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1
Why Teach Evolution?

Why is it so important to teach evolution? After all, many questions in biology can be answered without mentioning evolution: How do birds fly? How can certain plants grow in the desert? Why do children resemble their parents? Each of these questions has an immediate answer involving aerodynamics, the storage and use of water by plants, or the mechanisms of heredity. Students ask about such things all the time.

The answers to these questions often raise deeper questions that are sometimes asked by students: How did things come to be that way? What is the advantage to birds of flying? How did desert plants come to differ from others? How did an individual organism come to have its particular genetic endowment? Answering questions like these requires a historical context—a framework of understanding that recognizes change through time.

People who study nature closely have always asked these kinds of questions. Over time, two observations have proved to be especially perplexing. The older of these has to do with the diversity of life: Why are there so many different kinds of plants and animals? The more we explore the world, the more impressed we are with the multiplicity of kinds of organisms. In the mid-nineteenth century, when Charles Darwin was writing *On the Origin of Species*, naturalists recognized several tens of thousands of different plant and animal species. By the middle of the twentieth century, biologists had paid more attention to less conspicuous forms of life, from insects to microorganisms, and the estimate was up to 1 or 2 million. Since then, investigations in tropical rain forests—the center of much of the world's biological diversity—have multiplied those estimates at least tenfold. What process has created this extraordinary variety of life?

The second question involves the inverse of life's diversity. How can the similarities among organisms be explained? Humans have always noticed the similarities among closely related species, but it gradually became apparent that even distantly related species share many anatomical and functional characteristics. The bones in a whale's front flippers are arranged in much the same way as the bones in our own arms. As organisms grow from fertilized egg cells into embryos, they pass through many similar developmental stages. Furthermore, as paleontologists studied the fossil record, they discovered countless extinct species that are clearly related in various ways to organisms living today.

This question has emerged with even greater force as modern experimental biology has focused on processes at the cellular and molecular level. From bacteria to yeast to mice to humans, all living things use the same biochemical machinery to carry out the basic processes of life. Many of the proteins that make up cells and catalyze chemical reactions in the body are virtually identical across species. Certain human genes that code for proteins differ little from the corresponding genes in fruit flies, Investigations of forest ecosystems have helped reveal the incredible diversity of earth's living things.

mice, and primates. All living things use the same biochemical system to pass genetic information from one generation to another.

From a scientific standpoint, there is one compelling answer to questions about life's commonalities. Different kinds of organisms share so many characteristics of structure and function because they are related to one another. But how?

Solving the Puzzle

The concept of biological evolution addresses both of these fundamental questions. It accounts for the relatedness among organisms by explaining that the millions of different species of plants, animals, and microorganisms that live on earth today are related by descent from common ancestors—like distant cousins. Organisms in nature typically produce more offspring than can survive and reproduce given the constraints of food, space, and other resources in the environment. These offspring often differ from one another in ways that are heritable—that is, they can pass on the differences genetically to their own offspring. If competing offspring have traits that are advantageous in a given environment, they will survive and pass on those traits. As differences continue to accumulate over generations, populations of organisms diverge from their ancestors.

This straightforward process, which is a natural consequence of biologically reproducing organisms competing for limited resources, is responsible for one of the most magnificent chronicles known to science. Over billions of years, it has led the earliest organisms on earth to diversify into all of the plants, animals, and microorganisms that exist today. Though humans, fish, and bacteria would seem to be so different as to defy comparison, they all share some of the characteristics of their common ancestors.

Evolution also explains the great diversity of modern species. Populations of organisms

Living fish and fossil fish share many similarities, but the fossil fish clearly belongs to a different species that no longer exists. The progression of species found in the fossil record provides powerful evidence for evolution.

with characteristics enabling them to occupy ecological niches not occupied by similar organisms have a greater chance of surviving. Over time—as the next chapter discusses in more detail—species have diversified and have occupied more and more ecological niches to take advantage of new resources.

Evolution explains something else as well. During the billions of years that life has been on earth, it has played an increasingly important role in altering the planet's physical environment. For example, the composition of our atmosphere is partly a consequence of living systems. During photosynthesis, which is a product of evolution, green plants absorb carbon dioxide and water, produce organic compounds, and release oxygen. This process has created and continues to maintain an atmosphere rich in oxygen. Living communities also profoundly affect weather and the movement of water among the oceans, atmosphere, and land. Much of the rainfall in the forests of the western Amazon basin consists of water that has already made one or more recent trips through a living plant. In addition, plants and soil microorganisms exert important controls over global temperature by absorbing or emitting "greenhouse gases" (such as carbon dioxide and methane) that increase the earth's capacity to retain heat.

In short, biological evolution accounts for three of the most fundamental features of the world around us: the similarities among living things, the diversity of life, and many features of the physical world we inhabit. Explanations of these phenomena in terms of evolution draw on results from physics, chemistry, geology, many areas of biology, and other sciences. Thus, evolution is the central organizing principle that biologists use to understand the world. To teach biology without explaining evolution deprives students of a powerful concept that brings great order and coherence to our understanding of life.

The teaching of evolution also has great practical value for students. Directly or indirectly, evolutionary biology has made many contributions to society. Evolution explains why many human pathogens have been developing resistance to formerly effective drugs and suggests ways of confronting this increasingly serious problem (this issue is discussed in greater detail in Chapter 2). Evolutionary biology has also

Living things have altered the earth's oceans, land surfaces, and atmosphere. For example, photosynthetic organisms are responsible for the oxygen that makes up about a fifth of the earth's atmosphere. The rapid accumulation of atmospheric oxygen about 2 billion years ago led to the evolution of more structured eucaryotic cells, which in turn gave rise to multicellular plants and animals.

contributed to many important agricultural advances by explaining the relationships among wild and domesticated plants and animals and their natural enemies. An understanding of evolution has been essential in finding and using natural resources, such as fossil fuels, and it will be indispensable as human societies strive to establish sustainable relationships with the natural environment.

Such examples can be multiplied many times. Evolutionary research is one of the most active fields of biology today, and discoveries with important practical applications occur on a regular basis.

Those who oppose the teaching of evolution in public schools sometimes ask that teachers present "the evidence against evolution." However, there is no debate within the scientific community over whether evolution occurred, and there is no evidence that evolution has not occurred. Some of the details of how evolution occurs are still being investigated. But scientists continue to debate only the particular mechanisms that result in evolution, not the overall accuracy of evolution as the explanation of life's history.

Evolution and the Nature of Science

Teaching about evolution has another important function. Because some people see evolution as conflicting with widely held beliefs, the teaching of evolution offers educators a superb opportunity to illuminate the nature of science and to differentiate science from other forms of human endeavor and understanding.

Chapter 3 describes the nature of science in detail. However, it is important from the outset to understand how the meanings of certain key words in science differ from the way that those words are used in everyday life.

Think, for example, of how people usually use the word "theory." Someone might refer to an idea and then add, "But that's only a theory." Or someone might preface a remark by saying, "My theory is …." In common usage, theory often means "guess" or "hunch."

In science, the word "theory" means something quite different. It refers to an overarching explanation that has been well substantiated. Science has many other powerful theories besides evolution. Cell theory says that all living things are composed of

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cells. The heliocentric theory says that the earth revolves around the sun rather than vice versa. Such concepts are supported by such abundant observational and experimental evidence that they are no longer questioned in science.

Sometimes scientists themselves use the word "theory" loosely and apply it to tentative explanations that lack well-established evidence. But it is important to distinguish these casual uses of the word "theory" with its use to describe concepts such as evolution that are supported by overwhelming evidence. Scientists might wish that they had a word other than "theory" to apply to such enduring explanations of the natural world, but the term is too deeply engrained in science to be discarded.

As with all scientific knowledge, a theory can be refined or even replaced by an alternative theory in light of new and compelling evidence. For example, Chapter 3 describes how the geocentric theory that the sun revolves around the earth was replaced by the heliocentric theory of the earth's rotation on its axis and revolution around the sun. However, ideas are not referred to as "theories" in science unless they are supported by bodies of evidence that make their subsequent abandonment very unlikely. When a theory is supported by as much evidence as evolution, it is held with a very high degree of confidence.

In science, the word "hypothesis" conveys the tentativeness inherent in the common use of the word "theory." A hypothesis is a testable statement about the natural world. Through experiment and observation, hypotheses can be supported or rejected. As the earliest level of understanding, hypotheses can be used to construct more complex inferences and explanations.

Like "theory," the word "fact" has a different meaning in science than it does in common usage. A scientific fact is an observation that has been confirmed over and over. However, observations are gathered by our senses, which can never be trusted entirely. Observations also can change with better technologies or with better ways of looking at data. For example, it was held as a scientific fact for many years that human cells have 24 pairs of chromosomes, until improved techniques of microscopy revealed that they actually have 23. Ironically, facts in science often are more susceptible to change than theories—which is one reason why the word "fact" is not much used in science.

Finally, "laws" in science are typically descriptions of how the physical world behaves under certain circumstances. For example, the laws of motion describe how objects move when subjected to certain forces. These laws can be very useful in supporting hypotheses and theories, but like all elements of science they can be altered with new information and observations.

Glossary of Terms Used in Teaching About the Nature of Science

Fact: In science, an observation that has been repeatedly confirmed.

Law: A descriptive generalization about how some aspect of the natural world behaves under stated circumstances.

Hypothesis: A testable statement about the natural world that can be used to build more complex inferences and explanations.

Theory: In science, a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypot

Scientists examining the head of *Chasmosaurus mariscalensis* hone their understanding of nature by comparing it against observations of the world. Clockwise from upper right: Prof. Paul Sereno, Univ. of Chicago; assistant Cathy Forster, Univ. of Chicago; students Hilary Tindle and Tom Evans, who discovered the skull in the field in March 1991 in Big Bend National Park, Texas.

Those who oppose the teaching of evolution often say that evolution should be taught as a "theory, not as a fact." This statement confuses the common use of these words with the scientific use. In science, theories do not turn into facts through the accumulation of evidence. Rather, theories are the end points of science. They are understandings that develop from extensive observation, experimentation, and creative reflection. They incorporate a large body of scientific facts, laws, tested hypotheses, and logical inferences. In this sense, evolution is one of the strongest and most useful scientific theories we have.

Evolution and Everyday Life

The concept of evolution has an importance in education that goes beyond its power as a scientific explanation. All of us live in a world where the pace of change is accelerating. Today's children will face more new experiences and different conditions than their parents or teachers have had to face in their lives.

The story of evolution is one chapter—perhaps the most important one—in a scientific revolution that has occupied much of the past four centuries. The central feature of this revolution has been the abandonment of one notion about stability after another: that the earth was the center of the universe, that the world's living things are unchangeable, that the continents of the earth are held rigidly in place, and so on. Fluidity and change have become central to our understanding of the world around us. To accept the probability of change—and to see change as an agent of opportunity rather than as a threat—is a silent message and challenge in the lesson of evolution.

The following dialogue dramatizes some of the problems educators encounter in teaching evolution and demonstrates ways of overcoming these obstacles. Chapter 2 returns to the basic themes that characterize evolutionary theory, and Chapter 3 takes a closer look at the nature of science.

Dialogue

THE CHALLENGE TO TEACHERS

Teaching evolution presents special challenges to science teachers. Sources of support upon which teachers can draw include high-quality curricula, adequate preparation, exposure to information useful in documenting the evidence for evolution, and resources and contacts provided by professional associations.

One important source of support for teachers is to share problems and explore solutions with other teachers. The following vignette illustrates how a group of teachers—in this case, three biology teachers at a large public high school—can work together to solve problems and learn from each other.

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It is the first week of classes at Central High School. As the bell rings for third period, Karen, the newest teacher on the faculty, walks into the teachers' lounge. She greets her colleagues, Barbara and Doug.

"How are your first few days going?" asks Doug.

"Fine," Karen replies. "The second-period Biology I class is full, but it'll be okay. By the way, Barbara, thanks for letting me see your syllabus for Bio I. But I wanted to ask you about teaching evolution—I didn't see it there."

"You didn't see it on my syllabus because it's not a separate topic," Barbara says. "I use evolution as a theme to tie the course together, so it comes into just about every unit. You'll see a section called 'History of Life' on the second page, and there's a section called 'Natural Selection.' But I don't treat evolution separately because it is related to almost every other topic in biology."[1]

"Wait a minute, Barbara," Doug says. "Is that good advice for a new teacher? I mean, evolution is a controversial subject, and a lot of us just don't get around to teaching it. I don't. You do, but you're braver than most of us."

"It's not a matter of bravery, Doug," Barbara replies. "It's a matter of what needs to be taught if we want students to understand biology. Teaching biology without evolution would be like teaching civics and never mentioning the United States Constitution."

"But how can you be sure that evolution is all that important. Aren't there a lot of scientists who don't believe in evolution? Say it's too improbable?"

"The debate in science is over some of the details of how evolution occurred, not whether evolution happened or not. A lot of science and science education organizations have made statements about why it is important to teach evolution. …"[2]

"I saw a news report when I was a student," Karen interjects, "about a school district or state that put a disclaimer against evolution in all their biology textbooks. It said that students didn't need to believe in evolution because it wasn't a fact, only a theory. The argument was that no one really knows how life began or how it evolved because no one was there to see it happen."[3]

"If I taught evolution, I'd sure teach it as a theory—not a fact," says Doug.

"Just like gravity," Barbara says.

"Now, Barbara, gravity is a fact, not a theory."

"Not in scientific terms. The fact is that things fall. The explanation for why things fall is the theory of gravitation. Our problem is definitions. You're using 'fact' and 'theory' the way we use them in everyday life, but we need to use them as scientists use them. In science, a 'fact' is an observation that has

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A fossil of *Archaeopteryx*, a bird that lived about 150 million years ago and had many reptilian characteristics, was discovered in 1861 and helped support the hypothesis of evolution proposed by Charles Darwin in *The Origin of Species* two years earlier.

been made so many times that it's assumed to be okay. How facts are explained is where theories come in: theories are explanations of what we observe. One place where students get confused about evolution is that they think of 'theory' as meaning 'guess' or 'hunch.' But evolution isn't a hunch. It's a scientific explanation, and a very good one."

"But how good a theory is it?" asks Doug. "We don't know everything about evolution."

"That's true," says Karen. "A student in one of my classes at the university told me that there are big gaps in the fossil record. Do you know anything about that?"

"Well, there's *Archaeopteryx*," says Doug. "It's a fossil that has feathers like a bird but the skeleton of a small dinosaur. It's one of those missing links that's not missing any more."

"In fact, there are good transitional fossils between primitive fish and amphibians and between reptiles and mammals," Barbara says. "Our knowledge of fossil intermediates is actually pretty good.[4] And, Doug, it sounds like you know more about evolution than you're letting on. Why don't you teach it?"

"I don't want any trouble. Every time I teach evolution, I have a student announce that 'evolution is against his religion.'"

"But most of the major religious denominations have taken official positions that accept evolution," says Barbara. "One semester a friend of mine in the middle school started out her Life Science unit by having her students interview their ministers or priests or rabbis about their religion's views on evolution. She said that most of her students came back really surprised. 'Hey,' they said, 'evolution is okay.' It defused the controversy in her class."

"She didn't have Stanley in her class," says Doug.

"Who's Stanley?" asks Karen.

"The son of a school board member. Given his family's religious views, I'm sure he would not come back saying evolution was okay."

"That can be a hard situation," says Barbara. "But even if Stanley came back to class saying that his religion does not accept evolution, it could help a teacher show that there are many different religious views about evolution. That's the point: religious people can still accept evolution."

"Stanley will never believe in evolution."

"We talk about 'believing' in evolution, but that's not necessarily the right word. We accept evolution as the best scientific explanation for a lot of observations—about fossils and biochemistry and evolutionary changes we can actually see, like how bacteria become resistant to certain medicines. That's why people accepted the idea that the earth goes around the sun—because it accounted for many different observations that we make. In science, when a better explanation comes around, it replaces earlier ones."

"Does that mean that evolution will be replaced by a better theory some day?" asks Karen.

"It's not likely. Not all old theories are

replaced, and evolution has been tested and has a lot of evidence to support it. The point is that doing science requires being willing to refine our theories to be consistent with new information."

"But there's still Stanley," says Doug. "He doesn't even want to hear about evolution."

"I had Stanley's sister in AP biology one year," Barbara replies. "She raised a fuss about evolution, and I told her that I wasn't going to grade her on her opinion of evolution but on her knowledge of the facts and concepts. She seemed satisfied with that and actually got an A in the class."

"I still think that if you teach evolution, it's only fair to teach both."

"What do you mean by both?" asks Barbara. "If you mean both evolution and creationism, what kind of creationism do you want to teach? Will you teach evolution and the Bible? What about other religions like Buddhism or the views of Native Americans? It's hard to argue for 'both' when there are a whole lot more than two options."

"I can't teach a whole bunch of creation stories in my Bio class," says Doug.

"That's the point. We can't add subjects to the science curriculum to be fair to groups that hold certain beliefs. Teaching ecology isn't fair to the polluter, either. Biology is a science class, and what should be taught is science."

"But isn't there something called 'creation science'?" asks Karen. "Can creationism be made scientific?"

"That's an interesting story. 'Creation science' is the idea that scientific evidence can support a literal interpretation of Genesis—that the whole universe was created all at once about 10,000 years ago."

"It doesn't sound very likely."

"It's not. Scientists have looked at the arguments and have found they are not supported by verifiable data. Still, back in the early 1980s, some states passed laws requiring that 'creation science' be taught whenever evolution was taught. But the Supreme Court threw out 'equal time' laws, saying that because creationism was inherently a religious and not a scientific idea, it couldn't be presented as 'truth' in science classes in the public schools."[5]

"Well, I'm willing to teach evolution," says Karen, "and I'd like to try it your way, Barbara, as a theme that ties biology together. But I really don't know enough about evolution to do it. Do you have any suggestions about where I can get information?"

"Sure, I'd be glad to share what I have. But an important part of teaching evolution has to do with explaining the nature of science. I'm trying out a demonstration after school today that I'm going to use with my Bio I class tomorrow. Why don't you both come by and we can try it out?"

"Okay," say Karen and Doug. "We'll see you then."

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Barbara, Doug, and Karen's discussion of evolution and the nature of science resumes following Chapter 2.

NOTES

1. The *National Science Education Standards* cite "evolution and equilibrium" as one of five central concepts that unify all of the sciences. (See www.nap.edu/readingroom/books/nses)
2. Appendix C contains statements from science and science education organizations that support the need to teach evolution.
3. In 1995, the Alabama board of education ordered that all biology textbooks in public schools carry inserts that read, in part, as follows: "This textbook discusses evolution, a controversial theory some scientists present as a scientific explanation for the origin of living things, such as plants, animals, and humans. No one was present when life first appeared on earth. Therefore, any statement about life's origins should be considered theory, not fact." Other districts have required similar disclaimers.
4. The book *From So Simple a Beginning: The Book of Evolution* by Philip Whitfield (New

York: Macmillan, 1993) presents a well-illustrated overview of evolutionary history. *Evolution* by Monroe W. Strickberger (Boston: Jones and Bartlett, 2nd edition, 1995) is a thorough text written at the undergraduate level.

5. In the 1987 case *Edwards v. Aguillard*, the U.S. Supreme Court reaffirmed the 1982 decision of a federal district court that the teaching of "creation science" in public schools violates the First Amendment of the U.S. Constitution.

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Teaching About Evolution and the Nature of Science (1998)

Chapter: Chapter 2: Major Themes in Evolution

« Previous: *Chapter 1: Why Teach Evolution?*

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Major Themes in Evolution

The world around us changes. This simple fact is obvious everywhere we look. Streams wash dirt and stones from higher places to lower places. Untended gardens fill with weeds.

Other changes are more gradual but much more dramatic when viewed over long time scales. Powerful telescopes reveal new stars coalescing from galactic dust, just as our sun did more than 4.5 billion years ago. The earth itself formed shortly thereafter, when rock, dust, and gas circling the sun condensed into the planets of our solar system. Fossils of primitive microorganisms show that life had emerged on earth by about 3.8 billion years ago.

Similarly, the fossil record reveals profound changes in the kinds of living things that have inhabited our planet over its long history. Trilobites that populated the seas hundreds of millions of years ago no longer crawl about. Mammals now live in a world that was once dominated by reptilian giants such as *Tyrannosaurus rex*. More than 99 percent of the species that have ever lived on the earth are now extinct, either because all of the members of the species died, the species evolved into a new species, or it split into two or more new species.

Many kinds of cumulative change through time have been described by the term "evolution," and the term is used in astronomy, geology, biology, anthropology, and other sciences. This document focuses on the changes in living things during the long history of life on earth—on what is called biological evolution. The ancient Greeks were already speculating about the origins of life and changes in species over time. More than 2,500 years ago, the Greek philosopher Anaximander thought that a gradual evolution had created the world's organic coherence from a formless condition, and he had a fairly modern view of the transformation of aquatic species into terrestrial ones. Following the rise of Christianity, Westerners generally accepted the explanation provided in Genesis, the first book of the Judeo-Christian-Muslim Bible, that God created everything in its present form over the course of six days. However, other explanations existed even then. Among Christian theologians, for example, Saint Thomas Aquinas (1225 to 1274) stated that the earth had received the power to produce organisms and criticized the idea that species had originated in accordance with the timetables in Genesis.[1]

During the early 1800s, many naturalists speculated about changes in organisms, especially as geological investigations revealed the rich story laid out in the fossilized remains of extinct creatures. But although ideas about evolution were proposed, they never gained wide acceptance because no one was able to propose a plausible mechanism for how the form of an organism might change from one generation to another. Then, in 1858, two English naturalists—Charles Darwin and Alfred Russel Wallace—simultaneously issued papers proposing such a mechanism. Both

The Hubble Space Telescope has revealed many astronomical phenomena that ground-based telescopes cannot see. The top images show disks of matter around young stars that could give rise to planets. In the image below, stars are forming in the tendrils of gas and dust extending from a gigantic nebula.

men observed that the individual members of a particular species are not identical but can differ in many ways. For example, some will be able to run a little faster, have a different color, or respond to the same circumstance in different ways. (Humans—including any class of high school students—have many such differences.) Both men further observed that many of these differences are inherited and can be passed on to offspring. This conclusion was evident from the experiences of plant and animal breeders.

Darwin and Wallace were both deeply influenced by the realization that, even though most species produce an abundance of offspring, the size of the overall population usually remains about the same. Thus, an oak tree might produce many thousands of acorns each year, but few, if any, will survive to become full-grown trees.

Darwin—who conceived of his ideas in the 1830s but did not publish them until Wallace came to similar conclusions—presented the case for evolution in detail in his 1859 book *On the Origin of Species by Natural Selection*. Darwin proposed that there will be differences between offspring that survive and reproduce and those that do not. In particular, individuals that have heritable characteristics making them more likely to survive and reproduce in their particular environment will, on average, have a better chance of passing those characteristics on to their own offspring. In this way, as many generations pass, nature would select those individuals best suited to particular environments, a process Darwin called natural selection. Over very long times, Darwin argued, natural selection acting on varying individuals within a population of organisms could account for all of the great variety of organisms we see today, as well as for the species found as fossils.

If the central requirement of natural selection is variation within populations, what is the ultimate source of this variation? This problem plagued Darwin, and he never

From top left, Charles Darwin (1809-1882), Alfred Russel Wallace (1823-1913), and Gregor Mendel (1822-1884) laid the foundations of modern evolutionary theory.

Glossary of Terms Used in Teaching About Evolution

Evolution: Change in the hereditary characteristics of groups of organisms over the course of generations. (Darwin referred to this process as "descent with modification.")

Species: In general, a group of organisms that can potentially breed with each other to produce fertile offspring and cannot breed with the members of other such groups.

Variation: Genetically determined differences in the characteristics of members of the same species.

Natural selection: Greater reproductive success among particular members of a species arising from genetically determined characteristics that confer an advantage in a particular environment.

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found the answer, although he proposed some hypotheses. Darwin did not know that a contemporary, Gregor Mendel, had provided an important part of the solution. In his classic 1865 paper describing crossbreeding of varieties of peas, Mendel demonstrated that organisms acquire traits through discrete units of heredity which later came to be known as genes. The variation produced through these inherited traits is the raw material on which natural selection acts.

Mendel's paper was all but forgotten until 1890, when it was rediscovered and contributed to a growing wave of interest and research in genetics. But it was not immediately clear how to reconcile new findings about the mechanisms of inheritance with evolution through natural selection. Then, in the 1930s, a group of biologists demonstrated how the results of genetics research could both buttress and extend evolutionary theory. They showed that all variations, both slight and dramatic, arose through changes, or mutations, in genes. If a mutation enabled an organism to survive or reproduce more effectively, that mutation would tend to be preserved and spread in a population through natural selection. Evolution was thus seen to depend both on genetic mutations and on natural selection. Mutations provided abundant genetic variation, and natural selection sorted out the useful changes from the deleterious ones.

Selection by natural processes of favored variants explained many observations on the geography of species differences—why, for example, members of the same bird species might be larger and darker in the northern part of their range, and smaller and paler in the southern part. In this case, differences might be explained by the advantages of large size and dark coloration in forested, cold regions. And, if the species occupied the entire range continuously, genes favoring light color and small size would be able to flow into the northern population, and vice versa—prohibiting their separation into distinct species that are reproductively isolated from one another.

How new species are formed was a mystery that eluded biologists until information about genetics and the geographical distribution of animals and plants could be put together. As a result, it became clear that the most important source of new species is the process of geographical isolation—through which barriers to gene flow can be created. In the earlier example, the interposition of a major mountain barrier, or the origin of an intermediate desert, might create the needed isolation.

Other situations also encourage the formation of new species. Consider fish in a river that, over time, changes course so as to isolate a tributary. Or think of a set of oceanic islands, distant from the mainland and just far enough from one another that interchange among their populations is rare. These are ideal circumstances for creating reproductive barriers and allowing populations of the same species to diverge from one another under the influence of natural selection. After a time, the species become sufficiently different that even when reunited they remain reproductively isolated. They have become so different that they are unable to interbreed.

In the 1950s, the study of evolution entered a new phase. Biologists began to be able to determine the exact molecular structure of the proteins in living things—that is, the actual sequences of the amino acids that make up each protein. Almost immediately, it became clear that certain proteins that serve the same function in different species have very similar amino acid sequences. The protein evidence was completely consistent with the idea of a common evolutionary history for the planet's living things. Even more important, this knowledge provided important clues about the history of evolution that could not be obtained through the fossil record.

The discovery of the structure of DNA by Francis Crick and James Watson in 1953 extended the study of evolution to the most

fundamental level. The sequence of the chemical bases in DNA both specifies the order of amino acids in proteins and determines which proteins are synthesized in which cells. In this way, DNA is the ultimate source of both change and continuity in evolution. The modification of DNA through occasional changes or rearrangements in the base sequences underlies the emergence of new traits, and thus of new species, in evolution. At the same time, all organisms use the same molecular codes to translate DNA base sequences into protein amino acid sequences. This uniformity in the genetic code is powerful evidence for the interrelatedness of living things, suggesting that all organisms presently alive share a common ancestor that can be traced back to the origins of life on earth.

One common misconception among students is that individual organisms change their characteristics in response to the environment. In other words, students often think that the environment acts on individual organisms to generate physical characteristics that can then be passed on genetically to offspring. But selection can work only on the genetic variation that already is present in any new generation, and genetic variation occurs randomly, not in response

Discovery of a Missing Link

As a zoologist I have discovered many phenomena that can be rationally explained only as products of evolution, but none so striking as the ancestor of the ants. Prior to 1967 the fossil record had yielded no specimens of wasps or other *Hymenopterous*insects that might be interpreted as the ancestors of the ants. This hypothetical form was a missing link of major importance in the study of evolution. We did have many fossils of ants dating back 50 million years. These were different species from those existing today, but their bodies still possessed the basic body form of modern ants. The missing link of ant evolution was often cited by creationists as evidence against evolution. Other ant specialists and I were convinced that the linking fossils would be found, and that most likely they would be associated with the late Mesozoic era, a time when many dinosaur and other vertebrate bones were fossilized but few insects. And that is exactly what happened. In 1967 I had the pleasure of studying two specimens collected in amber (fossilized resin) from New Jersey, and dating to the late Mesozoic about 90 million years ago. They were nearly exact intermediates between solitary wasps and the highly

social modern ants, and so I gave them the scientific name *Sphecomyrma*, meaning "wasp ant." Since that time many more *Sphecomyrma* specimens of similar age have been found in the United States, Canada, and Siberia, but none belonging to the modern type. With each passing year, such fossils and other kinds of evidence tighten our conception of the evolutionary origin of this important group of insects.

—Edward O. Wilson

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to the needs of a population or organism. In this sense, as Francois Jacob has written, evolution is a "tinkerer, not an engineer."[2] Evolution does not design new organisms; rather, new organisms emerge from the inherent genetic variation that occurs in organisms.

Genetic variation is random, but natural selection is not. Natural selection tests the combinations of genes represented in the members of a species and allows to proliferate those that confer the greatest ability to survive and reproduce. In this sense, evolution is not the simple product of random chance.

The booklet *Science and Creationism: A View from the National Academy of Sciences*[3] summarizes several compelling lines of evidence that demonstrate beyond any reasonable doubt that evolution occurred as a historical process and continues today. In brief:

- Fossils found in rocks of increasing age attest to the interrelated lineage of living things, from the single-celled organisms that lived billions of years ago to *Homo sapiens*. The most recent fossils closely resemble the organisms alive today, whereas increasingly older fossils are progressively different, providing compelling evidence of change through time.
- Even a casual look at different kinds of organisms reveals striking similarities among species, and anatomists have discovered that these similarities are more than skin deep. All vertebrates, for example, from fish to humans, have a common body plan characterized by a segmented body and a hollow main nerve cord along the back. The best available scientific explanation for these common structures is that all vertebrates are descended from a common ancestor species and that they have diverged through evolution.
- In the past, evolutionary relationships could be studied only by examining the consequences of genetic information, such as the anatomy, physiology, and embryology of living organisms. But the advent of molecular biology has made it possible to read the history of evolution that

is written in every organism's DNA. This information has allowed organisms to be placed into a common evolutionary family tree in a much more detailed way than possible from previous evidence. For example, as described in Chapter 3, comparisons of the differences in DNA sequences among organisms provides evidence for many evolutionary events that cannot be found in the fossil record.

Evolution is the only plausible scientific explanation that accounts for the extensive array of observations summarized above. The concept of evolution through random genetic variation and natural selection makes sense of what would otherwise be a huge body of unconnected observations. It is no longer possible to sustain scientifically the view that the living things we see today did not evolve from earlier forms or that the human species was not produced by the same evolutionary mechanisms that apply to the rest of the living world.

The following two sections of this chapter examine two important themes in evolutionary theory. The first concerns the occurrence of evolution in "real time"—how changes come about and result in new kinds of species. The second is the ecological framework that underlies evolution, which is needed to understand the expansion of biological diversity.

Evolution as a Contemporary Process

Evolution by natural selection is not only a historical process—it still operates today. For example, the continual evolution

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The North American lacewing species *Chrysoperla carnea*and *Chrysoperla downesi* separated from a common ancestor species recently in evolutionary time and are very similar. But they are different in color, reflecting their different habitats, and they breed at different times of the year.

of human pathogens has come to pose one of the most serious public health problems now facing human societies. Many strains of bacteria have become increasingly resistant to once-effective antibiotics as natural selection has amplified resistant strains that arose through naturally occurring genetic variation. The microorganisms that cause malaria, gonorrhea, tuberculosis, and many other diseases have demonstrated greatly increased resistance to the antibiotics and other drugs used to treat them in the past. The continued use and overuse of antibiotics has had the effect of selecting for resistant populations because the antibiotics give these strains an advantage over nonresistant strains.[4]

Similar episodes of rapid evolution are occurring in many different organisms. Rats have developed resistance to the poison warfarin. Many hundreds of insect species and other agricultural pests have evolved resistance to the pesticides used to combat them—and even to chemical defenses genetically engineered into plants. Species of plants have evolved tolerance to toxic metals and have reduced their interbreeding with nearby nontolerant plants—an initial step in the formation of separate species. New species of plants have arisen through the crossbreeding of native plants with plants introduced from elsewhere in the world.

The creation of a new species from a pre-existing species generally requires

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Modern whales evolved from a primitive group of hoofed mammals into species that were progressively more adapted to life in the water.

thousands of years, so over a lifetime a single human usually can witness only a tiny part of the speciation process. Yet even that glimpse of evolution at work powerfully confirms our ideas about the history and mechanisms of evolution. For example, many closely related species have been identified that split from a common ancestor very recently in evolutionary terms. An example is provided by the North American lacewings *Chrysoperla carnea* and *Chrysoperla downesi*. The former lives in deciduous woodlands and is pale green in summer and brown in winter. The latter lives among evergreen conifers and is dark green all year round. The two species are genetically and morphologically very similar. Yet they occupy different habitats and breed at different times of the year and so are reproductively isolated from each other.

The fossil record also sheds light on speciation. A particularly dramatic example comes from recently discovered fossil evidence documenting the evolution of whales and dolphins. The fossil record shows that these cetaceans evolved from a primitive group of hoofed mammals called *Mesonychids*. Some of these mammals crushed and ate turtles, as evidenced by the shape of their teeth. This mammal gave rise to a species with front forelimbs and powerful hind legs with large feet that were adapted for paddling. This animal, known as *Ambulocetus* , could have moved between sea and land. Its fossilized vertebrae also show that this animal could move its back in a strong up and down motion, which is the method modern cetaceans use to swim and dive. A later fossil in the series from Pakistan shows an animal with smaller functional hind limbs and even greater back flexibility. This species, *Rodhocetus*, probably did not venture onto land very often, if at all. Finally, *Basilosaurus* fossils from Egypt and the United States present a recognizable whale, with front flippers for steering and a completely flexible backbone. But this animal still has hind limbs (thought to have been nonfunctional),

Ongoing Evolution Among Darwin's Finches

A particularly interesting example of contemporary evolution involves the 13 species of finches studied by Darwin on the Galapagos Islands, now known as Darwin's finches. A research group led by Peter and Rosemary Grant of Princeton University has shown that a single year of drought on the islands can drive evolutionary changes in the finches.[6] Drought diminishes supplies of easily cracked nuts but permits the survival of plants that produce larger, tougher nuts. Drought thus favors birds with strong, wide beaks that can break these tougher seeds, producing populations of birds with these traits. The Grants have estimated that if droughts occur about once every 10 years on the islands, a new species of finch might arise in only about 200 years.[7]

which have become further reduced in modern whales.[5]

Another focus of research has been the evolution of ancient apelike creatures through many intermediate forms into modern humans. *Homo sapiens*, one of 185 known living species in the primate order, is a member of the hominoids, a category that includes orangutans, gorillas, and chimpanzees. The succession of species that would give rise to humans seems to have separated from the succession that would lead to the apes about 5 to 8 million years ago. The first members of our genus, *Homo*, had evolved by about 1.5 million years ago. According to recent evidence—based on the sequencing of DNA found in a part of human cells known as mitochondria—it has been proposed that a small group of modern humans evolved in Africa about 150,000 years ago and spread throughout the world, replacing archaic populations of *Homo sapiens*.

Evolution and Ecology

Animals and plants do not live in isolation, nor do they evolve in isolation. Indeed, much of the pressure toward diversification comes not only from physical factors in the environment but from the presence of other species. Any animal is a potential host for parasites or prey for a carnivore. A plant has other plants as competitors for space and light, can be a host for parasites, and provides food for herbivores. The interactions within the complex communities, or ecosystems, in which organisms live can generate powerful evolutionary forces.

Evolution in natural communities arises from both constraints and opportunities. The constraints come from competitors, primarily among the same species. There are only so many nest holes for bluebirds and so much food for mice. Genetically different individuals that are able to move to a different resource—a new food supply, for example, or a hitherto uninhabited area—are

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Early hominids had smaller brains and larger faces than species belonging to the genus *Homo*, including our own species, *Homo sapiens*. White parts of the skulls are reconstructions, and the skulls are not all on the same scale.

able to exploit that resource free of competition. As a result, the trait that opened up the new opportunity will be favored by natural selection because the individuals possessing it are able to survive and reproduce better than other members of their species in the new environment.

An ecologist would say that the variant had occupied a new niche—a term that defines the "job description" of an organism. (For example, a bluebird would have the niche of insect- and fruit-eater, inhabitant of forest edges and meadows, tree-hole nester, and so on.) One often finds closely related species in the same place and occupying what look like identical niches. However, if the niches were truly identical, one of the species should have a competitive advantage over the other and eventually drive the less fit species to extinction or to a different niche. That leads to a tentative hypothesis: where we find such a situation, careful observation should reveal subtle niche specialization of the apparently competing species.

This hypothesis has been tested by many biologists. For example, in the 1960s Robert MacArthur carefully studied three North American warblers of the same genus that were regularly seen feeding on insects in coniferous trees in the same areas—indeed, often in the same trees. MacArthur's painstaking observations revealed that the three were actually specialists: one fed on insects on the major branches near the trunk; another occupied the mid-regions of branches and ate from different parts of the foliage; and the third fed on insects occupying the finest needles near the periphery of the tree. Although the three warblers occurred together, they were in fact not competitors for the same food resources.

Often, species that are evolving together in the same ecosystem do so through a highly interactive process. For example, natural selection will favor organisms with defenses against predation; in turn, predators experience selection for traits that overcome those defenses. Such coevolutionary competitions are common in nature. Many

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A Chemical Distress Signal

J. H. Tumlinson and colleagues at the U.S. Department of Agriculture's Research Service Laboratories in Gainesville, Florida, have explored a fascinating case that illustrates the intricacy of many ecological relationships. Cotton plants, like many other crops, are attacked by caterpillars. One destructive cotton pest, the army worm, produces a complex series of reactions when it feeds on the plant—a reaction that involves the caterpillar itself, the tissues of the plant, and a third participant, a wasp that preys on the caterpillar. When the caterpillar chews on the cotton plant leaf, a reaction occurs that causes the plant to synthesize and release a class of volatile chemicals that escape into the air and travel rapidly downwind. The chemicals are detected by wasps, who follow the scent

and are able to find the caterpillars and deposit eggs within them. The eggs hatch, and the wasp larvae destroy the caterpillar.[8]

This complex case of "chemical ecology" required a series of linked coevolutionary events: the response of the plant to a special signal from its predator, and the response of the wasp to a special signal from the host of its prey.

plants manufacture and store chemicals that deter herbivorous insects; but usually one or more insect species will have evolved biochemical mechanisms for inactivating the deterrent, providing them with a plant they can eat relatively free of competitors.

Another classic example of coevolution involves the introduction of rabbits and the myxomatosis virus into Australia. After rabbits were brought to Australia, they multiplied rapidly and threatened the wool industry because they grazed on the same plants as sheep. To control the rabbit population, a virulent pathogen of rabbits, the myxomatosis virus, also was introduced into Australia. Within a decade, rabbits had become more resistant to the virus, and the virus had evolved into a less virulent form, allowing both the host and pathogen to coexist.[9]

Conclusion

As the examples in this chapter demonstrate, evolutionary biology provides an extremely active and rich source of new insights into the world. By exploring the history of life on earth and shedding light on how evolution works, evolutionary biology is linking fundamental scientific research to knowledge needed to meet important societal needs, including the preservation of our environment. Few other ideas in science have had such a far-reaching impact on our thinking about ourselves and how we relate to the world.

NOTES

1. Biological Sciences Curriculum Study. 1978. *Biology Teachers' Handbook*. 3rd ed. William V. Mayer, ed. New York: John Wiley and Sons.
2. Francois Jacob. June 10, 1977. Evolution and tinkering. *Science* 196:1161-1166.
3. National Academy of Sciences. (in press). *Science and Creationism: A View from the National Academy of Sciences*. Washington, DC: National Academy Press. (See www.nap.edu)
4. P. Ewald. 1994. *The Evolution of Infectious Disease*. New York: Oxford University Press.
5. "Evolution, Science, and Society: A White Paper on Behalf of the Field of Evolutionary Biology," Draft, June 4, 1997.
6. Jonathan Weiner. 1994. *The Beak of the Finch*. New York: Alfred A. Knopf.
7. Peter R. Grant. 1991. Natural selection and Darwin's finches. *Scientific American*, October, pp. 82-87.
8. James H. Tumlinson, W. Joe Lewis, and Louise E. M. Vet. 1993. How parasitic wasps find their hosts. *Scientific American*, March, pp. 100-106.
9. F. Fenner and F.N. Ratcliffe. 1965. *Myxomatosis*. Cambridge: Cambridge University Press.