BIOLOGY TODAY

An Issues Approach

ELI C. MINKOFF AND PAMELA J. BAKER

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Eli C. Minkoff
Pamela J. Baker
Department of Biology
Bates College,
Lewiston, Maine

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Preface

Those who have been teaching introductory biology for the last two or three decades have been burdened with the supposition that *absolutely everything* needs to be covered in a single course. Textbooks written in this tradition are weighty, encyclopedic works with a thousand or more pages and hefty pricetags. Students are exposed to the *results* of biology without gaining understanding of biology as a *process of discovery.* Students soon forget much of the information because it lacks meaning to them. Studies have shown that many students are discouraged from further biology courses by their experiences with introductory courses that use an encyclopedic approach.

Our book represents an attempt to get away from this "tyranny of coverage" by using an issues-oriented approach to the teaching of biology, one that emphasizes coherent understanding of selected issues rather than an attempt to cover everything. The issues we have chosen are current topics that students are likely to see in the news or to read about in books of general interest. It is our feeling that students (especially those not majoring in biology) are more likely to remember this material if it is meaningfully related to issues of concern to them. Our approach accordingly helps students to experience the connections among the fields of biology, the interdisciplinary nature of today's biology, and the intimate connections between biological and social issues. We also hope to instill in students the feeling that biology is both interesting and relevant to their lives, and that a further understanding of biology can be a delight rather than a burden.

We are also committed as teachers to fostering understanding of biology, what some now call "biological literacy." Thus, we have not overlooked the teaching of "facts," but we have chosen to teach these facts in a context that emphasizes how these facts are produced, organized, and used to solve problems. Thus the issues we have selected are ones that are not only of current importance, but ones that lend themselves as vehicles for teaching the major concepts of biology. One such list of major concepts is contained in the pamphlet *Developing Biological Literacy,* issued by the Biological Sciences Curriculum Study (BSCS). As the table following this Preface shows, we have covered all of these concepts, some of them in several places. We have also endeavored to cover them in a way that enables students to see the connections between them, and we have provided a list of further connections at the end of each chapter.

Biology as a discipline has become fragmented to the extent that different perspectives on the same problem, for example, molecular perspectives and environmental perspectives, are often taught in separate courses with no reference to each other. We aim for a more comprehensive view of each issue. The current understanding of each issue is covered from different perspectives, which often include cellular and molecular perspectives, organismal or individual perspectives, and global or population perspectives, combined as appropriate. Coverage of each issue also includes its social context, both historical and contemporary. Phrasing ideas as "our current understanding" will help students to realize the ongoing nature of discovery and to identify the processes that are necessary for new ideas to be accepted. In no case should students assume that we have covered all there is to say on any issue.

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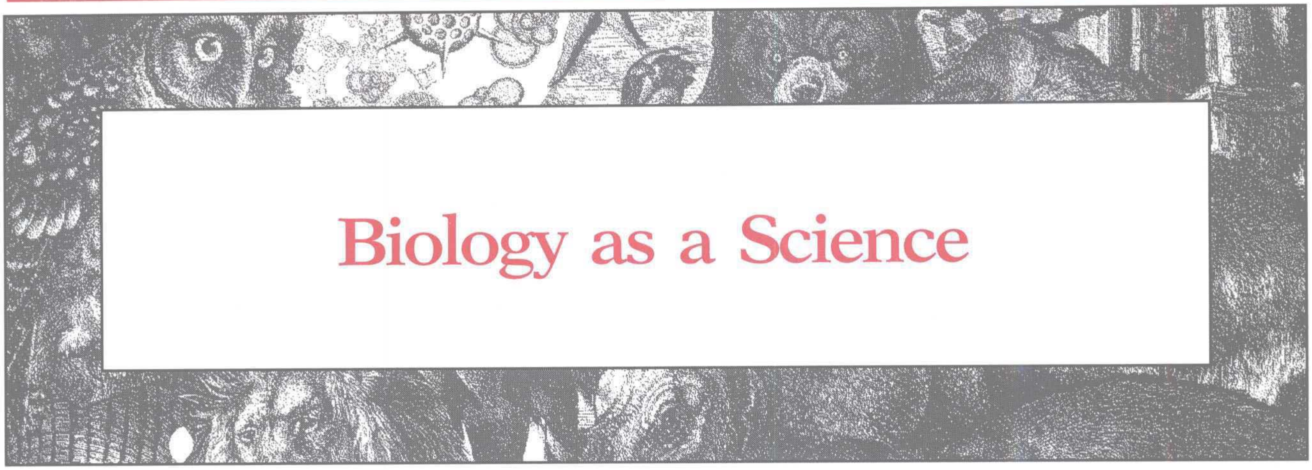

Biology as a Science

Biology is the scientific study of living systems. Our gardens, our pets, our trees, and our fellow humans are all examples of living systems. We can look at them, admire them, write poems about them, and enjoy their company. The Nuer, a pastoral people of Africa, care for their cattle and attach great emotional value to each of them. They write poetry about—and occasionally to—their cattle, they name themselves after their favorite cows or bulls, and they move from place to place according to the needs of their cattle for new pastures. They come to know individual cattle very well, almost as members of the family. Like many other people who live close to the land, the Nuer have also acquired a vast store of useful knowledge about the many animal and plant species that occur in their region. Scientific understanding grew out of a thorough familiarity with the environment, supplemented by a tradition of systematic testing. This chapter deals with the methods of science in general, and with the application of those methods to the study of living systems.

Living systems share all or most of the properties listed in Box 1.1, a set of properties on which most biologists agree. Because living systems are complex and continually changing, an understanding of these systems often requires special methods of investigation or ways of formulating thoughts. This chapter deals with those special methods, a type of investigation that has come to be called **science.** Many people think that science is defined by its subject matter, but this is not correct. *Science is defined instead by its methods.*

Science is a distinctly human activity. As such, it cannot be divorced from other aspects of human life. Science has always been affected by the lives of individual scientists, including their lives outside the laboratory. Religious ideas, political ideas, and social prejudices have all found their way into theories that have been labeled scientific by their adherents. Most scientists seek to reduce the effect of such influences; the first step in doing so is to admit that influences of this kind are always present.

A. Science Is Based on Testing Falsifiable Hypotheses

Hypotheses Are Central to Science

The essence of science is the formulation and testing of certain kinds of statements called **hypotheses.** At the moment of its inception, a hypothesis is a tentative explanation of events that occur or of how something works. What makes science distinctive is that its hypotheses are then subjected to rigorous testing. One result of the testing process is that many hypotheses are rejected as false. Eliminating one hypothesis often helps us frame the next hypothesis.

Hypotheses must be statements about the observable universe. These hypotheses must also be

BOX 1.1 CHARACTERISTICS OF LIVING SYSTEMS

Anything is considered to be a living system if it exhibits growth, metabolism, homeostasis, and selective response at some time during its existence. Living systems are composed of organisms that can be either single-celled or multicellular. Organisms belong to populations of similar organisms, at least some of which are capable of reproducing.

- Metabolism. All living things take energy-rich materials from their environment and release other materials that, on the average, have a lower energy content. Some of the energy is used to carry on life processes, but some also accumulates and is released only upon death.
- Motion. Most (but not all) living systems convert some of the energy they use into motion of some sort, including internal motion within cells.
- Selective response. All living systems have some capability of responding selectively to certain external stimuli and not to others. Many organisms respond to offensive stimuli by withdrawing. All organisms have some capacity to distinguish needed nutrients from other chemicals and to respond appropriately in most cases.
- Homeostasis. All living systems have at least some capacity to change potentially harmful or threatening conditions into conditions more favorable to their continuing existence, e.g., by metabolizing certain toxic chemicals into less harmful ones.
- Growth and biosynthesis. All living things go through phases during which they make more of their own material at the expense of some of the materials around them.
- Genetic material. All living organisms contain hereditary information derived from previously existing organisms. This genetic material takes the form of a nucleic acid (either DNA or RNA) in all known cases.
- Reproduction. All living beings have some capacity to make other organisms similar to themselves by transmitting at least some of their genetic material.
- Population structure. All living organisms belong to populations of similar organisms. Populations can be defined retrospectively as organisms related by common descent. Among organisms capable of sexual processes, populations may also be defined prospectively to include all those organisms that can interbreed with one another.

Viruses strain these definitions of living systems. Viruses contain genetic material yet they do not exist as cells, and replicate only inside and with the help of some other organism.

formulated in such a way that they can be tested by comparison to the world of experience. To be a hypothesis, a statement must be either **verifiable** (confirmable) or **falsifiable** (capable of being shown to be untrue). This process of testing by comparison to the observable universe is called *empirical testing*. Observations gathered in testing any hypothesis are generally called **data.**

Statements that are not hypotheses. It follows from the above definition of hypotheses that certain types of statements cannot be used as scientific hypotheses.

Moral judgments and religious concepts are excluded from science because they are not falsifiable. For example, the statement "there is a God" cannot be disproven or falsified by any possible demonstration of empirical fact or observation.

Moral or ethical views concerning human conduct have an influence on science, but such moral questions cannot be decided by evidence alone (Chapter 2).

Judgments about what ideas or things are valuable are not subject to falsification by hypothesis testing. Well-designed opinion surveys can gather and summarize data about how many people agree or disagree with a particular value judgment—for example, "Education is important for its own sake"—but survey results cannot be used as evidence that any particular judgment is "true."

Judgments of what things are beautiful or likable are called esthetic judgments. The statements "Jazz is good music," "Salsa is better than ketchup," and "My roommate is a nice person" are examples of esthetic judgments and are not falsifiable hypotheses. Poetry, literature, and art are judged by esthetic criteria unrelated to the scientific principle of falsifiability.

Specific versus general hypotheses. Hypotheses that are easy to verify generally tell us very little. For example, the hypothesis "The sun will rise in the east tomorrow morning" can be tested by awakening early, facing east, and observing what happens. If the sun does rise, then our hypothesis is verified, or confirmed; if the sun does not rise, then our hypothesis is falsified, or disconfirmed. However, the confirmation of this hypothesis is far from an important scientific discovery. It is relatively unimportant because it is too specific, which is exactly what makes it verifiable.

Suppose, now, that we examine the much bolder hypothesis "The sun will rise in the east *every* morning." We can test this second hypothesis in the same way that the first hypothesis was tested, by rising early and facing east, and we can also declare that the hypothesis would be falsified if the sun failed to rise. But what if the sun does rise? Does this verify that the sun will rise *every* morning? Suppose we decide to watch the sunrise five days in a row, or five thousand? A single failure of the sun to rise will absolutely falsify the hypothesis, but no finite number of sunrises would be sufficient to verify the hypothesis for all time. This is the kind of hypothesis that science usually examines: hypotheses that are absolutely falsifiable, but not absolutely verifiable.

Falsified hypotheses are rejected, and new hypotheses (which may in some cases be modifications of the original hypotheses) are suggested in their place. If testing a hypothesis does not reject it, we may want to generalize the hypothesis. For example, if a hypothesis tested using rats has not been falsified, we may want to apply the hypothesis to people as well, or to all animals. However, we can never know how far we can extrapolate (generalize) results unless we continue to try to falsify our premise under different conditions. In this way, the testing of hypotheses allows us to draw conclusions about the observable world, but only to the extent that we have tested many possible circumstances and conditions.

The importance of falsifiable hypotheses in science was first emphasized by the philosopher Karl Popper. In particular, it was Popper who first pointed out that the distinction between science and other disciplines can be based upon the fact that scientists are always seeking to test falsifiable hypotheses. According to Popper, scientists perform the curious exercise of trying to falsify the hypotheses that they believe in, then publishing the results. Scientists convince each other to believe in certain hypotheses according to how rigorously or how often they have tried to falsify these hypotheses and failed.

A definition of science. **Science** may now be defined as a method of investigation based on the testing of falsifiable hypotheses that take the form of universal generalizations that can be falsified but never absolutely verified. Notice that this makes scientific statements *tentative,* or provisional, subject to possible falsification on the next occasion that a test is conducted. Even the most cherished scientific belief can be falsified—for example, the sun may fail to rise tomorrow morning. Repeated exposure of our hypotheses to possible falsification increases our confidence in these hypotheses when they are not falsified, but no amount of testing can guarantee absolute truth.

Any hypothesis that is tested again and again without ever being falsified is considered to be well supported and comes to be generally accepted. It may be used as the basis for formulating further hypotheses, so there is soon a cluster of related hypotheses, supported by the results of many tests, which is then called a *theory,* as described below.

Ways of devising hypotheses. **Deduction** is reasoning from the general to the specific. Deductive logic of the "If . . . then" form is frequently used to set up testable hypotheses: "*If* organisms of type X require oxygen to live, *then* this individual of type X will die if I put it in an atmosphere without oxygen." Often contrasted with deduction is another type of reasoning called **induction** (or, more properly, *inductive generalization*), reasoning from the specific to the general. This type of reasoning is commonly used in day-to-day life: "I like the pizza in restaurants A, B, C, and D; therefore I will like pizza in any other restaurant." Induction never guarantees the truth of any conclusions drawn—"The next restaurant may serve pizza that I don't like." As we have seen above, science also uses inductive methods to generalize from specific hypotheses. If a certain drug slows down the heart rate in this rat and that rat, perhaps it will also have the same effect in other mammals. If it also slows the heart rate in two humans and a turtle, then maybe it will do so in many other animals, perhaps all animals. Induction also produces the "ah hah" moments for scientists, in which a series of seemingly unrelated observations suddenly coalesce into a cohesive picture.

Deduction and induction are only two of the many ways in which scientists go about the business of formulating hypotheses. Other ways include (1) intuition or imagination, (2) esthetic preferences, (3) religious and philosophical ideas, (4) comparison and analogy with other processes, and (5) serendipity, or the discovery of one thing while looking for something else. Moreover, these ways may be mixed or combined. For example, Albert Einstein declared that he arrived at his hypotheses about the physics of the universe by considering esthetic qualities such as beauty or simplicity and by asking, "If I were God, how would I have made the world?" Einstein also said that "imagination is more important than knowledge," a remark that is particularly true for the formulation of hypotheses (Fig. 1.1). Nobel prize–winning physicist Niels Bohr said that his hypothesis of atomic structure (the heavy nucleus in the center, with the electrons circling rapidly around it, "like a miniature solar system") first occurred to him by analogy with our solar system. Alexander Fleming found the first antibiotic as the result of a laboratory accident: On dishes of bacteria that should have been thrown away earlier, he observed clear areas where fungi had overgrown the bacteria. His hypothesis, that a product of the fungi had killed the bacteria, was validated by tests and that fungal product is what we now know as penicillin. As these several examples show, *hypotheses are formed by all kinds of logical and extralogical processes,* which is one more reason why they must be subjected to rigorous testing afterward.

Hypothesis testing in variable systems. Biological systems are complex and variable. No individual animal or plant is exactly like any other animal or plant. At any instant in time, they may differ in their internal conditions, in their external conditions, or in the way these conditions are interacting. Further, the same individual is not exactly the same from one day to the next. Because living systems vary, tests must be repeated. If a hypothesis is tested in one animal, or one cell, and the organism responds in a particular way, the re-

FIGURE 1.1
Imaginative hypotheses may originate from various logical or extralogical processes, especially from young scientists. Does the idea shown here qualify as a scientific hypothesis?

sult is far less reliable as a means of prediction than it would be if 10 animals, or 100 cells, all responded in the same way. What often happens, however, is that 9 out of 10 animals, or 94 of 100 cells, respond in one way and the remainder in another way. When some individuals respond differently from the rest, it may be the result of a source of variation that has not yet been identified. Scientists who devote their attention to the anomalous cases may sometimes discover new phenomena that were previously ignored.

Interpretation of the results from tests on variable systems usually requires statistical treatment to find out whether the observed differences are "real" or can be explained by random variation.

For example, scientists who suspected that dietary fats were contributing to the risks for heart disease obtained important evidence on this hypothesis by comparing heart attack rates in populations with low fat consumption with heart attack rates in populations with high fat consumption. Once the rates of heart attack in the populations under study had been determined, the results were analyzed statistically to determine whether the preliminary findings—that high fat consumption was associated with increased risk of heart attack—were meaningful or could have arisen by chance or from sampling error. (Error occurs when the people picked for the sample studied are not representative of the general population, either because the sample is too small or because it was not chosen randomly.) Studies of the relationship between high fat diets and heart disease have indeed found significantly higher heart attack rates (and also significantly higher breast cancer rates) in populations with higher levels of dietary fat consumption.

What Is a Theory?

A **theory** is a cluster of related hypotheses that share a common vocabulary and a common subject matter. Theories develop after the results of many tests have accumulated. The language of the theory nearly always refers to certain entities that cannot be seen, and are hence "theoretical." Examples of such entities are *electron, force, gene, enzyme, reflex, fitness, species, ecosystem, extinction, community, aversion,* and *family.* Each unseen entity can be defined in terms of the observable effects that it produces. For example, geneticists observe that the offspring of individual organisms, behave *as if* certain hereditary factors (genes) are present. Physicists have observed that metallic foils behave *as if* they are composed of atoms. We can even distinguish different types of genes or types of atoms, but they remain unseen nevertheless.

The language of science. Scientists sometimes coin words to denote new theoretical concepts and sometimes they give existing words new meaning in the context of the new theory. The intent is to foster accurate communication among scientists, but sometimes the specialized use of familiar words (like *altruism* by population ecologists and sociobiologists or *self* by immunologists) serves as a barrier to communication between scientists and nonscientists and even between scientists from different fields.

In any case, we should recognize that scientific terms mean only what a particular theory says they mean, or what scientists who support that theory understand them to mean. When opposing theories are in conflict, a frequently occurring problem is that the same word is used by different groups of scientists to mean different things, or that the same thing is described in different words by the supporters of different theories.

Productive theories. One of the most important features of a good theory is that it will often suggest new and different hypotheses to test. A theory of this kind is a stimulus to further research and is sometimes called a *productive* theory. Sometimes, two or more theories may offer competing explanations for the same data, a situation that almost always stimulates research from several directions. A theory may be productive for a while and then no longer stimulate new research, in part because research is a peculiarly human endeavor. The theories that last are the ones that remain productive the longest, while the less productive theories are often abandoned without ever being fully disproved. In some cases, it is the falsification of one of its hypotheses (or the failure of a crucial test) that causes a theory to be rejected—remember that the hypotheses that make up a theory are always subject to possible falsification. Even a long-cherished theory may be abandoned (or greatly modified) if it no longer holds predictive or explanatory power.

Theoretical models. Many theories can be communicated using a simplified mathematical or visual form, called a **model.** Such a model, while not a formal part of the theory, can nevertheless be an important teaching tool in helping communicate the theory to other people. For example, Bohr's conceptualization of the atom in terms of electrons circling around the nucleus like a miniature solar system was the model of atomic structure for generations of students. However, models are analogies. Like other analogies, models are comparable to the phenomena they describe only so far, and no further. Attempts to determine *how far* an analogy holds often suggest new hypotheses to test or lead to new ways of testing old hypotheses. The planetary model of atomic structure is a case in point. With the development of quantum physics, it became clear that the solar system model was inadequate to explain the behavior of atomic particles. Similarly, the model of genes on a chromosome as a linear sequence, "like beads on a string," which was popularized by early twentieth-century geneticists, has been supplanted by the double-helix model. Thus, theories and models are not simply opinions or points of view; they are mechanisms for generating ideas that can be tested and for communicating these ideas.

THOUGHT QUESTIONS

1. In a group, discuss the hypothesis shown in Fig. 1.1. Is it falsifiable? If you believe so, then explain what sorts of observations might falsify it. How could we go about testing such an idea?
2. Which of the following are falsifiable statements? For each statement that you think is falsifiable, explain what sort of observation might falsify it.
   - This horse is a cinch to win in the next race.
   - Pearl Jam is a better musical group than The Rolling Stones.
   - In a maze that they have never seen before, rats will turn right just about as often as they will turn left.
   - The hungry cat will eat because hunger awakens the food spirits within the cat.
   - The hungry cat will eat because hunger awakens an innate food-seeking drive within the cat.
   - The angles of a triangle always add up to 180 degrees.
   - If these two plants are crossed, approximately half of the offspring will resemble one parent and half will resemble the other.
   - It is wrong to inflict pain on a cat.
   - Restaurant A is better than restaurant B.
   - The average science major at this school gets better grades than the average humanities major.
   - All people should be treated equally under the law.
3. Which of the following are examples of inductive reasoning? Which are deductive?
   - All green leaves I have ever tested contain chlorophyll, so the green leaves on that tree contain chlorophyll, too.
   - If chlorophyll is soluble in alcohol, and if this leaf contains chlorophyll, then I should be able to dissolve the chlorophyll from this leaf by soaking it in alcohol.
   - If all adult female birds lay eggs, then this female chick will lay eggs if raised to maturity.
   - If all known species of birds are egg-laying, then the next species to be discovered will be egg-laying, too.
   - If chemical X destroys vitamin C, then I should be able to produce the symptoms of vitamin C deficiency by feeding these animals only food that has been treated with chemical X.

B. Testing Hypotheses Varies in Different Branches of Science

Hypotheses are tested by comparing them to the real world, i.e., by making empirical observations. In this, science differs from pure mathematics, which examines only theoretically defined concepts. The sciences differ from one another, however, in the ways in which hypotheses are tested.

Experimental Science

Some scientists test hypotheses by conducting **experiments**—artificially contrived situations set up for the express purpose of testing some hypothesis. Most **experimental sciences** aim, in one way or another, to answer questions of the form "How does X work?" The scientist designs an experiment such that a certain outcome is expected (or not expected); then the results of the experiment are determined *objectively,* which means, in this context, *without bias either for or against the hypothesis being tested*, or *without any bias that would impair the falsifiability of the hypothesis.*

Many experiments involve comparison of an experimental situation or group with a *control* situation or **control group** in which all variables are ideally held the same except for the one being tested. For example, animals given a new drug are compared to a similar group of animals—the control group—that are not given the drug. To make the results strictly comparable, the control group should be given a substance similar to whatever is given to the experimental group, but lacking the one ingredient thought to be essential. In order to make sure that any difference in outcome can be attributed to the presence or absence of the drug, care must be taken to ensure that the two groups are equivalent in every other way: similar animals, similar cages, similar temperatures, similar diets, and so on.

The use of the word *control* in an experimental context is different from the usual use of the word. Scientists try to control (standardize) the possible sources of variation in their experiments. They are not exercising authority over the animals or predetermining the outcome of the experiment. We often see confusion over the term *control* in the caricature of the "mad scientist," a literary character who usually prides himself (nearly always *him*self) on his ability to control everything, often extending into a quest to control the world.

As an example of the experimental approach, consider the following experiment in bacterial genetics that was conducted by Joshua and Esther Lederberg, part of the basis for Joshua's subsequent Nobel prize. Most bacteria are killed by an antibiotic like streptomycin, but the Lederbergs exposed the common intestinal bacterium *Escherichia coli* to this drug and were able to isolate a number of streptomycin-resistant bacteria. They allowed these bacteria to reproduce and were able to show that resistance to streptomycin was inherited by their offspring. In other words, a permanent genetic change had occurred; such changes are called *mutations* (Chapter 3). Now, the Lederbergs had two hypotheses to test. The first hypothesis was that the mutation had been *induced,* or caused, by exposure to the streptomycin. The second was that the mutation had occurred before (and therefore independently of) exposure to the streptomycin. In order to distinguish between these hypotheses, the Lederbergs devised the experiment shown in Fig. 1.2. In this experiment, a copy, or replica, of the original plate of bacteria was made. Only the replica, not the original, was exposed to streptomycin, and the position of each bacterial colony was noted. The induced mutation hypothesis predicted that the mutation would occur whenever a bacterium was exposed to streptomycin. In fact, most of the bacteria died (thus falsifying this hypothesis), but an occasional colony proved to be streptomycin-resistant. The prior mutation hypothesis predicted that the mutation for streptomycin resistance had occurred before the exposure to streptomycin. To test this second hypothesis, the Lederbergs went back and tested the colonies from the original plate. They discovered that the same colonies that were streptomycin-resistant on the replica plate were also streptomycin-resistant on the original plate. This finding was consistent with the prior mutation hypothesis for this particular sample of bacteria.

The prior mutation hypothesis had been tested and not falsified in the case of one mutation for drug resistance in one species of bacteria. How far could the finding be generalized? From this one experiment alone, one cannot tell. However, other investigators repeated the experiment for other mutations and other species of microorganisms. So far, the hypothesis of prior mutation has not been falsified. It is difficult to test the hypothesis in large or long-lived organisms, but most scientists are willing to assume the truth of the hypothesis for *all* organisms. There are many species (and thousands of mutations for each species) that have never been tested in this way, which leaves a good deal of opportunity for the hypothesis to be falsified at some time in the future.