Data Visualization and Effective Graphics
Daniel Lo

Introduction

Stories. Since the day we were born, they have been with us, teaching us principles about the world we live in, expanding the horizons of our experiences, entertaining us. Storytelling is perhaps also the most common communication technique we use, organizing otherwise disparate pieces of information into a coherent whole which can then easily be grasped and retained by the mind. Indeed, many cultures around the world have legends that have been passed down from generation to generation, today forming the cores of their worldviews, their identities and their practices.

The scientific tradition is no different. Storytelling is used for describing both general laws about the physical world and the specific instances under study which inspired those general laws. Storytelling is conducted in a variety of settings, each imposing its own unique set of constraints that determines the style and focus of the stories being told. A talk at a scientific conference seeks to present a nugget of interesting information, with a focus on the significance and implications of the new information. On the other hand, a scientific paper presents an argument, going into detail about why a new idea is scientific sound. The differences in audience, purpose and format for the different settings translate into differences in the presentations of the same story.

Graphics are integral to storytelling, aggregating large amounts of data to illustrate particular general ideas in a form that is easily observable by the mental eye. As the saying goes, a picture is worth a thousand words (except in cases such as when one is submitting to Geophysical Research Letters, where a picture is worth 500 words). The best graphics are those that are able to combine multivariate data to tell a story that can be immediately grasped by the audience without further verbal explanation.

The goal of this handout is to introduce some principles for effective graphics design, and examples to illustrate these principles. Much of the content is derived from a series of books by Edward Tufte: The Visual Display of Quantitative Information, Envisioning Information, Beautiful Evidence and Visual Explanations.

Once upon a time...

Figure 1 shows a well-known graphic by Charles Joseph Minard showing the French invasion of Russia by Napoleon I in 1812. On first look, the eye is immediately drawn to the thick tan and black lines that span the entire width of the graphic, and also centered vertically. These two elements describe the key message of the graphic, and all other elements in the graphic are muted to avoid competition with the two key elements. On further inspection, we find that the two lines represent the size of the Grande Armée over the course of the Russian campaign as it advanced (tan) and retreated (black). The use of the line width to describe the size of the Grande Armée is natural – one can literally see the army becoming “smaller” as it moves over the simplified map of various cities and rivers in the background. At various points, numbers next to the lines provide the absolute “anchors” to calibrate the relative size described by the width of the lines. The choice of colors for the two lines is also sensible, with the softer tan for the thicker “advance” line and the sharper black for the thinner “retreat” line. This difference in colors cancels out the difference in visual impact arising from the different thicknesses of the lines, with the final result of both elements have an equal visual priority in the graphic.
As one examines the “retreat” line, the eye is directed by thin lines to a temperature plot at the bottom of the graphic. These thin lines are subtle and do not fight with the rest of the graphic for attention, but are effective in indicating the temperatures at various stages of the retreat. The description at the top of the graphic does not (as it should not) provide much additional information crucial to the story. The title “Figurative Map of the successive losses in men of the French Army in the Russian campaign 1812-1813” sets the context for the map. What follows serves to reinforce the natural interpretation of the graphic: “The numbers of men present are represented by the widths of the colored zones in a rate of one millimeter for ten thousand men; these are also written beside the zones. Red designates men moving into Russia, black those on retreat.”

Figure 1: Charles Joseph Minard’s famous graph showing the decreasing size of the Grande Armée during the Russian campaign of 1812.
The intricate challenges and rewards all who examine it.

Minard’s map of the Grande Armée is a perfect example of how multivariate data can be synthesized into a single graphic to tell an elaborate story. With only a few seconds of inspection, one immediately gains information about the course taken by the Grande Armée, how its size changed over the course, and the harsh wintry conditions experienced on the retreat. Closer inspection reveals smaller details such as the difficulty in the various river crossings.

The density of information conveyed in a graphic is much higher than that in a paragraph of text, which in turn is much higher than that in a speech. This implies that where possible, information is best conveyed through graphics, with text and speech playing the secondary role of guiding the audience through the graphics and providing supplementary information. Understanding this implication is particularly important. It is rare to quote a paragraph of text from a scientific paper, but figures are commonly reproduced without the supplementary text. Indeed, some scientists begin the paper writing process thinking about the figures they would use. Thus, graphics should be designed to be self-sufficient in telling their story. In a scientific talk, the slow rate of information transfer via speech means that the visual aid should always provide more details than the spoken words.

The effectiveness of graphics as a medium for information transfer hinges on the special ability of the eye in identifying trends and differences. This means that subtle differences in the data can be made visually conspicuous with the appropriate design. Figure 2 shows two plots of the same data with different aspect ratios. The “spikes” in the top plot are visually jarring, almost preventing the viewer from dwelling too long on the graphic. A simple rescaling such that the slopes are ~45° makes the plot much more visually pleasing, allowing the eye to slowly digest the graphic to reveal subtle details such as variations in the rates of increase and decrease in the number of sunspots. The improved graphic reveals that sunspot cycles tend to rise rapidly and decline slowly, with the most active cycles exhibiting the largest difference in the rates.

In situations where the focus is on the absolute values of the quantities rather than trends in the data, well-organized tables tend to be very effective. The eye is able to quickly scan through the table entries and grasp the general structure of the dataset. The viewer can then be directed by any accompanying text to look more carefully at particular subsets of the data, using the mental roadmap derived from first inspection. Data such as schedules and budgets are often best presented in a tabular format.

Lead me not into temptation, but deliver me from evil.

The natural tendency for the mind to interpret patterns can also mislead, finding spurious correlations where none exists and inadvertently throwing the audience off the intended story. It is thus crucial for
the graphic designer to be aware of any possible ambiguity, and to minimize the possibility of the audience being led astray.

A huge source of error when reading graphics arises from chartjunk – elements of the graphic that does not tell the viewer anything new. Figure 3 shows a typical graphic one would find in the newspaper. The image of the road serves no informational purpose, and its central position draws attention away from the key message of the graphic (the change in fuel economy standards over the years). Furthermore, the road forces the numbers into unintuitive positions, making the graphic harder to interpret than a simple table. The horizontal lines are also misleading, with lengths appearing to correspond to the numbers immediately right of them when it is actually not the case. The perspective view adds to the confusion.


Figure 4 shows another common example of distortion by unnecessary decorative elements. The representation of oil prices as barrels makes it unclear whether the height, area or perceived volume of the barrels actually correlate with the oil prices. In addition, just like in the previous example, the perspective view of the barrels one after another places a further unnecessary hurdle in correctly gleaning the numerical trend. It is also difficult to read the numbers describing the years, due to low contrasts from a poor color choice and clumping of small text for the earlier years.

Another common cause for misleading visual artifacts come from a poor choice of colormaps. While colors are highly useful for representing another dimension of the data, poor colormaps force the viewer into an unnatural interpretation of the colors which runs up against the intuition, resulting in confusion. Colormaps should be picked such that variations in the quantity being represented can be naturally qualitatively correlated with variations in the color tones without the use of a colorbar.

Figure 4: Oil prices 1973 – 1979. [Time, Apr 9, 1979]
One popular but bad colormap is the rainbow. Figure 5 illustrates the problems of the rainbow colormap. There are three main problems associated with the rainbow colormap. Firstly, although the ordering of the colors in the rainbow is well-known, it is still unintuitive and requires some degree of mental processing to interpret. Secondly, the rainbow colormap does not have a monotonic trend in intensity and lightness (Figure 6), and the natural tendency to read into the lightness becomes confused by the arbitrary ordering of lightness of the colors of the colormap. Thirdly, the perceived change in color does not correspond to a similar change in the represented quantity. Indeed, we can see from Figure 6 that the combination of a small hue discrimination and a high lightness value results in the sharp visual edge associated with yellow.

Perceptual colormaps are specially designed to have equal hue discrimination over their spectra and a relatively linear correlation between the hue lightness and the value of the represented quantity. These
colormaps avoid artificial sharp edges, and facilitate a much more intuitive interpretation of the colors. Unfortunately, many plotting software have yet to make such perceptual colormaps available. A notable exception is Python/Matplotlib, which have the perceptual colormaps \texttt{viridis}, \texttt{inferno}, \texttt{plasma} and \texttt{magma}. Ander Biguri has created some perceptual colormaps for MATLAB, available on the File Exchange at \url{https://www.mathworks.com/matlabcentral/fileexchange/51986-perceptually-uniform-colormaps}. A description of how to make your own perceptual colormaps is available from Matteo’s Niccoli’s \url{https://mycarta.wordpress.com/2013/02/21/perceptual-rainbow-palette-the-method}.

\textit{Only against a dim background can the bright really shine.}

The most fundamental aspect of good graphics design is good audience attention management. The most important element of the graphic has to be first to capture the attention of the viewer. It should have a central position, occupy a large fraction of the area of the graphic, and be drawn with thicker lines and in bolder colors. Other elements should be subdued and muted accordingly to reflect their relative importance.

Other than being misleading, another problem with chartjunk is that they draw attention away from the important parts of the graphic, effectively masking the story behind the graphic. Chartjunk essentially has a similar effect as the elaborate tiled floor in Figure 7. The noisy and attention-grabbing pattern of the tiles make it very difficult to discern where the steps actually are, resulting in inadvertent stumbling, or at the very least, a reduced speed in climbing the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure6.png}
\caption{Figure 6: Variation of lightness and smallest observable difference in hue ($\Delta\lambda$/nm) of pure colors. [Derived from \textit{Eye and Brain}, Richard Gregory; \textit{MyCarta}, Matteo Niccoli]}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure7.png}
\caption{Figure 7. [\textit{Guidelines for Stair Safety}, John Archea, Belinda Collins, Fred Stahl]}
\end{figure}
steps. Similarly, unnecessary detail in a graphic hinders quick apprehension of the data, resulting in the eye having to slowly search for a visual anchor in the graphic, and then moving from there carefully to avoid being lost in the noise.

Figure 8 shows the drastic improvement in the visibility of the data when the background grid is instead drawn with much thinner lines. Grids are useful in cases when the absolute values of the dependent variable are important at all values of the independent variable, such as in a data reference sheet. Most of the time however, only approximate values of the dependent variable are needed, and only at specific key points. In those cases, subtle lines linking the plot to the axes rather than a full non-committal grid would be more effective.

Figure 9 shows another train schedule. The thick lines in the original version (top) compete with the data for the viewer’s attention. The train number, an unimportant piece of information to most riders, is placed right at the top where it would be the first to be seen. The line of A.M.’s and P.M.’s ironically makes it unclear where the transition between morning and afternoon times is. The redesign (bottom) gets rid of the grid, instead using alternating strips of light colors to divide up the data, making the entire graphic more visually comfortable. The train number is moved to the bottom as supplementary information, while a single “am” is now placed prominently and unambiguously as a marker for the times that follow.
Figure 10 illustrates similar principles. In the original graphic (top), the labels for each individual data point compete with the data points for attention, being of a similar size and color. The arrows add to the clutter. In addition, the label for the vertical axis is rotated to run vertically. While this saves a bit of space, the unusual orientation hinders fast registration of the words, and unnecessarily require disproportionately large mental effort for an unimportant element of the graphic. In the redesign (bottom), the labels for the data points are changed to be grey, while the data points themselves are an eye-catching red. The labels are also entirely in lower case, to further mute them relative to the data points. Similarly, the lines making up the axes are grey to decrease the visual clutter, while the numbers are in black due to their relative
importance over the grid. Finally, the clever use of large and small cases in the axis labels distinguishes between the quantities and the units, and the label for the vertical axis is rotated to a more natural orientation.

We saw from the previous two examples how the deft use of colors can help to group data and to tune the relative visual prominence of the various elements in the graphic. Figure 11 shows other functions that colors can play – to distinguish between different elements in the graphic, and to provide a thematic link among elements over the entire graphic. The improved version (bottom) uses 3 prominent colors. The reds in the graphic indicate motion. The yellows indicate the position of the marshalling wands. The labels are in black. The figures of the marshal are in grey for two reasons. First the figure is not of primary importance in the graphic. It does not change significantly over the various signals, and the main message is already contained in the position of the yellow marshalling wands. Secondly, the large area occupied by the figures means that having a strong color (such as in the original graphic at the top) would result in the figures being the most prominent elements in the graphic.

The choice of colors is very important. Bold colors should only be used sparingly to make particular parts of the graphic stand out. If large areas of the graphic has to be colored, a lighter tone should be used instead. Even if the graphic element in question is the most important and hence should be emphasized over other elements, it should not be given strong colors if it spans a large area of the graphic. Strong colors call out to the viewer, and large swaths of strong colors make for a very loud graphic, almost causing the viewer to avert his/her eyes to avoid the din of colors. Figure 12 shows a comparison of the visual effect arising from having bold colors verses having more muted colors. In addition to the use of the bad rainbow color map, the cacophony of colors in the right graphic essentially blind the viewer so much that it is physically difficult for the eye to dwell on the graphic for a prolonged period of time to digest the smaller details.
Figure 12. General Bathymetric Chart of the Oceans [International Hydrographic Organization; Visual Explanations, Edward Tufte].

Figure 13. [Studies in Visual Communication, Marta Braun]
**Some useful devices**

Parallelism is the juxtaposition of similar graphical elements next to one another. The eye is immediately able to register the relationship among the graphical elements, and automatically picks out any similarities and differences. Indeed, this particular graphical device has been used numerous times in the figures above to highlight the visual effect of a good verses a bad graphic, in order to demonstrate the principles of effective graphic design. Parallelism can also be used for explanatory purposes, such as in Figure 13. The original photograph has a lot of detail, and adding labels on top of the photograph will result in competition between the labels and the photograph, hindering both reading of the labels and appreciation of the photograph. Viewing the graphic, the eye is naturally able to draw the connection between the upper photograph and the stylized figures at the bottom, and then interpreting the labels to refer to the people in the photograph.

Sparklines are small, simple and high-density graphics designed to provide quick impressions of trends in the data. Figure 14 shows some examples of sparklines. A clear label describes what the graphic is about, while the black lines describe trends in the quantity. Light shading is used to convey the normal range, while the numbers, linked to the final measurement on the line by the same color red, provide the quantitative anchor to the line.

The scatterplot is one of the most common ways to display bivariate data. Often however, little thought is given to the design of the axes for the scatterplots. Figure 15 shows some ways the traditional axis design can be improved on. On the left, the axes are partially erased to show the range of the data along the two dimensions. The ticks remain, outside the range and thus unconnected to the main “axis line”, providing the quantitative context for the data. On the right, the axes are transformed to show the marginal distribution of each variable, providing a different perspective of the same data.

![Figure 15: Alternative scatterplot axis styles](Visual Display of Quantitative Information, Edward Tufte)

**Final Words**

A graphic encapsulates a discovery process, with the creator entertaining the viewer with some new information about the world. The best graphics are eternal, not because their creators will always be there to use them, but because they are able to tell their stories by themselves in the absence of their creators.
Acknowledgments

Many thanks go to Nicholas Schneider, for funding my enrolment for Edward Tufte’s seminar *Presenting Data and Information* (which supplied the four books), and for picking on the details in the graphics that I create for my presentations. Also thanks to Maria Steinrück for the discussion on the choice of colormaps, which formed the foundation upon which I elaborated on above.