Chapter 1

About Science

1.2 The Scientific Method

Science is a process of gathering and organizing human knowledge about nature. The practice of science, including biology, involves keen observations, rational analysis, and experimentation. In the 17th century, Galileo and the English philosopher Francis Bacon were the first to formalize a particular method for doing science. What they outlined has come to be known as the classic **scientific method**.
It essentially includes the following steps:

1. **Observe**

   Closely observe the physical world around you.

2. **Question**

   Recognize a question or a problem.

3. **Hypothesize**

   Make an educated guess—a *hypothesis*—to answer the question.

4. **Predict**

   Predict consequences that can be observed if the hypothesis is correct. The consequences should be *absent* if the hypothesis is not correct.

5. **Test predictions**

   Do experiments to see if the consequences you predicted are present.

6. **Draw a conclusion**

   Formulate the simplest general rule that organizes the hypothesis, predicted effects, and experimental findings.

Although the traditional scientific method is powerful, good science is often done differently, in a less systematic way. In the example later in this section, you will see a recent application of the classic scientific method. However, many scientific advances involve trial and error, experimenting without guessing, or just plain accidental discovery.

More important than a particular method, the success of science has to do with an attitude common to scientists. This attitude is one of inquiry, experimentation, and humility before the facts. Let's take a closer look at some key components of the scientific method.

The Scientific Hypothesis

A scientific **hypothesis** is an educated guess that tentatively answers a question or solves a problem in regard to the natural world. Typically, experiments are done to test hypotheses.

The cardinal rule in science is that all hypotheses must be testable—in other words, they must, at least in principle, be capable of being shown wrong.

In science, it is more important that there be a means of proving an idea wrong than that there be a means of proving it right. This is a major feature that distinguishes science from nonscience. The idea that scientific hypotheses must be capable of being proven wrong is a pillar of the philosophy of science, and it is stated formally as the **principle of falsifiability**:

For a hypothesis to be considered scientific it must be testable—it must, in principle, be capable of being proven wrong.

At first this principle may seem strange, for when we wonder about most things, we concern ourselves with ways of finding out whether they are true. Scientific hypotheses are different. In fact, if you want to determine whether a hypothesis is scientific or not, look to see whether there is a test for proving it wrong. If there is no test for possible wrongness, then the hypothesis is not scientific. One famous scientist, the physicist Albert Einstein, put it well: "No number of experiments can prove me right; a single experiment can prove me wrong."

Here are some examples of hypotheses that are testable and capable of being proven wrong: "When it rains and the sun is out, there will be a visible rainbow in the sky." "Robins and house finches eat some of the same foods, and they compete for these foods." "If opossums 'play dead' upon encountering a predator, they are less likely to be attacked." "After a fire, new species of plants, not seen prior to the fire, will germinate."

On the other hand, consider this hypothesis: "Finding a four-leaf clover means you will have good luck." Many people believe it, but this hypothesis is not scientific. It cannot be proven wrong. It is speculation.

Likewise, the hypothesis "Intelligent life exists on planets somewhere in the universe besides Earth" is not scientific. Although it can be proven correct by the verification of a single instance of life existing elsewhere in the universe, there is no way to prove it wrong if no life is ever found. If we searched the far reaches of the universe for eons and found no life, we would not prove that it doesn't exist "around the next corner." A hypothesis that is capable of being proven right but not capable of being proven wrong is not a scientific hypothesis. That does not necessarily mean that it is of no interest, however. For example, scientists are still interested in searching for intelligent life elsewhere in the universe—in fact, some scientists are working on just that right now, and it will be a memorable day if they are ever successful.

The Scientific Experiment

Once scientists have a hypothesis, it can be tested. Scientists do this by making predictions based on their hypothesis and then performing experiments to see if the expected predictions are observed.

Scientists must accept their experimental findings even when they would like them to be different. They must strive to distinguish between the results they see and those they wish to see. This is not easy. Scientists, like most people, are capable of fooling themselves. People have always tended to adopt general rules, beliefs, creeds, ideas, and hypotheses without thoroughly questioning their validity. And sometimes we retain these ideas long after they have been shown to be meaningless, false, or at least questionable. The most widespread assumptions are often the least questioned. Too often, when an idea is adopted, great attention is given to the instances that support it. Contrary evidence is often distorted, belittled, or ignored.

The fact that scientific statements will be thoroughly tested before they are believed helps to keep science honest. Sooner or later, mistakes (or deceptions) are found out. A scientist exposed for cheating doesn't get a second chance in the community of scientists. Honesty, so important to the progress of science, thus becomes a matter of self-interest to scientists. There is relatively little bluffing in a game where all bets are called.

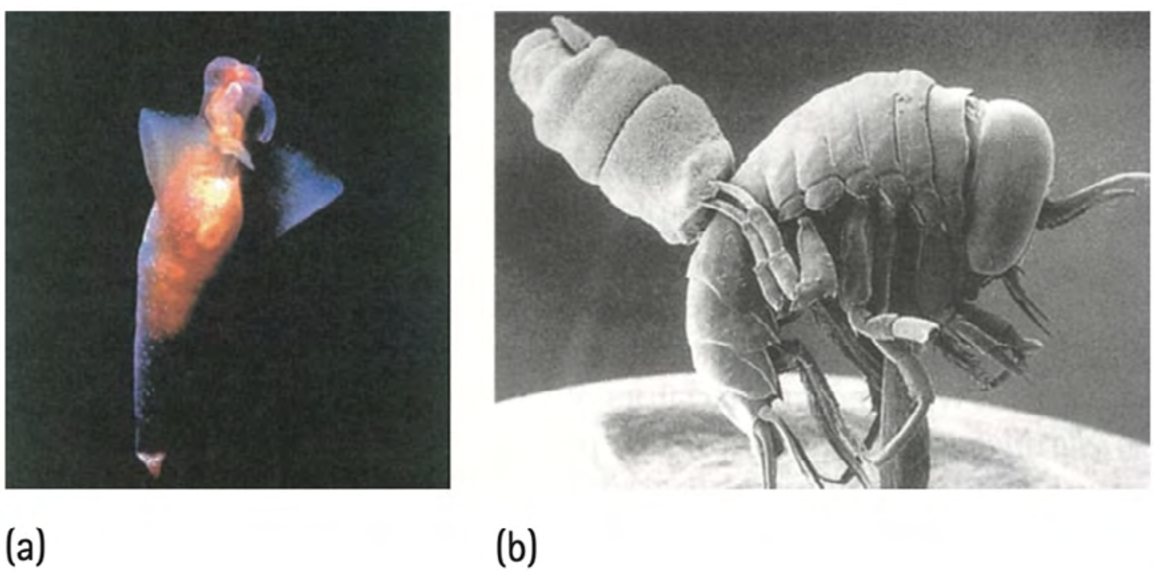

FIGURE 1.4

(a) The graceful Antarctic sea butterfly is a species of snail that does not have a shell. (b) The shrimplike amphipod attaches a sea butterfly to its back even though doing so limits the amphipod's mobility.

Example: Sea Butterflies

Let's consider an example of a recent scientific research project that shows how the scientific method can be put to work. Along the way, we'll get a taste of how biology and chemistry are integrated in the physical world.

The Antarctic research team headed by James McClintock, Professor of Biology at the University of Alabama at Birmingham, and Bill Baker, Professor of Chemistry at the University of South Florida, was studying the toxic chemicals Antarctic marine organisms secrete to defend themselves against predators.

McClintock and Baker observed an unusual relationship between two animal species, a sea butterfly and an amphipod— a relationship that led to a question, a scientific hypothesis, a prediction, tests concerning the chemicals involved in the relationship, and finally a conclusion. The research generally proceeded according to the steps of the classic scientific method.

1. Observe The sea butterfly *Clione antarctica* is a brightly colored, shell-less snail with winglike extensions used in swimming (Figure 1.4a), and the amphipod *Hyperiella dilatata* resembles a small shrimp. McClintock and Baker observed a large percentage of amphipods carrying sea butterflies on their backs, with the sea butterflies held tightly by the legs of the amphipods (Figure 1.4b). Any amphipod that lost its sea butterfly would quickly seek another—the amphipods were actively abducting the sea butterflies!

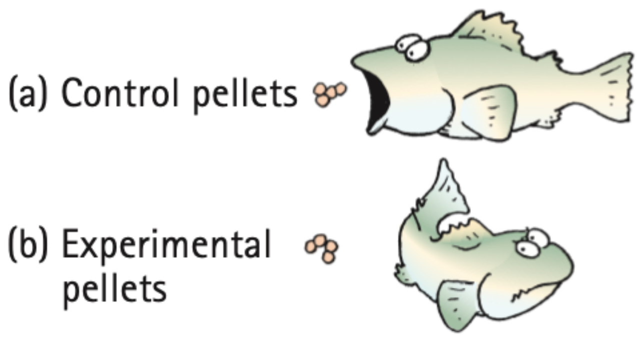

FIGURE 1.6

The predator fish (a) ate the control pellets but (b) rejected the experimental pellets, which contained sea butterfly extract.

2. Question McClintock and Baker noted that amphipods carrying butterflies were slowed considerably. This seemed like it would make the amphipods more vulnerable to predators and less adept at catching prey. Why then did the amphipods abduct and hang on to the sea butterflies?

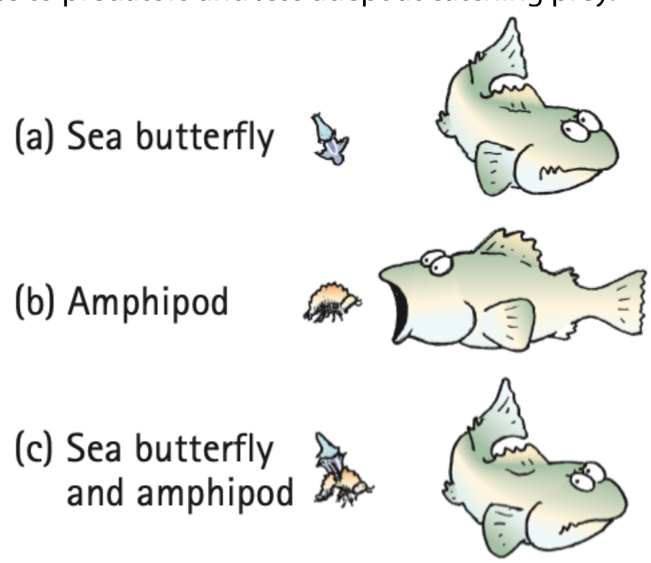

FIGURE 1.5

In McClintock and Baker's initial experiment, a predatory fish

(a) rejected the sea butterfly,
(b) ate the free- swimming amphipod, and
(c) rejected the amphipod coupled with a sea butterfly.

3. Hypothesize Given their experience with the chemical defense systems of various sea organisms, the research team hypothesized that amphipods carry sea butterflies to take advantage of a chemical that deters a predator of the amphipod.

4. Predict Based on their hypothesis, they predicted (a) that they would be able to isolate this chemical and (b) that an amphipod predator would be deterred by it.

5. Test predictions To test their hypothesis and predictions, the researchers captured several predator fish species and conducted the test shown in Figure 1.5. The fish were presented with solitary sea butterflies, which they took into their mouths but promptly spat back out. The fish readily ate uncoupled amphipods but spit out any amphipod coupled with a sea butterfly. These are the results expected if the sea butterfly was secreting some sort of chemical deterrent. The same results would be obtained,

however, if a predator fish simply didn't like the feel of a sea butterfly in its mouth. The results of this simple test were therefore ambiguous. A conclusion could not yet be drawn.

This experiment highlights that all scientific tests need to minimize the number of possible conclusions. Often this is done by running an experimental test along with a *control*. Ideally, the experimental test and the control should differ by only one variable. Any differences in results can then be attributed to how the experimental test differed from the control.

To confirm that the deterrent was chemical and not physical, the researchers made one set of food pellets containing both fish meal and sea butterfly extract (the experimental pellets). For their control test, they made a physically identical set containing only fish meal (the control pellets). As shown in Figure 1.6, the predator fish readily ate the control pellets but not the experimental ones. These results strongly supported the chemical hypothesis.

Further processing of the sea butterfly extract yielded five major chemical compounds, only one of which deterred the predator fish from eating the pellets. Chemical analysis of this compound revealed it to be the previously unknown molecule that the scientists named pteroenone.

6. Draw a conclusion In addition to running control tests, scientists confirm experimental results by repeated testing. In this case, the Antarctic researchers made many food pellets, both experimental and control, so that each test could be repeated many times. Only after obtaining consistent results in repeated tests can a scientist draw a conclusion. McClintock and Baker were thus able to conclude that amphipods abduct sea butterflies in order to use the sea butterflies' secretion of pteroenone as a defense against predator fish.

Yet, this conclusion might still be regarded with skepticism in the scientific community. Why? There is a great potential for unseen error in any experiment. A laboratory may have faulty equipment that leads to consistently wrong results, for example. Because of the potential for unseen error from any particular research group, experimental results must be *reproducible* to be considered valid. This means that other scientists must be able to reproduce the same experimental findings in separate experiments. Thus, you can see that it is a long road from a bright idea to accepted scientific finding! The plodding, painstaking nature of this process is beneficial, though—it is the very reason that scientific knowledge is highly trustworthy.

As frequently happens in science, McClintock and Baker's results led to new questions. What are the properties of pteroenone? Does this substance have applications—for example, can it be used as a pest repellent? Could it be useful for treating human disease? In fact, a majority of the chemicals we use were originally discovered in natural sources. This illustrates that there is an important reason for preserving marine habitats, tropical rainforests, and the other diverse natural environments on Earth—they are storehouses of countless yet-to-be-discovered substances.

READING CHECK

Which of the statements below are *scientific* hypotheses?

a. The stock market has good days when the planets Venus, Earth, and Mars are aligned.

b. Atoms are the smallest particles of matter that exist.

c. The Moon is made of Swiss cheese.

d. Outer space contains a kind of matter whose existence can't be detected or tested.

e. Charles Darwin was the greatest biologist of the 19th century.

CHECK YOUR ANSWERS

All these statements are hypotheses, but only statements a, b, and c are scientific hypotheses because they are testable statement.

a. Can be tested (and proven wrong) by researching the performance of the stock market during times when these planets were aligned. Not only can statement

b. Be tested; it has been tested. Although the statement has been found to be untrue (many particles smaller than atoms have been discovered), the statement is nevertheless a testable scientific hypothesis. Likewise for statement

c. Where visits to the Moon have proven that the statement is wrong. Statement

d. On the other hand, is easily seen to be unscientific, since it can't be tested. Last, statement

e. Is an assertion that has no test. What possible test, beyond collective opinion, could prove that Darwin was the greatest biologist? How could we know? Greatness is a quality that cannot be measured in an objective way.

To read more about the scientific method, check out the websites below:

https://www.livescience.com/21490-what-is-a-scientific-hypothesis-definition-of-hypothesis.html

https://www.livescience.com/20896-science-scientific-method.html