Chapter 4
Figures and Tables

Figures are an extremely important part of any scientific publication. It is a rare paper that contains no figures (such papers are mostly of the theoretical variety, though even a pure theory paper often benefits from a good graph). As the renowned guru of graphics Edward Tufte put it, "At their best, graphics are instruments for reasoning about quantitative information."[1] Because almost all scientific publications include quantitative information to be reasoned about, figures are almost always necessary.

4.1 The Goals of Using Figures

As a form of communication, figures (and in particular, the graphical display of quantitative data) are uniquely suited to conveying information from complex data sets quickly and effectively. Whereas statistical analysis aims for data reduction (expressing a mass of data by a few simple metrics), graphing retains the full information of the data. Graphs take advantage of the magnificent power of the human brain to recognize visual/spatial patterns and to quickly change focus from the big picture to small details. Graphs are used for data analysis[2] and for data communication, though only the latter application will be discussed here. Graphs are extremely popular in scientific literature[3] for the simple reason that they work so well.

But like all forms of communication, graphics can be used to explain and clarify but also to confuse or deceive. Thus, the first rule of graphics is a simple one: they must help to reveal the truth. Just as disorganized writing often indicates disorganized thinking, a chart that fails to tell the story of the data usually means the author does not recognize what story should be told. Thus, sufficient care should be given to the design and execution of graphics, just as in the design and execution of the written paper itself.

What does a graph aim to do? Here are some of the more important goals of using a graphic for communication in a scientific publication:

- Document the data (a graph is often the only place the data get published);
- Make comparisons (such as displaying trends);
- Allow for inferences of cause and effect;

- Tell a story, or at least be an integral part of the tale; and
- Integrate with the text to enhance the overall communication of the paper.

The first choice in designing a graphic is what data to present. "Displays of evidence implicitly but powerfully define the scope of the relevant, as presented data are selected from a larger pool of material. Like magicians, chartmakers reveal what they choose to reveal."[4] Thus, this first choice is probably the most important because it defines what the graph (and the paper) will and will not be about. Graphs should communicate the essence of the results from the paper and not get bogged down in detail.

The design of the graph itself should be driven by the structure in the data and what story the data have to tell. Because most graphics make comparisons (theory to experiment, condition A to condition B, etc.), the selection of the comparison to display defines the arc of the plot that unfolds. There is a fine line, however, between allowing the data to speak for themselves and forcing the story you want to tell. Well-presented data should encourage the consideration of alternate explanations, not just your preferred explanation.

Overall, the process of creating a graphical display follows these basic steps:[5] choose the data to be presented, define the message to be conveyed, pick a style of graph that supports the message, construct the graph seeking clarity, and then revise it until it is right.

As Tufte has pointed out,[6] the design and execution of a graphic are not unlike the overall scientific enterprise. We are searching for a quantitative and demonstrable cause-and-effect mechanism, and we use scientific reasoning about quantitative evidence to lead us there. Because science is about building models that describe our experiences, graphs should aid in finding and evaluating these models.

4.2 Errors in Graphs

Given the complexities involved in graphing large data sets, there are many ways for errors to creep in. Still, I was very surprised to read in a study by William S. Cleveland that 30% of all graphs published in volume 207 of *Science* (1980) contained errors.[3] The error types he found were classified as mistakes of construction (mislabels, wrong tick marks or scales, missing items: 6% of graphs), poor reproduction (with some aspect of the graph missing as a result: 6% of graphs), poor discrimination (items such as symbol types and line styles could not be distinguished: 10% of graphs), and poor explanation (something on the graph is not explained, neither in the caption nor the text: 15% of graphs). This total, by the way, only included graphs with actual errors, not graphs that were merely poor at performing the function of communication (of which there were many more, according to Cleveland).

Since 1980, a lot about the process of producing graphs has changed. It is likely that ubiquitous computing and graphing software has diminished the frequency of some error types. But though such tools can make producing quality graphs much faster and easier, they also make it easier to produce bad graphs. The most common type of error—incomplete explanation of what is on the graph—is outside the technical process of producing the graph itself, so it is doubtful that our software tools have helped much with this error type. Unfortunately, I am forced to admit that Cleveland's 30% error rate is probably not too different from today's performance.

4.3 Graphical Integrity

As with every aspect of science writing, integrity plays a key role in designing and executing figures and tables. A graph is a powerful tool for communicating, and one must *choose* to communicate truth rather than falsehood. Tufte suggests these questions as a test for graphical integrity:[7]

- Is the display revealing the truth?
- Is the representation accurate?
- Are the data carefully documented?
- Do the methods of display avoid spurious readings of the data?
- Are appropriate comparisons and contexts shown?

To these I would add three more:

- Have you chosen the right data to display?
- Can uncertainty in the data be properly assessed?
- Can others validate your conclusions based on the information you provided?

This last question is part of the overriding ethic of scientific publishing: for a result to be scientific and contribute to the body of scientific knowledge, it must be described sufficiently so that the paper's conclusions can be validated by others. As a straightforward example, any graph that does not numerically label its axes cannot be published.

Working to ensure both graphical integrity and low error rates in the execution of a graph will greatly enhance the ability of the graph to meet its goals and the goals of the paper. A well-written paper with poor graphs will never be remembered as a well-written paper.

4.4 A Few Guidelines

Graphs come in an extremely wide variety of types, a testament to the innovations from the last two centuries of chart making. Still, rapid communication is generally best served using one of several familiar chart types, as familiarity speeds cognition. The overriding principles of design should be to seek clarity and avoid clutter.[8] With that in mind, here are some miscellaneous guidelines for good graphics that might prove useful on different occasions:

- Remember that a piece of data has four parts: a description (what is it?), a number, a unit, and an uncertainty estimate. If any one of these four things is missing, then the data are essentially useless. When plotting data, try to put all four parts of the data in the figure.
- If any data points have been removed, explain why.
- If error bars are present (and they almost always should be), explain clearly what they represent (one standard deviation of the data sample, one standard error of the mean, a specific confidence interval, etc.).
- Context is always important with data, and so also with the display of data. "Graphics must not quote data out of context."[9]
- Make the data stand out—do not let it get lost in a jumble of lines and labels. A quick glance should allow you to discriminate each data point from everything else on the graph.
- Tables are best for looking up specific information or exact values, and graphs excel at displaying trends and making comparisons. If you think readers will try to read numbers off the graph, consider a table (instead or in addition).
- When the number of data points is small, a table is generally preferred over a graph. As Tufte put it, "The simple things belong in tables or in the text; graphics can give a sense of a large and complex data set that cannot be managed in any other way."[10]
- Higher data density is good, so long as accuracy and clarity are not sacrificed. The writing advice of Charles Caleb Colton applies equally well to graphics: "That writer does the most who gives his reader the most knowledge and takes from him the least time."
- By all means, use color when it can enhance your graphic (most articles are now read online), but make sure that no information is lost when printed in black and white.
- Label within the graph or in the caption as necessary to minimize the need to refer back and forth from the text. If possible, the figure should be interpretable on its own.
- Figure captions should not be an afterthought—they are an integral part of the figure. Plan the caption to work with the graphic to present context and explanation of the data. Again, the goal is to make the figure interpretable on its own if possible.
- Ideally, a figure caption will do three things:[11] describe everything in the graph, draw attention to its important features, and (when practical) describe the main conclusions to be drawn from it.
- Graphs should not have a title. Put the title information in the figure caption.

- Make sure that every element of the graph is fully explained, if not in the graph or its caption, then in the text.
- Pie charts are almost never the best option.
- Use bar charts only when you cannot find a better option. Bar charts should only be used to plot categorical data, but if the categories have a natural order, then a line plot will usually work better. Because the length of the bar represents the magnitude of the number, the bars must be thin (so that the bar area does not confuse the reader) and the *y* axis must always start at zero (this limitation is one of the reasons that other graph types are often preferred over bar charts).
- Side-by-side bars are generally better for comparisons than stacked bars because undulations in the bottom of the stack can make the upper parts of the stack hard to interpret. Stacked line charts suffer from these same difficulties.
- Avoid all spurious three-dimensional (3D) effects, such as the use of 3D bars in a bar chart. They only lead to confusion, never to greater clarity.
- Graphs should be as simple as possible, and in no way should a graph be more complex than the data it represents.
- Use log-scales to reveal trends in the data, not hide them. Log-scales emphasize relative changes, whereas linear scales are best at showing absolute changes.
- Consider using two scales for each axis, if appropriate (for example, one that shows the actual value and one that shows the percent change of that value from a reference).
- Data aggregation or reduction (putting data into groups and plotting group summaries) can suppress noise and reveal trends, but only when done properly. Histograms are often very sensitive to bin size and starting points, for example. Time-series plots can be sensitive to the chosen start time and interval as well. Be very careful if your conclusions about the data change based on arbitrarily chosen aggregation parameters.
- Choose plot scales (*x*- and *y*-axis start and stop values, for example) to avoid white space: try to use at least 80% of each scale to display data.
- Baselines are sometimes important for making comparisons, but if there is no natural baseline, beware of how an arbitrary choice can push a certain interpretation on the reader. Zero may be a natural baseline, but do not force zero on the plot scale if it results in wasted graph space.
- Never use scale breaks or change the scale on the axis of a single graph. If two scales are needed to show the data, use two graphs (or try using a log-scale for better resolution).

- You cannot fix bad data with a good graph.

4.5 The *x-y* Scatterplot

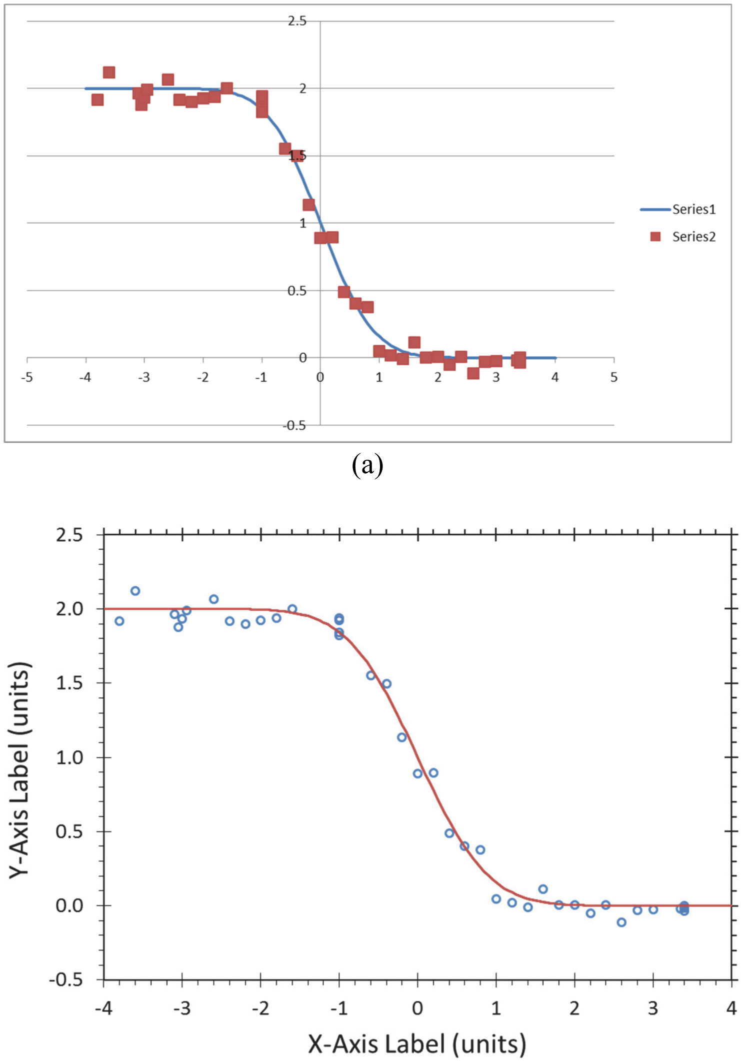
The great statistician and graphical expert John Tukey said, "The greatest value of a picture is when it forces us to notice what we never expected to see."[12] Although many graphic forms can help us accomplish this goal, the most useful for science has proven to be the *x-y* scatterplot. In 2012, about 1/3 of all figures in the *Journal of Micro/Nanolithography, MEMS, and MOEMS* (JM^3), and about 70% of all data plots, were *x-y* scatterplots (see Section 4.7). The first modern scatterplot is attributed to John Herschel (1792–1871), son of William Herschel, the discoverer of Uranus and infrared light.[13] In 1833, John Herschel used a scatterplot of noisy binary star measurements to extract a trend "by bringing in the aid of the eye and hand to guide the judgment,"[14] thus fulfilling Tukey's goal. The scatterplot allows the viewer to visualize the important trends the data suggests, and possibly offer a theory to explain them, by imagining a line that passes "not through, but among them," as Herschel so aptly said.[14] By 1920, the scatterplot had come into widespread use as the tool of science as we now know it.

The *x-y* scatterplot is "a diagram having two variates plotted along its two axes and in which points are placed to show the values of these variates for each of a number of subjects, so that the form of the association between the variates can be seen."[15] If the *x* axis plots time, we generally call the graph a time-series plot and often use unique analysis or interpretive frameworks for the data due to the unique role of time in causality. Here, I will talk only to the more general *x-y* scatterplot and not to time-series plots specifically. I will also (mostly) ignore the role of *x-y* scatterplots as a projection of multivariate data (three or more variables), as interesting and important as that role is, and instead concentrate on the basics of this most popular of science graphs.

What makes for a good *x-y* scatterplot? As for all graphs, the goal should be to allow the data to tell its story efficiently and effectively. The first rule of a graph is that it must help to reveal the truth. The design and execution of an *x-y* scatterplot can either help or hinder this goal. And although graphs can aid both in data exploration and data presentation, I will focus only on the latter here through the use of examples.

4.5.1 The *x-y* scatterplot in Excel

Many authors use Microsoft Excel to create their *x-y* plots (as well as most other graphs in their papers). Thus, my first example will explain how to turn the seriously awful default scatterplot of Excel into an acceptable graph for



(a)

(b)

Figure 4.1 Excel graphs of the same data: (a) default scatterplot settings, and (b) after proper formatting. Symbols show data, and the solid line shows the fitted equation.

submission to a scientific journal. My example will be simple: a plot of (made-up) experimental data along with an equation that models that data. The before and after plots are shown in Fig. 4.1.

Here is the sequence of steps I went through in Excel to move from the default (Fig. 4.1(a)) to the final graph (Fig. 4.1(b)). I assumed that the final graph will fit within a single column in a two-page-per-column format. For journals with other page formats, some adjustments to these directions may be required.

1. Set the chart area size to be 5 in. tall by 6.75 in. wide (this is 2× the final size required by most journals, but it will shrink 50% when published because most scatterplots will fit in one column). The chart area height can be adjusted as needed, if the data suggest a better shape, but the 4:3 aspect ratio used here is a good default.
2. Set the chart font size to be 14 points (the size will be 7 pt after shrinking the graph 50%).
3. Remove the legend if not needed (try to put labels inside the graph if they fit rather than using a legend). If using a legend, see if there is room within the plot area to put it. In Fig. 4.1, using the convention of symbols for data and a line for the theoretical equation means that the legend can be embedded in the caption.
4. Remove all gridlines.
5. Change the axes' line color from gray (the Excel default) to black and set it to 1 pt thick.
6. Change the major tick mark to "cross" and minor tick mark to "outside."
7. Format the chart area to have no border.
8. Format the plot area to have a solid black border (1 pt thick) and no fill.
9. Set the "axis crosses" point so that the two axes meet at the lower-left corner.
10. Adjust the axes' label numbers so that they have the proper number of decimal points.
11. If necessary, adjust the axes' min and max values (Excel defaults are often poor). Remember that the goal is to use up almost all of the graph space with data, but try to keep the data points from overlapping onto the solid border surrounding the plot area.
12. Add axis titles, set to 18 pt (less if titles are too long), no bold, and use a rotated vertical title.
13. Format the "data series" to have the preferred color and symbol or line type/style for maximum readability and differentiation between data series. I typically use a weight of 1.5 pt for my lines, and my preferred symbol is the open circle when more than one thing is being plotted at a time or when data points overlap.
14. If using line segments to connect data points, never turn on the "smoothed line" feature.
15. Make sure that there is no title.
16. Add a baseline in the graph if doing so is helpful for interpreting the data, but do not include a $y = 0$ line by default.

17. Preferred: put tick marks on the right and top of the plot area bounding box (this is tricky to do in Excel; use a "secondary axis").

That is a lot of steps, but every step left out produces a less adequate graph. Note that some of these steps can be described as aesthetic, though making a graph more pleasing to the eye is generally synonymous with making it more readable. For example, the open-circle data symbols enable one to see behind the symbol to the line and to other data points. In the original graph with the solid square symbols, can you tell how many data points are at $x = -1$ and $x = 3.4$? When using more than one symbol, be sure to consider the symbols' size and shape for maximum visibility when there is overlap.

4.5.2 Other scatterplot examples

The next example (Fig. 4.2) shows how labels can sometimes be fit into the graph to avoid the need to refer back and forth to a legend.

A regular problem I encounter is a graph with data that fails to use up the space in the plot area. In Fig. 4.3, the authors wish to show the stability of their laser, so they stretch the y-axis range to be ten times the data range. As result, we cannot see the variation in the data. So why bother showing the graph? A similar

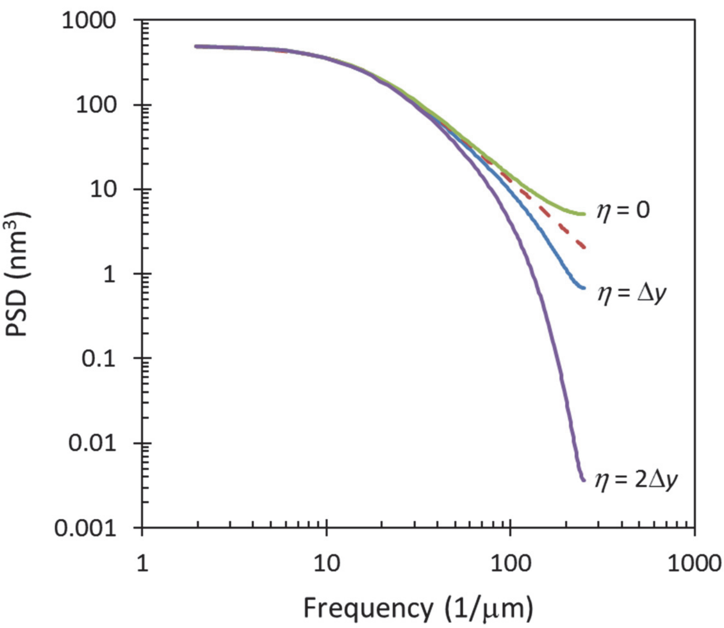


Figure 4.2 Labels within the graph avoid the need for a legend. The color used here improves readability online but is not needed for comprehension when printed in black and white. The dotted line is explained as being the reference curve in the figure caption of the original.[16]

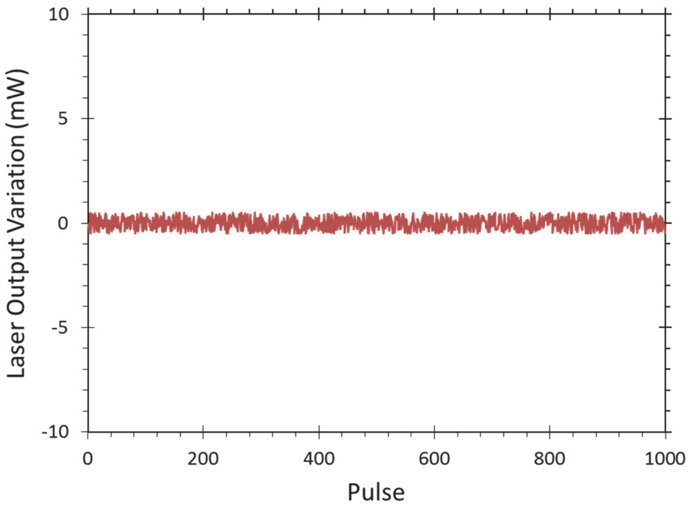


Figure 4.3 A wasted graph. The *y* axis is chosen to give the impression that the there is little variation in the output, but if we cannot see any variation in the data, why show the graph?

effect can be obtained by including zero on the *y*-axis scale even though no data are near zero (imagine a plot of Earth's global surface temperature in Kelvin over time, then starting the *y* axis at zero—global warming would disappear). This is an example of advocating rather than informing, i.e., using graphs to hide rather than reveal the truth. If there is nothing in the data worth seeing, the graph should be replaced with simple statistics: mean, standard deviation, min/max of the output, and maybe a statement that a linear regression gave a slope that was not statistically different from zero. If there is something worth seeing in the data, then adjust the *y*-axis scale so that it can be seen.

There are other ways to mislead with an *x*-*y* scatterplot, some not as subtle as the previous example. Unitless axes are a favorite of those who, at a minimum, do not wish to reveal the whole truth. An axis with ambiguous labeling should never be allowed. Using "arbitrary units" for a *y*-axis is a bit trickier because there are some cases where such a label is appropriate (a relative measure, based on a local uncalibrated standard that can be used to compare similar measurements). A common example is the relative intensity used in spectral analysis. Arbitrary units are never preferred but sometimes necessary. Arbitrary units should never be used to hide known units that the author does not want to reveal. Additionally, arbitrary units have an arbitrary scale but not an arbitrary zero point. Thus, when arbitrary units are used the graph must mark the zero point on the scale. One solution is to use a relative scale rather than arbitrary units, with the original clearly defined.

One common and important application of the *x*-*y* scatterplot compares different graphs (thus adding a third variable, sometimes more). Figure 4.4 shows a 2×3 array of graph multiples, matching the *x*-axis and *y*-axis scales to allow easy comparison. With small multiples, many more graphs can be compared.

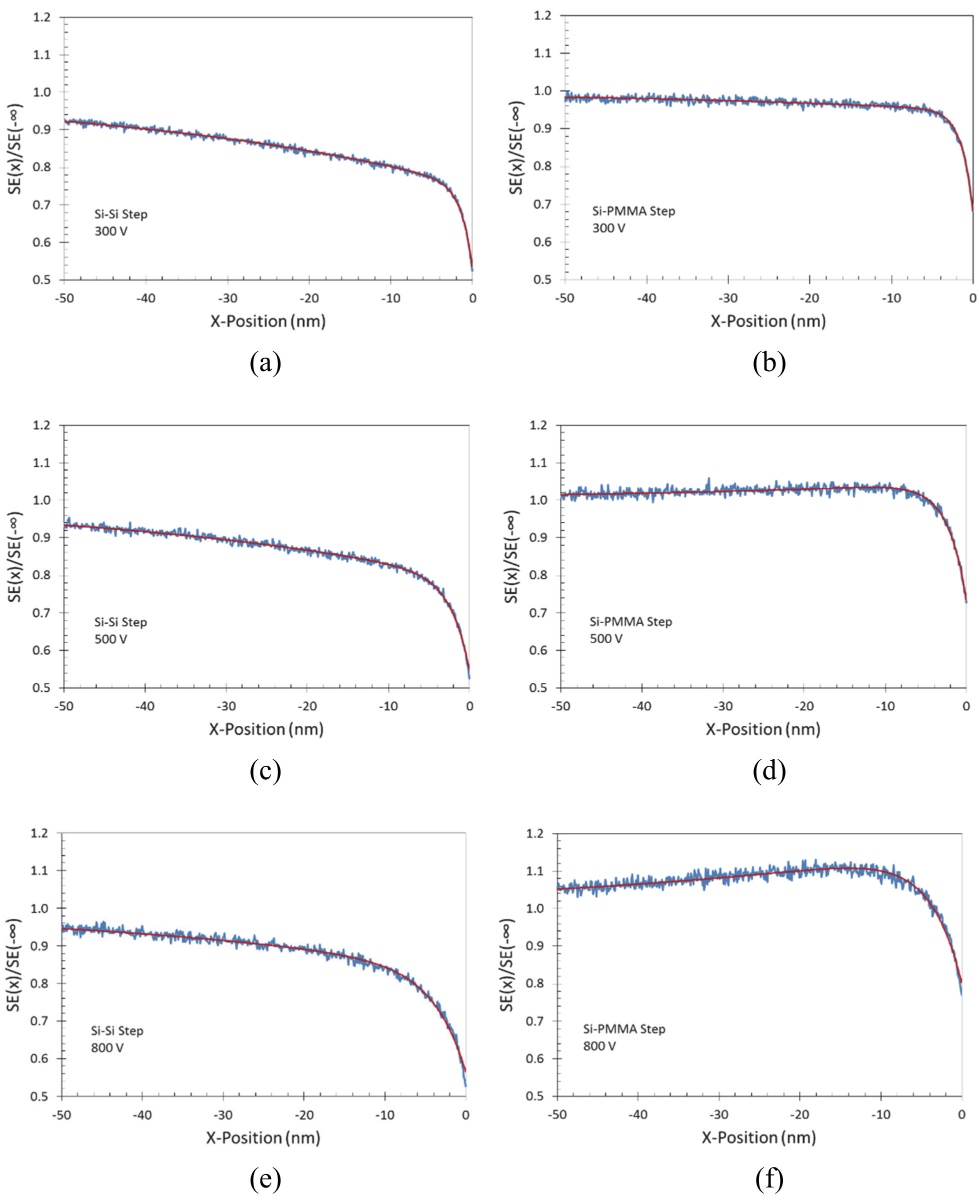


Figure 4.4 Comparison of Monte Carlo simulations to an analytical model.[17] The smooth (red) line is the equation and the jagged (blue) line is the Monte Carlo simulation results. Both vertical and horizontal comparisons between graphs are enabled by matching the *x*-axis and *y*-axis scales of every graph. Note that in this case redundant axes labels could be removed.

4.6 Figure Quality from a Production Standpoint

The final step in ensuring a good quality figure in your published paper is to make sure that the submitted figure matches the production requirements of the journal. (I speak here specifically about JM^3 requirements, but I do not think they are much different from most other journals.) A few of the largest publications, such as *Nature* or *Science*, employ professional editors who can reset a graph to the standards of the journal. For most publications, however, it is up to the author to get the graph right. Below are some hints, given to me by the SPIE publications staff, that will make the production process go more smoothly and produce higher-quality graphs:

- Submit high-resolution figures. The quality of the published figure is only as good as the original file—it cannot be improved by the typesetter. A resolution of 100 dpi (dots per inch) looks great on a computer screen but is inadequate for print. A minimum of 300 dpi is required, but 600 dpi is preferred. Thus, a one-column wide photograph must be at least 1000 pixels across.
- Submit full-size figures (7 in. wide), but remember that they will, in general, be reduced 50% to fit within one column. Make sure that the fonts, lines, and other elements of the graph will hold up to this reduction (see my font-size suggestions in the earlier Excel example). Try shrinking the graph 50% and printing it out yourself as a test.
- High-contrast color graphics are great for online viewing, but the figures still need to be readable in grayscale for black-and-white printing (unless you pay for color printing). Colors such as red and blue, which are easy to distinguish online, are the same shade of gray when printed in black and white. If lines or symbols must be distinguished in a legend or caption, use different line styles and symbols instead of relying solely on color.
- Do not submit JPG files—the image compression often compromises the quality of the figure. TIF files have no compression, but if the file size is unmanageable try using "LZW" compression.
- If a figure contains multiple parts (such as Fig. 4.4), they should all be laid out in one file, not submitted as individual files. This is important because it lets the author determine how a figure should be arranged for the reader (horizontal versus vertical, for example). The parts should be clearly labeled with lowercase Roman text in parentheses, i.e., (a), (b), etc.

4.7 Tables

Tables present data directly and are preferred over graphs when the exact numerical values of the data are needed. Still, tables often have a goal similar to that for figures: enabling comparisons. When presenting data in two or more dimensions, the layout and order of the table entries can make a huge difference in the ability of the reader to make the proper comparisons and see the important trends. It is easier for a reader to compare numbers arranged within a row than within a column. It is also easier to compare numbers that are close to each other (preferably next to each other).

Often, 2D tables will benefit from marginal analysis, where rows and columns are totaled or expressed as a percentage of the total. The table in the next section shows an example of such marginal statistics.

As with figures, tables should be made comprehensible on their own, without reference to the text of the paper, if possible. This means that a table should have a good caption, and the items presented should be clearly defined within the table. Do not forget units and uncertainty estimates.

Different journals have different formatting requirements for tables. For example, many journals allow only horizontal lines in the table. Before submitting your manuscript, review the table formatting guidelines (or just look through the journal for examples of tables) and render your table in that format. A table arranged to look good in your preferred style may not work so well in the journals' required style.

4.8 Example: Figures and Tables in JM^3

How are graphs used in my journal, JM^3? Table 4.1 shows my counts of figures and tables found in the 2012 issues of JM^3. The graph types I used are somewhat arbitrary (as all categories are), but hopefully useful. JM^3 papers in 2012 had an average of 19 figures and one table per paper, attesting to the importance of figures in our field. About 20% of the figures were used to explain the theory or experimental setup, and the rest showed results. By far the most common figure was the ubiquitous *x*-*y* plot, accounting for 1/3 of all figures and tables. Results micrographs (optical and scanning electron micrographs, as well as atomic force microscope renderings) made up 25% of the figures. Contour and 3D plots were used about 10% of the time, with other types of charts filling in the remainder.

While I made no attempt to rate or judge the quality of the figures, it was clear to me from my survey that there were many excellent examples of figures and tables in all categories. There were some poor ones as well.

As an exercise, I rendered the data from the "Results" figures of Table 4.1 into a variety of bar charts (see Fig. 4.5). Most of them fail the test of staying "on message." The first four draw attention to the variations between issues, either in actual numbers or in percentages, though the per-issue variation is not important to my story here. The last two correctly keep the emphasis on the relative frequency of each figure type, with the horizontal bar chart being far more

Table 4.1 Figure and table counts for JM^3 papers published in 2012.

	Issue #1	Issue #2	Issue #3	Issue #4	Total	**% of Total**
No. Papers	24	43	22	12	101	
Methods						
Photos	11	56	7	3	77	**3.9%**
Diagrams	92	120	85	25	322	**16.3%**
Tables	6	11	4	12	33	**1.7%**
Setup Total	109	187	96	40	432	**21.9%**
Results						
x-y Plots	138	281	120	114	653	**33.1%**
Contour Plots	47	52	25	62	186	**9.4%**
3D Plots	2	10	17	13	42	**2.1%**
Micrographs	89	131	222	40	482	**24.4%**
Histograms	6	6	4	0	16	**0.8%**
Bar Charts	10	2	4	11	27	**1.4%**
Wafer Maps	6	0	1	1	8	**0.4%**
Tables	25	53	23	10	111	**5.6%**
Other	6	4	3	4	17	**0.9%**
Results Total	329	539	419	255	1542	**78.1%**
Tables and Figures Total	438	726	515	295	1974	
Tables and Figures/Paper	**18.3**	**16.9**	**23.4**	**24.6**	**19.5**	

aesthetically pleasing. But then, they do not do a better job of conveying the message compared to the table, and the table is far richer and denser in information (and has the added benefit of documenting the data better). This conclusion is quite frequently true of bar charts: a table would be better.

4.9 Conclusions

When presenting results, a good graph is like a good scientific theory: once you see it, everything just makes sense. But arriving at such a point takes care and consideration. Keeping in mind the advice from this chapter will, I hope, lead to graphs that help you, the author, achieve your goal of effective and efficient communication.

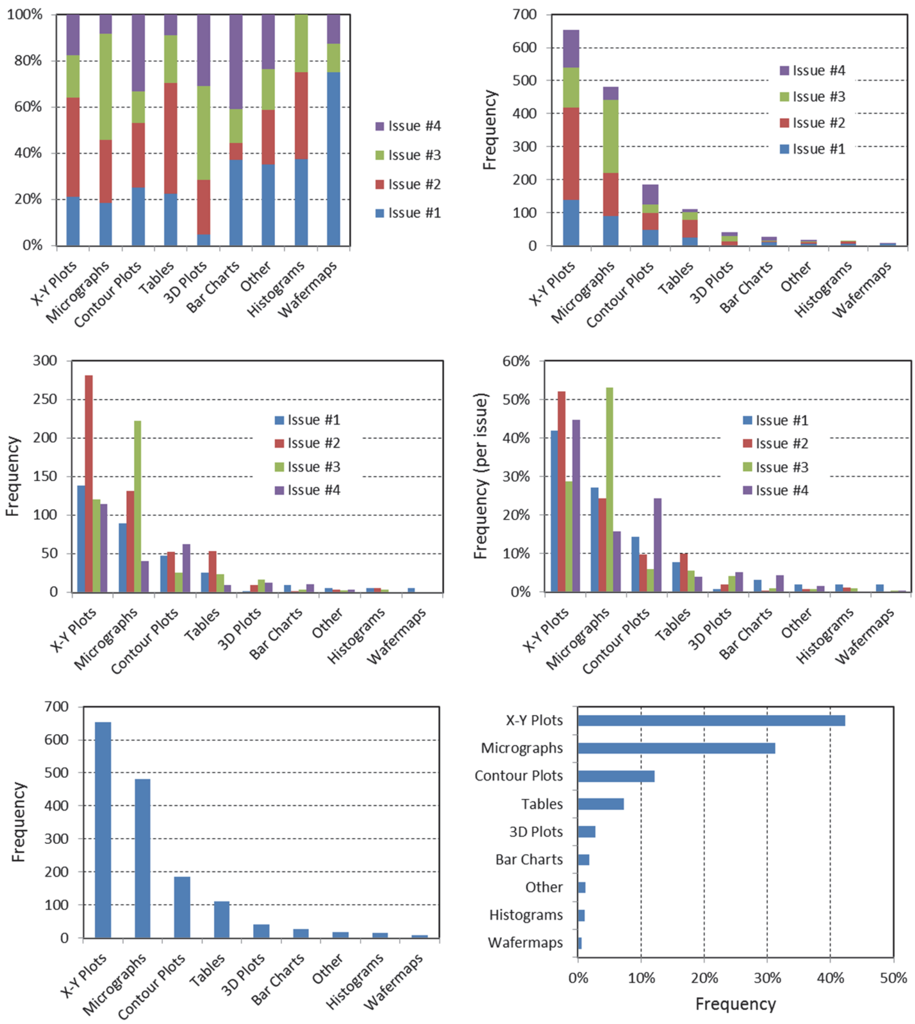


Figure 4.5 A comparison of six different bar charts based on the data from the "Results" section of the table. The top four graphs are "off-message," emphasizing the per-issue variation. The bottom two have the proper emphasis but are not very data-dense.

They say a picture is worth a thousand words. In a scientific journal, each figure occupies the space of anywhere from 150 to 500 words. So at the very least, a figure should convey more information than the words it displaces. Otherwise, valuable space has been wasted. A good graph can certainly do that, though not all figures do. As the abstract artist Ad Reinhardt so aptly put it, "As for a picture, if it isn't worth a thousand words, the hell with it."

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