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How to Write a Good Scientific Paper: Figures, Part 1

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This is the sixth in a series of editorials covering all aspects of good science writing.

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] Since almost all scientific publications include quantitative information to be reasoned about, figures are almost always called for.

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. While 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 later 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 (often a graph is the only place the data gets 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
- 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 since 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 has to tell. Since most graphics make comparisons (theory to experiment, condition A to condition B, etc.), deciding on 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 itself 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, 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. Since science is about building models that describe our experiences, graphs should aid in finding and evaluating these models.

1 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 while such tools can make producing quality graphs much faster and easier, they also make it easier to produce bad graphs. Since the most common type of error, incomplete explanation of what is on the graph, is outside the technical process of producing the graph itself, 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.

2 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 reproduce your results 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 it could be reproduced by others. As a straightforward example, any graph that does not numerically label its axes cannot be published (and unfortunately, we sometimes get those graphs submitted to JM^3).

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.

3 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, since 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 is 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.
- 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—don't 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 generally is 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 (since most articles are now read on-line), 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 can't 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. Since 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, since 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 (3-D) effects, such as the use of 3-D 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, while 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 don't force zero to be 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

Table 1 Figure and table counts for JM^3 papers published in 2012.

	Issue #1	Issue #2	Issue #3	Issue #4	Total for 2012	**% of total**
No. Papers	24	43	22	12	101	
			Theory, Experimental Setup			
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%**
3-D 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**	

data, use two graphs (or try using a log-scale for better resolution).

- You can't fix bad data with a good graph.

I'm sure that there are many more tidbits of advice that would be valuable to share, but these are the first that come to mind. I'd be interested in hearing from the readers of JM[3] about their experiences, good and bad, with graphs.

4 Figures and Tables in JM[3]

How are graphs used in our journal, JM[3]? The table below 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 3-D 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. I hope this editorial

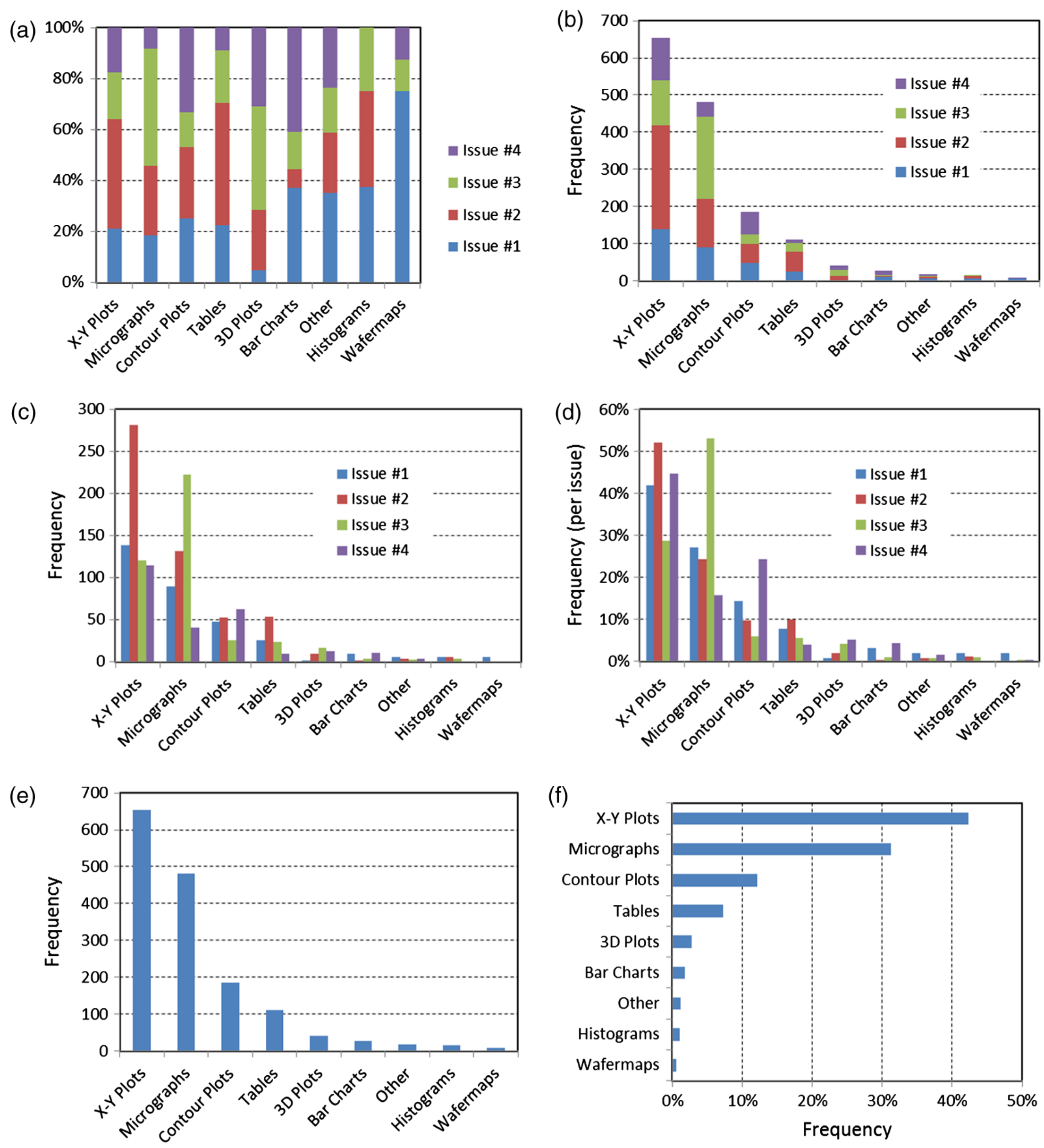

Fig. 1 A comparison of six different bar charts based on the data from the "Results" section of the table. (a)–(d) are "off-message," emphasizing the per-issue variation. (e) and (f) have the proper emphasis but are not very data-dense.

will spur attention to the difficult process of building quality graphs and that the JM^3 figure quality will improve over time.

As an exercise, I rendered the data from the "Results" figures of the above table into a variety of bar charts (see Figure 1). 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. But then, they don't do a better job of conveying the message compared to the table, and the table is far more rich and dense with 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.

5 Conclusions

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."

Next time I'll focus on how to make the most of one specific graph type: the ever-popular x-y scatter plot.

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