# Evolution vs. Creationism

## *An Introduction*

Second Edition

EUGENIE C. SCOTT

FOREWORD BY NILES ELDREDGE

FOREWORD TO SECOND EDITION BY JUDGE JOHN E. JONES III

GREENWOOD PRESS
Westport, Connecticut • London

Library of Congress Cataloging-in-Publication Data

Scott, Eugenie Carol, 1945–
  Evolution vs. creationism : an introduction / Eugenie C. Scott; foreword by Niles Eldredge ; foreword to second edition by Judge John E. Jones III. — 2nd ed.
    p. cm.
  Includes bibliographical references and index.
  ISBN 978–0–313–34427–5 (alk. paper)
  1. Evolution (Biology) 2. Creationism. I. Title.
  QH367.S395 2009
  576.8—dc22 2008033529

British Library Cataloguing in Publication Data is available.

Library of Congress Catalog Card Number: 2008033529
ISBN: 978–0–313–34427–5

First published in 2009

Greenwood Press, 88 Post Road West, Westport, CT 06881
An imprint of Greenwood Publishing Group, Inc.
www.greenwood.com

Printed in the United States of America

The paper used in this book complies with the
Permanent Paper Standard issued by the National
Information Standards Organization (Z39.48–1984).

10 9 8 7 6 5 4 3 2 1

## CHAPTER 1

# Science: Truth without Certainty

We live in a universe made up of matter and energy, a material universe. To understand and explain this material universe is the goal of science, which is a methodology as well as a body of knowledge obtained through that methodology. Science is limited to matter and energy, but as will become clear when we discuss religion, most individuals believe that reality includes something other than matter and energy. The methodology of science is a topic on which any college library has dozens of feet of shelves of books and journals, so obviously just one chapter won't go much beyond sketching out the bare essentials. Still, I will try to show how science differs from many other ways of knowing and how it is particularly well suited to explaining our material universe.

## WAYS OF KNOWING

Science requires the testing of explanations of the natural world against nature itself and the discarding of those explanations that do not work. What distinguishes science from other ways of knowing is its reliance upon the natural world as the arbiter of truth. There are many things that people are interested in, are concerned about, or want to know about that science does not address. Whether the music of Madonna or Mozart is superior may be of interest (especially to parents of teenagers), but it is not something that science addresses. Aesthetics is clearly something outside of science. Similarly, literature or music might generate or help to understand or cope with emotions and feelings in a way that science is not equipped to do. But if one wishes to know about the natural world and how it works, science is superior to other ways of knowing. Let's consider some other ways of knowing about the natural world.

### Authority

Dr. Jones says, "Male lions taking over a pride will kill young cubs." Should you believe her? You might know that Dr. Jones is a famous specialist in lion behavior who has studied lions for twenty years in the field. Authority leads one to believe that Dr. Jones's statement is true. In a public bathroom, I once saw a little girl of perhaps four or five years old marvel at faucets that automatically turned on when hands were placed below the spigot. She asked her mother, "Why does the water come out, Mommy?" Her mother answered brightly, if unhelpfully, "It's magic, dear!" When we are small, we rely on the authority of our parents and other older people, but authority clearly can mislead us, as in the case of the magic spigots. And Dr. Jones might be wrong about lion infanticide, even if in the past she has made statements about animal behavior that have been reliable. Yet it is not "wrong" to take some things on authority. In northern California, a popular bumper sticker reads Question Authority. Whenever I see one of these, I am tempted to pencil in "but stop at stop signs." We all accept some things on authority, but we should do so critically.

### Revelation

Sometimes people believe a statement because they are told it comes from a source that is unquestionable: from God, or the gods, or some other supernatural power. Seekers of advice from the Greek oracle at Delphi believed what they were told because they believed that the oracle received information directly from Apollo; similarly, Muslims believe the contents of the Koran were revealed to Muhammad by God; and Christians believe the New Testament is true because the authors were directly inspired by God. A problem with revealed truth, however, is that one must accept the worldview of the speaker in order to accept the statement; there is no outside referent. If you don't believe in Apollo, you're not going to trust the Delphic oracle's pronouncements; if you're not a Mormon or a Catholic, you are not likely to believe that God speaks directly to the Mormon president or the pope. Information obtained through revelation is difficult to verify because there is not an outside referent that all parties are likely to agree upon.

### Logic

A way of knowing that is highly reliable is logic, which is the foundation for mathematics. Among other things, logic presents rules for how to tell whether something is true or false, and it is extremely useful. However, logic in and of itself, with no reference to the real world, is not complete. It is logically correct to say, "All cows are brown. Bossy is not brown. Therefore Bossy is not a cow." The problem with the statement is the truth of the premise that all cows are brown, when many are not. To know that the proposition about cows is empirically wrong even if logically true requires reference to the real world outside the logical structure of the three sentences. To say, "All wood has carbon atoms. My computer chip has no carbon atoms. Therefore my computer chip is not made of wood" is both logically and empirically true.

### Science

Science does include logic—statements that are not logically true cannot be scientifically true—but what distinguishes the scientific way of knowing is the requirement of going to nature to verify claims. Statements about the natural world are tested against the natural world, which is the final arbiter. Of course, this approach is not perfect: one's information about the natural world comes from experiencing the natural world through the senses (touch, smell, taste, vision, hearing) and instrumental extensions of these senses (e.g., microscopes, telescopes, telemetry, chemical analysis), any of which can be faulty or incomplete. As a result, science, more than any of the other ways of knowing described here, is more tentative in its claims. Ironically, the tentativeness of science ultimately leads to more confidence in scientific understanding: the willingness to change one's explanation with more or better data, or a different way of looking at the same data, is one of the great strengths of the scientific method. The anthropologist Ashley Montagu summarized science rather nicely when he wrote, "The scientist believes in proof without certainty, the bigot in certainty without proof" (Montagu 1984: 9).

Thus science requires deciding among alternative explanations of the natural world by going to the natural world itself to test them. There are many ways of testing an explanation, but virtually all of them involve the idea of holding constant some factors that might influence the explanation so that some alternative explanations can be eliminated. The most familiar kind of test is the direct experiment, which is so familiar that it is even used to sell us products on television.

## DIRECT EXPERIMENTATION

Does RealClean detergent make your clothes cleaner? The smiling company representative in the television commercial takes two identical shirts, pours something messy on each one, and drops them into identical washing machines. RealClean brand detergent goes into one machine and the recommended amount of a rival brand into the other. Each washing machine is set to the same cycle, for the same period of time, and the ad fast-forwards to show the continuously smiling representative taking the two shirts out. Guess which one is cleaner.

Now, it would be very easy to rig the demonstration so that RealClean does a better job: the representative could use less of the other detergent, use an inferior-performing washing machine, put the RealClean shirt on a soak cycle forty-five minutes longer than for the other brand, employ different temperatures, wash the competitor's shirt on the delicate rather than regular cycle—I'm sure you can think of a lot of ways that RealClean's manufacturer could ensure that its product comes out ahead. It would be a bad sales technique, however, because we're familiar with the direct experimental type of test, and someone would very quickly call, "Foul!" To convince you that they have a better product, the makers of the commercial have to remove every factor that might possibly explain why the shirt came out cleaner when washed in their product. They have to hold constant or control all these other factors—type of machine, length of cycle, temperature of the water, and so on—so that the only reasonable explanation for the cleaner shirt is that RealClean is a better product. The experimental method—performed fairly—is a very good way to persuade people that your explanation is correct. In science, too, someone will call, "Foul!" (or at least, "You blew it!") if a test doesn't consider other relevant factors.

Direct experimentation is a very powerful—as well as familiar—research design. As a result, some people think that this is the only way that science works. Actually, what matters in science is that explanations be tested, and direct experimentation is only one kind of testing. The key element to testing an explanation is to hold variables constant, and one can hold variables constant in many ways other than being able to directly manipulate them (as one can manipulate water temperature in a washing machine). In fact, the more complicated the science, the less likely an experimenter is to use direct experimentation.

In some tests, variables are controlled statistically; in others, especially in biological field research or in social sciences, one can find circumstances in which important variables are controlled by the nature of the experimental situation itself. These observational research designs are another type of direct experimentation.

Noticing that male guppies are brightly colored and smaller than the drab females, you might wonder whether having bright colors makes male guppies easier prey. How would you test this idea? If conditions allowed, you might be able to perform a direct experiment by moving brightly colored guppies to a high-predation environment and monitoring them over several generations to see how they do. If not, though, you could still perform an observational experiment by looking for natural populations of the same or related species of guppies in environments where predation was high and in other environments where predation was low. You would also want to pick environments where the amount of food was roughly the same—can you explain why? What other environmental factors would you want to hold constant at both sites?

When you find guppy habitats that naturally vary only in the amount of predation and not in other ways, then you're ready to compare the brightness of color in the males. Does the color of male guppies differ in the two environments? If males were less brightly colored in environments with high predation, this would support the idea that brighter guppy color makes males easier prey. (What if in the two kinds of environments, male guppy color is the same?)

Indirect experimentation is used for scientific problems where the phenomena being studied—unlike color in guppies—cannot be directly observed.

## INDIRECT EXPERIMENTATION

In some fields, not only is it impossible to directly control variables but also the phenomena themselves may not be directly observable. A research design known as indirect experimentation is often used in such fields. Explanations can be tested even if the phenomena being studied are too far away, too small, or too far back in time to be observed directly. For example, giant planets recently have been discovered orbiting distant stars—though we cannot directly observe them. Their presence is indicated by the gravitational effects they have on the suns around which they revolve: because of what we know about how the theory of gravitation works, we can infer that the passage of a big planet around a sun will make the sun wobble. Through the application of principles and laws in which we have confidence, it is possible to infer that these planetary giants do exist and to make estimates of their size and speed of revolution.

Similarly, the subatomic particles that physicists study are too small to be observed directly, but particle physicists certainly are able to test their explanations. By applying knowledge about how particles behave, they are able to create indirect experiments to test claims about the nature of particles. Let's say that a physicist wants to ascertain properties of a particle—its mass, charge, or speed. On the basis of observations of similar particles, he makes an informed estimate of the speed. To test the estimate, he might bombard it with another particle of known mass, because if the unknown particle has a mass of $m$, it will cause the known particle to ricochet at velocity $v$. If the known particle does ricochet as predicted, this would support the hypothesis about the mass of the unknown particle. Thus, theory is built piece by piece, through inference based on accepted principles.

In truth, most scientific problems are of this if-then type, whether or not the phenomena investigated are directly observable. If male guppy color is related to predation, then we should see duller males in high-predation environments. If a new drug stimulates the immune system, then individuals taking it should have fewer colds than the controls do. If human hunters were involved in the destruction of large Australian land mammals, we should see extinction events that correlate with the appearance of the first Aborigines. We test by consequence in science all the time. Of course—because scientific problems are never solved so simply—if we get the consequence we predict, this does not mean we have proved our explanation. If you found that guppy color does vary in environments where predation differs, this does not mean you've proved yourself right about the relationship between color and predation. To understand why, we need to consider what we mean by proof and disproof in science.

## PROOF AND DISPROOF

### Proof

Scientists don't usually talk about proving themselves right, because *proof* suggests certainty (remember Ashley Montagu's truth without certainty!). The testing of explanations is in reality a lot messier than the simplistic descriptions given previously. One can rarely be sure that all the possible factors that might explain why a test produced a positive result have been considered. In the guppy case, for example, let's say that you found two habitats that differed in the number of predators but were the same in terms of amount of food, water temperature, and number and type of hiding places—you tried to hold constant as many factors as you could think of. If you find that guppies are less colorful in the high-predation environment, you might think you have made the link, but some other scientist may come along and discover that your two environments differ in water turbidity. If turbidity affects predation—or the ability of female guppies to select the more colorful males—this scientist can claim that you were premature to conclude that color is associated with predation. In science we rarely claim to prove a theory—but positive results allow us to claim that we are likely to be on the right track. And then you or some other scientist can go out and test some more. Eventually we may achieve a consensus about guppy color being related to predation, but we wouldn't conclude this after one or a few tests. This back-and-forth testing of explanations provides a reliable understanding of nature, but the procedure is neither formulaic nor especially tidy over the short run. Sometimes it's a matter of two steps forward, a step to the side (maybe down a blind alley), half a step back—but gradually the procedure, and with it human knowledge, lurches forward, leaving us with a clearer knowledge of the natural world and how it works.

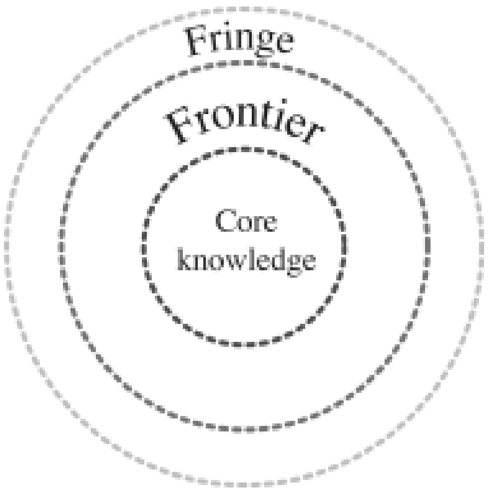
In addition, most tests of anything other than the most trivial of scientific claims result not in slam-dunk, now-I've-nailed-it, put-it-on-the-T-shirt conclusions, but rather in more or less tentative statements: a statement is weakly, moderately, or strongly supported, depending on the quality and completeness of the test. Scientific claims become accepted or rejected depending on how confident the scientific community is about whether the experimental results could have occurred that way just by chance—which is why statistical analysis is such an important part of most scientific tests. Animal behaviorists note that some social species share care of their offspring. Does this make a difference in the survival of the young? Some female African silver-backed jackals, for example, don't breed in a given season but help to feed and guard the offspring of a breeding adult. If the helper phenomenon is directly related to pup survival, then more pups should survive in families with a helper.

One study tested this claim by comparing the reproductive success of jackal packs with and without helpers, and found that for every extra helper a mother jackal had, she successfully raised one extra pup per litter over the average survival rate (Hrdy 2001). These results might encourage you to accept the claim that helpers contribute to the survival of young, but only one test on one population is not going to be convincing. Other tests on other groups of jackals would have to be conducted to confirm the results, and to be able to generalize to other species the principle that reproductive success is improved by having a helper would require conducting tests on other social species. Such studies in fact have been performed across a wide range of birds and mammals, and a consensus is emerging about the basic idea of helpers increasing survivability of the young. But there are many remaining questions, such as whether a genetic relationship always exists between the helper and either the offspring or the helped mother.

Science is quintessentially an open-ended procedure in which ideas are constantly tested and rejected or modified. Dogma—an idea held by belief or faith—is anathema to science. A friend of mine once was asked to explain how he ended up a scientist. His tongue-in-cheek answer illustrates rather nicely the nondogmatic nature of science: "As an adolescent I aspired to lasting fame, I craved factual certainty, and I thirsted for a meaningful vision of human life—so I became a scientist. This is like becoming an archbishop so you can meet girls" (Cartmill 1988: 452).

In principle, all scientific ideas may change, though in reality there are some scientific claims that are held with confidence, even if details may be modified. The physicist James Trefil (1978) suggested that scientific claims can be conceived of as arranged in a series of three concentric circles (see Figure 1.1). In the center circle are the core ideas of science: the theories and facts in which we have great confidence because they work so well to explain nature. Heliocentrism, gravitation, atomic theory, and evolution are examples. The next concentric circle outward is the frontier area of science, where research and debate are actively taking place on new theories or modifications and additions to core theories. Clearly no one is arguing with the basic principle of heliocentrism, but on the frontier, planetary astronomers still are learning things and testing ideas about the solar system. That matter is composed of atoms is not being challenged, but the discoveries of quantum physics are adding to and modifying atomic theory.

Figure 1.1
Scientific concepts and theories can be arranged as a set of nested categories with core ideas at the center, frontier ideas surrounding them, and fringe ideas at the edge (after Trefil 1978). Courtesy of Alan Gishlick.



The outermost circle is the fringe, a breeding ground for ideas that very few professional scientists are spending time on: unidentified flying objects, telepathy and the like, perpetual motion machines, and so on. Generally the fringe is not a source of new ideas for the frontier, but occasionally (very occasionally!) ideas on the fringe will muster enough support to warrant a closer look and will move into the frontier. They may well be rejected and end up back in the fringe or be discarded completely, but occasionally they may become accepted and perhaps eventually become core ideas of science. That the continents move began as a fringe idea, then it moved to the frontier as data began to accumulate in its favor, and finally it became a core idea of geology when seafloor spreading was discovered and the theory of plate tectonics was developed.

Indeed, we must be prepared to realize that even core ideas may be wrong, and that somewhere, sometime, there may be a set of circumstances that could refute even our most confidently held theory. But for practical purposes, one needn't fall into a slough of despond over the relative tentativeness of scientific explanation. That the theory of gravitation may be modified or supplemented sometime in the future is no reason to give up riding elevators (or, even less advisedly, to jump off the roof). Science gives us reliable, dependable, and workable explanations of the natural world—even if it is good philosophy of science to keep in mind that in principle anything can change.

On the other hand, even if it is usually not possible absolutely to prove a scientific explanation correct—there might always be some set of circumstances or observations somewhere in the universe that would show your explanation wrong—to disprove a scientific explanation is possible. If you hypothesize that it is raining outside, and walk out the door to find the sun is shining and the ground is dry, you have indeed disproved your hypothesis (assuming you are not hallucinating). So disproving an explanation is easier than proving one true, and, in fact, progress in scientific explanation has largely come by rejecting alternative explanations. The ones that haven't been disconfirmed yet are the ones we work with—and some of those we feel very confident about.

## Disproof

Now, if you are a scientist, obviously you will collect observations that support your explanation, but others are not likely to be persuaded just by a list of confirmations. Like proving RealClean detergent washes clothes best, it's easy to find—or concoct—circumstances that favor your view, which is why you have to bend over backward in setting up your test so that it is fair. So you set the temperature on both washing machines to be the same, you use the same volume of water, you use the recommended amount of detergent, and so forth. In the guppy case, you want to hold constant the amount of food in high-predation environments and low-predation environments, and so on. If you are wrong about the ability of RealClean to get the stains out, there won't be any difference between the two loads of clothes, because you have controlled or held constant all the other factors that might explain why one load of clothes emerged with fewer stains. You will have disproved your hypothesis about the allegedly superior stain-cleaning qualities of RealClean. You are conducting a fair test of your hypothesis if you set up the test so that everything that might give your hypothesis an advantage has been excluded. If you don't, another scientist will very quickly point out your error, so it's better to do it yourself and save yourself the embarrassment!

What makes science challenging—and sometimes the most difficult part of a scientific investigation—is coming up with a testable statement. Is the African AIDS epidemic the result of tainted oral polio vaccine (OPV) administered to Congolese in the 1950s? Chimpanzees carry simian immunodeficiency virus, which researchers believe is the source of the AIDS-causing virus HIV (human immunodeficiency virus). Poliovirus is grown on chimp kidney culture or monkey kidney culture. Was a batch of OPV grown on kidneys from chimps infected with simian immunodeficiency virus the source of African AIDS? If chimpanzee DNA could be found in the fifty-year-old vaccine, that would strongly support the hypothesis. If careful analysis did not find chimpanzee DNA, that would fail to support the hypothesis, and you would have less confidence in it. Such a test was conducted, and after very careful analysis, no chimp DNA was found in samples of the old vaccine. Instead, macaque monkey DNA was found (Poinar, Kuch, and Pääbo 2001).

The study by Poinar and colleagues did not disprove the hypothesis that African AIDS was caused by tainted OPV (perhaps some unknown batch of OPV is the culprit), but it is strong evidence against it. Again, as in most science, we are dealing with probabilities: if all four batches of OPV sent to Africa in the 1950s were prepared in the same manner, at the same time, and in the same laboratory, what is the probability that one would be completely free of chimp DNA and one or more other samples would be tainted? Low, presumably, but because the probability is not 0 percent, we cannot say for certain that the OPV-AIDS link is out of the question. However, we have research from other laboratories on other samples, and they also were unable to find any chimpanzee genes in the vaccine (Weiss 2001). Part of science is to repeat tests of the hypothesis, and when such repeated tests confirm the conclusions of early tests, it greatly increases confidence in the answers. Because the positive evidence for this hypothesis for the origin of AIDS was thin to begin with, few people now are taking the hypothesis seriously. Both disproof of hypotheses and failure to confirm are critical means by which we eliminate explanations and therefore increase our understanding of the natural world.

Now, you might notice that although I have not defined them, I already have used two scientific terms in this discussion: **theory** and **hypothesis**. You may already know what these terms mean—probably everyone has heard that evolution is "just a theory," and many times you have probably said to someone with whom you disagree, "Well, that's just a hypothesis." You might be surprised to hear that scientists don't use these terms in these ways.

## FACTS, HYPOTHESES, LAWS, AND THEORIES

How do you think scientists would rank the terms **fact**, **hypothesis**, **law**, and **theory**? How would you list these four from most important to least? Most people list facts on top, as the most important, followed by laws, then theories, and then hypotheses as least important at the bottom:

***Most important***
Facts
Laws
Theories
Hypotheses
***Least important***

You may be surprised that scientists rearrange this list, as follows:

***Most important***
Theories
Laws
Hypotheses
Facts
***Least important***

Why is there this difference? Clearly, scientists must have different definitions of these terms compared to how we use them on the street. Let's start with facts.

### Facts

If someone said to you, "List five scientific facts," you could probably do so with little difficulty. Living things are composed of cells. Gravity causes things to fall. The speed of light is about 186,000 miles/second. Continents move across the surface of

Earth. Earth revolves around the sun—and so on. Scientific facts, most people think, are claims that are rock solid, about which scientists will never change their minds. Most people think that facts are just about the most important part of science, and that the job of the scientist is to collect more and more facts.

Actually, facts are useful and important, but they are far from being the most important elements of a scientific explanation. In science, facts are confirmed observations. When the same result is obtained after numerous observations, scientists will accept something as a fact and no longer continue to test it. If you hold up a pencil between your thumb and forefinger, and then stop supporting it, it will fall to the floor. All of us have experienced unsupported objects falling; we've leaped to catch the table lamp as a toddler accidentally pulls the lamp cord. We consider it a fact that unsupported objects fall. It is always possible, however, that some circumstance may arise when a fact is shown not to be correct. If you were holding that pencil while orbiting Earth on the space shuttle and then let it go, it would not fall (it would float). It also would not fall if you were on an elevator with a broken cable that was hurtling at 9.8 meters/second$^2$ toward the bottom of a skyscraper—but let's not dwell on that scenario. So technically, unsupported objects don't always fall, but the rule holds well enough for ordinary use. One is not frequently on either the space shuttle or a runaway elevator, or in other circumstances in which the confirmed observation of unsupported items falling will not hold. It would in fact be perverse for one to reject the conclusion that unsupported objects fall just because of the existence of helium balloons.

Other scientific facts (i.e., confirmed observations) have been shown not to be true. Before better cell-staining techniques revealed that humans have twenty-three pairs of chromosomes, it was thought that we had twenty-four pairs. A fact has changed, in this case with more accurate means of measurement. At one point, we had confirmed observations of twenty-four chromosome pairs, but now there are more confirmations of twenty-three pairs, so we accept the latter—although at different times, both were considered facts. Another example of something considered a fact—an observation—was that the continents of Earth were stationary, which anyone can see! With better measurement techniques, including using observations from satellites, it is clear that continents do move, albeit very slowly (only a few inches each year).

So facts are important but not immutable; they can change. An observation, though, doesn't tell you very much about how something works. It's a first step toward knowledge, but by itself it doesn't get you very far, which is why scientists put it at the bottom of the hierarchy of explanation.

## Hypotheses

Hypotheses are statements of the relationships among things, often taking the form of if-then statements. If brightly colored male guppies are more likely to attract predators, then in environments with high predation, guppies will be less brightly colored. If levels of lead in the bloodstream of children is inversely associated with IQ scores, then children in environments with greater amounts of lead should have lower IQ scores. Elephant groups are led by matriarchs, the eldest females. If the age (and thus experience) of the matriarch is important for the survival of the group, then groups with younger matriarchs will have higher infant mortality than those led by older ones. Each of these hypotheses is directly testable and can be either disconfirmed or confirmed (note that hypotheses are not proved "right"—any more than any scientific explanation is proved). Hypotheses are very important in the development of scientific explanations. Whether rejected or confirmed, tested hypotheses help to build explanations by removing incorrect approaches and encouraging the further testing of fruitful ones. Much hypothesis testing in science depends on demonstrating that a result found in a comparison occurs more or less frequently than would be the case if only chance were operating; statistics and probability are important components of scientific hypothesis testing.

## Laws

There are many laws in science (e.g., the laws of thermodynamics, Mendel's laws of heredity, Newton's inverse square law, the Hardy-Weinberg law). Laws are extremely useful empirical generalizations: they state what will happen under certain conditions. During cell division, under Mendel's law of independent assortment, we expect genes to act like particles and separate independently of one another. Under conditions found in most places on Earth's surface, masses will attract one another in inverse proportion to the square of the distance between them, following the inverse square law. If a population of organisms is larger than a certain size, is not undergoing natural selection, and has random mating, the frequency of genotypes of a two-gene system will be in the proportion $p2 + 2pq + q2$. This relationship is called the Hardy-Weinberg law.

Outside of science, we also use the term law. It is the law that everyone must stop for a stoplight. Laws are uniform and, in that they apply to everyone in the society, universal. We don't usually think of laws changing, but of course they do: the legal system has a history, and we can see that the legal code used in the United States has evolved over several centuries primarily from legal codes in England. Still, laws must be relatively stable or people would not be able to conduct business or know which practices or behaviors will get them in trouble. One will not anticipate that if today everyone drives on the right side of the street, tomorrow everyone will begin driving on the left. Perhaps because of the stability of societal laws, we tend to think of scientific laws as also stable and unchanging.

However, scientific laws can change or not hold under some conditions. Mendel's law of independent assortment tells us that the hereditary particles will behave independently as they are passed down from generation to generation. For example, the color of a pea flower is passed on independently from the trait for stem length. But after more study, geneticists found that the law of independent assortment can be "broken" if the genes are very closely associated on the same chromosome. So minimally, this law had to be modified in terms of new information—which is standard behavior in science. Some laws will not hold if certain conditions are changed. Laws, then, can change just as facts can.

Laws are important, but as descriptive generalizations, they rarely explain natural phenomena. That is the role of the final stage in the hierarchy of explanation: theory. Theories explain laws and facts. Theories therefore are more important than laws and facts, and thus scientists place them at the top of the hierarchy of explanation.

### Theories

The word **theory** is perhaps the most misunderstood word in science. In everyday usage, the synonym of theory is **guess** or **hunch**. Yet according to the National Academy of Sciences (2008: 11), "The formal scientific definition of theory is quite different from the everyday meaning of the word. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence." A theory, then, is an explanation rather than a guess. Many high school (and even, unfortunately, some college) textbooks describe theories as tested hypotheses, as if a hypothesis that is confirmed is somehow promoted to a theory, and a really, really good theory gets crowned as a law. But rather than being inferior to facts and laws, a scientific theory incorporates "facts, laws, inferences, and tested hypotheses" (National Academy of Sciences 1998: 7). Theories explain laws! To explain something scientifically requires an interconnected combination of laws, tested hypotheses, and other theories.

## EVOLUTION AND TESTING

What about the theory of evolution? Is it scientific? Some have claimed that because no one was present millions of years ago to see evolution occur, evolution is not a scientific field. Yet we can study evolution in a laboratory even if no one was present to see zebras and horses emerge from a common ancestor. A theory can be scientific even if its phenomena are not directly observable. Evolutionary theory is built in the same way that theory is built in particle physics or any other field that uses indirect testing—and some aspects of evolutionary theory can be directly tested. I will devote chapter 2 to discussing evolution in detail, but let me concentrate here on the question of whether it is testable—and especially whether evolution is falsifiable.

The big idea of biological evolution (as will be discussed more fully in the next chapter) is descent with modification. Evolution is a statement about history and refers to something that happened, to the branching of species through time from common ancestors. The pattern that this branching takes and the mechanisms that bring it about are other components of evolution. We can therefore look at the testing of evolution in three senses: Can the big idea of evolution (descent with modification, common ancestry) be tested? Can the pattern of evolution be tested? Can the mechanisms of evolution be tested?

### Testing the Big Idea

Hypotheses about evolutionary phenomena are tested just like hypotheses about other scientific topics: the trick (as in most science!) is to figure out how to formulate your question so it can be tested. The big idea of evolution, that living things have shared common ancestors, can be tested using the if-then approach—testing by consequences—that all scientists use. The biologist John A. Moore suggested a number of these if-then statements that could be used to test whether evolution occurred:

1. If living things descended with modification from common ancestors, then we would expect that "species that lived in the remote past must be different from the species alive today" (Moore 1984: 486). When we look at the geological record, this is indeed what we see.

There are a few standout species that seem to have changed very little over hundreds of millions of years, but the rule is that the farther back in time one looks, the more creatures differ from present forms.

2. If evolution occurred, we "would expect to find only the simplest organisms in the very oldest fossiliferous [fossil-containing] strata and the more complex ones to appear in more recent strata" (Moore 1984: 486). Again going to the fossil record, we find that this is true. In the oldest strata, we find single-celled organisms, then simple multicelled organisms, and then simple versions of more complex invertebrate multicelled organisms (during the early Cambrian period). In later strata, we see the invasion of the land by simple plants, and then the evolution of complex seed-bearing plants, and then the development of the land vertebrates.
3. If evolution occurred, then "there should have been connecting forms between the major groups (phyla, classes, orders)" (Moore 1984: 489). To test this requires going again to the fossil record, but matters are complicated by the fact that not all connecting forms have the same probability of being preserved. For example, connecting forms between the very earliest invertebrate groups are less likely to be found because of their soft bodies, which do not preserve as well as hard body parts such as shells and bones, which can be fossilized. These early invertebrates also lived in shallow marine environments, where the probability of a creature's preservation is different depending on whether it lived under or on the surface of the seafloor: surface-living forms have a better record of fossilization due to surface sediments being glued together by bacteria. Fossilized burrowing forms haven't been found—although their burrows have. It might be expected to find connections between vertebrate groups because vertebrates are large animals with large calcium-rich bones and teeth that have a higher probability of fossilization than do the soft body parts of the earliest invertebrates. There are, in fact, good transitions that have been found between fish and amphibians, and there are especially good transitions between reptiles and mammals. More and more fossils are being found that show structural transitions between reptiles (dinosaurs) and birds. Within a vertebrate lineage, there are often fossils showing good transitional structures. We have good evidence of transitional structures showing the evolution of whales from land mammals, and modern, large, single-hoofed horses from small, three-toed ancestors. Other examples can be found in reference books on vertebrate evolution such as those by Carroll (1998) or Prothero (2007).

In addition to the if-then statements predicting what one would find if evolution occurred, one can also make predictions about what one would not find. If evolution occurred and living things have branched off the tree of life as lineages split from common ancestors, one would not find a major branch of the tree totally out of place. That is, if evolution occurred, paleontologists would not find mammals in the Devonian age of fishes or seed-bearing plants back in the Cambrian. Geologists are daily examining strata around the world as they search for minerals, or oil, or other resources, and at no time has a major branch of the tree of life been found seriously out of place. Reports of "man tracks" being found with dinosaur footprints have been shown to be carvings, or eroded dinosaur tracks, or natural erosional features. If indeed there had not been an evolutionary, gradual emergence of branches of the tree of life, then there is no scientific reason why all strata would not show remains of living things all jumbled together.

In fact, one of the strongest sources of evidence for evolution is the consistency of the fossil record around the world. Another piece of evidence is the fact that when we look at the relationships among living things we see that it is possible to group organisms in gradually broader classifications. There is a naturally occurring hierarchy of organisms that has been recognized since the seventeenth century: species can be grouped into genera, genera can be grouped into families, and on and on into higher categories. The branching process of evolution generates hierarchy; the fact that animals and plants can be arranged in a tree of life is predicted and explained by the inference of common descent.

We can test not only the big idea of evolution but also more specific claims within that big idea. Such claims concern pattern and process, which require explanations of their own.

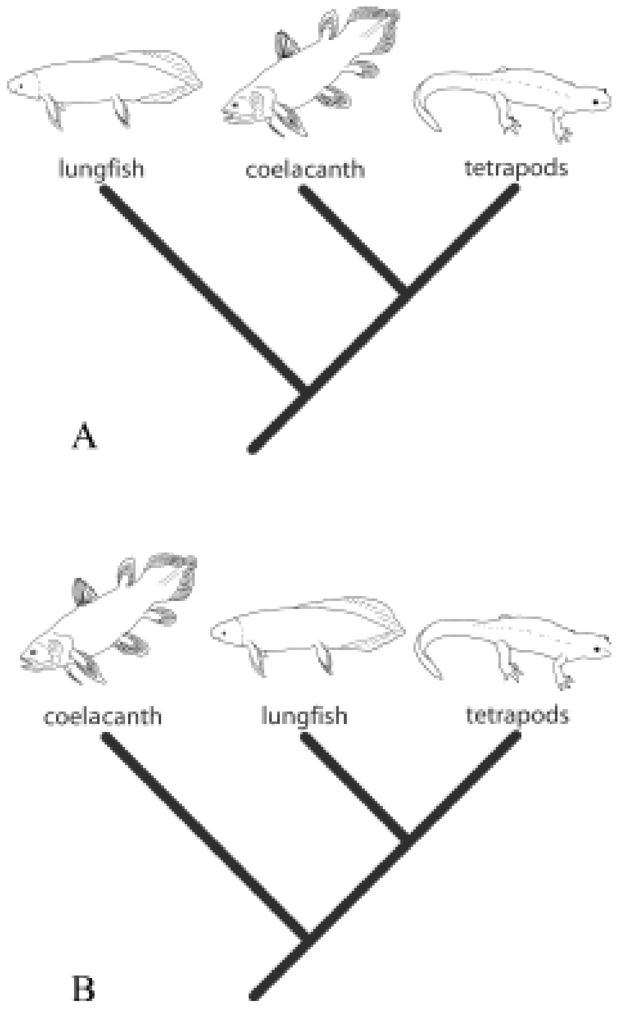
## Pattern and Process

**Pattern.** Consider that if evolution is fundamentally an aspect of history, then certain things happened and other things didn't. It is the job of evolutionary biologists and geologists to reconstruct the past as best they can and to try to ascertain what actually happened as the tree of life developed and branched. This is the pattern of evolution, and indeed, along with the general agreement about the gradual appearance of modern forms over the past 3.8 billion years, the scientific literature is replete with disputes among scientists about specific details of the tree of life, about which structures represent transitions between groups and how different groups are related. Morphologically, most Neanderthal physical traits can be placed within the range of variation of living humans, but there are tests on fossil mitochondrial DNA that suggest that modern humans and Neanderthals shared a common ancestor very, very long ago—no more recently than 300,000 years ago (Ovchinnikov et al. 2000). So are Neanderthals ancestral to modern humans or not? There is plenty of room for argument about exactly what happened in evolution. But how do you test such statements?

Tests of hypotheses of relationships commonly use the fossil record. Unfortunately, sometimes one has to wait a long time before hypotheses can be tested. The fossil evidence has to exist (i.e., be capable of being preserved and actually be preserved), be discovered, and be painstakingly (and expensively) extracted. Only then can the analysis begin. Fortunately, we can test hypotheses about the pattern of evolution—and the idea of descent with modification itself—by using types of data other than the fossil record: anatomical, embryological, or biochemical evidence from living groups. One reason why evolution—the inference of common descent—is such a robust scientific idea is that so many different sources of information lead to the same conclusions.

We can use different sources of information to test a hypothesis about the evolution of the first primitive amphibians that colonized land. There are two main types of bony fish: the very large group of familiar ray-finned fish (e.g., trout, salmon, sunfish) and the lobe-finned fish, represented today by only three species of lungfish and one species of coelacanth. In the Devonian, though, there were nineteen families of lungfish and three families of coelacanths. Because of their many anatomical specializations, we know that ray-finned fish are not part of tetrapod (four-legged land vertebrate) ancestry; we and all other land vertebrates are descended from the lobe-fin line. Early tetrapods and lobe-fins both had teeth with wrinkly enamel and shared characteristics of the shoulder girdle and jaws, plus a sac off the gut used for breathing (Prothero 1998:

Figure 1.2
Are tetrapods more closely related to lungfish or to coelacanths? Courtesy of Alan Gishlick.



358). But are we tetrapods more closely related to lungfish or to coelacanths? Is the relationship among these three groups more like Figure 1.2A or Figure 1.2B? We can treat the two diagrams as hypotheses and examine data from comparative anatomy, the fossil record, biochemistry, and embryology to confirm or disconfirm A or B.

Anatomical and fossil data support hypothesis B (Thomson 1994). Studies on the embryological development of tetrapod and fish limbs also support hypothesis B. Now, when contemplating Figure 1.2, remember that these two diagrams omit the many known fossil forms and show only living groups. It isn't that tetrapods evolved from lungfish, of course, but that lungfish and tetrapods shared a common ancestor, and they shared that common ancestor with each other more recently than they shared a common ancestor with coelacanths. There is a large series of fossils filling the morphological gaps between ancestors of lungfish and tetrapods (Carroll 1998) and more are being discovered (Shubin, Daeschler, and Jenkins 2006).

Another interesting puzzle about the pattern of evolution is ascertaining the relationships among the phyla, which are very large groupings of kinds of animals. All the many kinds of fish, amphibians, reptiles, birds, and mammals are lumped together in one phylum (Chordata) with some invertebrate animals such as sea squirts and the wormlike lancelet (amphioxus). Another phylum (Arthropoda) consists of a very diverse group of invertebrates that includes insects, crustaceans, spiders, millipedes, horseshoe crabs, and the extinct trilobites. So you can see that phyla contain a lot of diversity. Figuring out how such large groups might be related to one another is a challenging undertaking.

Phyla are diagnosed on the basis of basic anatomical body plans—the presence of such features as segmentation, possession of shells, possession of jointed appendages, and so forth. Fossil evidence for most of these transitions is not presently available, so scientists have looked for other ways to ascertain relationships among these large groups. The recent explosions of knowledge in molecular biology and of developmental biology are opening up new avenues to test hypotheses of relationships—including those generated from anatomical and fossil data. Chordates for a long time have been thought to be related to echinoderms on the basis of anatomical comparisons (larvae of some echinoderms are very similar to primitive chordates) and this relationship is being confirmed through biochemical comparisons (e.g., ribosomal RNA) (Runnegar 1992). Ideas about the pattern of evolution can be and are being tested.

**Process.** Scientists studying evolution want to know not only the pattern of evolution but also the processes behind it: the mechanisms that cause cumulative biological change through time. The most important is natural selection (discussed in chapter 2), but there are other mechanisms (mostly operating in small populations, like genetic drift) that also are thought to bring about change. One interesting current debate, for example, is over the role of genetic factors operating early in embryological development. How important are they in determining differences among—and the evolution of—the basic body plans of living things? Are the similarities of early-acting developmental genes in annelid worms and in primitive chordates like amphioxus indicative of common ancestry? Another debate has to do with the rate and pace of evolution: do changes in most lineages proceed slowly and gradually, or do most lineages remain much the same for long periods that once in a while are punctuated with periods of rapid evolution? We know that individuals in a population compete with one another, and that populations of a species may outbreed one another, but can there be natural selection between lineages of species through time? Are there rules that govern the branching of a lineage through time? Members of many vertebrate lineages have tended to increase in size through time; is there a general rule governing size or other trends? All of these issues and many more constitute the processes or mechanisms of evolution. Researchers are attempting to understand these processes by testing hypotheses against the fossil and geological records as well as other sources of information from molecular biology and developmental biology (embryology).

Natural selection and other genetically based mechanisms are regularly tested and are regularly shown to work. By now there are copious examples of natural selection operating in our modern world, and it is not unreasonable to extend its operation into the past. Farmers and agricultural experts are very aware of natural selection as insects, fungi, and other crop pests become resistant to chemical controls. Physicians similarly are very aware of natural selection as they try to counter antibiotic-resistant microbes. The operation of natural selection is not disputed in the creationism/evolution controversy: both supporters and detractors of evolution accept that natural selection works. Creationists, however, claim that natural selection cannot bring about differences from one "kind" to another.

Pattern and process are both of interest in evolutionary biology, and each can be evaluated independently. Disputes about the pattern of evolutionary change are largely independent of disputes about the process. That is, arguments among specialists about how fast evolution can operate, or whether it is gradual or punctuated, are irrelevant to arguments over whether Neanderthals are ancestral to modern Europeans and vice versa. Similarly, arguments about either process or pattern are irrelevant to whether evolution took place (i.e., the big idea of descent with modification). This is relevant to the creationism/evolution controversy because some of the arguments about pattern or process are erroneously used to support the claim that descent with modification did not occur. Such arguments confuse different levels of understanding.

## CREATIONISM AND TESTING

The topic of religion constitutes chapter 3, and creationism is a religious concept. Religion will be defined as a set of ideas concerning a nonmaterial reality; thus, it would appear that—given science's concern for material explanations—science and creationism have little in common. Yet the creationism/evolution controversy includes the claim made by some that creationism is scientific, or can be made scientific, or has scientific elements. The question naturally arises, then, Is creationism testable?

As discussed, science operates by testing explanations of natural phenomena against the natural world. Explanations that are disproved are rejected; explanations that are not disproved—that are corroborated—are provisionally accepted (though at a later time they may be rejected or modified with new information). An important element of testing is being able to hold constant some of the conditions of the test, so that a causative effect can be correctly assigned.

The ultimate statement of creationism—that the present universe came about as the result of the action or actions of a divine creator—is thus outside the abilities of science to test. If there is an omnipotent force in the universe, it would by definition be impossible to hold constant (to control) its effects. A scientist could control for the effects of temperature, light, humidity, or predators—but it would be impossible to control for the actions of God!

The question of whether God created cannot be evaluated by science. Most believers conceive of God as omnipotent, so God could have created everything just as we see it today, a theological position known as **special creationism**, or God could have created through a natural process such as evolution, a theological position known as **theistic evolution**. An omnipotent being could create the universe to appear as if it had evolved but actually have created everything five minutes ago. The reason that the ultimate statement of creationism cannot be tested is simple: the actions of an omnipotent creator are compatible with any and all observations of the natural world. The methods of science cannot choose among the possible actions of an omnipotent creator because by definition God is unconstrained.

Science is thus powerless to test the ultimate claim of creationism and must be agnostic about whether God did or did not create the material world. However, some types of creationism go beyond the basic statement "God created" to make claims of fact about the natural world. Many times these fact claims, such as those concerning the age of Earth, are greatly at variance with observations of science, and creationists sometimes invoke scientific support to support these fact claims. One creationist claim, for example, is that the Grand Canyon was laid down by the receding waters of Noah's flood. In cases like this, scientific methods can be used to test creationist claims, because the claims are claims of fact. Of course, it is always possible to claim that the creator performed miracles (that the layers of rocks in Grand Canyon were specially created by an omnipotent creator), but at this point one passes from science to some other way of knowing. If fact claims are made—assuming the claimer argues scientific support for such claims—then such claims can be tested by the methods of science; some scientific views are better supported than others, and some will be rejected as a result of comparing data and methodology. But if miracles are invoked, such occasions leave the realm of science for that of religion.

## CONCLUSION

First, a caveat: the presentation of the nature of science and even the definitions of facts, hypotheses, laws, and theories I presented is very, very simplified and unnuanced, for which I apologize to philosophers of science. I encourage readers to consult some of the literature in philosophy of science; I think you'll find it a very interesting topic.

Science is an especially good way of knowing about the natural world. It involves testing explanations against the natural world, discarding the ones that don't work, and provisionally accepting the ones that do.

Theory building is the goal of science. Theories explain natural phenomena and are logically constructed of facts, laws, and confirmed hypotheses. Knowledge in science, whether expressed in theories, laws, tested hypotheses, or facts, is provisional, though reliable. Although any scientific explanation may be modified, there are core ideas of science that have been tested so many times that we are very confident about them and believe that there is an extremely low probability of their being discarded. The willingness of scientists to modify their explanations (theories) is one of the strengths of the method of science, and it is the major reason that knowledge of the natural world has increased exponentially over the past couple of hundred years.

Evolution, like other sciences, requires that natural explanations be tested against the natural world. Indirect observation and experimentation, involving if-then structuring of questions and testing by consequence, are the normal mode of testing in sciences such as particle physics and evolution, where phenomena cannot be directly observed.

The three elements of biological evolution—descent with modification, the pattern of evolution, and the process or mechanisms of evolution—can all be tested through the methods of science. The heart of creationism—that an omnipotent being created—is not testable by science, but fact claims about the natural world made by creationists can be.

In the next chapter, I will turn to the science of evolution itself.

## REFERENCES

Carroll, Robert L. 1998. Vertebrate paleontology and evolution. New York: W. H. Freeman.

Cartmill, Matt. 1988. Seventy-five reasons to become a scientist: American Scientist celebrates its seventy-fifth anniversary. American Scientist 76: 450–463.

Hrdy, Sarah Blaffer. 2001. Mothers and others. Natural History (May): 50–62.

Montagu, M. F. Ashley. 1984. Science and creationism. New York: Oxford University Press.

Moore, John A. 1984. Science as a way of knowing—Evolutionary biology. American Zoologist 24 (2): 467–534.

National Academy of Sciences. 1998. Teaching about evolution and the nature of science. Washington, DC: National Academies Press.

National Academy of Sciences and Institute of Medicine. 2008. Science, Evolution, and Creationism. Washington, DC: National Academies Press.

Ovchinnikov, I. V., A. Gotherstrom, G. P. Romanova, V. M. Kharitonov, K. Liden, and W. Goodwin. 2000. Molecular analysis of Neanderthal DNA from the northern Caucasus. Nature 404: 490–493.

Poinar, Hendrik, Melanie Kuch, and Svante Pääbo. 2001. Molecular analysis of oral polio vaccine samples. Science 292 (5517): 743–744.

Prothero, Donald R. 1998. Bringing fossils to life: An introduction to paleontology. Boston: WCB.

Prothero, Donald R. 2007. Evolution: What the fossils say and why it matters. New York: Columbia University Press.

Runnegar, Bruce. 1992. Evolution of the earliest animals. In Major events in the history of life, ed. J. W. Schopf. Boston: Jones and Bartlett. pp. 64–93.

Shubin, Neil H., Edward B. Daeschler, and Farish A. Jenkins Jr. 2006. A Devonian tetrapod-like fish and the evolution of the tetrapod body plan. Nature 440: 757–763.

Thomson, Keith Stewart. 1994. The origin of the tetrapods. In Major features of vertebrate evolution, ed. D. R. Prothero and R. M. Schoch. Pittsburgh, PA: Paleontological Society. pp. 85–107.

Trefil, James. 1978. A consumer's guide to pseudoscience. Saturday Review, April 29, 16–21.

Weiss, Robin A. 2001. Polio vaccines exonerated. Nature 410: 1035–1036.