Chapter 1

Figuring Out the Scientific Method

In This Chapter

- Testing hypotheses using the scientific method
- Conducting scientific experiments the right way
- Distinguishing between hypotheses and theories

Biology is the branch of science that deals with living things. Biology wouldn't have gotten very far as a science if biologists hadn't used structured processes to conduct their research and hadn't communicated the results of that research with others. You can use what you learn in this chapter in your everyday life to take a closer look at the information that swirls all around you. Does that diet plan really work? What studies did they do? Ninety-seven percent of scientists agree that global warming is really happening. Why do they think that? What evidence are they looking at? This chapter introduces you to the methods that scientists (whether they're biologists, physicists, or chemists) use to investigate the world around them and helps you learn to analyze scientific experiments.

Developing Hypotheses

The true heart of science isn't a bunch of facts; it's the method that scientists use to gather those facts. Science is about exploring the natural world, making observations using the five senses and intellect, and attempting to make sense of those observations.

When scientists seek out, observe, and describe living things, they're engaging in *discovery science.* Scientists practice discovery science as they explore new environments, like the deep sea, describing the organisms they find there. As scientists study the natural world, they look for patterns and attempt to make sense of how things work. When a scientist proposes an untested explanation for how things work, the tentative explanation is called a *hypothesis.* When scientists test their understanding of the world through experimentation, they're engaging in *hypothesis-based science,* which usually calls for following some variation of a process called the *scientific method* (see the section "Practicing the Scientific Method" later in the chapter). For a hypothesis to be accepted by scientists, it must be *testable* or *falsifiable.* In other words, it must be an idea that you can support or reject by exploring the situation further and collecting observations using your five senses.

For example, let's say that you have a bird feeder in your backyard. You keep filling the feeder with birdseed, but every day when you get up, it's empty again. When you examine the feeder, you notice some scratches near the feeder hole that look like marks from animal claws, so you think that squirrels may be getting into your birdseed. So you take some wire screen and nail it over the feeder hole to reduce the size of the openings. After that, your birdseed lasts for days, and you observe birds eating at your bird feeder.

In my example, you took a scientific approach to solving your bird feeder problem.

- You made initial observations about your bird feeder constantly being emptied and further observed the scratch marks around the feeder hole.
- You came up with a hypothesis about the cause of the disappearing food: If a squirrel is stealing the food, then a smaller opening on the bird feeder would prevent that.
- You were able to test your hypothesis by making a change (creating a smaller opening) and then making new observations.

If an explanation isn't testable, it's not considered a scientific hypothesis.

In the bird feeder example, you may have thought, "Squirrels really enjoy annoying birds, and that's why they're stealing the food." This explanation relates to your observations, but unless you're an expert in reading squirrel emotions, it's not really something you can test and it wouldn't be considered a scientific hypothesis.

See if you can think like a scientist by answering these questions about observations and hypotheses:

1. Two scientists are mapping the locations of mushrooms in the Amazon rain forest. Thus, they're practicing

    a. Discovery science

    b. Hypothesis-based science

    c. Making observations

    d. Discovery science and making observations

2. One night as it gets dark, the scientists notice that some mushrooms glow in the dark. Which of the following would be a valid scientific hypothesis about this observation?

    a. The mushrooms glow because they're scared of the dark.

    b. The mushrooms glow to attract certain insects.

    c. The glowing mushrooms appear yellow-green in color.

Practicing the Scientific Method

Although the bird feeder and squirrel story from the preceding section is an everyday example, it illustrates the most important components of the scientific method. Scientists use the same procedure to make sense of the world whether they're studying squirrels in the backyard or the potential for life outside planet Earth, and that procedure is the scientific method.

The *scientific method* is basically a six-step plan that scientists follow while performing scientific experiments and writing up the results. By following the scientific method carefully, scientists make sure that their conclusions are based on observations and that other scientists can repeat their experiments. Here's the general process of the scientific method:

1. **First, make observations and come up with questions.**

   The scientific method starts by scientists noticing something and asking questions like "What's that?" or "How does it work?" — just like a child might when he sees something new, such as an earthworm wriggling in a puddle after a rainstorm.

2. **Then form a hypothesis.**

   Scientists form hypotheses using *inductive reasoning;* that is, they use specific observations to try and come up with general principles. Say, for example, a marine biologist is exploring a beach and finds a new worm-shaped creature he has never seen before. Using inductive reasoning, he may reach the hypothesis that the creature is some kind of worm because it's shaped like a worm.

3. **Next, make predictions and design experiments to test those ideas.**

   Predictions set up the framework for an experiment to test a hypothesis, and they're typically written as "if . . . then" statements. In the preceding worm example, the marine biologist predicts that if the creature is a worm, then its internal structures should look like those in other worms he has studied.

4. **Test the ideas through experimentation.**

   Scientists must design their experiments carefully to test just one idea at a time (I explain how to set up a good experiment in the "Designing Experiments" section, later in the chapter). As they conduct their experiments, scientists make observations using their five senses and record these observations as their *results* or *data.* Continuing with the worm example, the marine biologist tests his hypothesis by dissecting the wormlike creature, examining its internal parts carefully with the assistance of a microscope, and making detailed drawings of its internal structure.

   REMEMBER

   Any scientific experiment must have the ability to be duplicated because the "answer" the scientist comes up with (whether it supports or rejects the original hypothesis) can't become part of the scientific knowledge base unless other scientists can perform the exact same experiment and achieve the same results.

5. **Then make conclusions about the findings.**

   Scientists interpret the results of their experiments through *deductive reasoning,* using their specific observations to test their general hypothesis. When making deductive conclusions, scientists consider their original hypotheses and ask whether they could still be true in light of the new information gathered during the experiment. If so, the hypotheses can remain as possible explanations for how things work. If not, scientists reject the hypotheses and try to come up with alternate explanations (new hypotheses) that can explain what they've seen. In the earlier worm example, the marine biologist discovers that the internal structures of the wormlike creature look very similar to another type of worm he's familiar with. He can therefore conclude that the new animal is likely a relative of that other type of worm.

6. **Finally, communicate the conclusions with other scientists.**

   Communication is a huge part of science. Without it, discoveries wouldn't be passed on, and old conclusions wouldn't be tested with new experiments. When scientists complete some work, they write a paper that explains exactly what they did, what they saw, and what they concluded. Then they submit that paper to a scientific journal in their field. Scientists also present their work to other scientists at meetings, including those sponsored by scientific societies. In addition to sponsoring meetings, these societies support their respective disciplines by printing scientific journals and providing assistance to teachers and students in the field.

Continue testing your scientific thinking by answering these practice questions about the scientific method. Questions 3 through 5 refer to the following story:

Two scientists who are studying mushrooms in the Amazon rain forest discover a type of mushroom that glows in the dark. One of the scientists proposes that the mushrooms glow in order to attract a certain insect that will scatter the mushroom's reproductive spores. The scientists watch the mushrooms for several days, collecting samples of any insects that visit the mushrooms. Then, they take some of the mushrooms and insects back to their lab and test each type of insect to see whether it's attracted to the glowing mushroom. However, none of the insects shows any attraction to the glow. The scientists decide that the glow from the mushroom must have some other purpose than to attract any of the insects they collected.

3. Put yourself in the place of these scientists and write what you think they may have predicted for their experiment.

4. When the scientists decide that the glow from the mushroom has some other purpose than attracting any of the insects they collected, they're

a. Making an observation

b. Collecting data

c. Using inductive reasoning

d. Using deductive reasoning

5. Which of the following is an example of the type of data the scientists may have collected during their experiment?

a. The number of times a particular type of insect flew toward the glowing mushroom.

b. A comparison of the number of times an insect flew toward the glowing mushroom and away from the glowing mushroom.

c. The purpose of the glow may be to keep insects away from the mushroom.

d. The scientists ask their colleagues who work on glowing bacteria for information about what makes bacteria glow.

Designing Experiments

When a scientist designs an experiment to test her hypothesis, she tries to develop a plan that clearly shows the effect or importance of each factor tested by her experiment. Any factor that can be changed in an experiment is called a *variable.*

Three kinds of variables are especially important to consider when designing experiments:

- **Experimental variables:** Also called *independent variables,* these are the factors you want to test or that are controlled by the researcher.
- **Responding variables:** Also called *dependent variables,* these are the factors you measure. The dependent variable depends on the independent variable and is usually what ends up in your data table.
- **Controlled variables:** These are any factors that you want to remain the same regardless of the changes in the experimental variables.

Scientific experiments help people answer questions about the natural world. To design an experiment,

1. **Make observations about something you're interested in and use inductive reasoning to come up with a hypothesis that seems like a good explanation or answer to your question.**

   For example, you're a runner who trains with a group of friends, and you have a hunch that loading up on pasta, which has lots of carbohydrates, gives you the energy you need to run faster the next day.

2. **Think about how to test your hypothesis.**

   One way to help focus your thinking is to create a prediction about your hypothesis using an "if . . . then" format. Translate that hunch into a proper hypothesis, which looks something like this: If a runner consumes large quantities of carbohydrates before a race, he'll run faster.

3. **Decide on your experimental treatment.**

   The condition or situation you alter in your experiment is your experimental (independent) variable. You can test your hypothesis by convincing half of your friends to eat lots of pasta the night before the race. Because the factor you want to test is the effect of eating pasta, pasta consumption is your experimental variable.

4. **Decide what to measure and how often to make measurements.**

   The changes you measure are your responding (dependent) variables. Race duration is your responding variable because you determine the effect of eating pasta by timing how long each person in your group takes to run the race.

5. **Create two groups of individuals for your experiment.**

   One group is your *experimental group* and the other is a *control group*.

   a. The experimental group receives the experimental treatment; in other words, you vary the one condition you want to test. In this case, you feed your friends pasta.

   b. The control group should be as similar as possible to your experimental group except that it doesn't receive the experimental treatment — so, no pasta for this group.

      For example, you convince half of your friends to eat a meal without pasta the night before the race. For the best results in your experiment, this control group should be as similar as possible to your experimental group so you can be pretty sure that any effect you see is due to the pasta and not some other factor. So ideally, both groups of your friends are about the same age, same gender, and same fitness level. They also eat about the same thing before the race, with the sole exception of the amount of pasta they eat at dinner. All the factors that could be different between your two groups (age, gender, fitness, and diet) but that you try to control to keep them the same are your *controlled variables.*

      Don't confuse controlled variables with the control groups. Controlled variables are the conditions you keep the same for all your groups, while the control group is the group of subjects in your experiment that you don't add any experimental variables to.

6. **Conduct your experiment.**

   Your friends eat their assigned meals the night before the race and then compete in the race the next day.

7. **Make your planned measurements and record them in a notebook.**

   Be sure to date all your observations. The observations you make are the *data* or *results* of your experiment.

   a. *Quantitative data* is numerical data like height, weight, and number of individuals that show a change. You can analyze quantitative data with statistics and present it in graphs.

      Scientists carefully record exact measurements from their experiments and present that data in graphs, tables, or charts. For this example, you average the race times for your friends in each of the two groups and present the information in a small table.

   b. *Qualitative data* is descriptive data like color, health, and happiness. You usually present qualitative data in paragraphs or tables.

      For your race experiment, you might ask your friends how they felt during the race: Did they have lots of energy? Did their energy level feel constant, or did they tire quickly?

8. **Analyze your data by comparing the differences between your experimental and control groups.**

   You can calculate the averages for numerical data and create graphs that illustrate the differences, if any, between your two groups.

   Your graph shows that your pasta-eating friends ran the marathon an average of two minutes faster than your friends who didn't eat pasta.

9. **Use deductive reasoning to decide whether your experiment supports or rejects your hypothesis and to compare your results with those of other scientists.**

   Because your pasta-eating friends ran faster, you may conclude that your hypothesis is supported and that eating pasta does in fact help marathon runners run faster races. You might also look at studies on other factors, like drinking enough water, and how they affect marathon speeds in order to compare the effect of your study to those of other scientists. If the best any other study did was decrease marathon times by 30 seconds and you decreased them by 2 whole minutes, you might conclude that your experimental variable — eating pasta — was more important than the variables tested in the other studies.

10. **Report your results.**

    Explain your original ideas and how you conducted your experiment, present your results, and explain your conclusions.

For a small study like the one I've used as an example, you might just report it informally by telling your friends or writing about it on your blog. But if you were an exercise researcher who conducted a large, well-designed study with lots of marathon runners, you'd write an article about your work and how it compared to the work of other researchers. Scientists in every field have their own special magazines, called *scientific journals.* You'd find a journal appropriate to your work, like *The International Journal of Exercise Science,* and submit your article to the editor. The editor would send your article out to other scientists or your peers in the field so that they could examine your work and decide whether it was good work that was worthy of publishing. Peer review is incredibly important to the process of science because it gives strength to scientific conclusions when others scientists can evaluate the same data and reach the same conclusion.

Scientific articles go through a process called *peer review* before they're published in scientific journals. During peer review, experts in the same field as the article's author examine the scientist's work to decide whether the experiments were conducted properly and whether the author's conclusions are valid based on the evidence collected.

Analyzing an experiment and really understanding experimental design is tough stuff. To help you understand, revisit the mushroom scientists again and take a closer look at their experiments. Questions 6 through 10 refer to the following story:

Two scientists want to test whether a glow-in-the-dark mushroom glows in order to attract insects. To test their idea, they set up an experiment. First, they build three identical chambers that are completely dark. In one chamber, they put a glowing mushroom. In another chamber, they put a light that glows the exact same color as the mushroom. In the third chamber, they put a mushroom that's a close relative to the glowing mushroom but that doesn't glow. The scientists put the same species of insect into each chamber and observe whether the insect flies toward or away from the mushrooms or the light. They repeat this procedure several times in each chamber, using new insects of the same species each time.

6. What's the experimental variable in the scientists' experiment?

a. The type of insect used

b. The size of the chamber

c. The object placed in the chamber with the insect

d. The direction that the insect flies when placed in the chamber

7. What's an example of a controlled variable in the scientists' experiment?

a. The type of insect used

b. The light bulb placed in the chamber with the insect

c. The type of mushroom placed in the chamber with the insect

d. The direction that the insect flies when placed in the chamber

8. What's the control group in the scientists' experiment?

a. The type of insect used

b. The insects placed in the chamber with the glowing mushroom

c. The insects placed in the chamber with the nonglowing mushroom

d. The insects placed in the chamber with the glowing light bulb

9. Which of the following is an example of qualitative data that the scientists may have collected during their experiment?

a. The number of times the insects flew toward the test object

b. The number of times the insects flew away from the test object

c. The pattern of the insects' flight (straight lines versus wandering)

d. The speed at which the insects flew

10. What's the responding variable in the scientists' experiment?

a. The type of insect used

b. The light bulb placed in the chamber with the insect

c. The type of mushroom placed in the chamber with the insect

d. The direction that the insect flies when placed in the chamber

Making an Experiment Count

A scientist may consider all the variables carefully and design a good experiment, but in order for an experiment to be valid and significant to the scientific community, it must meet these standards:

- **Sample size:** The number of individuals that receive each treatment in an experiment is your *sample size.* To make any kind of scientific research valid, the sample size has to be large. If only four of your friends participate in the pasta experiment in the preceding "Designing Experiments" section, you'd have to conduct your experiment again on much larger groups of runners with hundreds of people per group before you could proudly proclaim that consuming large quantities of carbohydrates before a race helps marathon runners improve their speed. The larger the sample size, the more valid the conclusions from an experiment.
- **Replicates:** The number of times you repeat the entire experiment or the number of groups you have in each treatment category are your *replicates.* Suppose you have 60 marathon-running friends and you break them into six groups of 10 runners each. Three groups eat pasta and three groups don't, so you have three replicates of each treatment. (Your total sample size is therefore 30 for each treatment.)
- **Statistical significance:** The mathematical measure of an experiment's validity is referred to as *statistical significance.* Scientists analyze their data with statistics to determine whether the differences between groups are significant. If you perform an experiment repeatedly and the results are within a narrow margin, the results are said to be significant. In your experiment, if the race times for your friends were very similar within each group, and all your pasta-eating friends ran the race two minutes faster than your non-pasta-eating friends, then that two-minute difference actually means something. But what if some pasta-eating friends ran slower than non-pasta-eating friends, and one or two really fast friends in the pasta group lowered that group's overall average? Then you may question whether the two minutes is really significant or whether your two fastest friends just got put in the pasta group randomly.
- **Error:** Science is measured by people, and people make mistakes, which is why scientists always include a statement of possible sources of error when they report the results of their experiments. Consider the possible errors in your experiment. What if you didn't specify anything about the content of the meals without pasta to your non-pasta-eating friends? After the race, you may find out that some of your friends ate large amounts of other sources of carbohydrates, such as rice or bread. Because your hypothesis is about the effect of carbohydrate consumption on marathon running, a few friends eating rice or bread would represent a source of error in your experiment.

Whether a scientist's initial hypothesis is right or wrong isn't as important as whether he sets up well-designed, repeatable experiments that provide necessary information to advance the frontiers of scientific knowledge.

Practice identifying sample size and number of replicates by answering the following questions. Questions 11 and 12 refer to the following story:

Recall from the preceding section that the scientists who were testing glowing mushrooms built three identical chambers. In one chamber, they put a glowing mushroom. In another chamber, they put a light that glows the exact same color as the mushroom. In the third chamber, they put a mushroom that's a close relative to the glowing mushroom but that doesn't glow. To determine whether the glowing color of the mushroom was attracting the insects, the scientists put the same species of insect into each chamber and observed whether the insects flew toward or away from the mushrooms or the light. On Monday, the scientists tested ten insects in each chamber and recorded their results. On Tuesday, they returned to the lab and tested another ten insects in each chamber.

11. What's the sample size for each experimental variable for the scientists' experiment?

a. 3

b. 10

c. 30

d. 60

12. How many replicates did the scientists perform?

a. 2

b. 3

c. 10

d. 60

Building Theories

The knowledge that scientists gather continues to grow and even change slightly over time. Scientists are continually poking and prodding at ideas, always trying to get closer to "the truth." They try to keep their minds open to new ideas and to remain willing to retest old ideas with new technology. In a way, science is an adventure, with scientists as the explorers trying to map new territory. As scientists move into new areas, they create new maps. And as new tools become available, scientists refine old maps, making them more accurate. When a "map" of some particular idea isn't quite finished, scientists may argue over the details of how it should be drawn. Scientists encourage debate over ideas because it pushes them to test their ideas and ultimately adds to the strength of scientific knowledge. The goal in science isn't to win an argument but rather to find the explanation that best fits all the observable data.

Theories are scientific explanations based on a large body of evidence that usually comes from the efforts of many different scientists. Although hypotheses are also explanations, they're based on initial observations and haven't yet been subjected to rigorous testing.

The way scientists use the word *theory* is very different from the way most people use the word. In everyday language, people use the word *theory* to mean a guess, but in scientific language, a theory is as close as scientists get to saying an idea is true. Because scientists never stop exploring and adding to their knowledge, they tend to avoid saying that something is absolutely true or fact. They like to leave a little room open for ideas to be modified or expanded. However, theories are so well-supported by evidence that they rarely undergo big changes. Usually, changes to theories are more along the lines of minor modifications. Scientific theories that most people accept as true include the germ theory of disease (microbes like bacteria can cause disease), the theory of plate tectonics (Earth's surface is made up of separate plates that float upon the Earth's mantle), and the cell theory (all living things are made of cells). The theory of evolution by natural selection is also extremely well supported by many lines of scientific investigation and accepted by most scientists as true.

Can you tell the difference between a hypothesis and a theory? Try the following questions to find out:

13. Two scientists who are studying glowing mushrooms notice that the mushrooms glow the exact same color as some glowing bacteria in the lab next door. One of the scientists says, "I think the glowing chemical inside the mushroom is the same as the glowing chemical inside the bacteria." What type of statement is the scientist making?

a. Scientific (testable) hypothesis

b. Nonscientific guess

c. Scientific theory

d. Deductive reasoning

14. How does the statement made by the scientist in Question 13 compare to a scientific theory? If you think it's a scientific theory, explain why. If you don't think it's a scientific theory, explain how the statement is different from a scientific theory.

Answers to Questions on the Scientific Method

The following are answers to the practice questions presented in this chapter.

1 The answer is **d. Discovery science and making observations.**

The scientists are practicing discovery science because they're describing something rather than doing an experiment. They're making observations because they're using one of their five senses to see the mushrooms.

2 The answer is **b. The mushrooms glow to attract certain insects.**

A hypothesis is a tentative explanation that can be tested using the five senses. The idea that mushrooms are scared of the dark is a tentative explanation, but it's not testable using the five senses. The color of the mushrooms is a simple observation, not an explanation of how or why the mushrooms glow.

3 You should have written something like, "**If the mushrooms glow in order to attract insects, then some insects should be attracted to the glowing mushrooms.**" Remember that predictions are usually written as "if . . . then" statements.

4 The answer is **d. Using deductive reasoning.**

The key word in this question is "decide." The fact that the scientists are deciding something tells you that they've moved beyond making observations and collecting data. Now they're using their brains to make decisions, or conclusions. Their decision is based on the data they've collected, so they're using deductive reasoning.

5 The answer is **a. The number of times a particular type of insect flew toward the glowing mushroom.**

To look at the other possible answers, comparing data requires thinking, so that's part of decision-making. Deciding on a new possible explanation for the glow's purpose is forming a new hypothesis. And talking to colleagues represents communication and collaboration among scientists.

6 The answer is **c. The object placed in the chamber with the insect.**

The experimental variable is the factor that the scientists were testing and therefore changing between treatments.

7 The answer is **a. The type of insect used.**

Controlled variables are factors that the scientists try to keep the same between treatments so they don't affect the outcome of the experiment.

8 The answer is **b. The insects placed in the chamber with the glowing mushroom.**

The control group is a group of subjects that don't receive an experimental treatment. It's often a group that's exposed to what's considered normal conditions. The scientists would compare the results of treatments **c** and **d** with **b** to figure out the effect of type of mushroom versus glow on the insects.

9 The answer is **c. The pattern of the insects' flight (straight lines versus wandering).**

You can measure, or quantify, factors like number of times and speed, so they're examples of quantitative data.

10 The answer is **d. The direction that the insect flew when placed in the chamber.**

The responding variable is what scientists measure.

11 The answer is **b. 10.**

The sample size of an experiment is the number of individuals in a treatment. Each day, the scientists tested 10 individual flies in each chamber.

12 The answer is **a. 2.**

The number of replicates is how many times the scientists repeated their experiment. They did a complete run of their experiment on Monday and again on Tuesday.

13 The answer is **a. Scientific (testable) hypothesis.**

The scientist is proposing an idea based on an observation but not based on detailed testing of the idea.

14 The scientist's statement in Question 13 is a tentative or proposed explanation. To develop a theory, the scientists would have to study glowing mushrooms in a great amount of detail and compare their research to that of other scientists. For example, the scientists studying glowing mushrooms may be interested in understanding why mushrooms glow, how they glow, and whether the ability to glow has evolved many times in living things or just once. If they study their mushrooms and combine their information with that of other scientists to build a larger understanding of how and why living things glow, then they may be able to develop a theory. In science, theories often develop slowly over many years and even over many generations of scientists.