that this student is not simply trying to "get it over with," or simply writing down textbook facts and paraphrases of lecture notes; the student is clearly looking around and thinking—every instructor's dream.

Making Drawings

In both laboratory and fieldwork, it is often necessary to draw what you are seeing, particularly when working with living organisms. And perhaps the most important benefit is that **done properly, the act of drawing forces you to look more carefully at the object or organism before you.** As you draw, pay special attention to the relative sizes, shapes, and textures of different parts. Is part *A* connected to part *B*, or are they only adjacent to each other? Are the widths of parts *A* and *B* similar, or is one part wider than the other and, if so, how much wider? Is part *A* twice as wide as part *B* or 3 times as wide? The closer you look, the more you will see.

If possible, draw using a hard-lead pencil so that you can modify your drawings easily while you work. If you must use a pen, be sure the ink does not smear when wet. Try to figure out what things are as you draw, and label them as you go along. Be sure to indicate the approximate size of what you are drawing, and include a scale bar if appropriate. Most importantly, make your drawings *big* so that they can accommodate plenty of detail. Most beginning students make their drawings much too small; **think big.** Even if you are looking at something through a microscope, your drawing of that something should fill a 4-by-6-inch space. Remember, the goal is not to become a great artist; rather, the goal is to learn how to observe closely and how to record those observations accurately and in sufficient detail.

COMPONENTS OF THE RESEARCH REPORT

A research report is typically divided into 6 major sections:

1. *Abstract.* In the Abstract, you summarize the problem addressed, why the problem was addressed, your approach to the problem, and the major findings and conclusions of your study. This is probably the most difficult part of the report to write well; it summarizes the entire report, so save it for last.
2. *Introduction.* The Introduction, which is often only 1 or 2 paragraphs long, tells why the study was undertaken; a brief summary of relevant background facts leads to a statement of the specific problem being addressed. If appropriate, also describe the specific hypotheses that you set out to test, and the basis for those hypotheses.
3. *Materials and Methods.* This section is *your* reminder of what you did, and it also serves as a set of instructions for anyone wishing to repeat your study in the future.

4. *Results.* **This is the centerpiece of your report.** What were the major findings of the study? Present the data or summarize your observations using graphs and tables to reveal any trends you found. Point out major trends to the reader. If you prepare your tables and graphs carefully, the results can usually be presented in only 1 or 2 paragraphs of text; one picture is worth quite a few words. Avoid interpreting the data in this section.
5. *Discussion.* How do your results relate to the goals of the study, as stated in your Introduction, and how do they relate to the results that might have been expected from background information obtained in lectures, textbooks, or outside reading? Do your results support or argue against the hypotheses presented in your Introduction? What new hypotheses might now be formulated, and how might these hypotheses be tested? This section is typically the longest part of the report.
6. *Literature Cited ("References").* This section includes the full citations for any references (including textbooks, laboratory handouts, and Web sites) that you have cited in your report. Double-check your sources to be certain they are listed correctly; this list of citations will allow interested readers to confirm the accuracy of any factual statements you make and, often, to understand the basis for your interpretations of the data. With only one exception (p. 69), cite only material you have actually read. The proper formats for citing literature and presenting citations are described in Chapter 5.

You may also be asked to include an Acknowledgments section, in which you formally thank particular people for their contributions to the project or to the report. And of course, your report will need an informative title.

Before writing your report, first study a few short papers in a relevant biological journal, such as *Biological Bulletin*, *Developmental Biology*, *Ecology*, or *PLOS ONE*. Your instructor may provide you with a few especially good models. Reading these journal articles for content is unnecessary; you don't need to understand the topic of a paper to appreciate how the article is crafted. But do pay attention to the way the Introduction is constructed, the amount of detail included in the Materials and Methods section, and the material that is—and is not—included in the Results section.

While studying an article or two, note that figures and tables are always accompanied by explanatory captions (for figures) and legends (for tables), and that the axes of graphs and the columns and rows of tables are clearly labeled, with units of measure indicated. Note the location of figure captions and table legends. Study the captions and legends carefully, and imitate them (or improve them) in crafting your own.

WHERE TO START

Beginnings are hardest....How can you write the beginning of something till you know what it's the beginning of?

PETER ELBOW

Strangely enough, you should not begin writing your report with the title, the Abstract, or the Introduction. It is far easier to write the Introduction—and the title—toward the end of the job, after you have fully digested what it is that you have done. And because the Abstract should be a tight summary of the entire report, this would be the worst section to begin with: How can you summarize something you haven't yet written? Save the Abstract (and the title) for later. **Start work with either the Materials and Methods section or the Results section.** Better still, you may profitably work on the two in tandem: Working on the Results section sometimes helps clarify what should be included in the Materials and Methods section, and working on the Methods sometimes clarifies the order in which results should be presented in the Results section.

Because the Materials and Methods section requires the least mental effort, completing it is a good way to overcome inertia. You may not know why you did the experiment or what you found out by doing it, but you can probably reconstruct what you did without much difficulty. Moreover, reminiscing carefully about what you did puts you in the right frame of mind to consider *why* you did it.

WHEN TO START

Start as soon as you can, preferably within 24 hours of finishing the study. In particular, start writing the Materials and Methods section while what you did is still fresh in your mind. Allow time for at least one major revision of each section (Chapter 6). When doing original research, try writing a detailed Materials and Methods section before you even conduct your study. This forces you to think about what you plan to do, how you plan to do it, and why you plan to do it, and can lead to improvements in experimental design before you actually start collecting data.

WRITING THE MATERIALS AND METHODS SECTION

Results are meaningful in science only if they can be obtained over and over, whenever the experiment is repeated. And because the results of any study depend to a large extent on the way the study was done, it is essential that you describe your methods so that your experiment can be repeated in all its essential details. Perhaps the best reason for writing a detailed Materials and Methods section is that it helps you review what you have done in an organized way and starts you thinking about why you have done it. Developing a good Materials and Methods section also puts you in the right frame of mind to do an equally good job on the other sections of the report.

The difficulty in writing this section of a research report (or journal manuscript) is in selecting the right level of detail, as discussed in the next section. Students commonly give too little information; when informed of this defect, they may then give too much information. It's hard to hit it just right, but keeping your audience in mind (yourself and your fellow students) will help.

Determining the Correct Level of Detail

Many students begin with a one-sentence Materials and Methods section: "Methods were as described in the lab manual." Although this sentence meets the criterion of brevity, it is unacceptable as a stand-alone Materials and Methods section. For one thing, studies are rarely performed exactly as described in a laboratory manual or handout. Your instructions may call for the use of 15 animals, for example, but only 12 animals might be available for use on the day of your experiment. In addition, many details of a study will vary from year to year, from week to week, or from place to place and must therefore be omitted from your set of instructions.

Don't get carried away, however. Consider the following overly detailed description of a study involving the growth of radish seedlings:

> On March 5, I obtained 4 paper cups, 400 g of potting soil, and 12 radish seeds. I labeled the cups A, B, C, D and planted 3 seeds per cup, using a plastic spoon to cover each seed with about 1 cm of soil.

The author has used the first sentence simply to list the materials; whenever possible, it is far better to **mention each new material as you discuss what you did with it.** Furthermore, why do we need to know the weight of the soil obtained, or that the cups were labeled A–D rather than 1–4, or that a plastic spoon was used to add soil? Omitting the excess details and starting right in with what was done, we obtain the following:

> On March 5, I planted 3 radish seeds in each of 4 individually marked paper cups, covering the seeds with about 1 cm of potting soil.

Note that the essential details—individually marked cups, 3 seeds per cup, 1 cm of soil—not only survive in the edited version but now stand out clearly. The trick, then, is to determine which details are essential and which details are not. Happily, I've come up with a can't-fail method for getting this right.

Begin by listing all the factors that might have influenced your results. If, for example, you measured the feeding rates of caterpillars on several different diets, your list might look something like this:

Species of caterpillar used	Time of year
Diets used	Time of day
Amount of food provided per caterpillar	Air temperature in room

Manufacturer and model number of any specialized equipment used (e.g., balances, centrifuges, or spectrophotometers)
Size and age of caterpillars
Duration of the experiment
Container size or volume
Number of animals per container
Total number of individuals in the study
Precision of measurements made

Sometimes you will need to think carefully about whether a particular methodological detail might have influenced your results. Do you need to tell readers that you wore a red shirt the day you conducted the experiment? Not if you were studying the effect of different fertilizer concentrations on the growth rates of radish seedlings, but could the shirt have influenced your results if you were observing mating displays among sparrows? Possibly.

This list, which you do not turn in with your report, contains the bricks with which you will construct the Materials and Methods section. Each of the listed details must find its way into your report, although not necessarily in the order in which you jotted them down, because each gives information essential for later replication of the experiment. Some of this information may also help you explain why your results differed from those of others who have gone before you—a topic that will deserve some attention later—in the Discussion section of your report. Details that do not merit inclusion in the list are superfluous and should not appear in your Materials and Methods section.

In describing the procedures followed, **you must say what you did, but you should freely refer to your laboratory manual or handouts in describing how you did it.** For example, you might write

> The 3 diets were distributed to the caterpillars in random fashion, as described in the laboratory manual (Koegel, 2011).

The important point here is that the diets were distributed randomly; the outcome might be quite different if the largest caterpillars were to receive one diet and the smallest caterpillars another. The interested reader (including you, perhaps, at some later date) can refer to the stated source (Koegel, 2011) for detailed instruction in the method of randomization. You might want to append the relevant portion of your handout or manual at the end of your report as an appendix; this is a fine way to keep everything together for later use.

Be sure to note any departures from the given instructions. Suppose you were told to weigh the caterpillars individually but found that your balance was not sensitive enough to record the weight of a single animal. Your laboratory instructor, never at a loss for good ideas, probably suggested that you weigh the

individuals in each container as a group. Your report might then include the following information:

> Determining the weight gained by each caterpillar over the 3-hour period of the experiment required that both initial and final weights be determined. The caterpillars were too small to be weighed individually. Therefore, similar-sized caterpillars were weighed in groups of 3 at a time, to the nearest 0.1 g. The average weight of each caterpillar in the group was then calculated.

Giving Rationales

For your own benefit as well as that of your readers, mention why particular steps were taken whenever you think it might not be obvious. Imagine yourself explaining things to a classmate who has not yet performed the study. We might, for example, profitably rewrite the sentence given on the previous page:

> To avoid prejudicing the results by distributing food according to size of caterpillar, the 3 diets were distributed to the caterpillars in random fashion as described by Koegel (2011).

A similar strategy can be used in writing about studies in molecular genetics:

> To test the sensitivity of *lig4* mutants to ionizing radiation, *lig4*^{169}/*FM7w* females were crossed to *lig4*^{169}/Y males.*

Also be sure to indicate whether you included any controls in your study. For example, if you had been testing the effects of several concentrations of a pesticide on caterpillar feeding rates, you might say something like this:

> The effect of these insecticides on caterpillar feeding rates were tested at the following concentrations: 0 (control), 1, 5, and 10 ppm (Akhtar *et al.*, 2008).

Where necessary, indicate what the controls controlled for (see the example given in the Model Materials and Methods section on p. 157).

Describing Data Analysis

It is also usually appropriate to include any formulas used in analyzing your data. The following sentences, for example, would belong in a Materials and Methods section:

> The data were analyzed by a series of chi-square tests. The rate at which food was eaten was calculated by dividing the weight loss of

*Modified from McVey *et al.*, 2004. *Genetics* 168: 2067–2076.

the food by 3 hours, according to the following formula: Feeding rate = (Initial food weight – final food weight) ÷ 3 h.

Often this information is presented in a separate subsection at the end of the Materials and Methods section (as described in the next section).

Note in this example that **"rates" always have units of "per time."** If it doesn't have units of "per time," it is not a rate (p. 106).

Use of Subheadings

Unless your Materials and Methods section is short (e.g., a single paragraph), **use informative subheadings to help organize and present your material by topic.** The emphasis here is on the word *informative*. Here are some uninformative subheadings relating to a study of shell choice by hermit crabs, followed by more substantive revisions on the same topic.

Uninformative: Field experiment
Informative: Occupancy of damaged and intact shells in the field

Uninformative: Shell choice
Informative: Effect of shell condition on shell choice in the laboratory

Two subsections commonly included at the end of the Materials and Methods section are "Data Analysis" and a description of your study system or organism. An example of a Data Analysis subsection is given on pp. 157–158. Here is a sample subsection describing the study organism from a paper* reporting the role of environmental cues in stimulating larval metamorphosis:

Study Organism

Hydroides dianthus is a tube-dwelling serpulid polychaete found from New England through the West Indies, commonly on the underside of rocks (Hartman, 1969). Individuals are gonochoristic (i.e., they have separate sexes) and release gametes into seawater every 2–4 wk at 23°C (Zuraw and Leone, 1968). The larvae begin feeding 18–24 h after eggs are fertilized and become capable of metamorphosing after about 5 d at 23°C (Scheltema *et al.*, 1981; Bryan and Qian, 1997). The larvae undergo rapid and substantial morphological changes during metamorphosis that readily distinguish metamorphosed individuals from attached larvae (Scheltema *et al.*, 1981).

*Modified from Toonen, R., Pawlik, J.R., 2001. *Mar. Ecol. Progr. Ser.* 224: 103–114.

Alternatively, particularly if the organism or study site was chosen for specific attributes related to the nature of the research question, you could include this sort of information at the end of the Introduction (see pp. 200–201).

Notice how the use of references in this example increases the author's credibility.

A Model Materials and Methods Section

The Materials and Methods section of your report should be brief but informative. The following example completely describes an experiment designed to test the influence of decreased salinity on the body mass of a marine worm. **Note that it is written in the past tense.**

Obtaining and Maintaining Worms

The polychaete worms used in this study were *Nereis virens*, freshly collected from Nahant, MA, and ranging in length between 10 and 12 cm. All treatments were performed at room temperature, approximately 21°C, on April 15, 2013. One hundred ml of full-strength seawater was added to each of six 200-ml glass jars; these jars served as controls, to monitor changes in worm mass in the absence of salinity change. Another 6 jars were filled with 100 ml of seawater diluted by 50% with distilled water.

Monitoring Water Gain and Loss

Twelve polychaetes were quickly blotted with paper towels to remove adhering water and were then weighed to the nearest 0.1 g using a Model MX-200 Fisher/Ainsworth balance. Each worm was then added to one of the jars of seawater. Blotted worm masses were later determined 30, 60, and 120 minutes after the initial masses were determined.

Determining Osmotic Concentration

The initial and final osmotic concentrations of all test solutions were determined using a Wescor VAPRO vapor pressure osmometer, following instructions provided in the handout (Podolsky, 2010).

Data Analysis

The rate at which mass increased over time was examined by linear regression analysis, after log-transforming the independent variable (time). A series of Student's *t*-tests were used to assess the effect of salinity on the rate of mass increase, by comparing mean masses of worms in the 2 treatment groups at 30, 60, and 120 minutes.

Note that all essential details have been included: temperature, species used, size of animals used, number of animals used per treatment, number of animals per container, volume of fluid in the containers, type and size of containers, time of year, equipment used, units of measurement, and how the data were analyzed. After reading this Materials and Methods section, you could repeat the study if you wanted to (or had to). Note, too, that **the writer has made clear why certain steps were taken;** 3 jars of full-strength seawater served as controls, for example, and worms were blotted dry to remove external water. The fact that worms were blotted dry before their mass was determined was mentioned because that's a procedural detail that would obviously influence the results. On the other hand, the author does not describe how the balance and osmometer were operated because these techniques are standard, and the author does not tell us whether he or she used a clock or a stopwatch to monitor the passage of time because that choice could not have influenced the results obtained. The author has written a report that might be useful to someone in the future—and ends up with a top grade.

On to the Results!

WRITING THE RESULTS SECTION

The Results section is the most important part of any research report. Other parts of the report reflect the author's *interpretation* of the data. Interpretations necessarily reflect the author's biases, hopes, and opinions, and they are always subject to change, particularly as new information becomes available. In contrast, as long as a study was conducted carefully, and as long as the data were collected carefully, analyzed correctly, and presented accurately, the results are valid regardless of how interpretations change over time. Our understanding about how immune systems work has changed remarkably over the past few decades, for example, and the current interpretation of older data differs considerably from the original interpretation. But the older data are still valid. The *results* of any study are real; the *interpretations* often change. That's why the Results section is indeed the centerpiece of your report.

In this section, you summarize your findings, using tables, graphs, and words. The Results section is

1. Not the place to discuss why the experiment was performed.
2. Not the place to discuss how the experiment was performed.
3. Not the place to discuss whether the results were expected, unexpected, disappointing, or interesting.

Simply present the results, drawing the reader's attention to the major observations and key trends in the data. Don't interpret them here. Most of the work in preparing this section of the report involves constructing a clear and well-organized presentation of data in the form of tables and figures.

What Is a "Figure"?

Note that in all of the examples given in this chapter, data summaries are formally referred to as either tables or figures. **"Figures" include graphs of all types; photographs of all types, whether of organisms or of electrophoretic gels; drawings; maps (showing the location of a study site, for example); and flowcharts. Anything and everything, in fact, that is not a "table" is a figure.** Most of your data will probably be presented in the form of tables and graphs.

Summarizing Data Using Tables and Graphs

Before you even think about writing your Results section, you must work with your data. The observations you've made and the data you've collected most likely contain a story that is crying out for recognition. Contrary to popular opinion, the purpose of showing data in tables and graphs is not to add bulk to laboratory reports. Rather, **you wish to arrange the data in tables and graphs to reveal trends** and to make the most important points stand out, not only to your instructor but, more importantly, to yourself. The trick now is to organize the data so that (1) the underlying story is revealed and (2) the task of revealing the story to your reader is simplified.

There is no single right way to present data summaries; use any system that illustrates the trends clearly. First decide what relationships might be worth examining. Suppose we return to the experiment in which caterpillars fed for 3 hours on 3 diets. We determined both the initial mass of food provided and the mass of food remaining after the 3-hour period so that we could calculate the mass of food eaten per caterpillar per hour. In your report, you should provide a sample calculation so that if you make a mistake, your instructor can see where you went wrong. We also know the initial and final weights of the caterpillars for each diet and the initial and final weights of dishes of food in the absence of caterpillars; these control dishes will tell us the amount of water lost from the food by evaporation.

What relationships in the data might be especially worth examining? **The first step in answering this question is to make a list of specific questions that might be worth asking**, as follows:

1. Did the caterpillars feed at different rates on the different diets? That is, did feeding rate vary with diet?
2. Did larger caterpillars eat faster than smaller caterpillars? That is, did feeding rate vary with caterpillar size?

3. How does the mass gained by a caterpillar relate to the mass lost by the food?
4. Did the mass of the control dishes change, and, if so, by how much?

The first question on this list was inspired by the null hypothesis established at the start of the study (in this case, H_0 = diet has no effect on feeding rate; see Chapter 4). But the other issues arose only after the data were collected and examined. **In scrutinizing your data, do not limit yourself to the questions and hypotheses posed at the start of your study.**

As in preparing the Materials and Methods section, this list of questions is for your own use and is not to be included in your report. Don't take any shortcuts here. Write these questions in complete sentences. Once you have this list of questions, it is easy to list the relationships that must be examined in your Results section:

1. Feeding rate as a function of diet
2. Feeding rate as a function of caterpillar size
3. Caterpillar mass increase (g) versus loss in mass of food for each caterpillar
4. Decline in food mass (g) in the presence of caterpillars versus decline of food mass in controls

Note that your listing of specific questions can also serve as an excellent basis for preparing good figure captions, (as discussed on (pp. 163, 180).

Constructing a Summary Table

Now you must organize your data into a summary table in a way that will let you examine each of these relationships. Consider Table 9.1. This rough draft lists all the data obtained in the experiment. This summary table is for your own use; it is not usually something to be submitted as a formal part of your report. **Your goal here is to tidy up your data so that you can work with it more easily.**

For the first relationship in our list (feeding rate as a function of diet), a simple table will tell the entire story. For your report, you can simply present an abbreviated summary table, with explanatory caption, as in Table 9.2. Note that one of the caterpillars offered diet *A* ate no food and lost mass during the experiment. This individual died during the study, and the associated data were therefore omitted from Table 9.2. (The loss in mass for this caterpillar probably reflects evaporation of body water.)

To Graph or Not to Graph

Finally, the time has come to reveal more subtle trends that may be lurking in the data. These trends may not be readily apparent from the summary table

Table 9.1 Summary of raw data.

Diet	Initial Caterpillar Mass (g)	Final Caterpillar Mass (g)	Caterpillar Mass Change (g)	Mass of Food Lost (g) over 3 h	Feeding Rate (g food lost/h) of Caterpillar
A (Wheat germ)	8.05	9.55	+1.55	3.65	15.2×10^{-2}
A	4.80	5.80	+1.00	1.74	7.2×10^{-2}
A	5.50	7.00	+1.50	3.33	13.9×10^{-2}
A	5.50	4.70	~~−0.80~~	~~0.00~~	0
A	5.90	6.95	+1.05	1.35	5.6×10^{-2}
Average	5.95	6.80	+1.28	2.52	8.4×10^{-2}
B (sinigrin 10^5 M)	4.40	5.11	+0.71	2.19	9.1×10^{-2}
B	5.20	5.60	+0.40	1.25	5.2×10^{-2}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
Control 1 (no caterpillars)	—	—	—	0.22	—
2	—	—	—	0.10	—
3	—	—	—	0.16	—

Table 9.2 The effect of sinigrin (allyl glucosinolate) added to a basic wheat germ diet on food consumption of *Manduca sexta* caterpillars over 24 hours.

Diet	No. Caterpillars	(Mean g food eaten/ caterpillar/h)
Wheat germ control	4*	8.4×10^{-2}
Sinigrin (10^{-5} M)	5	7.9×10^{-2}
Sinigrin (10^{-3} M)	5	3.8×10^{-2}

**One individual died during the study without eating any food.*

(Table 9.1); the trends may be made visible, however, both to you and your reader, through carefully designed and executed graphing. A word of caution: **Do not automatically assume that your data must be graphed.** If you can tell your story clearly using only a table—for example, if you are not interested in visualizing trends—a graph is superfluous. In other cases, you may be able to summarize some aspects of the data without using any graphs or tables at all. You might write, for example, "No animals ate at temperatures below 15°C" and then present data only for animals held at higher temperatures. **In any event, never present the same data in both a graph and a table.**

See Technology Tip 7 at the end of this chapter if you will be using Excel to plot graphs. In this chapter, a "thumbs up" symbol indicates a well-constructed, model graph, whereas a "thumbs down" symbol indicates a graph that suffers one or more major defects.

Graphs in biology generally take one of two basic forms: scatter plots (point graphs) or histograms and bar graphs. For the second relationship we wish to examine using the caterpillar data—feeding rate versus caterpillar size—a scatter graph, like the one shown in Figure 9.4, will be especially appropriate.

In examining Figure 9.4, note the following:

1. Each axis of the graph is clearly labeled and includes units of measurement.
2. Tick marks on both axes are at intervals frequent enough to allow readers to estimate the value of each data point.
3. The meaning of each symbol is clearly indicated.
4. **The symbols chosen facilitate interpretation of the graph:** Darker symbols represent increasing concentrations of sinigrin in the diet.
5. **The symbols are large and easy to tell apart.** Avoid using squares and circles of the same type (e.g., open square and open circle) on the same graph; these symbols can be difficult to tell apart.

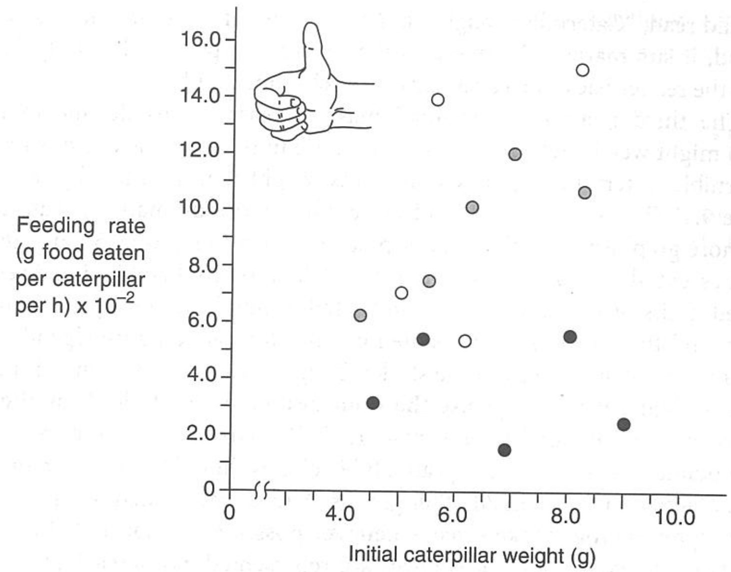


Figure 9.4 The relationship between initial caterpillar mass and rates of food consumption for *Manduca sexta* feeding for 3 hours on 1 of 3 diets at 24°C. Each point represents data from a different individual. Feeding rates varied from about 0.01 to 15 g eaten per caterpillar^{-1} h^{-1}. o = wheat germ control diet; ● = 10^{-5} M sinigrin; ● = 10^{-3} M sinigrin.

6. A detailed explanatory caption (figure legend) is below the figure. **Please note that a figure caption should never begin with a statement that simply repeats the axis labels. Rather, the caption should reflect the specific question that the figure addresses. For example, rather than beginning a caption with something like, "Plasma histamine concentrations in rats (*Rattus norvegicus*) as a function of time at different levels of neurotensin," you would instead write something like this: "The impact of neurotensin on plasma histamine concentrations in the rat, *Rattus norvegicus*."**

All of your graphs should exhibit these 6 characteristics. In Figure 9.4, it would be insufficient to simply label the *y*-axis "Feeding Rate." Feeding rates can be expressed as per minute, per hour, per day, or per year and as per animal, per group of animals, or per gram of body weight. Similarly, it is unacceptable to label the *x*-axis as "Weight," or even as "Caterpillar Weight." Don't make readers guess what you have done. From the figure caption, the axis labels, and the graph itself, the reader should be able to determine the question being asked, get a good idea of how the study was done, and be able to interpret the figure without referring to the text (see pp. 164 and 180–181). Similarly, note that the caption for Figure 9.5 does not simply restate the axis labels; if it did, it would read, "Caterpillar weight gain as function of the weight loss of food." Instead, it summarizes the question that drove this part of the study. Never make the reader back up; **a good graph is self-contained.**

The third relationship (animal mass increase versus decline in food mass) might well be left in table form because in this case the trend is readily discernible; caterpillars always gained less weight than that lost by the food (Table 9.1). The same trend could be revealed more dramatically (or, let us say, more graphically) with a scatter plot, as shown in Figure 9.5, but a graph is not essential here. Again, note the steps taken to avoid ambiguity: Axes are labeled, units of measurement are indicated, symbols are interpreted on the graph, and the figure is accompanied by an informative figure legend. Note also that the symbols used in the student's Figure 9.5 are consistent with their usage in Figure 9.4. **Always use the same system of symbols throughout a report** so as not to confuse your reader; if filled circles are used to represent data obtained on diet *A* in one graph, filled circles should be used to represent data obtained on diet *A* in all other graphs. And, as mentioned previously, **try to use symbols that make sense whenever possible.** In Figures 9.4 and 9.5, increasing concentrations of sinigrin are represented by increasingly darker symbols. Similarly, if you were comparing metabolic rates at different times of day, you could help readers interpret your data, for example, by representing daytime measurements with open symbols and nighttime measurements with solid symbols. Note also that the order of symbols in the key corresponds to their placement in the figure, in which most of the open symbols lie above most of the filled symbols. Do whatever you can do to ease interpretation for the reader.

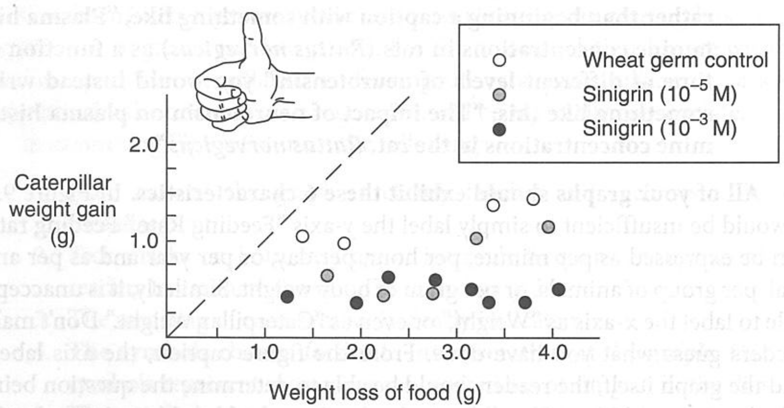


Figure 9.5 Increases in caterpillar mass as a function of food consumption for *Manduca sexta* fed for 3 hours on one of 3 diets at 24°C. Points falling on the dotted line would indicate equality between weight gained and food eaten. Each point represents data from a different individual.

The fourth relationship in our list considers weight loss by food in control dishes (no caterpillars). No graphs or tables are needed here; 2 sentences will do:

> Control containers exhibited less than a 3% loss in mass (N = 3 containers) during the 24-h period. In contrast, food in containers with caterpillars lost at least 23% of their initial mass.

If the loss in mass had been substantial, perhaps 5% to 10% or more of initial mass, you might wish to adjust all the data in your tables accordingly before making other calculations:

> Control containers lost 7.6% of their initial mass (N = 3 containers) over the 24-h period. We therefore adjusted our other measurements for this 7.6% evaporative loss before calculating feeding rates.

You would then provide a sample calculation, both for your instructor to examine and so that you will remember what you did if you consult your report again at a later date. A less desirable but nevertheless acceptable alternative would be to state the magnitude of the evaporative loss of mass in your Results section and then bring this point up again when interpreting your results in the Discussion section. In this case, you would label appropriate portions of graphs and tables as "Apparent Feeding Rates" rather than "Feeding Rates." Again,

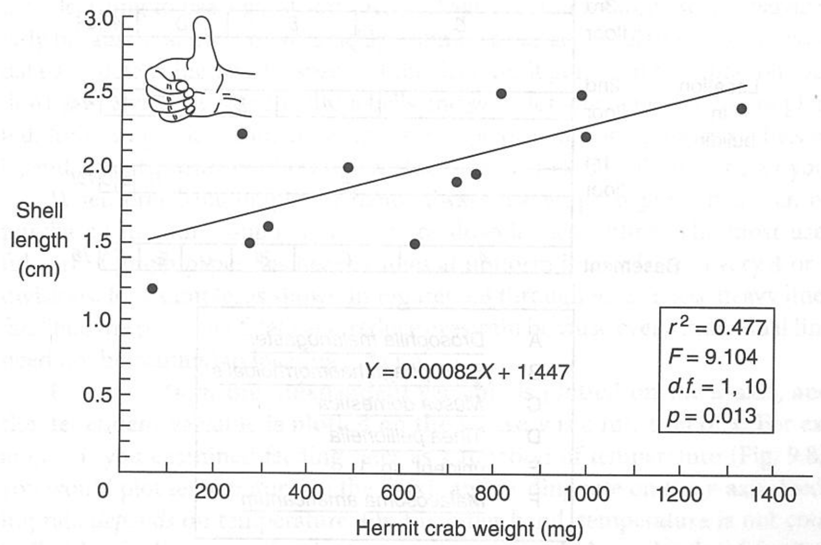


Figure 9.6 Relationship between wet weight (mg) of the hermit crab *Pagurus longicarpus* and the size of the periwinkle shells (*Littorina littorea*) occupied at Nahant, MA, on September 23, 2008 ($N = 12$). Each point represents a measurement on a single individual.

although there are many wrong ways to present the data, there is no single right way; you must simply be complete, logical, consistent, and clear.

Note that in Figure 9.5, the student has defined the symbols directly in the graph rather than in the figure caption (compare with Fig. 9.4). When appropriate, you can also use empty space to report the results of statistical analyses, as in Figure 9.6, thus making the figure even more self-sufficient. Don't do this, however, if it will make the graph cluttered and difficult to read; instead, put the information in the caption or in the text of the Results section.

If the slope of the regression line had not been significantly different from zero, by the way, the student would have included neither the line nor the equation of the line in the figure (or elsewhere in the report).

So far, we have looked only at examples of tables and point plots. If you were studying the differences in species composition of insect populations trapped in the light fixtures on 4 different floors of your biology building, a bar graph, as in Figure 9.7, might be more suitable. Note again that the axes are clearly labeled, including units of measurement, and that an explanatory

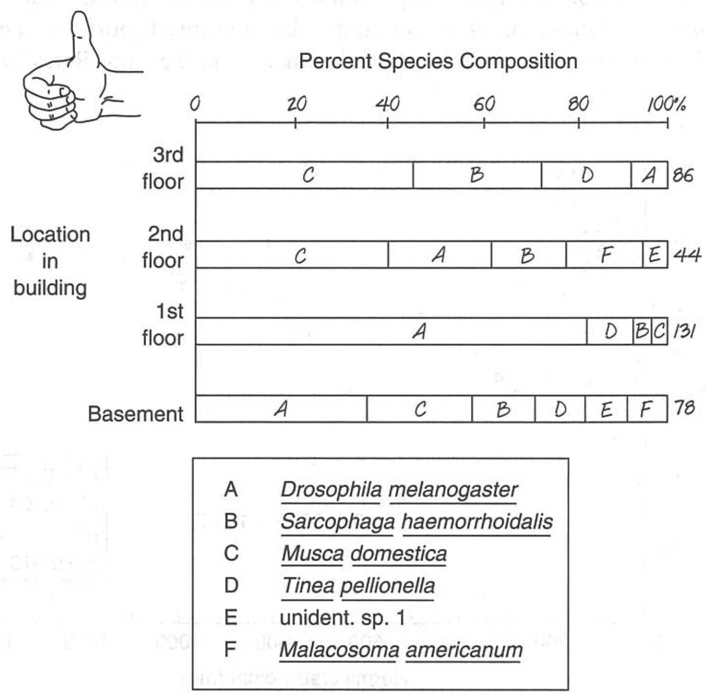


Figure 9.7 The distribution of insect species collected from light fixtures on 4 floors of the biology building on May 5, 2010. The number to the right of each bar gives the total number of insects collected on each floor.

legend accompanies the figure. Don't make readers back up; make each figure self-sufficient. Note also that the graph tells an interesting story; given that *A* is the fruit fly *Drosophila melanogaster*, it is not difficult to guess where the genetics laboratory is located!

Use tables and graphs only if they make your data work for you; if a table or graph fails to help you summarize some trend in your results, it contributes nothing to your report and should be left out. Be selective. Don't include a drawing, graph, or table unless you plan to discuss it, and include only those illustrations that best help you tell your story.

Preparing Graphs

Graphs may be constructed with the aid of a computer (see Technology Tip 7), but unless your instructor suggests otherwise, don't feel that you *must* submit computer-generated graphs to earn a top grade. Most instructors would rather see a carefully thought-out, neatly executed graph done by hand than a poorly thought-out, neatly executed piece of computer graphics. To emphasize the point, I have retained many hand-drawn graphs in this book. I have seen some gorgeous pieces of complete garbage prepared using computers: I would rather see beginning students spend less time learning to use software and more time thinking about what they present, how they present it, and why they present it.

On the other hand, once you have mastered the key principles of graphing data, learning to use a good software package is certainly worthwhile, particularly because it allows you to quickly examine a variety of relationships in your data and determine which aspects of the data merit graphical presentation. But don't get carried away with all the bells and whistles; once the graphs are plotted, for example, it is sometimes faster to type or hand-print the axis labels or legends than to figure out how to have the computer execute these steps for you.

When preparing graphs by hand, always use graph paper, which can be purchased in your campus bookstore or downloaded online. The most useful sort of graph paper has heavier lines at uniform intervals—at every 4 or 5 divisions, for example, as shown in Figures 9.8 through 9.12. These heavy lines facilitate the plotting of data and reduce eyestrain because every individual line need not be counted in locating data points.

By convention, the independent variable is plotted on the *x*-axis, and the dependent variable is plotted on the *y*-axis: *y* is a function of *x*. For example, if you examined feeding rates as a function of temperature (Fig. 9.8), you would plot temperature on the *x*-axis and feeding rate on the *y*-axis; feeding rate *depends* on temperature. On the other hand, temperature is not controlled by feeding rate; that is, temperature varies independently of feeding rate. Temperature is the independent variable and is plotted on the *x*-axis. Note that each point in Figure 9.8 represents data averaged from 5 individuals so

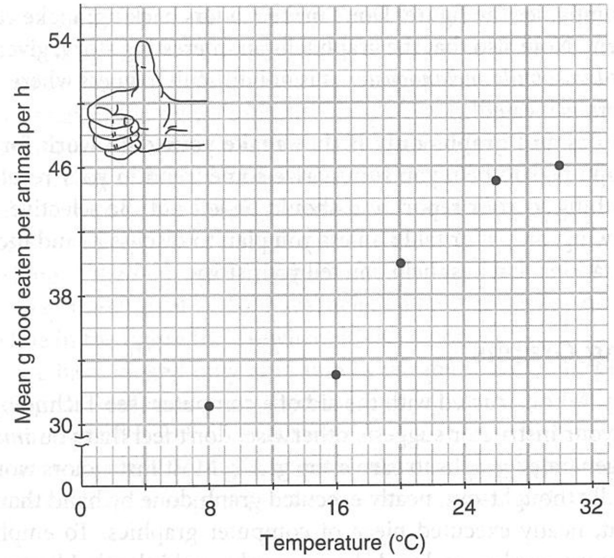


Figure 9.8 Feeding rate of *Manduca sexta* caterpillars on standard wheat germ diet as a function of environmental temperature. Each point represents the mean feeding rate of 5 individuals measured over 24 hours.

that each point is an average value, or a "mean" value. This is clearly indicated in the *y*-axis label and in the figure caption.

It is a good practice to label the axes of graphs beginning with 0. To avoid generating graphs with lots of empty, wasted space, breaks can be put in along one or both axes, as in Figure 9.8 (see also Fig. 9.4 and Figs. 9.11–9.13). If a break had not been inserted in the *y*-axis of Figure 9.8, for example, the graph would have been less compact, with much wasted space, as in Figure 9.9.

(Not) Falsifying Data

You cannot move, add, or delete data points to improve or create trends in your data. Report the data you actually collected. **Falsifying data is, perhaps even more than plagiarism, an unforgivable offense,** and one that can get you into serious trouble. Biologists build on the work of others, and that involves a lot of trust. Believe in the data that you collected, and present it unaltered. Sometimes unusual or unexpected results lead to interesting new questions or discoveries.

The Question: To Connect or Not to Connect the Dots?

After plotting data points, lines are often added to graphs to clarify trends in the data. It is especially important to add such lines if data from several treatments

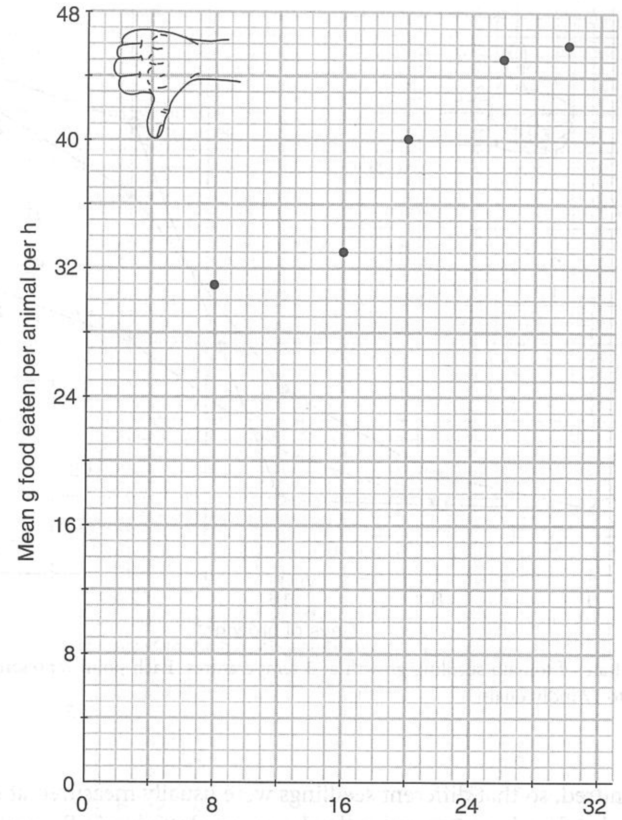


Figure 9.9 Feeding rate of *Manduca sexta* caterpillars on standard wheat germ diet as a function of environmental temperature. Each point represents the mean feeding rate of 5 individuals measured over 24 hours.

are plotted on a single graph, as in Figure 9.10. Note that this graph has been made easier to interpret by using different symbols for the data obtained at each temperature, and that the zero point on the *x*-axis has been displaced to the right, to prevent the first data point from lying on the *y*-axis, where it might be overlooked (compare with Figure 9.11, in which the first point does lie on the *y*-axis). Note also that each line is labeled. Using a key instead would have required readers to work a little harder in interpreting the graph.

In some cases, it makes more sense to draw smooth curves than to simply connect the dots. For example, suppose we have monitored the increase in height of tomato seedlings over some period of time in the laboratory. Every week, we randomly selected 15–20 seedlings to measure from the laboratory population of

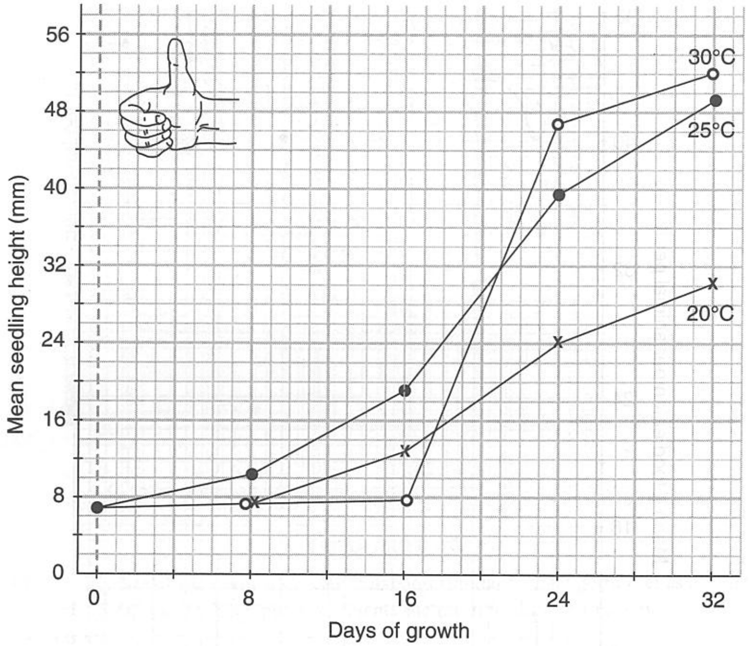


Figure 9.10 Rate of tomato seedling growth at 3 temperatures. Each point represents the mean height of 15 to 17 individuals.

several hundred, so that different seedlings were usually measured at each sampling period. After about 2 months, the data were plotted as in Figure 9.11.

Connecting the dots would not be the most sensible way to reveal trends in the data of Figure 9.11 because we know that the seedlings did not really shrink between days 20 and 28 or between days 36 and 44; simply connecting the points would suggest that shrinkage had occurred. The apparent decline in seedling height reflects the considerable variability in individual growth rates found within the same population, as well as the fact that we did not measure every seedling in the population on every sampling day. In this case, the trend in growth is best revealed by drawing a smooth curve, as shown in Figure 9.12.

When plotting average values (usually called *arithmetic means*) on a graph, **always include a visual summary of the amount of variation** present in the data by adding bars extending vertically from each point plotted (Fig. 9.12). You may, for example, choose to simply illustrate the range of values obtained in a given sample. More commonly, you would plot "error bars" (typically the standard error or standard deviation about the mean), giving a visual impression of how much individual data points differed from the calculated mean values, as in Figure 9.12. The less overlap there is between error bars, the more likely

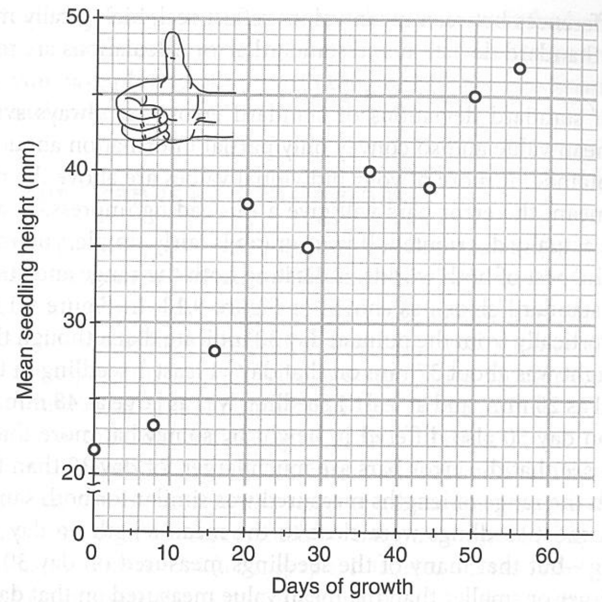


Figure 9.11 Rate of tomato seedling growth at 20°C. Fifteen to 20 seedlings, out of 205 seedlings in the population, were measured on each day of sampling.

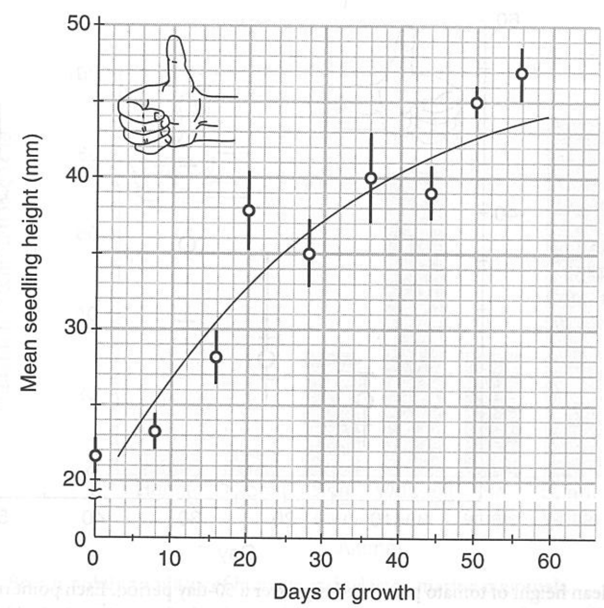


Figure 9.12 Rate of tomato seedling growth at 20°C. On each day of sampling, 15–20 seedlings were randomly sampled from a group of 205 seedlings and measured. Error bars represent one standard deviation about the mean.

it is that differences between mean values reflect real, biologically meaningful differences. Standard deviation and standard error calculations are reviewed in Chapter 4.

Plots of standard deviations or standard errors are always symmetrical about the mean value and so convey only partial information about the range of values obtained. If more of your individual values are above the mean than below the mean, the error bars will give a misleading impression about how the data are actually distributed. If your graph is fairly simple, you may be able to achieve the best of both worlds, indicating both the range and standard deviation (or standard error), as shown in Figure 9.13. In Figure 9.13, the bars extending vertically from the point at day 30 indicate that although the average seedling height was about 37 mm on that day, at least 1 seedling in the sample was as small as 25 mm, and at least 1 seedling was as large as 48 mm. Seedlings measured on day 50 also differed in height by somewhat more than 20 mm. But we also see that the error bars are much larger for day 30 than for day 50, even though the range of lengths measured was similar for both samples. This tells us that most seedlings were close to the mean length on day 50—about 42 mm long—but that many of the seedlings measured on day 30 were substantially larger or smaller than the mean value measured on that day.

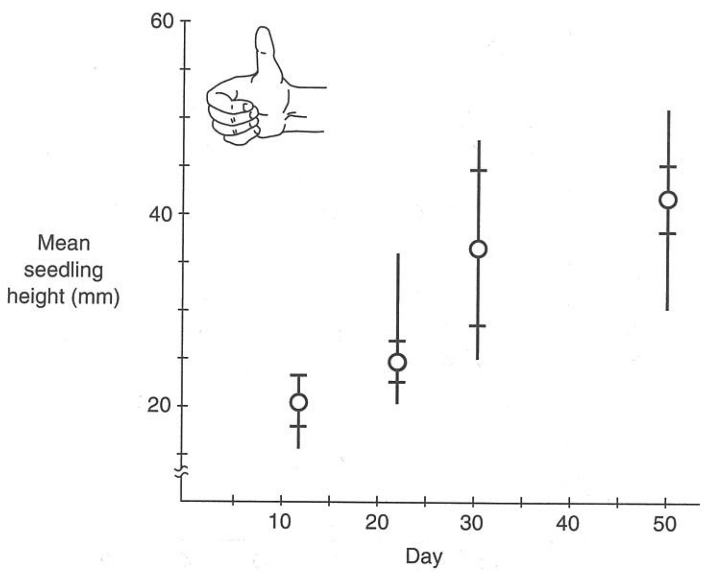


Figure 9.13 Mean height of tomato plant seedlings over a 50-day period. Each point represents the mean height of 18 seedlings raised at 20°C, with a photoperiod of 12L:12D. Vertical bars represent the range of heights; cross-bars represent 1 standard deviation about the mean.

Whether you choose to plot standard deviations, standard errors, ranges, or some other indicator of variation, **be sure to indicate in your figure caption what you have plotted, along with the number of measurements associated with each mean.**

Making Bar Graphs and Histograms

When the variable along the *x*-axis (the independent variable) is numerical and continuous, points can be plotted and trends can be indicated by lines or curves, as we have seen in Figures 9.4–9.12. In Figure 9.8, for example, the *x*-axis shows temperature rising continuously from 0°C to 32°C, with each centimeter along the *x*-axis corresponding to a 4°C rise in temperature. Similarly, the *x*-axes of Figures 9.11 and 9.12 reflect the march of time, from 0 to 60 days, with each centimeter along the *x*-axis reflecting 10 additional days.

When the independent variable is nonnumerical or discontinuous, or when the independent variable represents a range of measurements rather than a single measurement, the data are represented by bars, as shown in Figures 9.14 and 9.15. The *x*-axis of Figure 9.14 (a bar graph) is labeled with the names of different mammals. In contrast to the *x*-axes of Figures 9.4–9.13, the *x*-axis of Figure 9.14 does not represent a continuum: No particular quantity continually increases or decreases as one moves along the *x*-axis, and a line connecting the data for

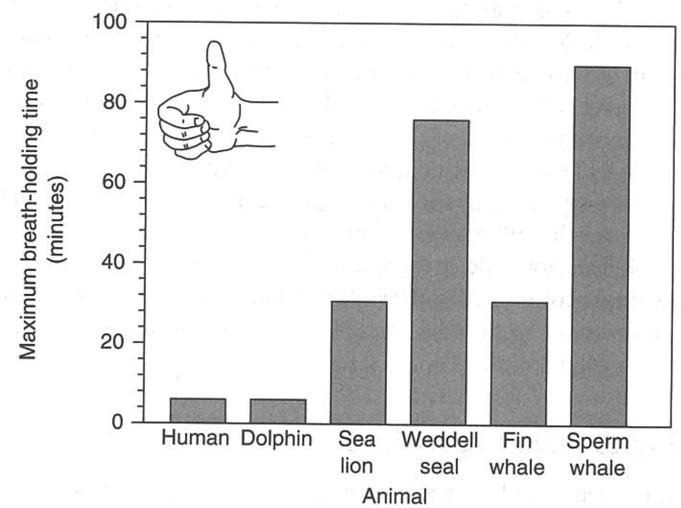


Figure 9.14 Breath-holding abilities of humans and selected marine mammals.

Data from Sumich, J.L. 1999. An Introduction to the Biology of Marine Life, *7th ed. WCB/McGraw-Hill, Publishers.*

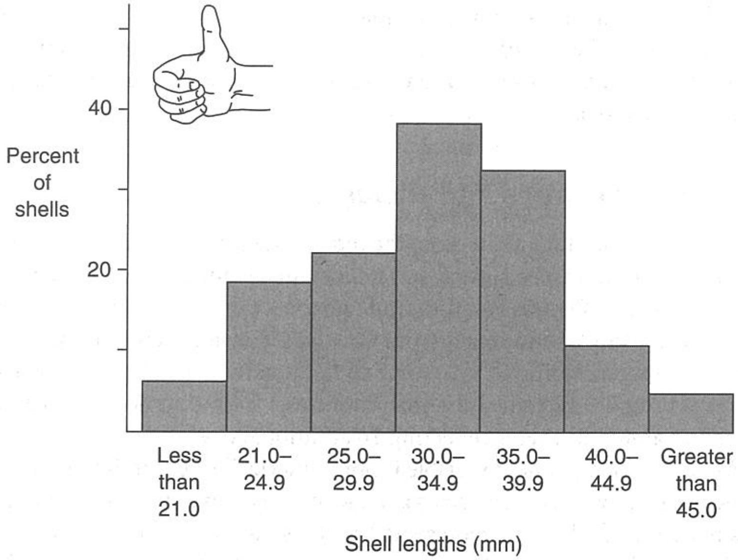


Figure 9.15 Size distribution of snail shells (*Littorina littorea*) collected from the low intertidal zone at Blissful Beach, MA, on August 15, 2010. Only living animals were measured. A total of 197 snails were included in the survey.

sea lion and Weddell seal would be meaningless. In Figure 9.15 (a histogram), the data for shell length are numerical but are grouped together (e.g., all shells 25.0–29.9 mm in length are treated as a single data point). Note also that the magnitude of the size categories represented by the different bars varies: The leftmost bar represents the percentage of shells found within a range of about 0.1–21 mm in length, whereas each of the next several bars to the right represents the percentage of shells found within a range of only about 5 mm in length. The size range of shells represented by the bar at the extreme right side of the graph is unknown. We know that all shells found in this category exceeded 45 mm in length, but the graph does not indicate the size of the largest shell.

Use a single color or fill pattern for all bars unless there is a logical reason not to do so. In Figures 9.14 and 9.15, for example, all bars should be the same color or fill pattern.

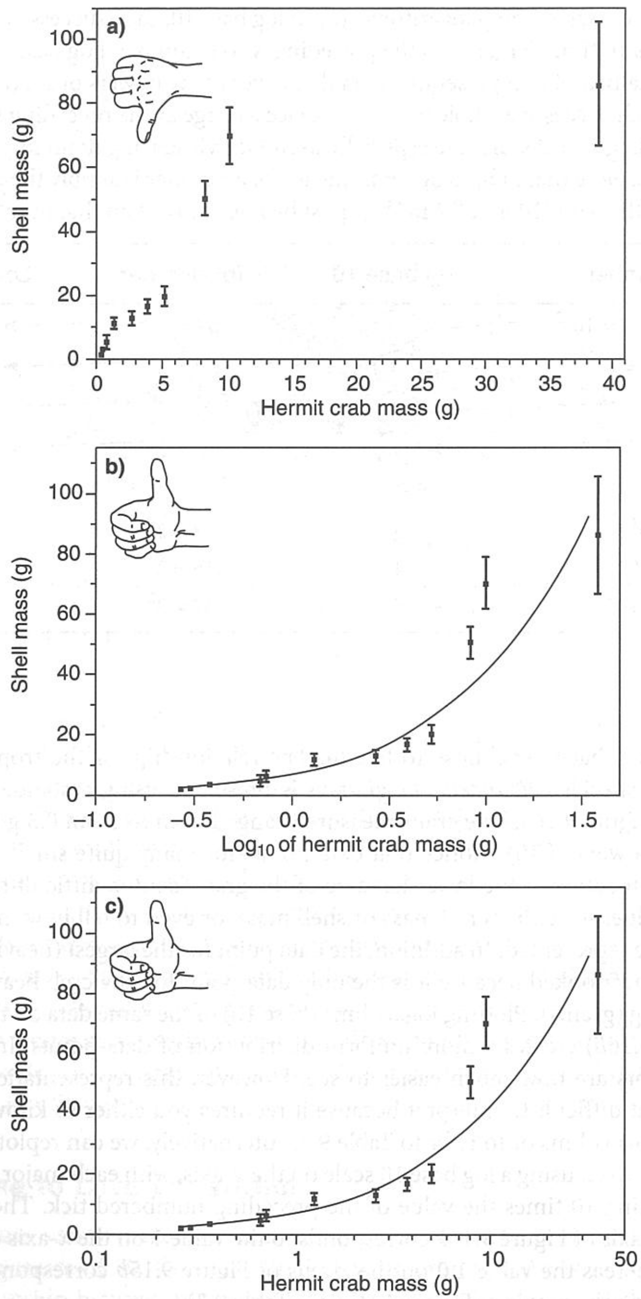
Learning to Love Logarithms

Logarithmic scales make excellent sense when the data presented cover 2 or more powers of 10. Consider the following example: We wish to explore the relationship between the size of hermit crabs and the mass of the empty

Table 9.3 Understanding logarithms. (a) In log base 10, each successive whole number is 10 times larger than the preceding whole number. Log base 10 scales are especially useful in presenting data that cover many powers of 10. (b) In log base 2, each successive whole number is twice as large as the preceding whole number. Log base 2 scales are especially useful for visualizing doublings of quantities. Note that in both systems, the log of a number is simply the exponent to which the base (10 in "a," 2 in "b") must be raised to obtain that number.

(a) Number	Log base 10	(b) Number	Log base 2
$0.01 = 1/100 = 10^{-2}$ →	−2	$1/4 = 2^{-2}$ →	−2
$0.1 = 1/10 = 10^{-1}$ →	−1	$1/2 = 2^{-1}$ →	−1
$1 = 10^0$ →	0	$1 = 2^0$ →	0
$10 = 10^1$ →	1	$2 = 2^1$ →	1
$100 = 10^2$	$4 = 2^2$	2	
$1{,}000 = 10^3$	3	$8 = 2^3$	3
$10{,}000 = 10^4$	4	$16 = 2^4$	4
$100{,}000 = 10^5$	5	$32 = 2^5$	5

snail shells that they choose to live in. The relationship for the tropical hermit crab species *Clibanarius longitarsus* is presented using a standard linear scale in Figure 9.16*a*. The crabs measured ranged in mass from 0.3 g to nearly 40 g (2 powers of 10). Notice that data points for many quite small crabs are crowded together at the lower left side of the graph so it is difficult to tell the actual values for either crab mass or shell mass, or even to tell how many data points are represented. In addition, the data point for the largest (heaviest) crab is easily overlooked because it is the only data point for any crab heavier than about 10 g (grams). Plotting logarithms (base 10) of the same data on the x-axis (Figure 9.16*b*) creates a more uniform distribution of data points. Individual data points are now much easier to see. However, this representation is still somewhat difficult to interpret because it requires you either to know how to decode logarithms or to refer to Table 9.3. Alternatively, we can replot the data of Figure 9.16*a* using a log base 10 scale on the x-axis, with each major tick now representing 10 times the value of the preceding numbered tick. The value 0 on the x-axis of Figure 9.16*b* corresponds to the value 1 on the x-axis of Figure 9.16*c*, whereas the value 1.0 on the x-axis of Figure 9.15*b* corresponds to the value 10 on the x-axis of Figure 9.16*c* (see Table 9.3).



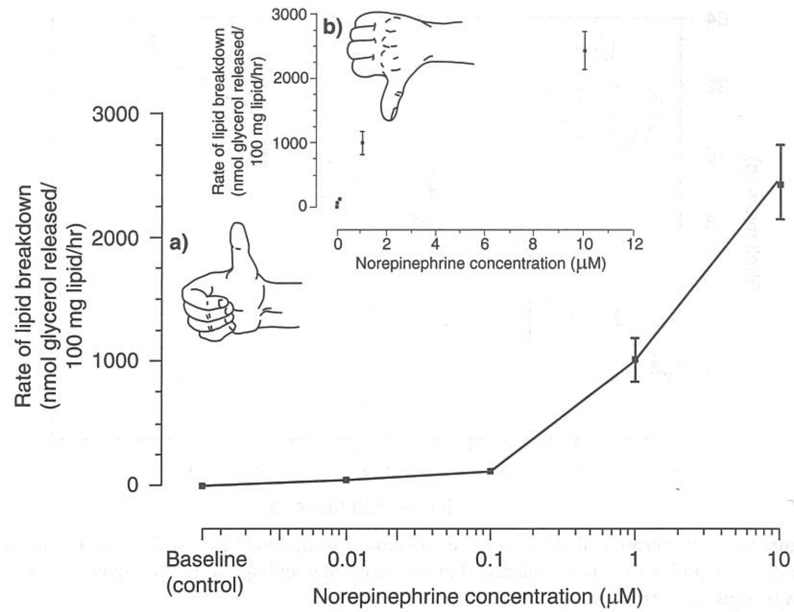


Figure 9.17 Influence of the neurotransmitter norepinephrine (= noradrenaline) on rate of lipid breakdown in the subcutaneous fatty tissue of hibernating marmots (*Marmota marmota*). Each point represents the mean of 11 determinations, and error bars represent 1 standard deviation about the mean. Note that the norepinephrine concentrations used in the study encompass 4 powers of 10, a situation that typically calls out for logarithmic data representation. (a) The data plotted using a log base 10 scale on the *x*-axis. (b, inset) The same data plotted much less effectively, using a normal linear scale.

Based on data of N. Cochet et al., 1999. Regional variation of white adipocyte lipolysis during the annual cycle of the alpine marmot. Comp. Biochem. Physiol. C *123: 225–232.*

Similarly, compare the clarity of Figure 9.17*a* with that of the inset (Figure 9.17*b*). In this case, the data extend through 4 powers of 10. Note how most of

Figure 9.16 The relationship between the mass of hermit crabs (*Clibanarius longitarsus*) from Mozambique and the mass of the shells they choose to occupy. (a) The data are plotted on a normal, linear scale. Note the large number of data points crowded together in the lower left corner of the graph. (b) The same data replotted after taking the log (base 10) of hermit crab mass. A value of 1 represents 10 g (grams; see Table 9.3). (c) The same data plotted using a logarithmic scale (base 10) for the *x*-axis. Hermit crab mass increases 10-fold from one numbered tick mark to the next. In both (b) and (c), note the more even distribution of points.

Based on data of Barnes, D.K.A., 1999. Ecology of tropical hermit crabs at Quirimba Island, Mozambique: shell characteristics and utilization. Mar. Ecol. Progr. Ser. *183: 241–251.*

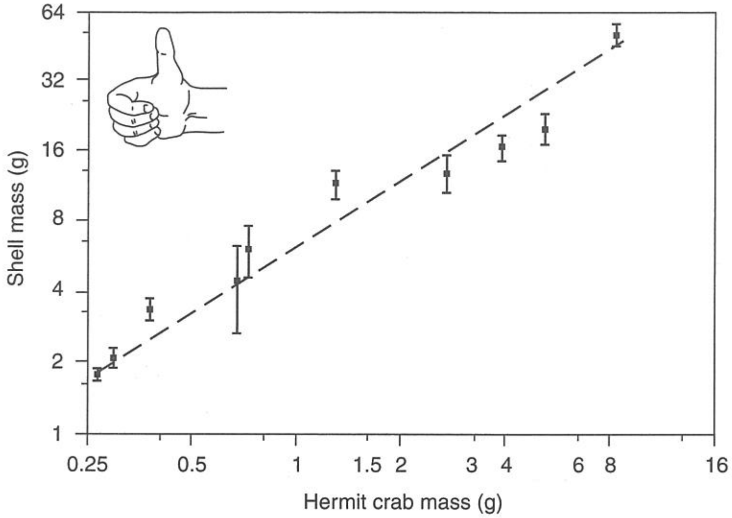


Figure 9.18 The hermit crab data of Figure 9.16 plotted using a log base 2 scale on each axis. Such scales are helpful when you are interested in the effects of doublings, or in how much of a change in x is required to produce a doubling of y.

the data form a difficult-to-decipher mess in the lower left corner of the inset but are spread out evenly using a scale of log base 10 on the x-axis of the main graph.

Although logarithmic graphs are usually plotted using scales in base 10, base 2 scales can also be useful. The hermit crab data of Figure 9.16*a* are replotted using this log base 2 scale for both axes in Figure 9.18; now each numbered major tick represents a doubling of crab or shell mass. A quick visual inspection of this graph shows that as the mass of the hermit crab approximately doubles, the mass of the shell it prefers to inhabit also doubles, something not so obvious in the previous plots of the same data (see Fig. 9.16).

In some cases, logarithms can also be useful in forcing data into straight lines. Figure 9.19 shows the relationship between the basal diameter of barnacles (*Balanus amphitrite*) and the dry weight of their tissues. Plotted on a linear scale (Figure 9.19*a*), tissue weight increases exponentially with increases in barnacle length. Replotting the same data using a double-log scale (base 10), we have essentially bent the data into a straight line (inset) so that the relationship can now be represented by a simple equation of the form $y = mx + b$.

Preparing Tables

Tables should always be organized with the data related to a given characteristic being presented vertically rather than horizontally. Tables 9.4 and 9.5 present the same information but in different formats. Table 9.4 correctly

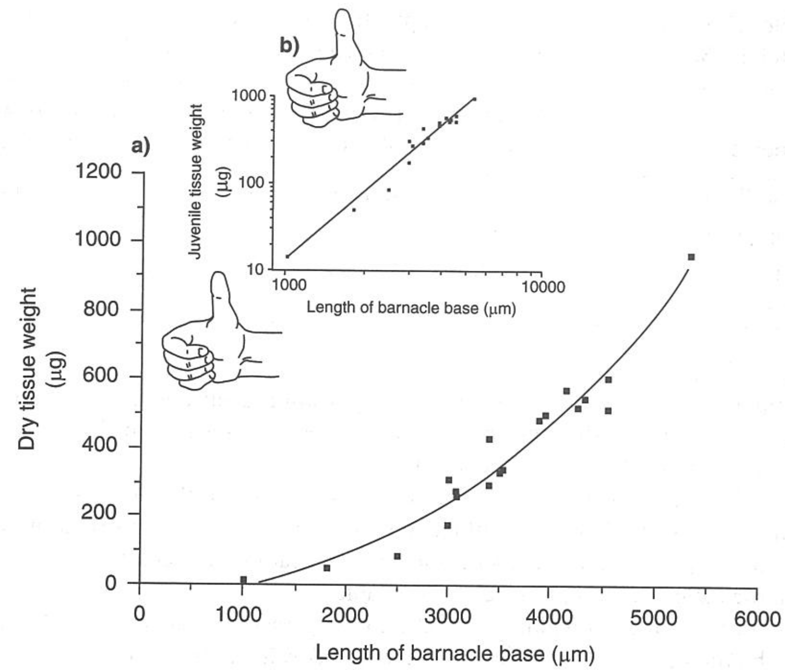


Figure 9.19 Relationship between barnacle size (in micrometers) and dry tissue weight (micrograms) for juveniles of *Balanus amphitrite.* Each point represents measurements on a single individual. (a) The data plotted on a normal linear scale. (b) The same data replotted using log base 10 scales for both axes. Notice that the exponential curve depicted in (a) becomes a straight line in (b).

Data from Pechenik et al., 1993. Influence of delayed metamorphosis on survival and growth of juvenile barnacles Balanus amphitrite. Mar. Biol. *115: 287–294.*

Table 9.4 Characteristics of 4 snail populations sampled at Nahant, MA, on October 13, 2011. Data are means of 4 replicate samples ± 1 standard error.

Species	Average Shell Length (cm)	Sample Size	Average No. Animals per m^2
Crepidula fornicata	1.63 ± 0.21	122 indiv.	32.1 ± 4.7
C. plana	1.01 ± 0.34	116	20.8 ± 10.6
Littorina littorea	0.87 ± 0.11	447	113.6 ± 29.1
L. saxatilus	0.40 ± 0.10	60	8.2 ± 5.2

places all information about a single species in one row so that readers can view the information for each species by scanning from left to right and can

Table 9.5 Characteristics of 4 snail populations sampled at Nahant, MA, on October 13, 2011. Data are means of 4 replicate samples ± 1 standard error.

Species	*Crepidula fornicata*	*Crepidula plana*	*Littorina littorea*	*Littorina saxatilus*
Av. shell length (cm)	1.63 ± 0.21	1.01 ± 0.34	0.87 ± 0.11	0.40 ± 0.10
Sample size	122 indiv.	116	447	60
Av. no. animals per m^2	32.1 ± 4.7	20.8 ± 10.6	113.6 ± 29.1	8.2 ± 5.2

compare data among different species by scanning up and down a single column. Note also that the independent variable ("species" in this case) is presented vertically in the first column.

Table 9.5 is incorrectly organized and so is more difficult to read. Like graphs, tables should be self-sufficient; note how much useful information the author has packed into the legend and column headings of Table 9.4. Note also that the table legend is placed above the table.

As mentioned previously (p. 162), do not present the same data in both a graph and a table: Choose the format that makes it easier for you to get your findings across to readers.

Making Your Figures and Tables Self-Sufficient

A properly executed figure or table is largely self-sufficient: Snipped out of your report along with its accompanying legend or caption, it should make perfectly good sense to any biology major you hand it to. By examining only the axes of a graph and reading the figure caption, for example, the reader should be able to determine the specific question that was asked, how the study was done, and what the main findings are, as discussed in Chapter 3 (pp. 35–38). Consider, for example, Figure 9.12.

We can tell quite a lot about how and why this study was done just by carefully studying the figure and its caption. The study was apparently undertaken to determine how fast tomato seedlings grow at one particular temperature, 20°C. We know that the growth of 205 seedlings was followed over nearly 2 months, and that seedlings were measured 9 times over that period, approximately once each week. We also know that not all 205 seedlings were measured every time; instead, the researchers subsampled 15–20 each time so that different seedlings were probably measured each time. Finally, we see that each point represents a mean value and that the vertical bars represent 1 standard deviation about the mean.

Similarly, from Figure 9.8 we know what species was studied and for how long. We also know that caterpillars were maintained at 1 of 5 temperatures, and we know what those temperatures were. Furthermore, we know the number of caterpillars maintained at each temperature.

Try to make your data presentations as self-sufficient as these examples are. In particular, **always indicate the species studied, the sample size** (e.g., Figure 9.15), **and the number of replicates** (e.g., Table 9.4). The easier you make it for readers to understand your data, the more likely it is that your work will be read and that you will get your point across intact. Additional advice about constructing good graphs and tables is given in books by W.S. Cleveland and by J. Quinn and M.J. Keough (see Appendix C).

Putting Your Figures and Tables in Order

Once you have your graphs (and other figures like drawings, maps, or photographs) and tables prepared, you need to decide in what order to present them. **Arrange them logically, in the order that you will discuss them.** The first figure that you refer to in the text of your report will be Figure 1, the second will be Figure 2, and so forth. Order your tables in the same way, with Table 1 the first table that you refer to, to facilitate a logical presentation of the data.

Incorporating Figures and Tables into Your Report (or Not)

Ask your instructor whether you should incorporate your graphs and tables into the text of the Results section, as they would appear in a published journal article, or whether you should print the figures and tables on separate pages and include them at the end of your report.

To incorporate figures directly into your report, click on the figure to be inserted, and then use the copy and paste function. Alternatively, you can use the Insert function in the Word menu.

Do not insert figures into the text unless your instructor asks you to. Many of us would prefer to see each figure—with its caption—on a separate page at the end of your report; larger figures are much easier to read and comment on.

Verbalizing Results: General Principles

One-sentence Results sections are common in student reports: "The results are shown in the following tables and graphs." However, *common* does not mean *acceptable*. **You must use words to draw the reader's attention to the key**

patterns in your data. But do not simply redraw the graphs in words, as in this description of Figure 9.10:

> At 20°C, the seedlings showed negligible growth for the first 8 days of study. However, between days 8 and 16, the average seedling grew nearly 5 mm, from about 8 mm to about 13 mm. Growth continued over the next 16 days, with the seedlings reaching an average height of 24 mm by day 24, and 30 mm by day 32.

Let the graph do this work for you; **your task is to summarize the most important findings displayed by the graph** and then to indicate briefly the basis for the statements you make.

First, **decide exactly what you want your reader to see when looking at each graph or table, and then stick the reader's nose right in it.** For example, you might write:

> Temperature had a pronounced effect on seedling growth rates (Fig. 9.10). In particular, seedlings at 25°C consistently grew more rapidly than those at 20°C.

Remember, in scientific writing every statement of fact or opinion must be backed up with evidence (p. 6). In the example just given, a general statement was supported by reference to a figure, followed by a specific detail that illustrates the point particularly well. In some cases, only a single sentence is required:

> Caterpillars generally fed more slowly on the diet of 10^{-3} M sinigrin than on the wheat germ controls (Fig. 9.4).

Readers can then look at Figure 9.4 and decide whether they see the same trend you did: One sentence and a figure say it all.

Note the use of the past tense in the statement about caterpillar feeding rates:

> Caterpillars generally fed at faster rates on diet *A*.

This statement is quite different from the following one, which uses the present tense:

> Caterpillars feed at faster rates on diet *A*.

By using the present tense, you would be making a broad generalization extending to all caterpillars, or at least to all caterpillars of the species tested. Before one can make such a broad statement, the experiment must be repeated many, many times, and similar results must be obtained each time. After all, the writer is making a statement about all caterpillars under all conditions. By sticking with the past tense here, you are clearly referring only to the results of your study. Be cautious: **Always present your results in the *past* tense.**

Note also that the authors of these examples **do not make the reader interpret the data.** You must tell your readers exactly what you want them to see when they look at your table or graph. Consider the following 2 examples. The data concern the shell lengths of a particular snail species collected along a rocky coastline from 2 regions between the high-tide level and the low-tide level. I have not included any figures or tables from this survey, so I refer to them only as "xx" in these examples:

> Although individual specimens of *Littorina littorea* varied considerably in shell length at each tidal height (Fig. xx), there was a significant (t = 26.3; *d.f.* = 47; $p < 0.05$) distributional effect of shore position on mean size (Table xx).

> Although individual specimens of *Littorina littorea* varied considerably in shell length at each tidal height (Fig. xx), the mean shell length was significantly greater (t = 26.3; *d.f.* = 47; $p < 0.05$) for snails collected higher up in the intertidal zone (Table xx); high shore animals were, on average, 26% larger than low-shore animals.

In the first of these examples, the author expects the readers to figure out what specific information is important in the data, possibly because the author has not taken the time to think carefully enough about the data. The modified version conveys quite a different impression: We know exactly what the author wants us to see, and we can then decide whether we agree with the author's statements.

Note that in the model example just presented, the lead factual statement was supported both by reference to a figure and by the results of statistical analyses. **Note also that the author provided not just the *p*-value associated with the result (to indicate how convincing the difference among means is) but also the name of the test statistic (a *t*-statistic in this example, resulting from a *t*-test) and the number of degrees of freedom associated with the analysis** (*d.f.*, related to sample size as discussed in Chapter 4). This allows readers to check the validity of the statistical test performed and the validity of the results obtained. Also note that the author correctly refers to the observed differences in shell length as being "significant." **Saying that differences are "significant" (or "not significant") implies that you have subjected your data to rigorous statistical testing.** If you have not conducted statistical analyses, it is perfectly fair to write "Temperature had a pronounced effect on seedling growth rates," or "Seedlings treated with nutrients appeared to grow at slightly faster rates than those treated with distilled water," referring readers to the appropriate table or figure. But if you cannot provide statistical support, you *cannot* say that seedlings in one treatment grew *significantly* faster than those in another treatment. Note also that the author of this example indicates the magnitude of the effect observed (i.e., the "effect size"); the size differences are not just statistically significant but are, in fact, quite large (26%).

As discussed more fully in Chapter 4, even if you analyze your data statistically, you must nevertheless be cautious in drawing conclusions. Your data may support one hypothesis more than another, but they cannot *prove* that any hypothesis is true or false. Chapter 4 is worth reading even if you are not required to conduct statistical analyses of your data; as biologists in training, the *why* of statistical analysis is more important to you than the *how*.

Verbalizing Results: Turning Principles into Action

Let us apply these principles to the caterpillar study discussed previously in this chapter. First, is there anything about the general response of the animals worth drawing attention to? You might, for example, be able to write:

> All the caterpillars were observed to eat throughout the experiment.

More likely, living things behaving as they do, you will say something like:

> One of the animals offered diet *A* and 2 of the animals offered diet *B* were not observed to eat during the 3 h experiment, and the results from these animals were therefore excluded from analysis.

Such a decision to exclude data from further analysis is fine, by the way—it won't be considered data falsification—as long as you indicate the reason for the decision, and as long as the decision is made objectively; as discussed previously, **you cannot exclude data simply because they violate a trend that would otherwise be apparent or because the data contradict a favored hypothesis.**

Next, go back to your initial list, and reword each question as a statement— For example, the first question posed on p. 159 ("Did the caterpillars feed at different rates on the different diets?") might be reworded as

> Caterpillars generally fed more slowly on the 10^{-3} M sinigrin diet than on the wheat germ controls (Fig. 9.4).

or

> Caterpillars fed at significantly slower rates on the 10^{-3} M sinigrin diet than on either the lower-concentration sinigrin diet or the wheat germ controls (Fig. 9.4; $F = 30.3$, $d.f. = 2, 11$; $p < 0.0001$).

If you follow this procedure for each question on your list, your Results section will be complete. The written part will generally be quite short.

Writing About Negative Results

An experiment that was correctly performed always "works." The results may not be what you had expected or hoped for, but this does not mean that the experiment has been a waste of time. If biologists threw away their data every time something unexpected happened, we would rarely learn anything new. Indeed, unexpected results are often more exciting than expected ones because they can sometimes lead the research in new directions. The data you collect are real; only the interpretation of those data is open to question. Therefore, always treat your data with respect. The lack of a trend, or the presence of a trend contrary to expectation, is itself a story worth telling. See also pp. 61 through 64 for related advice about dealing with statistical analyses that fail to support a favored hypothesis or expected outcome.

Writing About Numbers

According to the Council of Science Editors (*Scientific Style and Format: The CSE Manual for Authors, Editors, and Publishers,* 7th edition), you should **use numerals rather than words when writing about counted or measured items, percentages, decimals, magnifications, and abbreviated units of measurement** (see pp. 61–63): 6 larvae, 18 seedlings, 25 drops, 25%, 1.5 times greater, 50× magnification, a 3:1 ratio, 0.7 g, 18 ml.

All rules, however, have exceptions. Use words rather than numerals if beginning a sentence with a number or percentage:

> Twenty grams of NaCl were added to each of 4 flasks.

> Thirty percent of the tadpoles metamorphosed by the end of the second week.

Or, avoid starting sentences with numbers, as in this rewrite of the first example:

> To each of 4 flasks we added 20 g of NaCl.

When 2 numbers are written adjacent to each other without being separated by words or a comma, write one of the numbers in words:

> The sample was divided into five 25-seedling groups.

Better still, that sentence could easily be rewritten so that numerals are appropriate for both numbers:

> The samples were divided into 5 groups of 25 seedlings each.

Zero and one present special problems: a "0" is easily mistaken for the letter "O," and the numeral "1" is easily mistaken for the letters "l" (as in the abbreviation for "liters") or "I." Plus, it just looks odd to read, "I know that 1 day my prince will come." The Council of Science Editors has recently clarified its position on these issues. In most cases, unless the zero or one is followed by units of measure (e.g., "I added 1 mg of sucrose to the solution"), or is part of an equation (e.g., "$n = 1$"), or is part of a series that includes larger numbers ("1, 8, and 25 individuals..."), use words rather than numerals for zero and one.

When writing about numbers smaller than zero, precede the decimal point with a zero:

...and we then added 0.25 g NaCl to each flask.

When using ordinal numbers (e.g., first, fifth), the Council of Science Editors suggests using words for the first 9 numbers and numerals for the others ("the 25th replicate..."). However, you should be consistent within a series ("first, fifth, ninth" and "13th, 14th, 15th"; but "5th, 9th, 15th," rather than "fifth, ninth, 15th").

When writing about very large or very small numbers, particularly in association with concentrations or rates, **use scientific notation.** It is preferable, for example, to write about solute concentrations of 5.6×10^{-3} g/ml rather than 0.0056 g/ml, and about cell concentrations being approximately 1.8×10^5 cells/ml rather than about 180,000 cells/ml. Note that I could have avoided both scientific notation and commas in the first example by describing the solute concentration as 5.6 mg/ml. By the way, the word *per*, as in "cells per ml" or "distance per second," may be indicated using either a slash or an exponent: "1.8×10^5 cells/ml" and "1.8×10^5 cells ml^{-1}" are equally acceptable forms of expression. See Technology Tip 1 (p. 16) to learn about programming Word to produce such formatting automatically.

Finally, the Council of Science Editors recommends **using commas** only when numerals contain 5 or more numbers, as in the following example:

Only 1073 of the original 12,450 frog tadpoles died during the study.

In Anticipation—Preparing in Advance for Data Collection

Much of the work involved in putting together a good research report goes into preparing the Results section. You can save yourself considerable effort and frustration by planning ahead before you enter the laboratory to do the experiment. Be prepared to record your data in a format that will enable you to make your calculations easily. For the caterpillar experiment referred to previously, you could come to the laboratory with a data sheet set up like the one shown in Figure 9.20. Using this data sheet, the data would be recorded in the *x* areas during the laboratory period; the blank spaces would be filled in later, as you

Date and time started: ________
Date and time ended: ________

Caterpillar No.	Diet	Caterpillar wt. (g) Initial	Final	Weight Change (g)	Food wt. (g) Initial	Final	Food wt. Change (g)	Feeding rate g eaten/caterp./h
x	x	x	x		x	x		

Figure 9.20 Sample format for a laboratory data sheet.

make your calculations. Try to leave a few blank columns at the right to accommodate unanticipated needs discovered as you record or work up your data.

In introductory laboratory exercises, students are often provided with data sheets already set up in a useful format. Look carefully to understand how those sheets are organized; in more advanced laboratory courses, you will be responsible for organizing your own data sheets. As mentioned previously, **always follow any number you write down with the appropriate units,** such as mg (milligrams), cm (centimeters), or mm/min (millimeters per minute, often written as mm min^{-1}). This will avoid potential confusion later.

You can also enter your data directly into a computer if you set up a data sheet in advance (see Technology Tip 6).

TECHNOLOGY TIP 6

Using computer spreadsheets for data collection

One advantage of entering data directly into a spreadsheet (e.g., Excel) is that you can preprogram automatic calculations into the spreadsheet. Consider, for example, Table 9.1 (p. 161). If we enter data into columns 2, 3, and 5 (Initial Caterpillar Mass, Final Caterpillar Mass, and Mass of Food Lost), we can enter formulas into columns 4 and 6 so that Caterpillar Mass. Change and Feeding Rate will be calculated automatically. Before entering formulas in Excel, remember to first click on the appropriate box and then click "=" to indicate that a formula is on its way.

Whenever you enter formulas into a spreadsheet, make one sample calculation by hand or with a calculator to be sure that the formula you entered is correct. Also check to be sure that the formula is correctly applied to all entries in each column. Especially useful operators include SUM, AVERAGE, and STDEV. For example "= AVERAGE(B3:B21)" calculates the average of the numbers in columns B3–B21 of the spreadsheet, whereas "= STDEV(B3:B21)" returns the standard deviation about the mean.

Following the advice of the previous paragraph can save you hours of work later on. Even so, it takes time and care to put together an effective Results section. But this section is the heart of your report. Craft it properly, and the remainder of the work will be relatively easy.

CITING SOURCES

The next sections to prepare are the Discussion section and the Introduction. In both sections, you will be making statements of fact that require support, often from written sources. As stated in Chapter 1 (Rule 8, p. 6 and discussed more fully in Chapter 5, **every statement of fact or opinion must be supported**. Read Chapter 5 (pp. 66–70) for specific instructions on citing sources.

WHAT TO DO NEXT?

I usually draft my Discussion section next, although you might instead try drafting your Introduction (p. 195). See what works best for you. The key is to undertake neither one until you have your Materials and Methods section and your Results section in good order.

WRITING THE DISCUSSION SECTION

In the Discussion section of the report, you must interpret your results in the context of the specific questions you set out to address during your experiment and in the context of any relevant broader issues that have been raised in lectures, textbook readings, previous coursework, and possibly your library research. You will consider the following issues:

1. What did you expect to find, and why?
2. How did your actual results compare with the results you expected? If you set out to test specific hypotheses, do your data support one hypothesis more than another or allow you to eliminate one or more of them? Explain your logic.
3. How might you explain any unexpected results?
4. How might you test those potential explanations?
5. Based on your results, what question or questions might you logically want to ask next?

Clearly, if your results coincide exactly with those expected from prior knowledge, your Discussion section will be rather short, but such a high level of agreement is rarely obtained in 3- or 4-hour laboratory studies. Indeed, high degrees of variability characterize many aspects of research in biology, especially at the level of the whole organism. After all, genetically based variation in traits is the raw material of evolution: Without such variation, evolution by natural selection would not be possible. Often a study will need to be repeated many times, with very large sample sizes, before convincing trends emerge. This point is discussed further in Chapter 4, beginning on page 54. A short paper in a biological journal may well represent years of work by several competent, hardworking individuals. Even the simplest of questions is often not easily answered. Nevertheless, every experiment that was carried out properly tells you *something*, even if that something is not what you specifically intended to find out.

Expectations

State your expectations explicitly, and back up your statements with a reference. Scientific hypotheses are not simply random guesses. Your expectations must be based on facts and logical thinking, not opinions; these facts could come from lectures, laboratory manuals or handouts, textbooks, journal articles, or any other traceable source. In discussing a study on the effectiveness of different wavelengths of light in promoting photosynthesis, for example, you might write something like the following:

> All wavelengths of light are not equally effective in promoting photosynthesis: green light is said to be especially ineffective (Ellmore and Mirkin, 2009). This is because green light tends to be reflected rather than absorbed by plant pigments, which is why most plants look green (Ellmore and Crone, 2012). Our results supported this expectation. In particular...

Alternatively, a Discussion section might profitably begin as follows:

> The results of our experiment failed to support the hypothesis (McClaughlin and McVey, 2007) that caterpillars of *Manduca sexta* reared on one uniquely flavored diet will prefer that diet when subsequently given a choice of foods.

Here we have managed to state our expectations and compare them with our results in a single sentence. In both cases, we have begun our discussion on firm ground—with facts rather than unsupported opinions.

Note that in this last example, the expectations were based on previously published research. Your expectations might instead be based on a hypothesis stated in your Introduction and tested in the Results section.

Explaining Unexpected Results

When results refuse to meet expectations, students commonly blame the equipment, the laboratory instructor, their laboratory partners, or themselves. Generally, more scientifically interesting possibilities than experimenter incompetence are the culprits. A few years ago, I did an experiment with 2 colleagues to see if dopamine receptors were involved in the pathway that led to metamorphosis in a particular marine animal. The idea was to add to seawater a chemical known to disable dopamine receptors and then see if the larvae could nevertheless be made to metamorphose. Every time we did the experiment, we got a different result. Sometimes the chemical blocked metamorphosis, but in other experiments it actually stimulated larvae to metamorphose! What on earth was going on? It turned out that the response of competent larvae to the chemical changed predictably as the larvae aged—something never reported before. The paper we ended up publishing* was different from the paper we had originally envisioned. Yes, dopamine receptors are involved in the metamorphic pathway of this species, but this turned out to be, in my view, the least interesting aspect of the work.

Don't be too hard on yourself if your results don't fit your expectations, or if they don't disprove your null hypothesis (Chapter 4) when you expected them to. **Base your discussion on the data you obtain.** And don't limit yourself to assessing *a priori* hypotheses: Probe your data thoroughly, expect the unexpected, and consider all potential aspects of, and reasonable explanations for, your data. Take another look at the list of factors you wrote when beginning to work on your Materials and Methods section. Could any of these factors be sufficiently different from the normal or standard conditions under which the experiment is performed to account for the difference in results? Look again at your laboratory manual or handout. Are any of the conditions under which your experiment was performed substantially different from those assumed in the instruction manual? If you discover no obvious differences in the experimental conditions, or if the differences cannot account for your results, include this point in your report, as in this example:

> The discrepancy in results cannot be explained by the unusually low temperature in the laboratory on the day of the experiment because the control animals were subjected to the same conditions and yet behaved as expected.

If potentially important differences are noted, put this ammunition to good use:

> In prior years, these experiments have been performed using species *X* (Professor E. Iyengar, personal communication). Species *Y* may simply behave differently under the same experimental conditions.

*Pechenik, J.A., D.E. Cochrane, and W. Li, 2002. Timing is everything: The effects of putative dopamine antagonists on metamorphosis vary with larval age and experimental duration in the prosobranch gastropod *Crepidula fornicata*. *Biol. Bull.* 202: 137–147.

Note that the writer does not *conclude* that species *X* and species *Y* behave differently; the writer merely *suggests* this explanation as a possibility. **Always be careful to distinguish possibility from fact.** Suggesting a logical possibility won't get you into any trouble. Stating your idea as though it was an accepted fact, on the other hand, is sticking your neck out far enough to get your head chopped off.

Continue your discussion by indicating possible ways that the differences in behavioral responses **might be tested.** For example:

> This possibility can be examined by simultaneously exposing individuals of both species to the same experimental conditions. If species *X* behaves as expected and species *Y* behaves as it did in our experiment, that will support our hypothesis of species-specific behavioral differences. If species *X* and species *Y* both respond as species *Y* did in the present study, then some other explanation will be called for.

Continue in this vein, evaluating all the reasonable, testable possibilities you can think of. An instructor enjoys reading these sorts of analyses because they indicate that students have been thinking about what they've done.

Notice that in the preceding example, the writer did not say, "If species *X* behaves as expected and species *Y* behaves as it did in the present experiment, then the hypothesis will be supported." This writer remembers rule number 14 (p. 8): **Never make the reader back up.** Notice, too, that the writer did not say, "then the hypothesis will be true," or "then the hypothesis will be proven." **Experiments cannot** *prove* **anything; they can only support or not support specific hypotheses.** As scientists, our interpretations of phenomena may make excellent sense based on what we know at the moment, but those interpretations are not necessarily correct. New information often changes our interpretations of previously acquired data.

Analysis of Specific Examples

Example 1

In this study, tobacco hornworm caterpillars were raised for 4 days on one diet, and then tested for 3 hours to see if they preferred that food when given a choice of diets.

Student Presentation

> Our data indicate that the choice of food was not related to the food upon which the caterpillars had been reared. These data run counter to the hypothesis (Back and Reese, 1976) that hornworms are conditioned to respond to certain specific foods. Only one set of

data out of the 4 gave any indication of a preference for the original diet, and that indication was rather weak.

There are many possible explanations for data that are so contrary to previous experimental results. Inexperience of the experimenters, combined with the fact that 3 different people were recording data about the caterpillars, may account for part of the error. Keeping track of many worms and attempting to interpret their actions as having chosen a food or having merely been passing by may have proven to be too much for first-time hornworm watchers. The mere fact that each of 3 people will interpret actions differently and will have somewhat different methods of recording information introduces bias into the data.

Analysis

This Discussion section starts out well, with a comparison between the results expected and the results obtained. The hypothesis being discussed is clearly stated, and a supporting reference is given. The student even recognizes that "data are" rather than "data is." The second paragraph, however, betrays a total lack of confidence in the data obtained; the results could not possibly have turned out this way unless the researchers were incompetent, writes the student. Although inexperience can certainly contribute to suspicious results, are there no other possible explanations? Does it really take years of training to determine whether a caterpillar ate food *A* or food *B*?

Compare this report with the one in the next example. This Discussion section deals with the same experiment. In fact, the 2 students were laboratory partners.

Example 2

Contrary to expectation, our results suggest that caterpillars of this species showed no preference in the diet they touched first and the diet they spent the most time feeding on. Perhaps our caterpillars were not reared on the original diets long enough to acquire a lasting feeding preference. They were reared on the original diets for only 4 days, whereas the laboratory handout had suggested a pre-feeding period of 5–10 days (Orians and Starks, 2003). This possibility may be tested by performing the same experiment but varying the amount of time that the caterpillars are reared on the original diets. Such an experiment would determine whether there is a critical time that caterpillars should be reared on a particular diet before they will show a preference for that diet. Another possible explanation for our results is that the caterpillars used in our study were very young, weighing only 3–6 mg. Finally, this experiment lasted only 3 hours. Perhaps different results would have been obtained had the organisms been given more time to adjust to the test conditions. We suggest conducting an identical experiment for a longer period of time, such as 10–12 hours.

The author of this report produced a paper that clearly indicates thought. Which report do you suppose received the higher grade?

Example 3

In this experiment, several hundred milliliters (ml) of filtered pond water were inoculated with a small population of the ciliated protozoan *Paramecium multimicronucleatum* and then distributed among 3 small flasks. Over the next 5 days, changes in the numbers of individuals per ml of water in each flask were recorded.

Student Presentation

The large variation observed between the groups of 3 replicate populations suggests that the experimental technique was imperfect. The sampling error was high because it was difficult to be precise in counting the numbers of individuals. Some animals may have been missed while others were counted repeatedly. More accurate data may be obtained if the number of samples taken is increased, especially at the higher population densities. In addition, more than 3 replicate populations of each treatment could be established. Finally, extremely precise microscopes and pipets could be used by experienced operators to reduce sampling error.

Analysis

This writer, like the writer of Example 1, starts out by assuming that the experiment was a failure and then spends the rest of the report making excuses for this failure. The quality of the microscopes was certainly adequate to recognize moving objects, and *P. multimicronucleatum* was the only organism moving in the water: The author is grasping at straws. If the author had more confidence in his or her abilities, the paper might have been far different. Isn't there some chance that the experiment was performed correctly? Lacking confidence in the data, the student took the easy way out and looked no further, even though he or she actually had access to data that would have allowed several of the stated hypotheses to be assessed. On each day, for example, several sets of samples were taken from each flask, and each set gave similar estimates for the numbers of organisms per milliliter: This consistency of results suggests that the variation in population density from flask to flask was real and not the result of experimenter incompetence. In addition, although the student stated correctly that larger sample sizes would have been helpful, he or she should have supported that statement with additional data analysis. Fifteen drops were sampled from each flask for each set of samples. The student could have calculated the mean number of individuals in the first 3 drops, the first 6 drops, the first 9 drops, the first 12 drops, and then the full 15 drops, to see how the estimates of population size changed as the sample size increased. With such calculations, the student would probably have found that larger sample sizes are especially important when population density is low. (Why might this be so?)

Example 4

In this last study, a group of students went seining for fish in a local pond. Every fish was then identified to species. It turned out that 91% of the fish in the sample of 73 individuals belonged to a single species. The remaining fish were distributed among only 2 additional species.

Student Presentation

> I find the small number of species represented in our sample surprising, as the pond is fed by several streams that might be expected to introduce a variety of different species into it, assuming that the streams are not polluted. The lab manual states that 12 fish species have been found in the adjacent streams. It appears that the conditions in the pond at the time of our sampling were especially suitable for one species in particular out of all those that most likely have access to it. Perhaps the physical nature of the pond is such that the number of niches is small, in which case competition would become very keen; only one species can occupy a given niche at any one time (Ricklefs and Miller, 2000). The reproductive pattern of the fishes might also contribute to the observed results. The dominant species, *Lepomis macrochirus*, may lay more eggs than the others, or perhaps the young of this species survive better, or prey on the young of other species.
>
> Another possible explanation for our findings is that we sampled only the perimeter of the pond, as our seining was limited to a depth of water not exceeding the height of the seiners' waders. The species distribution could be different in the middle of the pond at a greater depth.

Analysis

I have not reproduced the entire Discussion section of the student's paper, but even this excerpt demonstrates that a little thinking goes a long way. Note

that the student did not require much specialized knowledge to write this Discussion section, only a bit of confidence in the data. Another student might well have written:

> Most likely, the fish were incorrectly identified; more species were probably present than could be recognized by our inexperienced team. It is also possible that the net had a large tear, which let the members of other species escape. I didn't notice this rip in the fabric, but my glasses were probably dirty, and then again, I'm not very observant.

WRITING THE INTRODUCTION SECTION

The Introduction section establishes the framework for the entire report. **It is *not* simply a literature review.** In this section, **you briefly present background information that leads to a clear statement of the specific issue or issues that will be addressed in the remainder of the report;** by the time you have finished writing the Materials and Methods, Results, and Discussion sections of your laboratory report, you should know what these issues are. In 1 or 2 paragraphs, then, you must present an argument explaining why the study was undertaken. More to the point, perhaps, the Introduction provides you with your first opportunity to convince your instructor that you understand why you have been asked to do the exercise.

Every topic that appears in later sections of your report should be anticipated clearly in the Introduction, and the Introduction should contain only information that is directly relevant to the rest of the report.

Stating the Question

Even though the statement of questions posed or of issues addressed generally concludes the Introduction section of a report, it is useful to deal with this issue first. What was the *specific* issue or question addressed in your study?

First, write the following words: "In this study" or "In this experiment." Then complete the sentence as specifically as possible. Three examples follow:

> In this study, the oxygen consumption of mice and rats was measured to investigate the relationships between metabolic rate, body weight, and body surface area.

> In this study, we collected fish from 2 local ponds and classified each fish into its proper taxonomic category.

> In this experiment, we asked the following question: Do the larvae of *Manduca sexta* prefer the diet on which they have been reared when offered a choice of diets?

Note that each statement of intent is phrased in the past tense; the students are describing studies that have now been completed.

The strong points of these statements are best revealed by examining a few unsatisfactory alternatives:

In this study, we measured the metabolic rate of rats and mice.

In this study, we worked with freshwater fish.

In this experiment, the feeding habits of *Manduca sexta* larvae were studied.

Each of these 3 unsatisfactory statements is vague; readers will assume, perhaps correctly, that you are as much in the dark about what you've done as your writing implies. **Be specific.** Here, in one sentence, you must come fully to grips with the goals of your study. There *was* some point to the time that you were asked to spend in the laboratory; find it.

If you go on to state specific expectations or to present specific hypotheses that you set out to test, **make the basis for those hypotheses clear**, as in the following example:

> We expected larger mice to respire faster than smaller mice, as larger mice support a greater biomass. However, we also predicted that respiration rates per gram of tissue would be similar in large and small individuals: dividing by weight should adjust for size differences.

As mentioned previously (p. 189), you must provide a rationale (e.g., logical argument or results from prior studies) for any expectations or specific hypotheses that you state.

An Aside: Studies versus Experiments

An experiment always involves manipulating something, such as an organism, an enzyme, or the environment, in a way that will permit specific relationships to be examined or hypotheses to be tested. Containers of protozoans in pond water could be distributed among 3 temperatures, for example, to test the influence of temperature on the reproductive rate of the particular species under study. The ability of salivary amylase to function over a range of pHs might be examined to test the hypothesis that the activity of this enzyme is pH sensitive. In the field, a population of marine snails from one location might be transplanted to another location and the subsequent survival and growth of the transplanted population studied so as to test the hypothesis that conditions in the new location are less hospitable for that species than in the location from which the original

population was obtained. As a control, of course, the survival and growth of animals not transplanted would also have to be monitored over the same period. Note that an experiment may be conducted in the laboratory or in the field.

It is permissible to refer to experiments as "studies," but not all studies are "experiments." In contrast to the preceding experiments, some exercises require you to collect, observe, enumerate, or describe. You should avoid referring to such studies as experiments; **when there are no manipulations, there are no experiments.** You might, for example, collect insects from light fixtures located at several different locations within the biology building and identify them to the species level, enabling you to examine the distribution of insect species within the building. Or you might be asked to provide a detailed description of the feeding activities of an insect. Or you might spend an afternoon documenting the depth to which light penetrates in various areas of a lake and then correlate that information with data on the distribution of aquatic plants in the different areas. In each case, you should refer to your work as a study, not as an experiment. For example:

> In this study, insects were collected from all light fixtures on floors 1, 3, and 5 of the Dana building, and the distribution of species among the different locations was determined.

Providing the Background

Having posed, in a single sentence, the question or issue that was addressed, it will now be easier to fill in the background needed to understand why the question was asked. A few general rules should be kept in mind:

1. **Support all statements of fact with a reference to your textbook, laboratory manual, outside reading, or lecture notes.** Unless you are told otherwise by your instructor, do not use footnotes. Rather, refer to your reference within the text, giving the author of the source and the year of publication, as in the following example:

   > Many marine gastropods enclose their fertilized eggs within complex encapsulating structures (Hunt, 1966; Tamarin and Carriker, 1968; Boisvert *et al.*, 2014).

   Note that the period concluding the sentence comes after the closing parenthesis. Do not cite any material that you have not read.
2. **Define specialized terminology.** Your instructor probably knows the meaning of the terms you will use in your report, but by defining them in your own words, you can convince the instructor that you, too, know what these words mean. Write to illuminate, not to impress. As always, if you write with your future self in mind as the audience, you will usually come out on top; write an Introduction you will be

able to understand 5 years from now. The following examples obey this and the preceding rule:

> A number of caterpillar species are known to exhibit induction of preference, which is a phenomenon in which an organism develops a preference for the particular flavor on which it has been reared (Westneat and Sesterhenn, 1983).

> The development of mature female gametes, which is a process termed oogenesis, is regulated by changing hormonal levels in the blood (Gilbert, 2006; McVey, 2010).

3. **Never set out to prove, verify, or demonstrate the truth of something.** Rather, set out to test, document, or describe. In biology (and science in general), truth is elusive; it is important to keep an open mind when you begin a study and when you write up the results of that study. It is not uncommon to repeat someone else's experiment or observations and obtain a different result or description. Responses will differ with species; time of year; and other, often subtle, changes in the conditions under which the study is conducted. To show that you had an open mind when you undertook your study, you would want to revise the following sentences before submitting them to your instructor:

> In this experiment, we attempted to demonstrate induction of preference in larvae of *Manduca sexta*.

> This experiment was designed to show that pepsin, which is an enzyme that promotes protein degradation in the vertebrate stomach, functions best at a pH of 2, as commonly reported (Bernheim and Cochrane, 1999).

The first example might be modified to read:

> In this experiment, we tested the hypothesis that young caterpillars of *Manduca sexta* demonstrate the phenomenon of induction of preference.

4. **Be brief.** The Introduction must not be a series of interesting but random facts about the topic you have investigated. Rather, **every sentence should be designed to directly prepare the reader for the statement of intent,** which will appear at the end of the Introduction section, as already discussed. If, for example, your study was undertaken to determine which wavelengths of light are most effective in promoting photosynthesis, there is no need to describe the detailed biochemical reactions that characterize photosynthesis. As another example of what not to do, consider these few sentences taken from a report describing an induction-of-preference study. Caterpillars were reared on one diet for 5 days and tested later to see if they chose that food over foods that the caterpillars had never before experienced.

> In this experiment, we explored the possibility that larvae of *Manduca sexta* could be induced to prefer a particular diet when later offered a choice of diets. The results of this experiment are important because induction of preference is apparently linked to (1) the release of electrophysiological signals by sensory cells in the animal's mouth and (2) the release of particular enzymes, produced during the period of induction, that facilitate the digestion and metabolism of secondary plant compounds (laboratory handout, 2010).

The entire last sentence does not belong in the Introduction. The work referred to in this example was a simple behavioral study: Students did not make electrophysiological recordings, and they did not isolate and characterize any enzymes. Although a consideration of these 2 topics might profitably be incorporated into a discussion of the results obtained, these issues should be excluded from the Introduction because they do not explain why this particular study was undertaken. **Include in your Introduction section only information that prepares the reader for the final statement of intent.** You might, on a separate piece of paper, jot down other ideas that occur to you for possible use in revising your Discussion section, but if they don't contribute to your Introduction, don't let them intrude. Be firm. Stay focused.

5. **Write an Introduction for the study that you ended up doing.** Sometimes it is necessary to modify a study for a particular set of conditions, with the result that the observations actually made no longer relate to the questions originally posed in your laboratory handout or laboratory manual. For example, the pH meter might not have been working on the day of your laboratory experience, and your instructor modified the experiment accordingly. Perhaps the experiment you actually performed dealt with the influence of temperature, rather than pH, on enzymatic reaction rates. In such an instance, you would not mention pH in your Introduction section because the work you ended up doing dealt only with the effects of temperature.
6. Once you have written a first draft of your Introduction, idea mapping (pp. 79–83) can help you decide which ideas to keep and help you to organize those ideas to best advantage. Start with a statement that makes the general topic sound interesting or important, and worth reading about. Then lead point by point in a logical way to the specific question or questions that you addressed in your study.

A Sample Introduction

The following paragraphs satisfy all the requirements of a valid Introduction. This Introduction section is brief but complete—and effective:

> Although it is well known that plants can use sunlight as an energy source for carbon fixation (Romero and Reed, 1993), all wavelengths of light need not be equally effective in promoting such photosynthesis. Indeed, the green coloration of most leaves suggests that wavelengths of approximately 550 nm are reflected rather than absorbed so that this wavelength would not be expected to produce much carbon fixation by green plants.
>
> During photosynthesis, oxygen is liberated in proportion to the rate at which carbon dioxide is fixed (Romero and Reed, 1993). Thus, rates of photosynthesis at any particular wavelength of light can be determined either by monitoring rates of oxygen production or by monitoring rates of carbon dioxide uptake. In this experiment, we monitored rates of oxygen production to test the hypothesis that wavelengths of light differ in their ability to promote carbon fixation by the aquatic plant *Elodea canadensis*.

Note how, in this Introduction, the material progressed from a rather general statement (plants photosynthesize) to more specific statements and, finally, to the specific research objectives of the study. You will see the same progression in the Introduction sections of most published studies. Your instructor should also see it in yours. Note also that every sentence leads the reader logically to the final sentence.

TALKING ABOUT YOUR STUDY ORGANISM OR FIELD SITE

If your study organism or field site was deliberately chosen because it was ideally suited to investigating the particular problem that you addressed, conclude your Introduction with a brief paragraph explaining your choice. Otherwise, that information would be more appropriate in your Materials and Methods section, as on pp. 156–157. Here is an example of how the material presented on p. 156 could be rewritten as a fine ending to an Introduction:

> The marine polychaete *Hydroides dianthus* is an excellent organism for such a study because its larvae can be obtained in great numbers almost year-round and reared in the laboratory with greater than 90% survival (Qian, 2000; Toonen and Pawlik, 2001). Moreover, the larvae become capable of metamorphosing within 4–6 days at 25°C (Scheltema, 1981; Bryan and Qian, 1997) and can be readily induced to metamorphose by simply elevating the potassium concentration of seawater by 15 mM* (Bryan and Qian, 1997).

DECIDING ON A TITLE

A good title summarizes, as specifically as possible, what lies within the Introduction and Results sections of the report. For this reason, **write your title after you have written the rest of your report.** Your instructor is a captive audience. In the real world of publications, however, your article will vie for attention with many other articles written by many other people; the busy potential reader of your paper will glance at the title of your report and promptly decide whether to stay or move on. **The more revealing your title, the more easily potential readers can assess the relevance of your paper to their interests.** A paper that delivers something other than what is promised by the title can lose you considerable goodwill when read by the wrong audience, and it may be overlooked by the very readers for whom the paper was intended. Indeed, many potential readers will miss your paper entirely because indexing services, such as *Biological Abstracts* and *ISI Web of Science*, use keywords from a paper's title in preparing their subject indexes.

Here is a list of mediocre titles, each followed by 1 or 2 more revealing counterparts:

1. **No:** Metabolic rate determinations

   Yes: Exploring the relationship between body size and oxygen consumption in mice

2. **No:** The role of a homeobox gene

   Yes: The homeobox gene *Irx5* is needed for retinal cell development in mice

3. **No:**

   a. Measuring the feeding behavior of caterpillars

   b. Food preferences of *Manduca sexta* larvae

   Yes:

   a. Measurements of feeding preferences in tobacco hornworm larvae (*Manduca sexta*) reared on 3 diets

   b. Can larvae of *Manduca sexta* (Arthropoda: Insecta) be induced to prefer a particular diet?

*millimolar = 10^{-3} moles per liter.

The original titles are too vague to be compelling. Why go out of your way to give potentially interested readers an excuse to ignore your paper? Of more immediate concern in writing up laboratory reports rather than journal articles is this suggestion: Why not use a title that demonstrates to your instructor that you have understood the point of the exercise? Win your reader's confidence right at the start of your report. (By the way, the title should appear on a separate page, along with your name and the date on which your report is submitted.)

WRITING AN ABSTRACT

The Abstract, if requested by your instructor, is placed at the beginning of your report, immediately following the title page. Yet it should be the last thing that you write, other than the title, because it must completely summarize the entire report: why the experiment was undertaken, what problem was addressed, how the problem was approached, what major results were found, and what major conclusions were drawn. And it should do all this in a single paragraph.

Despite its unimpressive length, a successful abstract is notoriously difficult to write. **In compact form, your abstract must present a complete and accurate summary of your work, and that summary must be fully self-contained**—that is, it must make perfect sense to someone who has not read any other part of your report, as in the following example:

> Because some wavelengths of light are known to be more effective in promoting photosynthesis than others, this study was undertaken to determine the wavelengths of light that are most effective for the aquatic plant *Elodea canadensis.* Rates of photosynthesis were determined at 25°C, using wavelengths of 400, 450, 500, 550, 600, 650, and 700 nm and measuring the rate of oxygen production for 1-h periods at each wavelength. Oxygen production was estimated from the rate of bubble production by the submerged plant. We tested 4 plants at each wavelength. The rate of oxygen production at 450 nm (approximately 2.5 ml O_2/mg wet weight of plant/h) was nearly 1.5·greater than that at any other wavelength tested, suggesting that light of this wavelength (blue) is most readily absorbed by the chlorophyll pigments. In contrast, light of 550 nm (green) produced no detectable photosynthesis, suggesting that light of this wavelength is reflected rather than absorbed by the chlorophyll.

Note also that the sample Abstract is informative. The author does not simply say that "Oxygen consumption varied with wavelength. These results are discussed in terms of the wavelengths that chlorophyll absorbs and reflects." Rather, the author provides a specific summary of the results and what they mean. Be sure that your Abstract is equally informative. **Clearly, this section of your report will be easier to write if you save it for last.**

PREPARING AN ACKNOWLEDGMENTS SECTION

Most biologists are aided by colleagues in various aspects of their research, and it is customary to thank those helpful people in an Acknowledgments section, which is the penultimate section of the report. Here is an example that might be found in a typical student report:

> I am happy to thank Casey Deiderich and Robert Burns for sharing their data with me, and Professor Collin Johnson for helpful discussions concerning the effects of temperature on metabolic rate. Professor C. Orians made me aware of the crucial Hendler (1999) reference. Finally, I am also indebted to Jean-François Vilain for lending me his graphics software, and to Sarah Campbell for teaching me how to use it.

As in the preceding example, you must include the last names of the people you are acknowledging and indicate the specific assistance that you received from each person named.

PREPARING THE LITERATURE CITED SECTION

In the Literature Cited section, the final section of your paper, you present the complete citations (in alphabetical order, according to last name of the first author of each paper or book) for all the factual material you refer to in the text of your report. This presentation provides a convenient way for readers to obtain additional information about a particular topic, as well as a means of verifying what you have written as fact. Detailed directions for preparing this section are given in Chapter 5 (pp. 71–76).

PREPARING A PAPER FOR FORMAL PUBLICATION

Papers submitted to an editor for possible publication must conform exactly to the requirements of the specific journal you have targeted. Before beginning a manuscript, you must determine which is the most appropriate journal for your work and then read carefully that journal's Instructions for Authors, typically found online and at the front or back of at least several issues each year. **It also helps to study similar papers published in recent issues of the targeted journal.** How are references cited in the text? How are they listed in the Literature Cited section? Does the journal permit (or require) subheadings in the Materials and Methods or Results section? If you fail to follow the relevant instructions, your paper may be returned unreviewed; at the least, you will annoy the editor and the reviewers.

Do not incorporate figures and tables into the text of the manuscript unless you are required to do so. Most manuscripts—including the figures—are now submitted online; follow the targeted journal's instructions for uploading the various components of your manuscript.

Before submitting your manuscript to the journal's editor, go through your work one last time, and be certain that every reference cited in the text is listed (and correctly so) in the Literature Cited section, and that the Literature Cited section contains no references not actually mentioned in the text.

Your manuscript should be accompanied by a brief cover letter, which should include the paper's title, the names of authors, and short summaries of the research goals and major findings. Here is an example:

Dear Dr. Grassle:

Please consider the enclosed manuscript titled "Understanding the effects of low salinity on fertilization success and early development in the sand dollar *Echinarachnius parma*," by J.D. Allen and J.A. Pechenik, for publication in *The Biological Bulletin*. Our goal was to determine whether the failure of embryos to develop at low salinities was caused by a failure of the eggs to be fertilized or a failure of the fertilized eggs to cleave. Our results were surprising, in that reproductive failure at low salinities in *E. parma* apparently reflects an inability of the fertilized egg to cleave more than an inability of sperm to fertilize the eggs. Drs. David Epel (Hopkins Marine Station, Stanford University) and John Havenhand (Tjärnö Marine Biological Laboratory Sweden) would be especially suitable reviewers for this manuscript. I can send the original figures and photographs immediately upon request.

My contact information follows:

phone (617-627-9999)

fax (617-627-3805)

e-mail: jan.pechenik@tufts.edu

Thank you for your attention.

Note that in this example, the author recommends specific reviewers for the submitted article. Although editors are happy to have you suggest appropriate reviewers, they won't necessarily take all of your suggestions. Recommend experienced people who will give honest and carefully considered reviews—if the manuscript has problems, you want them found out before publication. Once the paper is published, it's out there forever.

A NOTE ABOUT CO-AUTHORSHIP

Most research papers have multiple authors, all of whom are expected to have made intellectual contributions to the work in addition to any role in collecting the actual data. Intellectual contributions can include designing the study and analyzing and interpreting its results. Authors are also expected to have had a role in writing at least parts of the manuscript and to have read and approved the entire manuscript before its submission to the editor. People who have only helped collect the data or who have only provided equipment or space for the research should be mentioned in the Acknowledgments section but should not be listed as authors. Some research journals (e.g., *PLOS ONE*) now require all authors to indicate their specific roles in the research and in the preparation of the manuscript.

CHECKLIST FOR THE FINAL DRAFT

TITLE

- ❑ Title gives a specific indication of what the study is about (pp. 201–202)

ABSTRACT

- ❑ Background stated in 1 or 2 sentences (p. 202)
- ❑ Clear statement of specific question addressed and of specific hypotheses tested (p. 202)
- ❑ Methods summarized in no more than 3 or 4 sentences (p. 202)
- ❑ Major findings reported in no more than 2 or 3 sentences (p. 202)
- ❑ Concluding sentence relates to statement of specific question addressed (p. 202)
- ❑ Abstract is a single paragraph; if not, can it be rewritten as one paragraph? (p. 202)

INTRODUCTION

- ❑ Clear statement of specific question or issue addressed (pp. 195–196)
- ❑ Logical argument provided as to why the question or issue was addressed (pp. 198–199)
- ❑ Specific hypotheses are indicated, if appropriate, and a rationale for those expectations is provided (pp. 189, 195–196)
- ❑ Every sentence leads to the statement of what was done in this study (pp. 195, 198–199)
- ❑ All statements of fact or opinion are supported with a reference or example (p. 197)
- ❑ If appropriate, the rationale for choosing the study system or organism is given (p. 200)

MATERIALS AND METHODS

- ❑ Methods are presented in the past tense (p. 157)
- ❑ Design of study or experiment is clear and complete (pp. 152–155)
- ❑ Rationale for each step is self-evident or clearly indicated (pp. 155, 158)
- ❑ Each factor mentioned is likely to have influenced the outcome of this study, and all factors likely to have influenced the outcome are mentioned (pp. 153–155)
- ❑ Precision of all measurements is indicated (p. 155)
- ❑ Includes brief description of how data were analyzed (calculations made, statistical tests used) (pp. 155–156)
- ❑ If appropriate, the field site or study organism is described (pp. 156–157, 200)

RESULTS

- ❑ Text summarizes important findings in the data and does not simply repeat raw data from the graphs or tables (pp. 158, 182–186)
- ❑ Results are presented in the past tense (p. 182)
- ❑ Results are presented in active terms whenever possible (e.g., in terms of what organisms or enzymes did) (pp. 96–98)
- ❑ All general statements are supported with reference to data (and by results of statistical analysis when possible) (pp. 182–183)
- ❑ Major results are presented in words, but their implications are not discussed (pp. 150–151, 158)
- ❑ No raw data are presented (p. 160)
- ❑ Figures are referred to as "Figures" and not as graphs, drawings, or photographs (p. 159)
- ❑ The same data are not presented in both tabular and graphical form within the same report (pp. 162, 180)
- ❑ Every table or graph makes an important and unique contribution to the report (pp. 162, 165, 167)
- ❑ Each figure or table has an informative caption or legend, correctly placed (below figure, above table) (pp. 163, 166–167)
- ❑ Symbols are used consistently in all figures and are chosen to facilitate interpretation when possible (pp. 162–164)
- ❑ Tables and figures are numbered in the order in which they are first referred to in the paper (p. 181)
- ❑ Each figure or table is self-sufficient; readers can tell what question is being asked, what the major aspects of how the question was addressed are, and what the most important results are without reference to the rest of the paper (pp. 35–40, 162–164, 180–181)

- ❑ Numbers of individuals and numbers of replicates are clearly indicated in the graph, table, caption, or legend (pp. 173, 181)
- ❑ The meaning of error bars on figures is clearly indicated in the caption (e.g., one standard error about the mean) (pp. 170–173, 181)
- ❑ Results of statistical analyses are correctly incorporated into the text or figures (pp. 61–65)

DISCUSSION

- ❑ Data are clearly related to the expectations and hypotheses raised in the Introduction (pp. 190–195)
- ❑ Facts are carefully distinguished from speculation (p. 191)
- ❑ Unusual or unexpected findings are discussed logically, based on biology rather than apology (pp. 191–194)
- ❑ All statements of fact or opinion are supported with references to the literature, data, or an example (p. 192)
- ❑ Section suggests further studies that should be conducted, additional questions that should be posed, or ways that the present study should be modified in the future (pp. 191–192)

LITERATURE CITED

- ❑ Citations are provided for every reference cited in the report and are in the correct format (pp. 70–76, 203)
- ❑ Section includes no references that are not cited in the report (p. 71)
- ❑ Each citation includes names of all authors, title of paper, name of journal, year of publication, volume number, and page numbers (pp. 71–76)

ACKNOWLEDGMENTS

- ❑ People are mentioned by first and last names, and their specific contributions are noted (p. 203)

GENERAL

- ❑ Text of report is double-spaced (p. 12)
- ❑ First page shows name of author, name of lab section or instructor, and date submitted (p. 12)
- ❑ All information is presented in the appropriate section of the report (pp. 150–151)
- ❑ All pages are numbered (p. 12)

TECHNOLOGY TIP 7

Graphing with Excel

Excel was designed for businesspeople, not biologists, and for graphing it is less flexible and intuitive than some other programs, such as my favorite, GraphPad Prism. However, Excel is so widely used (and misused) by students in biology courses that it is worth pointing out some tips for using it effectively. I assume here that you already have some familiarity with the program.

Entering data. Enter your data in a new spreadsheet. For bar charts, enter the treatment names (the independent variable; e.g., human, dolphin, sea lion, and so on if you were plotting Fig. 9.14) in the first row. Enter your data starting with the second row.

If you are plotting data for a scatter plot (e.g., Figs. 9.4, 9.6, and 9.8), enter data for your *x*-axis (usually the independent variable, e.g., temperature in Fig. 9.8) in the first column. In Figure 9.8, feeding rate data would then be entered in the adjacent column. For Figure 9.4, you would enter feeding rate data for each of the 3 treatments in adjacent columns. Do not leave space between columns.

Save your worksheet frequently. I recommend including the date on which the study was conducted as part of the title you give the project.

Transforming data. You may wish to transform your data before plotting it. For example, you may need to convert your measurements to different units, or you may wish to plot the logarithms of the data collected. To transform a column of data, first click at the top of an empty column and label it. Then click in the first box of the new column and type an equal sign, which tells the program that you are about to enter a formula. Then, select Formulas on the menu bar, and then "fx Insert Function" at the left. The transform functions can be found within the Math and Trig category. Once you select the desired function, specify the row and values to be transformed. For example, suppose you have 8 values in Column B of your spreadsheet. To take the log (base 10) of those 8 data points and put those new values in Column D, first click in space D1 and type an equal sign. Then, select the Log10 function, enter A1 within the parentheses, and click *OK*. Next, click on the button in the lower right of the rectangle around space D1, and drag down to space D8. You should see the transformed values in all 8 rows of column D.

Table 9.6 The Excel decoder

What It Means	What Excel Calls It
Graph	Chart
x-axis	Category axis (Horizontal axis)
y-axis	Value axis (Vertical axis)
Area inside the axes of the graph	Plot area
Area outside the axes of the graph but inside the frame	Chart area
Data point	Marker
Scatter plot (a point graph)	XY (Scatter)
Don't use this!	Line (under Chart Type)
Key (for on-graph explanation of symbols used in graph)	Legend

Calculating statistics. To calculate averages, standard deviations, and other statistical functions for your data, select Formulas on the menu bar, and then choose the Statistical option under More Functions (e.g., Average, for calculating the mean, or StDev, for calculating the standard deviation). Next, specify the range of values to use (e.g., B1:B8), and click *OK*. Once you have calculated your statistic for one column of data, drag the calculation into adjacent columns to calculate the same statistics for those columns.

Making graphs. One of the many endearing idiosyncrasies of Excel is the terminology it uses, which agrees hardly at all with that used by biologists. I present an Excel decoder in Table 9.6.

Note the tool bar above the worksheet that contains your data. To plot a graph, first highlight the data you wish to plot. Usually you will highlight all the numbers entered (by holding the left mouse button and dragging over the screen), but sometimes you will want to select only certain columns (e.g., columns of transformed data) while holding down the Ctrl key. Then click the *Insert* tab and choose the desired chart type. When graphing with Excel, keep the following in mind:

- If you wish to plot a bar graph or histogram, select the Column option. Do not plot 3-dimensional graphs, which can be difficult to read.

(Continued)

- If you wish to produce a scatter plot (e.g., Figs. 9.4 and 9.8), choose XY Scatter.
- Do not select Line even when you wish to plot a line graph. Your *x*-axis values will not be properly spaced.
- For scatter plots, you have several options to choose from. Usually you will want to just plot the points without any lines (you can add a regression line later) or to connect the points with straight lines. Occasionally you will want to include smooth curves. **Never choose the options for plotting curves without data points.**
- To add a regression line to a scatter plot, first click on any point in the graph to identify the data set. Next choose the Layout tab, click *Trendline*, and then add the type of line you wish to add.
- Use white as a background color for all graphs to maximize contrast and clarity. To do so, double-click anywhere inside the graph, and select the No Fill option. At the same time, select None for Area, and also select No Line for Border (to remove the frame that Excel otherwise draws around each graph). As mentioned previously, do not choose the 3D option.
- If you will include a key to symbols used in your graph (i.e., if you are displaying more than one treatment, requiring the use of at least 2 symbols), use white as the background color for that as well. Double-click anywhere within the key area, and follow the instructions given previously.
- If space is available in the figure, move the key into the figure by clicking on it once and then dragging it into the figure.
- In the Layout option within Chart Tools, leave Chart Title blank. You will enter your title as part of your figure caption later. Be sure to enter the units (in parentheses) after the labels for the *x*- and *y*-axes.
- To add error bars to a point or bar, stay in the Layout section within Chart Tools and double-click on the point or bar for the desired data set, choose the Error Bars option at the far right, and then enter the desired type of error bars (e.g., standard error).
- To change the size of the points plotted in a scatter plot, double-click on any point, and change the size using the Marker Options part of the menu.

- To modify a graph at a later time, click anywhere inside the graph, and then select the desired option from the Chart Tools tab. If you wish to add or remove particular data points, add or delete the values on the spreadsheet and see if the appropriate changes automatically appear in your graph. Otherwise, right-click within the graph and choose the Select Data option.
- If you correct a data entry in the spreadsheet, the correction should appear automatically in your graph.

If you have trouble, click the *?* at the far upper right and ask for help with the specific issue.