THE CHICAGO GUIDE TO COMMUNICATING SCIENCE

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CHAPTER NINE

Graphics and Their Place

VISUAL LANGUAGE: SEPARATE BUT EQUAL

Modern science relies deeply upon illustration—graphs, charts, drawings, photographs, maps, models, and other forms. Technical knowledge today is inseparable from visual presentation, from its specific powers to order and convey information. Scientists, moreover, appreciate excellent graphics. Illustrations that offer data with clarity and elegance are a unique type of achievement—creative, efficient, even a source of delight.

Scientific illustration has an extremely rich and venerable history, reaching back to the written works of ancient Egypt, Greece, China, India, and medieval Islamic civilizations. Alloys between science, art, and draftsmanship, forged in the European Renaissance and after, are still evident in many aspects of contemporary image making—in drawings of specimens, attention paid to form and balance, three-dimensional effects, uses of color. Many of the most influential works in the history of science—Galileo's *Sidereus nuncius* or Vesalius's *De humani corporis fabrica,* for example—have been books of pictures as well as text.

That said, it should be stressed that the visual dimension to science forms a language all its own, a kind of pictorial rhetoric, if you will. By this I mean that graphics are often much more than a mere handmaiden to writing. They don't just restate the data or reduce the need for prose, but offer a kind of separate "text" for reading and interpretation. To assure yourself of this, take any well-illustrated article, copy the figures, and assemble them in order of appearance. You will find that they tell their own story, in some manner parallel to that of the writing, but in other ways different, enriching, though also with notable gaps.

Illustrations serve a variety of functions. Charts summarize data and make comparisons. Graphs provide analysis by revealing patterns, relationships, or possible correlations. Images, meanwhile, offer different kinds of evidence, explain and explore information, demonstrate specific points, represent concepts or theories. All in all, this is an impressive array of service—and it certainly helps point up (and justify) why scientists often browse through articles by reading the abstract and looking at the illustrations.

Perhaps most fundamental of all, however, visual discourse adds variety for the eye and enhanced appeal for the mind. Does this seem trivial? It shouldn't: the psychology of reading is not a little complex. The living brain very much appreciates intelligence expressed in different forms.

SPECIFICITY AND CHANGE

As a scientist-author, fresh on the trail of publication, it's a good idea to become intimately familiar with graphic elements used in your field. This may seem obvious. But there are two factors that raise it beyond mere common sense.

First, many visuals are highly field specific. Even graphs, maps, or other presumably standard figures can change considerably in form and style, as well as content, between disciplines. Moreover, there is the "journal effect" to consider: even within your own field, different periodicals have their own demands for how they want articles to look, just as they have standards for written copy.

A second reason to get familiar with graphics in your area is that many types of visuals are undergoing change, due mainly to the advent of digital technology, and will continue to evolve as this technology does. Indeed, the digital age has introduced a fertile array of new visual possibilities: satellite imagery, three-dimensional modeling, ultrasound technology, tomography, magnetic resonance imaging, various types of electron microscopy, and a dozen others. Science is replete with new powers of vision, new means of making the informed eye the instrument of study, analysis, and discovery. Color, too, has found a new and expanding role in scientific imagery and continues to revise older forms. Those who grew up in science before the 1980s can testify to a former universe of black and white, where the tones of text and image were identical. Since then, a great separation has taken place, with color now abloom in many fields, being much more easily and routinely achieved (though not cheaply, by any standard). More than ever, pictures today often demand and reward attentive study in themselves.

Becoming familiar with the graphics of your field is therefore essential—but it is not enough, in and of itself. The new sophistication in imagery depends upon software, which is also often designed for individual fields. Certainly, a number of generic programs exist to help scientists create graphs, charts, and tables. Most major software vendors offer programs that cover basic graphing capabilities, useful in many circumstances when simple plots will do (Microsoft Excel is one of the most widely used). For more complex demands, there are programs designed specifically for scientific uses (Sigma Plot and Axum are two popular choices). Beyond these general-purpose programs, software is likely to be specialized. Fields as diverse as molecular genetics, petroleum geology, climatology, and mechanical engineering now each have a large spectrum of dedicated graphics programs to use with particular types of data. This places new demands on the scientist, who often must learn at least some of these programs.

Finally, new visual possibilities are attached to Internet communication. Still very young, Internet science promises new types of nonwritten expression: real-time animation, interactive modeling, use of video and audio. In some areas, these capabilities have already been taken up—online journals in medicine and chemistry, for example, have included animated graphics, video, and interactive visuals of various types. Change is in the wind for scientific illustration, and on the ground.

All of which highlights, again, the need for the individual scientist to learn what is out there. Becoming an effective author means becoming literate in these forms of communication—learning how to read them, how to recognize good *and* bad examples, when and where to imitate the best.

CHOOSING MODELS: A HELP HERE, TOO

As with writing, you can learn a lot about producing good graphics by studying the admirable work done by others—and the opposite. Not only will this provide you with guiding examples to emulate and avoid, it will also help sharpen your critical faculty about what goes into such an image, what makes it effective, easily deciphered, informative, attractive. You can collect entire articles or only one or two illustrations from a paper. You might want to make a fairly large collection at first and then whittle it down to the very best: the exercise of doing this will decidedly focus your attention on details of quality. You might try gathering several nice examples of a single type of image, compare them side-by-side, and choose from there. Any method that helps you scrutinize and evaluate the images of your field is valuable. Find out what frustrates or irritates you (Too much type? Text too small? Figure too busy? Poor labeling?). The best questions to ask, as always, are, Is this something I wish I had done? or What would I do to make this better?

For every one of your choices, or for any graphic you find particularly worthy (or the opposite), stop and ask yourself what it is that seems especially good (or poor) to you. The more you come to understand your own preferences, the more you can use them consciously in preparing your own articles. Here are a few categories to help you judge individual illustrations and analyze your impressions.

- *Neatness.* Is the image clean and sharp; does it invite attention, or repel it?
- *Readability.* Can the eye move over it and pick up information, either quickly or with concentrated attention, or is there too much confusion, too much data (a "crammed" feel), a lack of integration?
- *Use of Type.* Is the font easily readable, large enough; is it placed well, or does it invade and distract; is there too much of it (a common error)? Is there a proper hierarchy among type sizes—do the largest words refer to the most important items, the smallest to the least important?
- *Size.* Is the image too small to be fully visible; do you find yourself drawing the page nearer to your face? On the other hand, does it fill the rectangular space to the edges, as it should, or does it have too much white space?
- *Aesthetics.* Is the image balanced, or does it seem lopsided? What aspects or portions draw the eye most, and are these significant in terms of content? Are the thickest lines on the graph the most important; do the patterns in a bar chart highlight the differences you want to show?
- *Use of Color.* Does it help distinguish content, increase readability; are colors appropriately distributed (e.g. blue for depth, red for height); is text minimized yet visible; is the legend (if needed to differentiate the meaning of each color) simple and easy to use? Are colors consistently coded among different images?

- *Consistency.* Do similar images (maps, charts, graphs, photographs, etc.) carry the same stylistic scheme in terms of line width, type font and size, labeling, scales, and so forth?
- *Room for Improvement.* Are there any changes you yourself might make to improve the quality of this image?

EXPERIMENT, EXPERIMENT

I said earlier that writing involves experimentation—trial and error, revision, working things out. This is equally true for figures. It is true even for seemingly simple visuals, such as charts or graphs. We often construct these from our data as tools to help us in our analysis, to make comparisons, look for trends, discover relationships. When we initially draft our illustrations, we are frequently performing what are akin to visual trials—recasting our information in new forms to see if something important and unforeseen steps into the light.

The experienced scientist-author knows, moreover, that it can be very helpful to take a single data set and graph it in different ways. This means trying out distinct analytical versions in order to discover what form offers the most effective, meaningful presentation. Today this can often be done for charts and graphs, in particular, with a few clicks of a computer mouse: histograms can be changed to line graphs, pie charts, dot graphs, and other forms, with or without labels, error bars, means, and averages. Current software gives you the power to play with data in productive ways. As with text, the process of creating any specific image can reveal new aspects or relationships previously unnoticed.

So it is entirely normal—indeed it should be expected—that you'll often create more illustrations than you need, and that you'll need to revise the ones you keep. Sometimes a particular graphic, one you may have worked hard on, will be unnecessary; its message can be stated in a sentence or two of text—if so, please (for the sake of scientists everywhere) delete it, grieve briefly, and move on.

Experimenting with graphics also means making decisions about appearance. In a good scientific illustration, everything visual qualifies as content. Choices therefore need to be made about such things as, how much text should be used; what type font and size are best; what shadings or colors are appropriate; what kind of scale should be used; how far should each axis extend; how wide should the bars or lines be on a chart or graph; what patterns should be used; is a legend needed and where should it go; and so on. For more complex figures, the decisions are likely to be even more numerous.

Luckily, the relevant answers to such questions are far from open-ended. There is much standardization in scientific imagery, and your models will help guide your choices. No example, however, is ever a final template. There will also be factors (let us hope) individual and original to your work, and these will require that you adapt particular graphical forms to your specific case. This may involve changing scales, altering colors used in a model, graphing an added variable.

Think of each figure, therefore, as a draft in the beginning, a kind of visual audition. No time spent trying things out intelligently is ever wasted. It is sometimes necessary to discover what graphical forms might work best with your data, which types of illustrations you are most comfortable using. After all, this too is an area where authors develop a certain style, however subtly expressed. Don't berate yourself for any dead ends; be thankful when you find and overcome them. Experimentation, in both writing and illustration, is one of the most crucial processes in learning how to communicate well.

Many articles need (but often don't have) an introductory illustration to help orient the reader. Could your document benefit from such a graphic? The answer might be yes, no, or maybe, but it's usually worth asking and thinking about the question. An introductory graphic can serve many of the same purposes as the introduction itself—it can provide setting, such as can be done with a map, large-scale model, and so forth; it can offer essential background, for example, in the form of a flow chart that shows a sequence of relationships, a schematic diagram of apparatus, a time-based graph or chart outlining the relationship under study. Again, a guiding principle is to think of what might help usher your reader into the domain of your investigation. What would you use in an oral presentation to do this?

Try to make sure that any diagrams and drawings are relatively pleasant to look at. Use a type style that can be read very easily. Lowercase lettering is usually more pleasant to read than all uppercase. Many journals prefer a sans serif font for illustrations: Arial and Helvetica are common choices. Others prefer serif styles or are nonspecific. Check this out *before* you create your images—spare yourself (or your artist) the agonies of unnecessary revision.

As with text, different journals will have different specifications for many aspects of the illustrations they agree to publish. At a general level, this is likely to involve such aspects as software format (preferred programs), sizing, method of delivery (whether on disk, via the Internet, or as printouts). Some journals, however, are quite specific about the detailed form your graphics should take, for example, type style and size, line thickness, use of borders and arrows, labeling (where and when), scale bars, and more. Be aware: certain periodicals spell all this out in their instructions to authors, but some do not. Some demand consistency of stylistic detail among articles, and some are less exacting. Thus, you really do need to take a close look at published examples in your journal of choice before spending the time to design and create your images.

SOME NECESSARY POINTERS

Keep text on your figures to a minimum. Use it mainly for labeling, not for explanation (leave this to the caption and main text). Also, be consistent from one figure to the next in the fonts you use, numbering and lettering style, and other such aspects.

Avoid any overly fanciful or arcane fonts for your images. They will distract the viewer (while drawing attention to yourself as the possible embodiment of bad or eccentric taste).

When needed, use different font sizes to indicate different levels of importance. Be consistent about your sizes and font styles from one graphic to the next. Alternatively, consider using boldface or italics as highlights or as a means to add a dash of visual interest. Be aware, however: too much variation is distracting, so keep your visual hierarchy simple, clean, efficient.

Design your figures so that they extend nearly to the edges of the frame: do not waste space. This will allow you to make each graphic as large as possible, which is very important, because—

Images in science are nearly always reduced considerably for printing, commonly 50% to 75% (one-half to one-quarter original size) or more. Therefore, *anticipate the effect of reduction* (not doing so is one of the most common errors made in scientific illustrations). Use a copy machine (or computer reduction, if the figure is a digital file) to reduce your images and test this out: make sure all text, lines, and details hold up. Another test is to take images that have been published and enlarge them to roughly the size of your own illustrations, then compare type size, line thickness, and so on.

Figures created for slide and computer presentations are almost *never* suitable for print journals, reports, or books. These presentation images must be translated, or even redone, for hard-copy debut. Frequent changes required include less text, smaller font sizes, thinner lines, and removal of color (simple gray-scaling very often isn't enough). In general, presentation images are similar to cartoon versions of what should appear in print.

Make sure all digital illustrations, whether originals or scans, have a resolution of 300 dpi (dots per inch) or higher. This is the absolute minimum required for printing; 600 dpi is usually better. Provide high-quality laser printouts of every figure.

Use a simple, clear system for naming digital files of your artwork. Common schemes include your last name (lead author) + figure number (Montgomery.2); one or two keywords + figure number (Apoptosis.2); and simple abbreviation of keywords + figure number (CrysRNA.2).

True elegance in science resides in simplicity and restraint.

EXAMPLES

In the pages that follow, I've tried to present a series of good and bad examples of illustrations taken from the published literature. In each case, a brief commentary, and possibly a question or two, are given in order to help you evaluate the relevant image and thus further your own critical ventures.

Charts and graphs are particularly well represented in figures 9.1–9.10. This is because these graphics are surely the most ubiquitous in all of science. My own unofficial survey of more than 150 journals in 57 fields (from insect physiology to mathematical physics) shows that they occur almost twice as often as any other type of visual. Indeed, in some periodicals, they are the *only* graphical form to be found. Thus, their importance is rather high.

Tables present exact numerical data, whereas charts and graphs take these data and give them a form of visual analysis. Use tables when you need to show specific or precise values; use charts and graphs when you want to find and express meaningful relationships from these numbers. Very rarely will you ever need to show both.

Notice in the figures that follow that, in most cases, the horizontal axis plots an independent variable—the data set that we select—whereas the vertical axis gives the dependent variable—what we measure.

Bar Charts

Bar charts or graphs, particularly histograms, are extremely common. The essence of such charts is usually to make comparisons between data

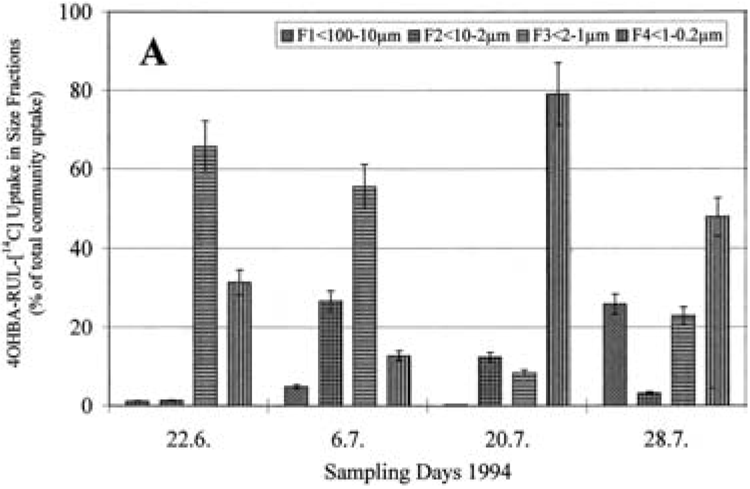

Figure 9.1 Example of a bar chart (from Munster et al. 1999, 118; used with permission of Schweizerbart Publishers, www.schweizerbart.de)

sets. They are thus particularly useful for showing differences, and are less suited for revealing trends or relationships.

Take figure 9.1. This shows the uptake of a particular carbon-bearing chemical by a forest lake, during a series of sampling-day intervals. Several aspects of this chart seem well done. First, the axes are labeled in type large enough to easily read, and a legend is provided. Second, the bars are of adequate thickness (this is not trivial) and show appropriate error ranges. Third, the different data sets are properly separated. Fourth, each data set shows the same order of bar patterns.

What can be done better? The *x*-axis is improperly labeled: shown are sampling *dates* (day, month), not days. The patterns for individual bars are much too similar to be easily distinguished. Note, too, that the legend is too small and cramped. These problems leave the data difficult to decipher and thus interpret. Solutions to any and all of these problems are simple and straightforward.

Now examine figure 9.2. This box-and-whiskers chart is an attempt to show the effect of parasitism on weight gain in two species of butterfly (*Heliothis virescens* and *Trichoplusia ni,* abbreviated "Hv" and "Tn" in the figure). Nearly everything is clearly labeled on this figure; the type is large and welcoming. Bar patterns are easy to distinguish, the legend is neatly done, and the interpretation of the data is clear (parasitism halts growth at an early stage). Moreover, the author has nested the bars for each individual species to highlight the comparisons being made.

Could anything be improved? The whiskers sticking out of the top of each bar could be explained (error bars?). The intervals on the horizontal axis could be a bit wider, allowing for a widening of the bars. d10 could be placed in its rightful interval, rather than in d9—which suggests that perhaps two-day intervals (d2, d4, d6, . . . , d10) might have been a superior choice for sampling. Finally, there is a larger question: would the data be more revealingly shown in a line graph? If the authors' point were to show only gross, overall patterns, then the answer would be no (or rather, not necessarily). But if ideas of developmental progress are at issue—ideas that depend on continuity through time—the answer would be yes, for discontinuous samplings would no longer suffice (why offer snapshots, when the entire movie is available at no extra charge?).

Now consider figure 9.3. This is a simple, vertically oriented chart, showing average measured porosity for petroleum-bearing rocks originally deposited in different settings. The data are averaged from a wide range of samplings and are thus quite generalized; the graph is meant to show only very large-scale comparisons. As a result, it probably doesn't need either the detail given in the vertical scale or the related horizontal ruling. We do need to know what average porosity is measured in, however; what do the numbers along the *y*-axis represent?

The bars are generous in width, but are not separated (as they should be), and the patterns are confusing—are we to assume some relation

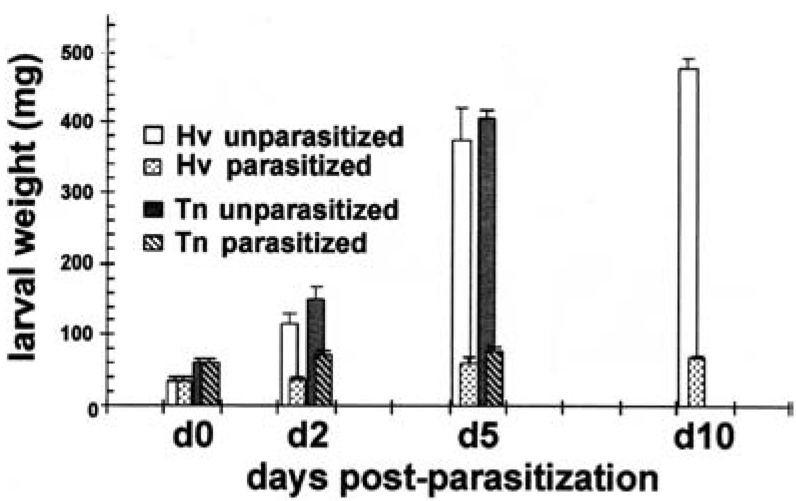

Figure 9.2 Example of a box-and-whiskers chart (reprinted from Cui, Soldevila, and Webb 2000, 1401; copyright 2000 Elsevier Science; used with permission)

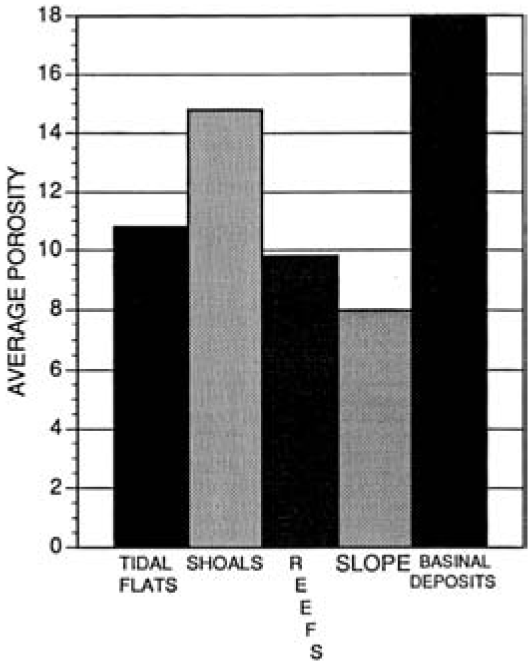

Figure 9.3 Example of a bar chart (from Jordan and Wilson 1994, 148)

between those similar patterns (e.g. shoals and slope)? Confusion is avoided if even a little space is added between each bar and a single pattern used. Note, too, the identifying text along the horizontal axis: again, are we being given clues that "Reefs" (written differently) and "Slope" (in larger type) merit particular attention? Uncertainty here can be averted in several ways, for example, by using different patterns for each bar and constructing a legend; by placing the respective label *above* each bar (which are at different heights) or even *within* it; or, again, separating the bars a little and making the type size a bit smaller and consistent.

Line Graphs

Nonbar graphs come in even more numerous varieties. With graphs you can show trends, correlations, and frequency distributions (various line graphs); rates of change (semilogarithmic graphs); changes in relative difference (area graphs); patterns among discrete random variables; and much more. The essence of a graph, however, in a majority of cases, is to show continuous relationships: data exist in some type of continuum defined by dependence between variables.

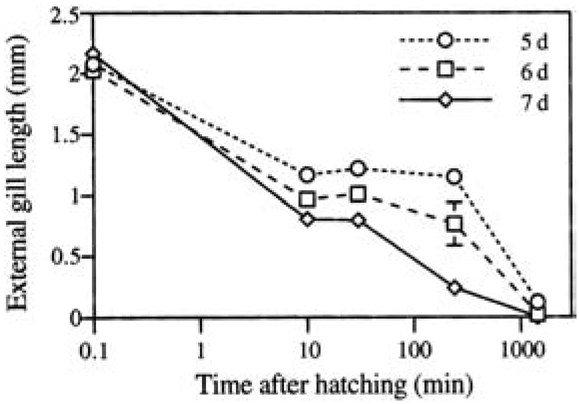

Figure 9.4 Example of a semilogarithmic graph (from Warkentin 2000, 559; used with permission)

Figure 9.4 presents a simple and wholly effective semilogarithmic graph, where time is the independent variable and is given in logarithmic scale. Nothing fancy is needed here; the graph compares changes in external gill length of tadpoles hatched at three different ages (5, 6, and 7 days). The text is clean, minimal, consistent. The axes are neatly labeled. The lines are clear and easily distinguished, and the data points are marked. Note that the logarithmic scale (x-axis) shows actual values (0.1, 1, 10, 100, etc.), not the logarithms (–1, 0, 1, 2, etc.). For much larger or smaller numbers, it is common to write in powers of ten, that is, 10^5, 10^6, 10^7 or 10^{-4}, 10^{-5}, 10^{-6}, and so on.

Compare this graph to figure 9.5, which includes three related plots, showing the concentrations of methane, carbon dioxide, and water in sediments of increasing depth below the sediment-water interface (marked as 0 on the vertical axis). Each graph carries six lines—six data sets—indicated by well-chosen standard symbols. There is some question as to whether the data for methane and carbon dioxide can be meaningfully distinguished and interpreted beyond general trends (which begs the question of why individual data lines are needed). In the graph for water content, meanwhile, this is less important, due to the tight clustering. How might the graph be improved? Here is a case where using color would make eminent sense. Possibly, the plots for methane and carbon dioxide would gain a bit of clarity (and meaning) if the intervals on the horizontal scale were widened. Finally, only one legend is really needed (it's the same for all three graphs).

Deciding how many lines to plot, how many correlations to reveal, is obviously very important and can require experimentation. As figure

9.6 shows, it is sometimes possible to include many lines in an effective manner. Notice here how well-chosen the line patterns are in terms of the eye's ability to differentiate—an aspect that adds both clarity and visual appeal. At the same time, however, this is possible only because the lines do not cross each other very much. Were they to do so, it would be necessary to break the data out into two or three separate graphs.

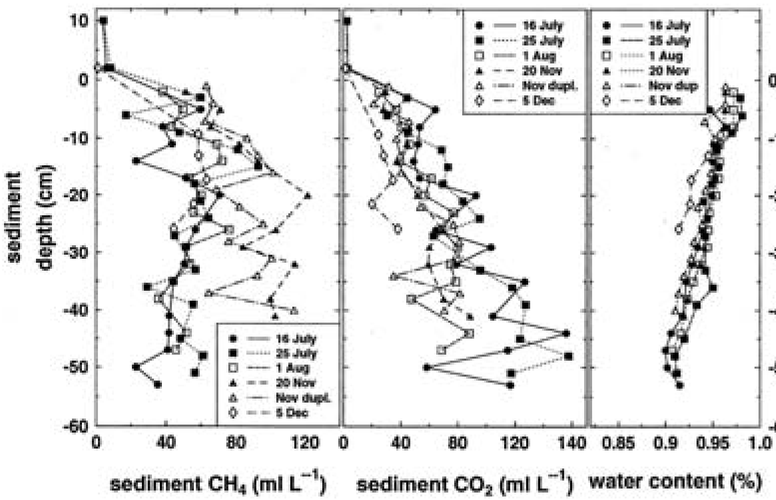

Figure 9.5 Example of a line graph (from Adams and Naguib 1999, 94; used with permission of Schweizerbart Publishers, www.schweizerbart.de)

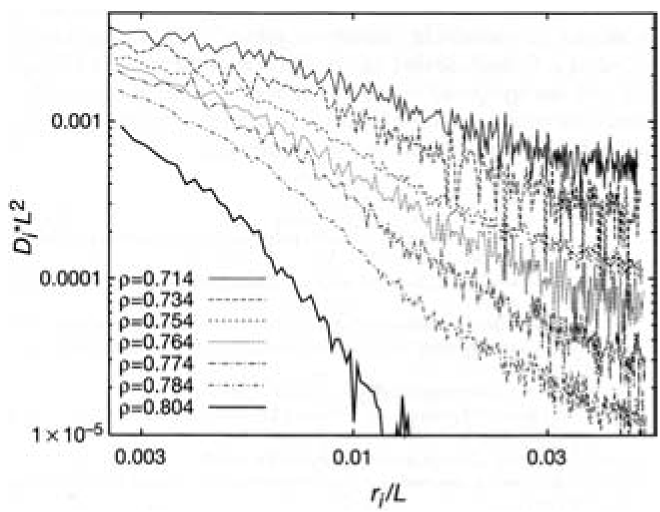

Figure 9.6 Example of a complex line graph (from Santen and Krauth 2000, 550; copyright 2000 *Nature;* used with permission)

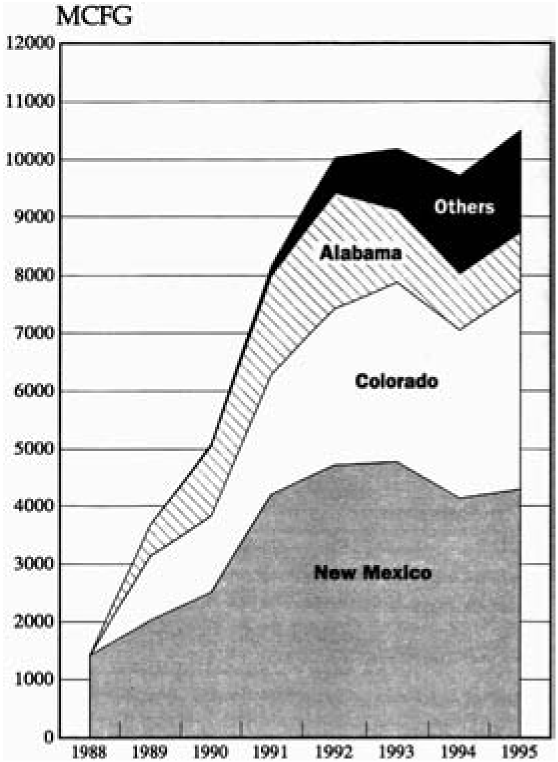

Figure 9.7 Example of an area graph (from Murray and Schwochow 1997, 32; used with permission)

Visually speaking, moreover, not all lines are created equal: note how the thicker, solid plots draw attention and imply importance, while the thinner, more broken ones carry much less psychological weight. Perhaps the only way to improve this example is to make the *y*-axis more consistent in interval labels, that is, 10^{-5} (we don't need the "1 ×"), 10^{-4}, and 10^{-3}.

Another type of line graph, sometimes called an area graph, appears in figure 9.7. This type of data display is used to show both progressive change and comparisons between different data fields. Note how important it is to use different and easily distinguished patterns within each data field. Color is not necessary here, but could be a help if a larger number of fields were plotted. Small improvements might be made: the axes might be better labeled (MCFG might be written out along the *y*-axis, "Million Cubic Feet of Gas"); we might want to extend the data fields through dashes (projected) to the right margin of the graph. On the whole, however, this is an informative and well-done figure.

Maps and Diagrams

Figures 9.8 and 9.9 show maps with a specific problem. Figure 9.8 is meant to compare precipitation levels associated with the 1997–1998 El Niño phenomenon, but the maps are far too small to read and interpret on any intelligent basis. In such cases, the editor of the journal and the authors of the article need to make a decision that favors their readers, not the data alone. If no more space could be allotted these images than is shown, they should have been deleted or else one map selected and shown at larger size. As it is, they provide more in the way of frustration than enlightenment.

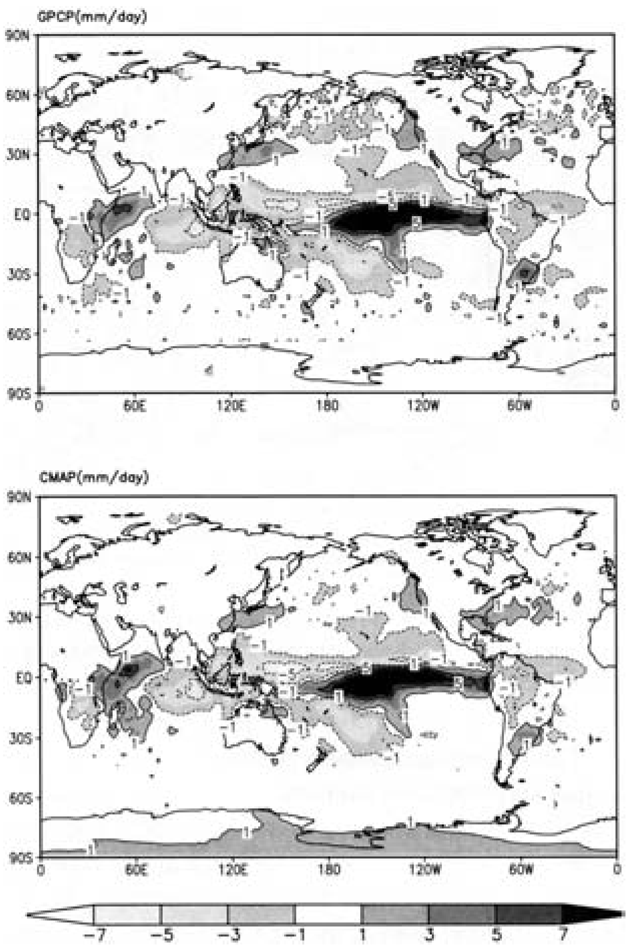

Figure 9.8 Example of maps that are too reduced to be easily read (from Guber et al. 2000, 2641; copyright American Meteorological Society; used with permission)

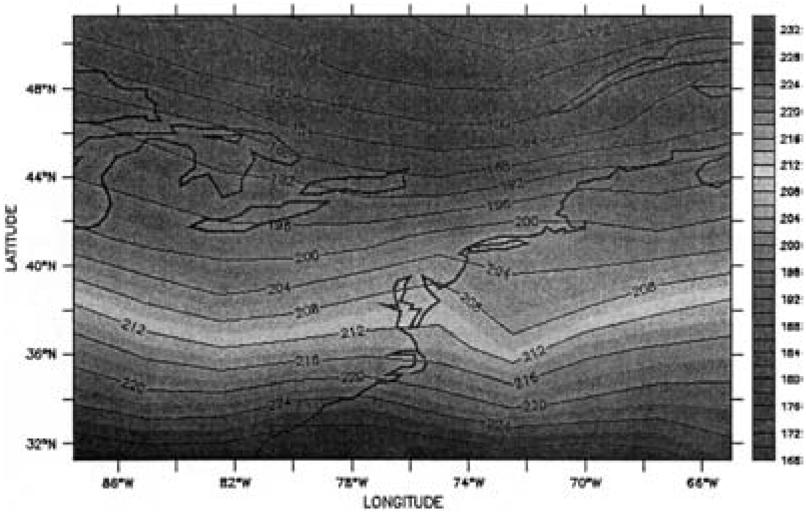

Figure 9.9 Example of a map that is difficult to read due to loss of color (from Bess et al. 2000, 2649; copyright American Meteorological Society; used with permission)

Figure 9.9, meanwhile, offers us another type of disappointment. Images originally drafted in color, for talks or poster presentations for example, do not always translate well into black and white or gray scale. Here, the data would be illegible if the contours weren't numerically labeled; certainly the scale on the right is of little help. The figure would have been clearer if it lacked shading altogether and merely offered its contours against a white background. Were color to be restored to this map, however, its message would be enhanced enormously, well beyond any black-and-white version. The power of color to reveal gradation and to highlight peaks and lows in such a data set is great indeed, and can offer the eye pleasure and the mind definite advantage. Such advantage, to be sure, must be weighed against cost. If color proves too expensive, yet is deeply integral to the meaning, the figure may need to be redrafted, as is the case here.

Which brings us to the example of figure 9.10. Let us admit, up front, that computer-generated presentations are a major advance for scientists. Indeed, they are far more simple, efficient, and (even) fun to create than the old, laborious, hand-drawn figures and typed-out tables we used to produce. But this new ease of creation comes with a price. In a great majority of cases, illustrations generated by computer for slide or other presentations do not make good visuals for published articles—unless revised with hard-copy standards in mind. Briefly put, we are dealing here with two very different media, each with its own distinct needs and limits. A graphic like the top panel of figure 9.10, with its verbiage surrounding and inhabiting the data, plays very well up on the big screen, but looks clumsy and amateurish in print. Much of the writing here is interpretive and belongs in the main body of the article itself. To appear in a high-quality journal, the graphic would need to be revised as shown in the bottom panel of figure 9.10: title removed, interpretive text deleted, axis labels reduced in size, lines thinned.

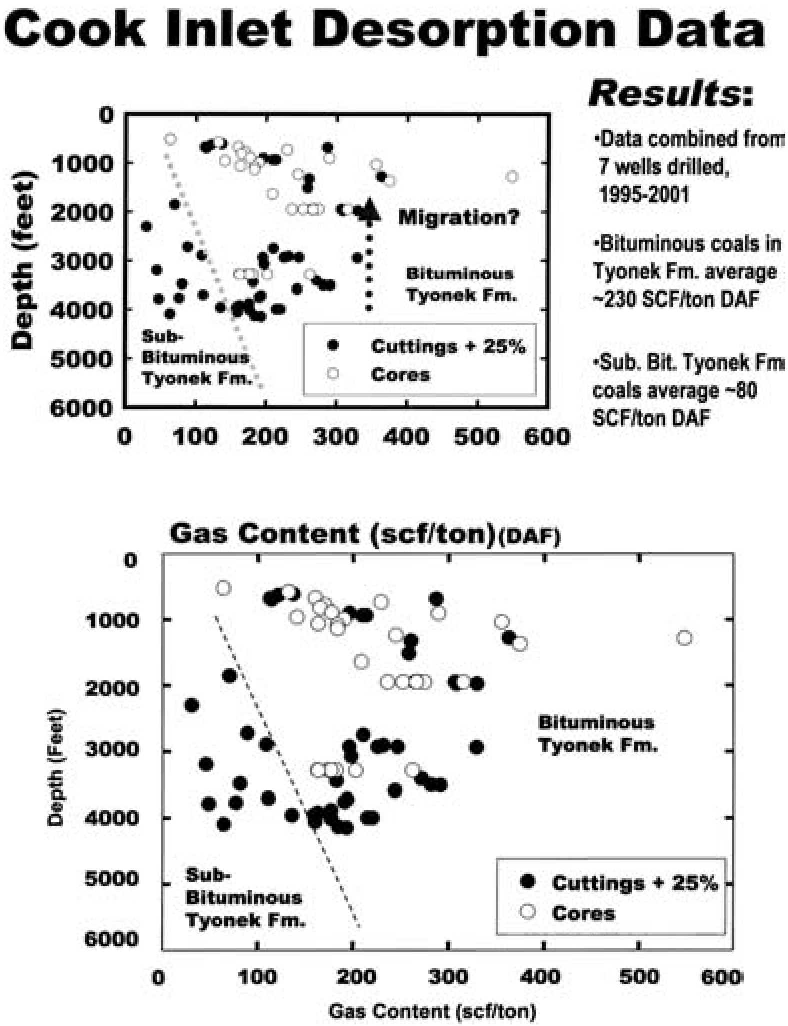

Figure 9.10 Example of computer-generated graphic. *Top,* unedited from use in oral presentation; *bottom,* properly edited for print

Schematic diagrams are quite common in science and, as their name implies, are usually most effective when kept as simple as possible. Figure 9.11 is an illustration of a dipolarization model that shows this very well. The image employs basic shapes and visual elements (circles, dots, arrows, different types and thicknesses of lines). It makes good use of space, being neither crowded nor too open. It includes a minimum of text; in fact, the use of words on the diagram is a good thing, since it gives us valuable orientation and prevents the figure as a whole from becoming a mosaic of single-letter symbols.

Another good example is figure 9.12, which depicts how a particular

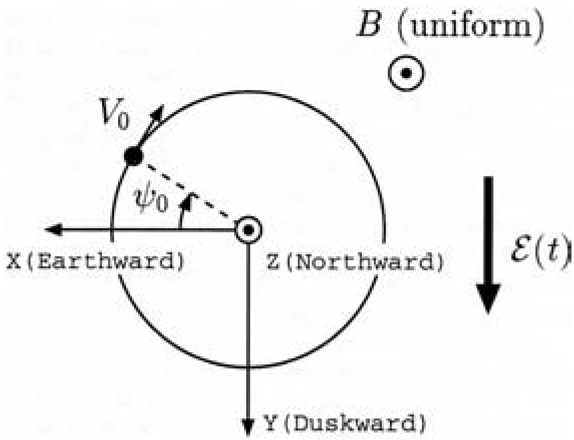

Figure 9.11 Example of a schematic diagram (from Nosé et al. 2000, 23283; copyright 2000 American Geophysical Union; reproduced with permission)

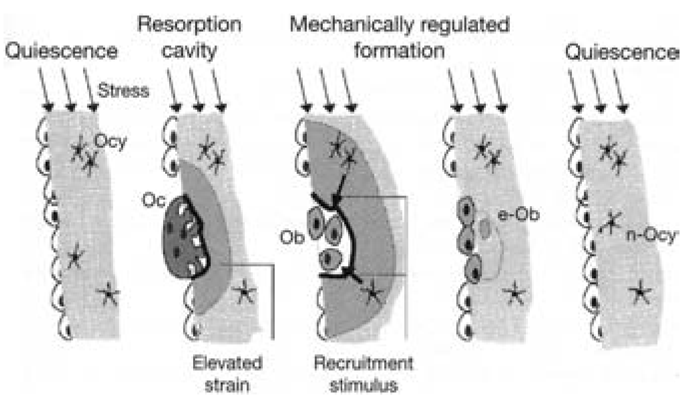

Figure 9.12 Example of a process diagram (from Huiskes et al. 2000, 705; copyright 2000 *Nature;* used with permission)

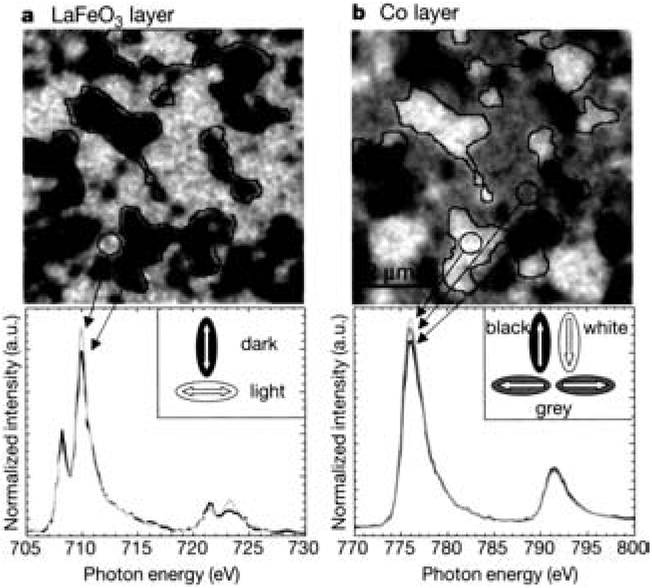

Figure 9.13 Example of a combination diagram, showing two types of images successfully integrated (from Nolting et al. 2000, 767; copyright 2000 *Nature;* used with permission)

type of bone responds to an applied stress. In this case, the diagram shows a cyclic progression of states, involving a temporary weakening of bone mass (through the formation of a cavity and resulting increase in strain) and its repair. A reader can follow the process easily, from left to right. Again, there is minimal text, just enough to identify crucial elements (all abbreviations are explained in the caption). Color is not needed here, since shading can accommodate everything shown. Is the figure perfect? No such phenomenon exists. Some scientists would find value in numbering each of the stages and using these to explain the process in the caption or main text; this would be efficient and effective and would not add overly to the information shown. Others might provide a legend explaining each of the shaded areas, as well as abbreviations.

Combination diagrams, in which two or more types of illustrations are grouped together, have become quite common in many scientific publications. This has led to many fertile blendings of visual information. In figure 9.13, images and spectral graphs are nicely juxtaposed to illustrate behavior of alternating ferromagnetic and antiferromagnetic layers within a given substance. This figure contains a large amount of information, but presents it clearly and even elegantly. Note, for exam-

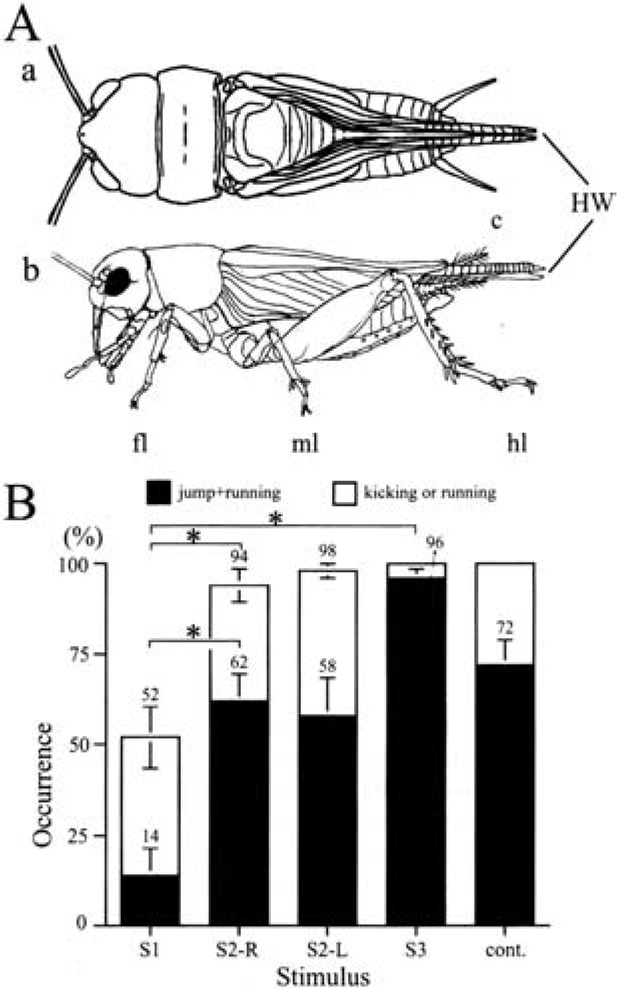

Figure 9.14 Example of a successful combination diagram (from Hiraguchi and Yamaguchi 2000, 1332; copyright 2000 Elsevier Science; used with permission)

ple, how each half of the total is visually balanced, with the legend inserted neatly into the upper right portion of the respective graph (which would otherwise show a lot of white space). Small arrows are used to tie portions of each image to its respective position on the spectral graph. Though the overall size of the figure is small, the text and numbers are large enough and in an appropriate font to be easily legible.

Another example is given in figure 9.14. Here a specimen drawing is combined with a histogram. The drawing indicates the few key anatomical features of the cricket relevant to the experiments, with the most prominent of these (HW) shown in capital letters to emphasize their central importance. The histogram, meanwhile, plots two types of escape behavior for four different kinds of stimuli (plus a control group), each of which was applied to the HW (hindwing tip). At first, everything looks to be in good order. But when we examine the details of the figure, a few problems emerge. Notice that there are two sets of *a* and *b* images, one in uppercase, the other in lowercase, plus a *c* designation on the upper specimen drawing. Probably the lowercase *a* and *b* could be replaced with numbers or deleted altogether. It would also help, to avoid any confusion, to place the legend (black box, open box) at the bottom. There is also enough space on the figure to write out the words for the anatomical features indicated on the drawing, none of which is very long (foreleg, midleg, hindleg, circus, hindwing). This would reduce the burdens on the caption to list and explain a large number of symbols, a consideration worthy to be granted the reader. There is one other problem with this figure that we will leave aside for a moment.

As a final example, I turn to an illustration that reveals how far the combining impulse has been taken in recent times. Figure 9.15, from the premier journal *Cell,* shows six different types of images merged into a single visual conglomerate. These images include a schematic drawing, two line graphs, a scattergram, a histogram, and two tunneling electron micrographs. The caption, not surprisingly, reads like a headline: "*Su*(*H*) Auto-Activation is Required for Normal Mechanoreceptor Function," with the following explanation of each segment (A–G) requiring nearly half a page.

Many editors, I imagine, would go to war over this sort of thing. But the fact is that it has become an established and often-used *modus illustratis* in certain branches of science and serves a valuable function. Not only does it offer more data, often important data, than would be possible if each graphic were given individual space; it also creates something like a miniarticle within the larger paper or report, thereby providing a kind of added expressive dimension to the whole. Obviously this is an approach that can easily be taken too far; visual chaos and confusion are the inevitable result if too many dissimilar graphics are crammed into a single space. Figure 9.15 suggests the limit, though (in my opinion) does not approach it. Such a medley should never be done pell-mell. A clear progression and logic must be established between the individual images. Data dumping is an affront to the reader, no matter if done in images or in writing.

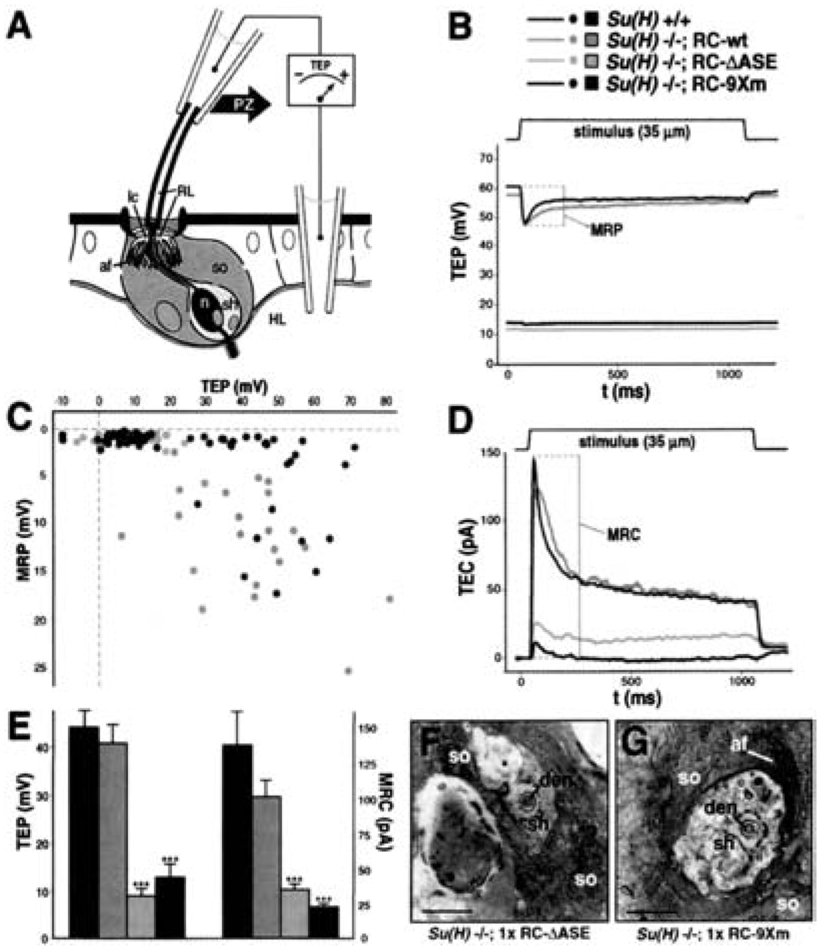

Figure 9.15 Example of a highly complex combination diagram, involving a wide range of image types (from Barolo et al. 2000, 964)

REFERRING TO ILLUSTRATIONS IN YOUR TEXT

Part of the craft (and sometimes art) of good scientific writing is knowing how to integrate graphical materials. Visually, illustrations are embedded in the text, like boulders in a stream, but you want them to be part of the flow as well. Perhaps a better metaphor is the quilt: graphics need to be sewn or woven into the larger pattern of meanings. The reader should be told their significance, why they are there and what they show, and this needs to be done at certain points in the narrative, and in certain ways. How and where you refer to your visuals can make a subtle but very important impact on the reader's experience of your document.

There are two basic ways to refer to figures in the text. One is indirect, with the reference placed in parentheses, for example, (fig. 1.2); this is the most common form. The other approach is direct and makes the graphic a subject of discussion, for example, "Figure 1.2 shows . . ." Deciding which form is best often means choosing whether you want your reader to glance over a particular figure, or study it in extensive detail.

No hard-and-fast rules exist to guide you in your decision. But some commonsense precepts can be applied. If a particular graphic is used to demonstrate or establish an important finding or to suggest a central interpretation or conclusion, it is appropriate (though not necessary) to mention it directly, making it the subject of one or more sentences, even a paragraph. On the other hand, if you include a visual to illustrate a point made in the text, to give an example, or to sketch a piece of apparatus, then indirect reference is probably sufficient.

Among our examples, a few figures that might deserve direct discussion are 9.2, 9.11, and 9.12. Each shows information that is central to the narrative, representing a major result of the experiments performed. Indirect reference, meanwhile, seems more appropriate to graphics like 9.3, 9.7, and 9.10, which provide generalized data or schematic representations. In the end, such decisions can often be subjective. If you have doubts about how to handle a particular graphic, look at your models or check the recent literature to see how other authors have dealt with similar images.

Having made your choice as to direct or indirect reference, where should you place it? In what part of a sentence or paragraph? Too many authors, when it comes to indirect mention (in parentheses), jump the gun and insert the reference before the reader is really ready. Examples abound in the literature. Here's one:

> The conventional structure of a bipolar transistor (Fig. 2A) requires three distinct material types: for example, a highly doped n-type layer . . . , a p-type base, and an n-type collector. (Cui and Lieber 2001, 852)

Note that the eye is told to abandon the sentence even before enough information is given for the figure to make sense. How are the authors using the figure? As written, they are emphasizing "conventional structure." But the actual message of the sentence and paragraph, and the figure too, focuses on the three parts of this structure, not its conventionality. Thus, it would be much better to place the figure reference either after the word "types" or, best of all, at the end of the sentence.

Another example relates to figure 9.7:

> Proved [natural gas] reserves estimated by the U.S. Energy Information Administration have risen from 1.4 BCFG in 1988 to 10.5 BCFG in 1995 (Fig. 2 [our figure 9.7]), more than 70% of which occurs in Colorado and New Mexico. (Murray and Schwochow 1997, 32)

Again, the reference belongs at the end of the sentence, after the pertinent information has been given. This cues the reader that *all* of the values mentioned are displayed on the figure, rather than reserves figures only. Note, too, that the reserve values given in the text are in BCFG (billion cubic feet of gas), rather than in thousand MCFG (million cubic feet of gas), as shown in the figure. This sort of discrepancy should be avoided. Using the same units in text and illustrations is needed to integrate the two.

Similarly, try to use phrases and terms in your captions that are picked up in the text. Much could be said (and has been) about how to write proper captions, what their length should be, whether to use full sentences or phrases, and so on. Standards here, as in so many other aspects, tend to change between fields and between journals. Make sure you're aware of any restrictions or rules given for your target journal or publisher. As always, where there is any doubt, use your models as guides.

A FINAL POINT

Scientific illustration, as it exists today in wondrous plenitude, can never be covered adequately by a single chapter such as this. Indeed, an abundance of volumes have been written on the topic, even on such seemingly humble forms as the chart or graph.[9] I've tried to cover some of the more obvious and necessary aspects of creating good graphics, and of evaluating those of others.

Beginning authors, once familiar with the literature, may feel (and even be thankful) that the types of illustrations available to them for their own writing appear to comprise a set of fixed formulae. Closer inspection will show that this is rarely, if ever, true. For many early-career scientists, it is helpful to stick to the most common patterns. But experienced scientist-authors understand that illustrations are actually

9. A few sturdy works in this field include Wolff and Yeager 1993, Anholt 1994, Briscoe 1996, and, of course, the several well-known books by Tufte: *The Visual Display of Quantitative Information* (1983), *Envisioning Information* (1990), and *Visual Explanations* (1997).

a flexible means of expression, and can be adapted, albeit conservatively, to individual cases. Close study of premier journals will prove this: different authors add modifications, sometimes small, sometimes significant, to what are otherwise standard graphical templates, and they do this in order to make their message a bit more efficient and elegant. Here, too, just as with writing itself, one can ultimately choose between functional and creative approaches.