pattern which hid them for centuries from predatory birds as they rest against lichen covered tree trunks. However, soot from the Industrial Revolution darkened the trees and destroyed their camouflage, selecting instead for the dark mutants which occasionally appeared. Gradually the population shifted to a dark color – an instance of natural selection that was directly observed by Englishmen of the time. Subsequent improvements in air pollution control have cleaned up the environment, and the English now note a new change: the trees have lightened, and moth populations are returning to their original coloration. These direct observations of natural selection would have delighted Darwin (except perhaps for the pollution) just a few years earlier.

Much more intentionally, biologists Peter and Rosemary Grant have devoted more than 30 years to a study of two species of Darwin’s finches on one of the Galapagos islands (**Figure** 12.34). Catching, weighing, and recording the seed species eaten by hundreds of these birds, they have witnessed changes in beak size which clearly correlate with changes in weather

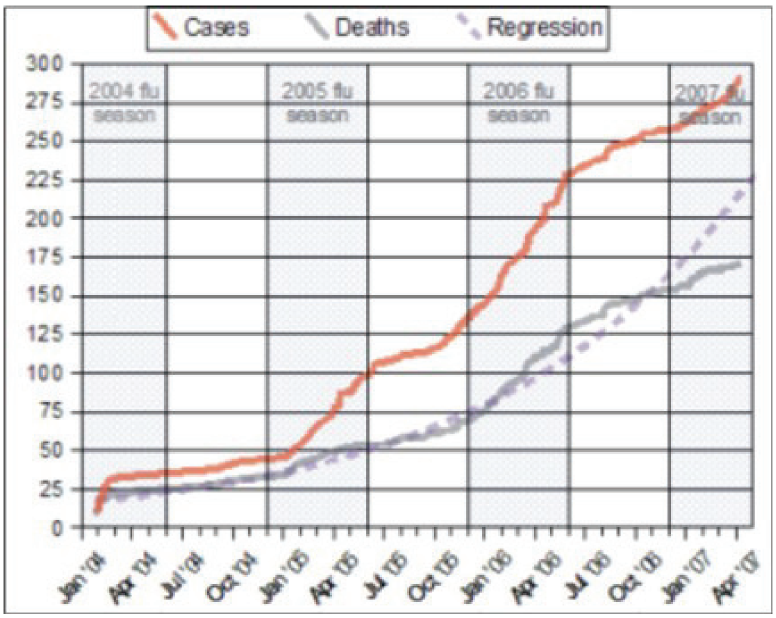

Figure 12.32: Human infections and deaths from avian flu, caused by the H5N1 subtype of influenza A virus, are clearly increasing. Mutations have adapted the virus for life in birds and humans, and for transmission from birds to birds, and from birds to humans. Some scientists think the probability is high that the virus will also evolve the means for effective transmission between humans and cause a serious pandemic. (30)

Figure 12.33: The peppered moth population changed from mostly light (left) to mostly dark (right) as the lichen-covered trees in England's forests absorbed soot from the Industrial Revolution. Now, as pollution is being cleaned up, the moth population is returning to its former proportion of light moths. These changes illustrate what famous idea? (28)

and availability of food. A severe drought and food shortage in 1977 led to a significant change. Birds whose small beaks could not crack the tough remaining seeds died, and the larger-beaked individuals who survived reproduced. The following year, offspring were larger bodied and larger-beaked, showing that natural selection led to evolution. A rainy winter in 1984-1985 reversed the trend; more soft seeds were produced, and the smaller beaked finches survived and reproduced in greater numbers than their large-beaked cousins.

Figure 12.34: A large cactus ground finch crushes a seed on the island of Espanola in the Galapagos archipelago. Peter and Rosemary Grant studied two closely related species of Darwin's finches and recorded changes in beak size and body size which paralleled changes in weather. How fitting that they should demonstrate natural selection in action – something Darwin did not think possible – using one of the species he made famous! (22)

Jonathan Winter eloquently describes the Grants' work and discoveries in his Pulitzer Prize-winning *The Beak of the Finch, A story of Evolution in our Time.* His words urging that we see evolution as ongoing for all life make a fitting conclusion to this lesson and chapter:

"For all species, including our own, the true figure of life is a perching bird, a passerine, alert and nervous in every part, ready to dart off in an instant. Life is always poised for flight. From a distance it looks still, silhouetted against the bright sky or the dark ground; but up close it is flitting this way and that, as if displaying to the world at every moment its perpetual readiness to take off in any of a thousand directions."

(*Source:* `http://en.wikiquote.org/wiki/Beak_of_the_Finch`)

Lesson Summary

- The process of evolution by natural selection continues to change our world and our selves, both despite and because of our best efforts to control it.
- Beyond Darwin's expectations, we have added direct observation of natural selection to the overwhelming evidence for evolution.

- Humans have designed and produced crops, work animals, and companions through artificial selection.
- Cultivation of crops gave us the freedom to develop civilization.
- Hybridization improves the yield of crop species and adapts them to various environments.
- Habitat destruction is destroying raw materials for hybridization, and "escape" of "artificial" genes is "polluting" wild species.
- Cloning has the potential to reproduce exact copies of selected individuals, but it goes against the principles which govern natural selection.
- Genetic engineering, like traditional methods of breeding and domestication, designs medicines, plants, and animals to suit our goals.
- Unlike traditional breeding, genetic engineering chooses single genes and can transfer them from one species to another completely unrelated species – making it faster, more precise, and far more powerful.
- In both GE and traditional breeding, the potential for genetic pollution remains. Pollution is probably more likely for genetic engineering because developments proceed so quickly.
- Products of genetic engineering include insulin and growth hormone, vaccines in milk and bananas, produce with longer growing season and shelf life and more nutrition.
- Michael Pollan suggests that we are coevolving with our domesticated crops, animals, and pets, rather than producing them – in other words, that our products are domesticating us as we domesticate them!

- Bacteria have developed serious levels of resistance to antibiotics because humans have introduced a new selective force into their environments (our bodies).
- An individual bacterium has its own set of genes. If these genes do not confer resistance to antibiotics, the bacterium by itself cannot develop resistance. A population can develop resistance if some of its members have, by chance, the gene for resistance.
- The evolution of antibiotic resistance has already resulted in a number of bacteria resistant to most known antibiotics; these are sometime called "superbugs."
- Actions you can take to prevent or slow the evolution of antibiotic resistance include:
- Don't take antibiotics for viral infections.
- Take prescribed antibiotics exactly as prescribed.
- Never take antibiotics which are left over or belong to someone else.
- Consider purchasing meats from animals not treated with antibiotics.

- Consider purchasing organic produce.
- Resist the use of pesticides in your own gardens.

- Viral epidemics occur when chance viral mutations adapt the virus to new hosts or new methods of transmission.
- Peppered moth populations changed color as the Industrial revolution changed the color of their habitat.
- Peter and Rosemary Grant studied two closely related species of Darwin's finches and recorded changes in beak size and body size which paralleled changes in weather.

Review Questions

1. List the ways in which we have directly observed evidence for evolution and/or natural selection.
2. Describe the importance of artificial selection to human life.
3. What is genetic pollution and why does it matter?
4. Compare cloning to natural selection.
5. Give examples of useful products of genetic engineering.
6. Explain Michael Pollan's ideas about our relationship with our domesticated crops, animals, and pets, and give your opinion about them, using examples from your own experience.
7. Use the concept of natural selection to explain the resistance of bacteria to antibiotics and insects to pesticides.
8. Explain why an individual bacterium cannot *on its own* change from sensitive to resistant to antibiotics.
9. Choose two actions you think would be most likely to control the increase in antibiotic resistance, and support your choices with examples from your own experience.
10. In what way do viral epidemics demonstrate evolution?

Further Reading / Supplemental Links

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Vocabulary

artificial selection Animal or plant breeding; artificially choosing which individuals will reproduce according to desirable traits.

cloning The process of creating an identical copy of an organism.

coevolution A pattern in which species influence each other's evolution and therefore evolve in tandem.

genetically modified organism (GMO) An organism whose genes have been altered by genetic engineering.

genetic engineering The manipulation of an organism's genes, usually involving the insertion of a gene or genes from one organism into another.

genetic pollution The natural hybridization or mixing of genes of a wild population with a domestic or feral population.

geologic time Time on the scale of the history of Earth, which spans 4.6 billion years.

mutation A change in the nucleotide sequence of DNA or RNA.

natural selection The process by which a certain trait becomes more common within a population, including heritable variation, overproduction of offspring, and differential survival and reproduction.

transgenic animal An animal which possesses genes of another species due to genetic engineering.

Points to Consider

- To what extent do you think that humans have removed themselves from natural selection?
- In what ways do you still feel subject to "natural" selective pressures?
- How effective do you think the measures to limit evolution of antibiotic resistance will be? Are you willing to support them?
- Do you think the benefits of genetic engineering outweigh the risks? Are there certain products you support, and others you oppose? Which ones, and why?

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