GENESIS
EVOLUTION
AND THE SEARCH FOR
A REASONED FAITH

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In 2009 the world rightly paused amid the calamitous cacophony of the global economic downturn and ongoing environmental crisis to celebrate the 200th anniversary of the birth of Charles Darwin (1809–1882). The year also marked the 150th anniversary of the publishing of Darwin's revolutionary *On the Origin of Species by Means of Natural Selection* (1859). This dual cause for celebration brought many to reflect on the contributions of evolutionary theory to humanity's understanding of itself, its place in the cosmos, and its relationship to the transcendent.

As is characteristic of this day and age, the public discussion of Darwin's great insight has not always enjoyed a nuanced treatment in the mainstream media. Given the popular presentation of evolution as a sort of celebrity death match between religion and science (*Only one can leave the ring alive!*), it is no wonder that many people think they must choose between religion and science, faith and reason, Genesis and evolution. Indeed, this is just what the contributors to this book have found in their classrooms; too frequently students appear to live in an intellectually and spiritually bifurcated world in which they must pick either evolution or creation and shun the other or hold both without considering how they work together. It is out of this fraught context that this book was born.

The idea for this project grew out of ongoing forums on religion and evolution coordinated by Rodica Stoicoiu at Mount St. Mary's University in Emmitsburg, Maryland.[1] In these informal roundtables, students come together with faculty from science, philosophy, and theology to discuss and debate the intersection of seemingly conflicting ideas around evolutionary biology and the Christian faith. Among the faculty participants have been the authors of this text, Mary Katherine Birge, SSJ (biblical studies), Brian G. Henning (philosophy), Rodica Stoicoiu (systematic theology), and Ryan Taylor (evolutionary biology). Despite their diverse disciplinary perspectives

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1. At that time (2006), all of the authors were teaching at Mount St. Mary's University. Taylor is now teaching at Salisbury University in Salisbury, Maryland, and Henning is now at Gonzaga University in Spokane, Washington.

and training, the authors each realized that they reject a false dichot-
omy between faith and science. The guiding principle of this text is
that a thoughtful individual need not choose between the two; there
is a way to proceed through the quagmire of well-intended presump-
tions about science and faith, and, more specifically, the theory of
evolution and the creation stories in the Book of Genesis. That way
is a dialogue among disciplines. Rather than eschew nuance and
gloss over complexity, *Genesis, Evolution, and the Search for a Reasoned
Faith* is the authors' attempt to bring together truths revealed by
evolutionary biology and religious faith. In an important sense, this
volume is the authors' joint attempt to model the sort of discussion
their students deserve to hear.

The simple structure of the text is intended to mirror this
dialogical impetus. In chapter 1, biblical scholar Birge examines
Genesis 1–3, exploring when it was written, who wrote it, what was
going on in the world of the authors and their audiences at the time
it was written, what those authors may have intended their work to
mean to those ancient audiences, and how a modern audience may
understand with a reasoned faith what the texts have to say. Birge
notes that *reading* what Genesis *says* is not the same as *understanding*
what the text *means*, though biblical literalists would suggest other-
wise. Approaching the creation accounts within the context of the
rich and complex history of the Isrealite people reveals that Genesis
is not a scientific treatise giving a play-by-play account of how God
created the universe. Rather, the creation stories in Genesis are a
deeply theological exploration of how human beings should see their
relationship to a transcendent creator. Taken in this vein, one may
see evolutionary science and religious faith as complementary, not
contradictory, attempts to understand humanity's origins.

In chapter 2, biologist Taylor begins by exploring the often-
misunderstood nature of scientific investigation, focusing in particu-
lar on what scientists mean when they talk about a scientific "fact" or
a scientific "theory." While in everyday usage *theory* might mean little
more than a formulated opinion or guess, in science *theory* denotes
a hypothesis (tentative explanation) that has never failed to be con-
firmed by empirical testing and observation—hardly a mere opinion.

Recognizing the empirical, inductive basis of all scientific inves-
tigation, Taylor notes that science cannot ask, much less answer,

questions concerning the meaning of human existence, or whether there is a supernatural creator. Take, for example, a hypothesis that longer-legged deer in a particular deer population have a "leg up" on their companions in the struggle for survival. This is a question that is open to scientific study. "Does God exist?" on the other hand, is not such a question. Scientific hypotheses must be testable questions that can either be supported or proved wrong. While scientists can design a series of experiments to test the deer hypothesis, the question of God's existence does not lend itself to such experimentation. As the body of data testing a scientific question builds over time and confidence climbs to ever higher degrees of certainty (though science never claims to be completely certain), these hypotheses come to be considered theories, as close to certainty as science can get. Evolution is one such theory.

The modern synthesis of the theory of evolution by natural selection, which takes into account the role of genetics, is accepted by most scientists as the unifying conceptual framework that explains the origins of our species, *Homo sapiens*, and the millions of other life-forms on our planet. Yet, Taylor notes, the methodological naturalism of evolutionary theory requires that scientists remain silent regarding transcendent questions. Questions concerning the meaning of human life or the existence of a transcendent creator must be left to philosophers and theologians.

Picking up these questions in chapter 3, philosopher Henning explores the ethical and philosophical significance of the theory of evolution by tracing the history of ideas that led up to and beyond Darwin's great discovery. This philosophical investigation leads Henning to ask such questions as, "Does modern evolutionary theory adequately explain the origins of consciousness?" "Is it possible for conscious beings to evolve from completely lifeless and mindless matter?" "Does the recognition of humanity's shared evolutionary heritage undermine our human-centered worldview, or require that we change, particularly with respect to how we treat nonhuman life?"

Henning notes the strong tendency in Western thought to place humans at the top of a hierarchy of being. Modern evolutionary theory fundamentally challenges the assumption that humans are utterly unique. Rather than being at the pinnacle of creation, distinct

from all other life-forms, the theory of evolution places humans on a continuum of being, a continuum that challenges the idea that those things that make us who we are, such as culture, language, reason, and so on, are unique to us. The theory of evolution opens the door to the idea that those beings from whom we developed and those that are genetically close to us today may hold these same characteristics, though perhaps to different degrees. Rather than being a singular exception to the forces that shaped the natural world, human beings are a great exemplification of such forces.

In recognizing this, Henning notes that evolutionary biology in turn must abandon the notion that physical reality is best understood as a valueless machine, deterministically playing out its programming. If, as evolutionary science teaches, humans evolved from simpler organisms, and if human beings are subjects who are free, conscious, and (at least intermittently) self-reflective, then this sense of freedom and subjectivity also must be found in humanity's evolutionary ancestors.

In the fourth and last chapter, systematic theologian Stoicoiu seeks to interweave the threads of conversation from the preceding chapters and demonstrate the fundamental intellectual inadequacy of not only atheistic evolutionary materialism and simplistic biblical creationism but also more sophisticated contemporary approaches, such as scientific creationism and intelligent design theory. Rather than seeing the theory of evolution as a threat to religious belief, Stoicoiu suggests that a theology that embraces evolution can deepen and broaden a faith seeking understanding. In this way, she rejects the impulse to save religion by retreating into "separatism" (the view that science and religion are nonoverlapping domains of inquiry). From the perspective of biblical creation stories, one can come to understand how these stories answer important transcendental questions, while realizing that one cannot also expect them to address questions posed by modern science. Today, one can build upon biblical creation accounts and, with the help of theology, address evolutionary theory, not as some construct that lies outside the theological sphere, but rather as a theory to be theologically engaged.

Stoicoiu concludes that one must respect the autonomy and veracity of evolutionary biology, recognize the reality and ubiquity of suffering in the world, and begin to move toward an evolutionary

theology that recognizes the richness that evolutionary theory can bring to one's understanding of the transcendent's relationship to creation. One of the great lessons theology can glean from a study of evolution is that all of reality is in the process of becoming. Theology recognizes this process and sees in it the means of drawing closer to the mystery of God. In this light, evolution is constantly offering us a world in transformation. Theology understands this transformation in light of a hope-filled promise of the future when the fulfillment of God's word will be realized. In the end, we need not choose between religion or science, faith or reason, Genesis or evolution. Evolution is not a threat to faith, but rather an enrichment of faith. A thorough faith seeking understanding brings together Genesis *and* evolution.

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Scientific Knowledge and Evolutionary Biology

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To critically evaluate the so-called debate between evolution and theology, one must first understand what science is and what it is not. Simply put, science is a framework for inquiry that generates knowledge about the natural world. Science is an incredibly powerful tool that has provided us with a profound understanding of the natural world. There are, however, limits to science. In this chapter, we will explore in some detail what scientific knowledge is, what evolution is, and finally what limits are imposed on scientific knowledge.

For many, the word *science* conjures up a variety of images: white mice, lab coats, glass beakers, Bunsen burners, and the like. While science often involves these things, the field of science is incredibly diverse and includes a dizzying array of approaches. Unfortunately, most scientists remain so involved with their day-to-day work that they don't take time to advance a better public understanding of their work. As a result, many non-scientists have a weak grasp of what science really is. Sadly, much criticism of science comes from those who do not understand it.

SCIENCE AND ITS METHODOLOGY

To gain knowledge through science, one must first develop an idea (or hypothesis) about how something in the world works. This

hypothesis will be derived from observation and experience. Next, this hypothesis will be tested using an experiment. Testability is truly the cornerstone of science; if a hypothesis is not testable, it is not scientific. To be testable, a hypothesis must be falsifiable (able to fail). Likewise, the experiment testing a hypothesis must be designed so that its results will either support or negate the hypothesis. For example, it is conceivable that an experiment could be designed such that no matter the outcome, the hypothesis would be supported. This would not be a scientific test. Given the twin requirements of test-ability and fallibility, it quickly becomes clear that science is limited to discovering information about the physical world. For example, consider the claim, "God exists." This claim cannot be scientifically tested because it cannot be proved false. As such, this claim cannot be used as a scientific hypothesis. Does this make the claim untrue? No, it simply is not a scientific claim.

Another common misperception about science is that it pro-duces a body of "facts" about the world. The term *fact* implies a certain and unchangeable knowledge about a particular subject. By this definition, much of scientific knowledge is certainly not fact. By its nature, science must follow an **inductive logic**. **Inductive logic** uses information from a set of specific examples to explain a general phenomenon. Science is limited to inductive reasoning because it is simply impossible to test all possible outcomes in the world. Because a scientist cannot test all possible cases, he or she must draw a general conclusion about the world based on a limited set of instances. This is the problem of induction.

As an example, consider a scientist who wants to know the migration path of a particular **species** of duck. The scientist will develop a hypothesis that the species follows a particular migration route. To test this, the scientist might attach GPS receivers to thirty captured ducks before the fall migration and then track the flight pattern of those individuals to their wintering grounds. If those thirty ducks follow the hypothesized route over several years of test-ing, then the scientist concludes that all ducks of this particular spe-cies follow that route. Time and financial constraints dictate that the scientist cannot radio track all of the tens of thousands of individual ducks that migrated in those years. So the scientist is left to draw an inductive conclusion about all ducks of this species based on the

limited sample of thirty. Although unlikely, it is possible that the scientist's conclusion is wrong. Perhaps the scientist's samples were biased by the fact that she was able to capture those particular ducks. Perhaps the stronger and faster ducks (most of the **population**) were able to evade capture by the scientist and followed a different migratory route than the slower ducks. If this were true, then the scientist would be wrong about this species' migratory route.

Any scientist worth their salt understands this problem of induction and draws only a tentative conclusion. The well-trained scientist in this example would claim that her hypothesis was supported and that it is *likely* this duck species travels the hypothesized route. What the scientist does not do is claim to have *proved* this duck species follows a particular route. Science never proves or guarantees anything with certainty and this is precisely what makes science dynamic and exciting. New research often reinforces old ideas, but it also provides new discoveries and turns old "knowledge" on its head.

The role of inductive logic in scientific reasoning is an important consideration in the discussion of evolution and theology. It is valid to ask how scientists can claim that evolution is the force driving the diversity of life on Earth if science cannot prove anything. Indeed, how can scientists make any claims at all for that matter? The answer lies in the process of science.

In any scientific field, such as biology, there are many subdisciplines, each with its own set of researchers interested in particular questions. Each generation of scientists continues to test and refine the questions of their particular field. Again and again these scientists test hypotheses using different techniques. They apply the same questions to different species. They ask fresh questions to attack a problem from different angles. Often, hypotheses are refuted and rejected from the body of scientific knowledge. Sometimes hypotheses continue to hold up to scrutiny. If a hypothesis continues to withstand the scrutiny of many experiments by many different scientists over many decades, then the hypothesis comes to be considered a theory.

Evolution is often dismissed as "just a theory." It is important to understand, however, that in science, *theory* means something very different from how the word is used in everyday speech. In everyday speech, *theory* often means "just a guess," as in, "My uncle Joe has a

theory on how the New York Yankees will do this season." A scientific theory is much more than just a guess; it is a claim about the world that has withstood decades of rigorous investigation by many different scientists. This means a scientific theory is a powerful claim about the world that is backed by an enormous amount of experimental support.

Evolution was first proposed in part by British naturalist Charles Darwin (1809–1882) with his publication of *On the Origin of Species by Means of Natural Selection* in 1859. Not surprisingly, his book caused tremendous social upheaval, but it also shook up the field of biology and ushered in a new era of research. Darwin's hypothesis of evolution by natural selection has withstood 150 years of rigorous and repeated testing, elevating it to the powerful status of scientific theory.

To put scientific theory into perspective, consider gravity. No one disputes that gravity is the force that keeps Earth in orbit around the Sun and causes objects to fall to the ground. No one has ever observed gravity directly—one can only see its effects, devise experiments to test it, and model it with mathematics. Gravity therefore is not a proven fact but "only" a scientific theory. When scientists discuss a theory, such as evolution by natural selection, they are discussing a conceptual explanation of the world that is supported by a huge volume of solid evidence.

■ THE HISTORY OF EVOLUTIONARY THEORY

Evolutionary biology is a field of science. Knowledge regarding evolution proceeds by the scientific process of developing and testing hypotheses. One meaning of the term *evolution* is simply "change." When used in a biological context, *evolution* refers to change in living organisms that occurs over the course of many generations. It is now understood that genetic change is the underlying mechanism of evolution, an area explored in detail later in this chapter.

Although today Darwin is universally acknowledged as discovering how evolution proceeds by natural selection, many people made early and important contributions to evolutionary thought. Jean-Baptiste Lamarck (1744–1829) proposed that species change over time as a result of the use of a particular part of the body. For

example, he proposed that giraffes have long necks because individuals stretched repeatedly to reach leaves high on a tree. This resulted in a giraffe's neck becoming longer over the course of its lifetime, and the long-necked trait, Lamarck reasoned, would then be passed on to its offspring. This would be akin to claiming that if a person were involved in an accident and lost a finger, then the person's children would be born also missing that finger. Lamarck's proposed mechanism for evolution was later shown to be largely false, but his ideas generated much interest in evolutionary thought.

Another notable contributor to evolutionary thought was Darwin's contemporary, Alfred Russell Wallace (1823–1913). Wallace developed the concept of natural selection independently of Darwin, although today Darwin is given the lion's share of credit for evolutionary theory because of his publications and the in-depth nature of his numerous observations and experiments.

From 1831–1836, during his voyage around the world aboard the HMS *Beagle*, Darwin began forming his concept of natural selection. He found a variety of fossils that suggested evolutionary change; many species in these fossils resembled living species but were larger or had other features that were distinct from living organisms. In the Galapagos Islands, Darwin also observed living species that looked similar to those on mainland South America but that had other, unique characteristics. Further, he noticed that there were distinct differences between similar bird species on the neighboring islands of the Galapagos. These differences among birds, some living within sight of each other, struck Darwin as odd. He reasoned that if God were responsible for creating all organisms in their present form, it would seem a wasted effort to create extremely similar yet distinct species on islands in such close proximity. Upon returning from his voyage, Darwin continued to develop his concept and compile support for his idea. After some twenty years, he finally published his groundbreaking *On the Origin of Species*. The extraordinary rigor and large body of amassed evidence in his book propelled the concept of natural selection to the forefront of scientific thought.

Shortly after the publication of *On the Origin of Species*, many biologists adopted Darwin's ideas about natural selection and common descent. What was not yet understood, however, was what led to variation among individuals or why offspring tend to look like

their parents (heritability). This was an important criticism of natural selection, and while many scientists of the late 1800s adopted Darwin's ideas, there were also many critics. It was not until the 1930s that a group of scientists applied the field of genetics to the concept of natural selection. This provided a solid foundation to explain inheritance and clarified how biological evolution could occur through genetic change based on observable variations in natural populations. These discoveries in the 1920s were termed the "modern synthesis" and ushered in a more complete understanding of evolution, now sometimes referred to as the neo-Darwinian evolution. This neo-Darwinian paradigm generated new research programs and unified formerly isolated fields such as genetics, anatomy, and ecology.

In the roughly sixty years since this modern synthesis, scientists have studied evolution on many different levels and made enormous strides in understanding the process of evolution. Molecular biologists have examined how proteins evolve. Population geneticists have examined how **genes** evolve within populations. Anatomists and organismal biologists have studied phenotypic (visible traits of organisms) evolution. And geologists and paleontologists have contributed to the understanding of species change over geologic time. Thousands of scientists have filled numerous volumes with rigorous evidence for evolution, and this evidence continues to grow every year.

■ THE MECHANISMS OF EVOLUTION

Evolution can proceed by several different mechanisms. One of the most important of these, natural selection, was described by Darwin before the discovery of genes. Despite not knowing that genes are responsible for heritable traits (i.e., traits that are passed on from parents to offspring), Darwin recognized that (1) variation exists within populations of organisms, (2) traits are heritable, and (3) individual organisms, with their own unique traits, have different rates of reproduction. These three conditions drive natural selection.

On the face of it, the process of natural selection is remarkably simple. Nearly all populations of organisms show some level of variation. This variation can be genetic and can manifest in obvious phenotypic differences (see figure 1). Darwin recognized that natural

IMAGE: RYAN TAYLOR

Figure 1. Phenotypic variation within a species. The three shells in this image belong to the same species of conch snail, but show color and size variation. Both genetic and phenotypic variations are present in most populations of organisms.

forces act on this variation, resulting in some individuals that survive and reproduce and others that die and fail to reproduce. Among individuals that survive, some produce more offspring than others. As an example, consider a population of deer that shows variation in leg length (and hence running speed). Individuals with longer legs are more likely to outrun wolf predators than their shorter-legged counterparts. A greater number of long-legged than short-legged deer thus survive and reach reproductive maturity. As a result, there are more long-legged than short-legged deer available to reproduce in the breeding season. Each reproducing deer passes on its genes (and associated **phenotypes**) to its offspring. Since more long-legged deer survive and reproduce, there are more long-legged than short-legged offspring produced. In the next generation, therefore, the average length of the legs will be slightly longer, but there will still be some variation in leg length among individual deer. Again, as wolves hunt the deer, they will prey most often on those with the shortest legs. Thus, with each passing generation, the average leg length will become slightly longer (see figures 2a and 2b).
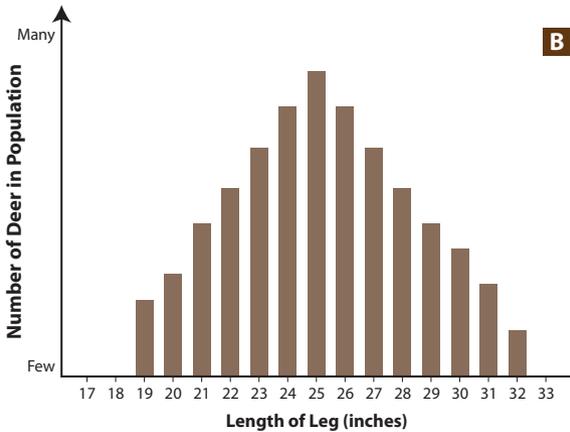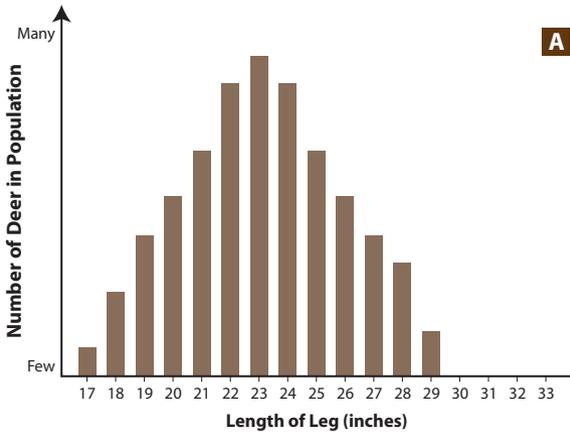
Figures 2A/B. Evolution of leg length in a deer population subject to predation pressure by wolves. (A) This graph shows the distribution of leg length that might be typical in a deer population. A small number of individuals have very short legs (17–18 inches), a small number have very long legs (28–29 inches), but most individuals have intermediate-length legs. In this population, the average is 23 inches. (B) This graph shows the distribution of leg lengths in the same deer population many generations later, if the deer with the shortest legs are eaten more frequently by wolves. Fewer short-legged individuals survive long enough to pass on the short-legged trait to their offspring. Over many generations, the average leg length tends to increase. Notice that there are now no deer in the population with 17- to 18-inch legs and a small number of deer with legs of 31–32 inches in length. The average leg length in the population has also shifted to become slightly longer at 25 inches. (Author illustration)

Darwin recognized that if this sort of gradual adaptive change continued long enough, the species would eventually change sufficiently to warrant being described as a completely different species. This sort of adaptive change is what Darwin referred to as "descent with modification." If an organism possesses a trait that improves survival and reproduction, it is considered better adapted to its environment than other members of its species. Over time, traits that are advantageous to survival become more common, and the species undergoes modification of traits with each passing generation. Biological evolution is the change in the frequency of genes contained in organisms within a particular population from one generation to the next.

Although Darwin did not know it at the time, every living organism possesses a set of genes that are responsible for passing traits from parents to offspring. The set of genes that each organism possesses varies to some degree between individuals. This is most evident when one looks at other humans. There is a tremendous variation in skin color, eye color, height, and so on. Most of this variation is due to differences in genes from one individual to the next. Individuals of a particular species (humans included) all have the same genes but often have different **alleles**. Alleles are the variants of one particular gene. Consider, for example, a gene that contributes to eye color. One allele may specify brown eyes and another, blue. Both are genes that control eye color, but each produces a different color. These different versions of the same gene are called alleles.

Genes (alleles) produce certain traits by creating proteins that perform a particular job in an organism's body. For example, there are proteins that provide structural support (like the proteins that make up your hair and fingernails). There are proteins that act as enzymes that help run an organism's metabolism. And there are proteins that help to maintain the biochemical environment needed to sustain life. Proteins are essential for nearly every aspect of the structure and function of living organisms.

The process by which genes build a body is quite complex, and even a single gene can have a profound effect on outward traits (the phenotype). Take, for example, the size of dogs. Current research suggests that just a single gene determines the size of domesticated dogs, producing the difference in size between a toy poodle and a

Great Dane, for example. Multiple genes may also work together to produce one trait. What is now understood is that different combinations of alleles produce variations of the phenotype, and these variations confer many possible advantages or disadvantages for the organisms that bear them.

Let us return for a moment to the example of wolves hunting deer. The variation in deer leg length is likely due to the variation in alleles for this trait that are present in the deer population. Suppose that eight alleles dictate the leg length in a deer. If a deer possesses a combination of eight particular alleles, it may have longer-than-average legs. If another deer has a combination of eight different alleles, it may have shorter-than-average legs. This begs an interesting question: why is there variation? There are really two answers to this question; the first is *genetic shuffling*. When two sexually reproducing organisms mate, there is a random shuffling of genes that are selected and passed on to the offspring. Since the mother and father each contribute only half of their genes to the offspring, the offspring inherits a random set of genes from each of its parents (see figure 3).

As an analogy, consider that you have two decks of cards, where each deck has eight cards numbered three through ten. Each deck represents the **genotype** of an individual deer parent and each card represents one allele that determines leg length of the deer. Each deer parent will contribute half of its genes to the offspring during mating. If the two card decks are shuffled and then four cards from each deck are dealt, thus forming a new deck of eight cards, the new deck would represent the genotype of the deer parents' offspring. Since each of the parental decks was shuffled and the cards dealt randomly, numerous combinations of cards would be possible. Consider a new deck combination (genotype of offspring) consisting of two threes, two fours, two fives, and two sixes. If the low cards (alleles) represent shorter legs, then this offspring would have shorter-than-average legs. If we have a combination of two sevens, two eights, two nines, and two tens, then this deer would have longer-than-average legs (alleles represented by higher value cards). Of course, both of these extreme combinations are unlikely. What is more likely to occur in the offspring is a random combination of low, medium, and high cards, resulting in a leg length somewhere around the average.

Child Blood Type	Parental Blood Type	
Possibility 1: (Type A)	Mother: **A** O — **A O** —	Father: B **O**
Possibility 2: (Type B)	Mother: A **O** — **O B** —	Father: **B** O
Possibility 3: (Type AB)	Mother: **A** O — **A B** —	Father: **B** O
Possibility 4: (Type O)	Mother: A **O** — **O O** —	Father: B **O**
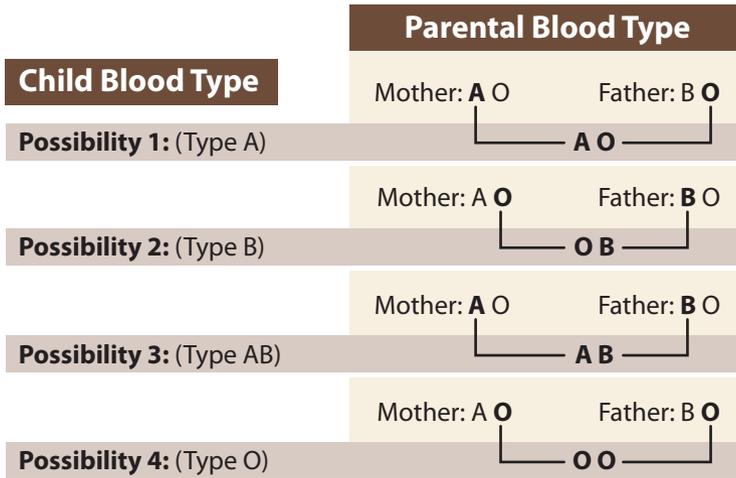
Mother's Blood Type

Father's Blood Type		A	O
	O	AO	OO
	B	AB	BO

Figure 3. An example of how sexual reproduction generates random shuffling that results in genetic variation. Three alleles affect blood type in humans, producing blood-types A, B, and O. Because every person contains two blood-type alleles (one from the mother and one from the father), several combinations can arise. Consider two parents, one with type A and the other with type B blood. The allele producing blood-type O is recessive; therefore, if a person has A or B as their other allele, they will have type A or B blood. Each parent can donate only one allele to the child; this means the child could have one of four possible blood types. The first diagram depicts the contribution of alleles from parent to child; the second diagram shows the same information written as a Punnett square (the standard format for working out possible gene combinations of offspring produced by parents from sexual reproduction). (Author illustration)

If we shuffled many pairs of such decks and dealt the cards to represent all the deer born into the population in a particular year, the deer offspring would end up with leg lengths that follow a roughly normal distribution (see figure 2a). A small number of individuals would have very short legs, a small number would have very long legs, and the majority would fall somewhere in between. Those individuals with longer legs would have an advantage in that they are more likely to evade wolves and survive to reproduce. Using the card example, consider that individuals in the bottom 10 percent of the leg-length distribution are eaten by wolves. These individuals had proportionally more lower-value cards. If one then takes the remaining 90 percent of individuals, shuffles their decks, pairs them up, and deals out new sets of offspring, the new generation now will have, on average, a slightly higher card value (because proportionally more lower-value cards have been removed from the deck—the representative gene pool). Thus, this new generation of deer will have slightly longer legs than the previous generation.

The second cause of variation in populations is **mutation**. When cells within organisms divide, the dividing cells must make new copies of the genes (a process called **replication**) that go into the new cell. Sometimes during replication a copying error occurs (i.e., a mutation) and the replicated gene receives a slightly different code. The mutated gene copy goes into the newly divided cell. If that mutated gene goes into a sperm or an egg cell, it may be passed on to the offspring during reproduction. These mutations are usually harmful. In extreme cases, the offspring with the mutation may die *in utero*. In less extreme cases, the offspring with the mutation will be born handicapped in a way that causes it to die earlier than normal. This early death may be due to any number of problems, including being unable to feed well or an increased susceptibility to disease. An early death means the individual with the mutated genes will either produce fewer than average offspring or none at all. When this happens, the mutation disappears from the population rather quickly, usually within a few generations. In rare cases, however, the mutation may be beneficial. If the mutation is beneficial because it confers some survival or reproductive benefit, then the individual will tend to leave more than the average number of offspring. In this situation, the mutated gene spreads and becomes more common in the population with each generation.

Mutation is the ultimate source of all genetic variation. The mutation of genes generally occurs at random and is not correlated with known factors affecting wild populations (chemicals that cause mutations resulting in cancer are an exception to this). One common misunderstanding about evolution involves the nature of the random process of mutation. It is commonly assumed that the entire process of evolution is random. Mutation is random, but natural selection is not. Within a population, genes occasionally mutate and are then thrust into the world to be "tested." If the gene provides a survival and hence reproductive advantage, the gene and its associated trait will become more common over time. If the gene is not beneficial for survival and reproduction, it is quickly eliminated from the population.

To summarize, mutation and genetic shuffling in sexual reproduction create random genetic variation. But natural forces such as predation, disease, and weather act on this variation and favor those organisms that are best suited to survive and reproduce within a particular environment. Individuals carrying beneficial genes (those best adapted) tend to produce more offspring and over many generations, the beneficial genes become more common in the population. If a gene is harmful, organisms bearing it produce few or no offspring, so over time, the gene disappears from the population. Thus, as this process is repeated over thousands to millions of generations, the environment affects which genes an organism is likely to carry and hence determines its appearance and physiological function. Given enough time, the small, adaptive (genetic) changes that are produced by environmental selection accumulate and can lead to dramatic changes in living form and function.

There is no set amount of time required for evolutionary change to take place. The amount of time required for change depends on the type of change and the generation time. For example, a genetic mutation can crop up in just two generations if a copying error is made during DNA replication and then passed on to an offspring. An important concept to keep in mind is that individuals do not evolve; change can only occur across generations. Thus, the faster an organism's generation time, the faster the species can evolve. A species of bacteria that can reproduce every twenty minutes will exhibit faster rates of evolution than an elephant species with a generation time of twenty years or more. Changes to large sections of an organism's

genome or the evolution of new species often take many thousands to millions of generations. Biologists consider changes that take place over tens of thousands of years to be rapid; changes occurring within species lineages that occur over millions of years are typical.

So far we have considered evolution as it occurs within one species over time. But how might evolution create a new species? Many closely related living species share similar traits: take snail species that build seashells, for example. Closely related snail species share features in common but also have unique characteristics that distinguish them from other snail species (see figures 4a and 4b). One of the most commonly accepted definitions of *species* is "individuals that can interbreed to produce viable offspring." If two organisms cannot produce viable offspring, they are considered to be of different species.

Several mechanisms can account for the evolution of many closely related species, which is known as **adaptive radiation**. One such mechanism is called **allopatric speciation**. For allopatric speciation to occur, a barrier must form within the geographic range of a particular species. This barrier could be a mountain range that is rising from geologic uplift, a river changing course, a glacier moving down a continent, or a variety of other natural processes. The barrier splits the species into two separate populations. If the barrier is sufficient to prevent migration between populations, then the populations do not interbreed. Over time, each population adapts to the conditions of its local environment. If at a later time the barrier is removed (the mountain range erodes, the river shifts course, etc.), then when the two populations again intermingle, they may have evolved genotypes that are sufficiently different to prevent interbreeding.

The formation of a mountain range provides a good example of how allopatric speciation works. When a mountain range pushes up near the coast, it often creates different habitats on either side. The coastal side is typically wet with frequent rainfall forming from ocean evaporation. The mountains block some air and cloud flow, creating a much drier habitat on the opposite side. Higher elevations are typically much colder than lower ones. Such a temperature difference would be sufficient to prevent many plant and animal species from crossing the mountains, and the populations split by the mountain range would adapt to the different habitats created by the mountain

IMAGE: RYAN TAYLOR

Figure 4a. The shells in this image represent the variation between distinct, but closely related, cone snails. They share common characteristics (note the similar shape and pattern of the shells), indicating that they evolved from a common ancestor. They do not interbreed, however, and thus represent distinct species.

IMAGE: RYAN TAYLOR

Figure 4b. These shells illustrate the variation between distinct, but closely related, auger snails. They share common characteristics (note the similar shape and pattern of the shells), indicating that they evolved from a common ancestor. They do not interbreed, however, and thus represent distinct species.

range. Another excellent example of allopatric speciation was created by the closing of the Isthmus of Panama. Closing the isthmus created different habitats in the formerly homogenous ocean. As Panama rose from the sea, the ocean on the Caribbean side developed into a clear, tropical sea, while the ocean on the Pacific side developed into a cooler, more turbid environment. Today, there are many "sister" species on each side of the isthmus that look similar but have evolved traits more suited for the marine environment on that side of the isthmus.

Natural selection is one of the most important mechanisms driving evolution. Other processes, however, can also drive evolutionary change. One of these is genetic drift. Genetic drift is a random process in which a particular allele by chance fails to be passed on to the next generation. This is most common when alleles are somewhat rare and the population is relatively small. Consider, for example, a population of deer in which there are only 100 individuals. Of these individuals, only two have a copy of a particular allele, let's call it allele X. In sexually reproducing populations, not every individual mates every year. If the two individuals with allele X do not reproduce and then die before getting the opportunity to reproduce in the following year, then allele X would be permanently lost from the population. Genetic drift generally does not drive adaptive changes that result in the appearance of new traits. But it can be an important factor that results in the loss of a trait or a process that reduces genetic variation in a population.

Another process driving evolution is sexual selection. Scientists have paid tremendous attention in recent decades to this process by which showy or conspicuous traits can evolve. A familiar example is the oversized tail of peacocks. Interestingly, the peacock's tail not only makes it a more visible target for predators but may also limit the male's ability to escape as it is burdened by a heavy train of feathers. Peahens are not troubled with such tail feathers. On the face of it, these showy traits seem to present a problem for the theory of natural selection. If natural forces continually shape organisms to be better suited for survival, then how can traits that reduce survival evolve? Darwin was extremely concerned about this and the problem that it presented to his theory of natural selection. He spent much time working on this problem and in 1871, proposed the mechanisms of sexual selection in his book, *The Descent of Man and*

Selection in Relation to Sex. Darwin described two processes by which large or showy (and seemingly maladaptive) traits could evolve.

The first of these mechanisms of sexual selection is what biologists typically refer to as female choice. Under this system, females do not randomly mate with males, but instead carefully select the males with whom they mate. This makes sense from an evolutionary standpoint. Females invest more in each act of reproduction. Eggs require more energy to produce than sperm. Further, in the case of mammals, females must gestate and feed their offspring for a considerable time. If a female makes a poor mate choice—selecting a male who abandons her to care for their offspring alone, for example—she has lost much more than would a male who makes a poor mate choice, such as mating with a genetically inferior female. In most cases, the male can abandon her to mate again. Because of the added time and energy constraint, females of most species simply cannot pass on their genes via reproduction as quickly as males. This sets up a situation in which females are selective about their mate choice and thus force males to compete for them. This nonrandom mating occurs when females choose to mate with males that have the showiest or most conspicuous courtship displays. A classic example is the research finding that peahens prefer to mate with peacocks whose tail fans are larger and have more eyespots.[1] Males with smaller-than-average tails are less likely to mate and will leave fewer offspring in the next generation; conversely, males with the largest tails will win more matings and produce relatively more offspring. Male offspring will be more likely to possess their father's larger tails. Over many generations, this female preference will drive the evolution of larger and larger tails in males. The peafowl are just one example of this process of female choice. This same process has been demonstrated in African widowbirds,[2] swordtail fish,[3] guppies,[4]

1. M. Petrie, T. Halliday, and C. Sanders, "Peahens Prefer Peacocks with Elaborate Trains," *Animal Behavior* 41 (1991): 323–31.

2. M. Andersson, "Female Choice Selects for Extreme Tail Length in a Widowbird," *Nature* 299 (1982): 818–20.

3. A. Basolo, "Female Preference Predates the Evolution of the Sword in Swordtail Fish," *Science* 250 (1990): 808–10.

4. A. Kodric-Brown and J. H. Brown, "Truth in Advertising: The Kinds of Traits Favoured by Sexual Selection," *American Naturalist* 124 (1984): 309–23.

spiders,[5] frogs,[6] and other species. In virtually every animal species where males possess some sort of increased color, ornamentation, or courtship display that females lack, there is evidence that female mating preferences have driven the evolution of the male trait.[7]

A second process of sexual selection occurs through male–male competition. In this process, males compete directly for females by fighting; thus, traits that provide males with a fighting advantage tend to be favored. A good example of this is antler size in deer. In most species, only males produce antlers and these are weapons for fighting. There is often considerable variation in antler size among males. Larger antlers provide better leverage for the shoving matches that males engage in; males with larger antlers tend to win fights. Those males that win these contests gain access to many females (the harem) and often sire multiple offspring. The losers often do not mate at all. Thus, large-antlered males tend to leave most of the offspring, and their offspring of course will have relatively large antlers.

Although large or showy ornamentation is likely to be detrimental to survival (consider a peacock trying to escape a fox while dragging a long tail train), these ornaments also confer a reproductive advantage. Evolutionary advantages are often spoken of in terms of survival and reproduction. Survival is obviously important; organisms cannot reproduce unless they are alive. In reality, it is only reproduction that matters. Consider the example of a population of peafowl. If males with the largest tails live an average of two years before being eaten by foxes, but sire forty offspring per year, then they leave eighty offspring in their lifetime. If males with the smallest tails live an average of four years, but produce only ten offspring per year, then they typically leave forty offspring in their lifetime. Even though the long-tailed males live significantly shorter lives, they are leaving proportionally more long-tailed offspring. Thus,

5. E. A. Hebets and G. W. Uetz, "Leg Ornamentation and the Efficacy of Courtship Display in Four Species of Wolf Spider (*Araneae: Lycosidae*)," *Behavioral Ecology and Sociobiology* 47 (2000): 280–86.

6. H. C. Gerhardt and F. Huber, *Acoustic Communication in Insects and Anurans: Common Problems and Diverse Solutions* (Chicago: University of Chicago Press, 2002); M. J. Ryan, *The Túngara Frog: A Study in Sexual Selection and Communication* (Chicago: University of Chicago Press, 1985).

7. M. Andersson, *Sexual Selection* (Princeton, NJ: Princeton University Press, 1994).

the average tail size of males in the population increases over time because proportionally more long-tailed genes are produced in the population with each generation.

Based on these processes of sexual selection, it would seem that male traits would always get larger and showier with each passing generation. Multiple evolutionary processes are often at work, however. In many cases, an upper limit may be placed on male ornamentation by the laws of physics dictating that at some point a male may simply become unable to carry the ornaments around. This is what is thought to have happened to the Irish elk. This species went extinct because their antlers grew to such an enormous size that they placed too great a burden on the animal, contributing to the demise of the species. Alternatively, predators may place an upper limit on the evolution of a trait. In many cases a balancing selection is reached between the trait increasing male mating success and the trait increasing the probability the male will be eaten by a predator. As an example, the male túngara frog of Central and South America produces either a simple or a complex courtship vocalization. The complex vocalization is more attractive to females and increases the male's chance of mating,[8] but it also attracts bat predators and increases the male's chance of being eaten. While the complex vocalization evolved through female mating preferences, its continued evolution may be limited by predators.

Another factor that may limit male ornamentation and contribute to variation is that alternative mating strategies may be equally successful. In some cases, being bigger and more colorful is not always the best strategy. In sunfish, for example, some males grow to be larger and more colorful than other males. These males are the preferred mates of females, and these larger males attract the vast majority of females in the population. But other males retain a small size and drab coloration upon maturity. These males have adopted a sneaking strategy that is quite effective. When a large male is courting a female, the small male slides in between the male and the female—in essence behaving like another female. The large male is fooled and continues to court the two fish as if they were both females. When the real female deposits her eggs in the nest,

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8. Ryan, *The Túngara Frog*.

the small sneaker male quickly dumps his sperm, fertilizes the eggs, and leaves the large male to care for his offspring.[9] In short, multiple evolutionary processes often work in tandem to limit the evolution of male sexually selected traits (e.g., by predation) or, in some cases, increase the diversity of male traits (e.g., multiple mating strategies).

▪ EVIDENCE FOR EVOLUTION

With the exception of some of the experimental studies cited in the section on sexual selection, this chapter has provided mostly conceptual explanations of how evolution works. The first section of the chapter also noted that a scientific theory is supported by a tremendous volume of evidence. The remaining portion of this section will consider the evidence scientists have for evolution.

One important piece of evidence suggesting that organisms undergo evolutionary change is the fossil record. The fossil record not only tells us that species which once lived became extinct (e.g., the dinosaurs) but also supplies a remarkably complete record of the evolutionary change that many organisms have undergone in the history of our planet. For example, there are a series of transitional fossils that show the evolution of reptiles (dinosaurs) into birds. Examples of these include dinosaurs that had forelimbs that looked like the forelimbs of reptiles but also had rudimentary feathers. The anatomical study of living birds and reptiles shows that scales and feathers develop from the same tissues, indicating that reptilian scales were modified over time into feathers. It is thought that the evolution of feathers from scales probably provided a thermal advantage for reptiles in a cooling climate. The selection pressures that caused feathers to evolve from scales are somewhat speculative, but the fossil record clearly shows the small steps whereby scales were modified into ever larger feathers. Beyond feathers, the fossil record shows a variety of other intermediate steps in the reptile-bird lineage. For example, modern birds do not have teeth as reptiles do. But the fossil record shows several species of early birds that had teeth; these prehistoric animals also had poorly developed wings that show

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9. M. R. Gross, "Sneakers, Satellites, and Parentals: Polymorphic Mating Strategies in North American Sunfishes," *Z. Tierpsychol* 60 (1982): 1–26.