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A Brief Guide to Designing Effective Figures for the Scientific Paper

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1. Figures in Science

In 1610, Galileo sent a letter to Cosimo de' Medici (his patron) describing the first telescopic observations. In his letter, Galileo included a small set of a large series of famous drawings depicting the earth's moon.^[1] Galileo employed these drawings to communicate his discoveries. In his book, *Sidereus Nuncius*, additional illustrations of the moon were used as critical support for Galileo's argument for a heliocentric system (Figure 1). As a true Renaissance man, Galileo was able to make these drawings because in addition to studying science at the University of Pisa, he also studied the fine arts, or "Disegno", even becoming an instructor at the Accademia delle Arti del Disegno in Florence.

Nowadays, very few scientists send letters to the de' Medici family, although we do send reports to funding agencies. Even fewer scientists study "Disegno" in Florence. However, contemporary scientists do still communicate their discoveries with figures in scientific papers.

The use of illustrations in scientific publications is a longstanding tradition that predates Galileo considerably. As early as 4000 B. C. in ancient Egypt and later on in Greece, drawings were used to document advances in astronomy, geometry, agriculture, and medicine. The first illustrated medical book *Fasciculo de Medicina* was printed in 1491 and is today considered the starting point of modern Western medicine.^[3] In the 18th century, during the Age of Enlightenment, illustrations were used broadly in scientific manuscripts to disseminate knowledge to the general public.^[4]

In the Middle Ages, books were written and illustrated by hand. Later, advances in printing craft and technology enabled illustrations to become an integral part of a scientific treatise. The current "digital age" has made the creation of illustrations

and figures for scientific publications even more accessible. While scientists no longer need to plot graphs by hand, it is often still by trial and error that figures are made. In 2004, the essay "Whitesides' Group: Writing a Paper"^[5] provided useful directions on how to approach the writing process. However, it has been more than half a century^[6] since a guide to making figures for the scientific paper has appeared in the literature. In this essay, we attempt to help scientists and engineers in their process of creating figures for publication with a brief series of suggestions.

2. Why Figures Matter

Figures are often the first part of a scientific paper that is reviewed by the editor, and if the paper is accepted, often the first part examined by your peers. Figures should not be seen as decoration or as attention-getting visual attraction. Visual representations can convey facts, ideas, and relationships far more clearly and concisely than descriptive text.^[7] Indeed, many advanced imaging tools and visualization methods were first developed for scientific purposes as a means towards discovering or quantifying patterns, trends, and comparisons. Figures are powerful tools to effectively and efficiently convey complex information. Well-designed figures can help the audience better understand the objectives and results of your research.

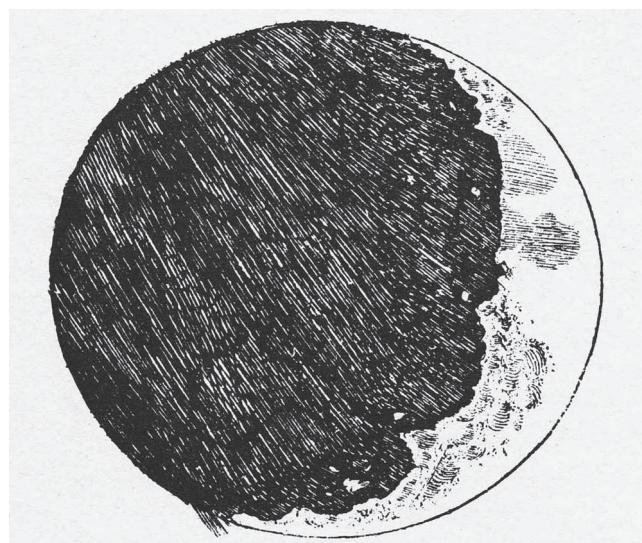


Figure 1. Engraving of the moon from Galileo's *Sidereus Nuncius* (III, 53-96) 1610. Reproduced with permission.^[2]

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3. How to Design Effective Figures

3.1. Design Figures for the Audience (Not for You)

Just like language, graphics communicate information to other people. It is crucial to keep these people, or addressees, in mind when the graphic is being constructed.^[8] Consider: 1) The make-up of the audience. A figure for a specialized journal may require a different design than a figure aimed at a broader readership. 2) The background knowledge of the audience. The audience may not know what you know. Graphics should provide all the information necessary for the audience to fully comprehend them. 3) Disciplinary conventions. Graphical conventions and norms exist in each field. Make sure you follow these practices. If you are submitting to a journal with a broader audience, consider using images and graphic elements that are generally recognized and clearly identifiable.

3.2. Focus on the Most Important Information

Whitesides stresses the importance of writing an outline for the basic organization of a scientific paper.^[5] We suggest that this outline include the figures and their placement. Most publications limit the number of figures due to space constraints. Therefore, the few figures that can be included need to be well focused. Before starting to design the figures: 1) Identify the storyline and how each figure will contribute to it. Ensure that every figure serves a well-defined purpose and is critical to the overall story. 2) Establish the key message for each figure. Every element in the figure should contribute to that message. Without sacrificing clarity, consider removing unnecessary detail (however, do not manipulate data!). Some results may be better suited for the Supporting Information, rather than being placed in an overwhelmingly complex (and hard to understand) figure. Follow “The Principle of Relevance”, which states “Communication is most effective when neither too much nor too little information is presented.”^[9]

3.3. Design a Clear Visual Structure

The most difficult part of designing a figure is determining an effective overall visual structure. To this end, the best design principle is “form follows function”, i.e., that the shape of an object should be based upon its intended purpose.^[10] In the case of figures, “form follows function” means that the visual composition should guide the viewer along a logical sequence of information. The viewer should be able to: 1) Easily enter the image. The top-left corner is a natural entry point for the viewer. Most people view an image by scanning from the top left to the lower right.^[11] Take advantage of this innate tendency by beginning the figure in this area. 2) Attain an overview of the most important information. Most viewers expect a left-to-right and/or top-to-bottom pattern of movement. Creating a “filmstrip” of images in either of these directions supports this convention. 3) Absorb additional details and secondary content. Viewers need an organizational structure to help guide them

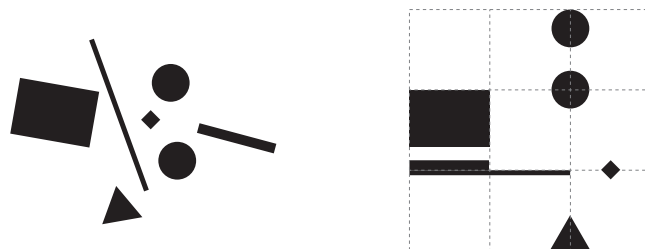


Figure 2. Grids can help to organize the spaces around and in-between elements.

through a figure. A grid can be a useful tool in creating this structure.^[12] In figures, grids can help organize disparate elements into visual groups that an audience can attend to and remember^[9] (Figure 2).

A wide variety of compositional structures (both with and without grids) are possible to accomplish the desired flow of information in a figure. In design, as in science, there are often multiple paths to multiple solutions. The specific composition of a figure will vary depending on the content, the number of parts in the figure, and the relationship of the parts to each other and to the whole.

3.4. Use Visual Contrast, But Keep Figures Simple

Use visual contrast to highlight the most important information. Vary the size, shape, position, orientation, or color of an element (or group of elements) in order to make the key part of the figure the most visually prominent.^[13] Typically, larger, darker, and brighter elements are more prominent than what is smaller, lighter, and duller (Figure 3).

1) Avoid incorporating every form of visual contrast. A single type of contrast (i.e., only shape, or only size, or only color) is usually sufficient. Too much contrast creates visual noise that

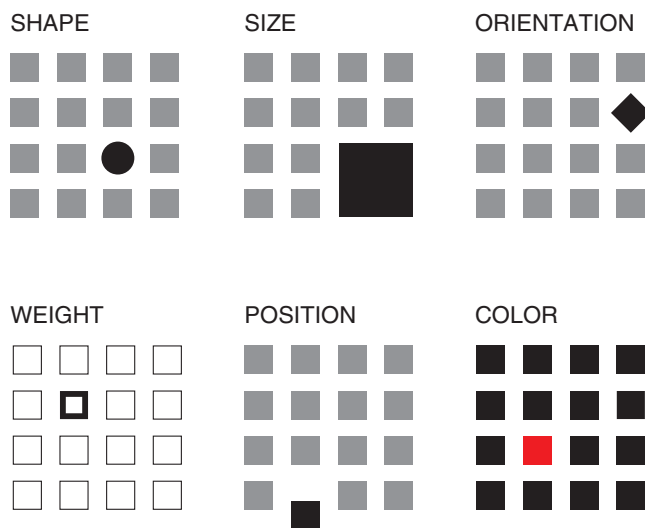


Figure 3. Vary the shape, size, orientation, weight, position, or color of an element (or group of elements) to make the key part of the figure visually clear.

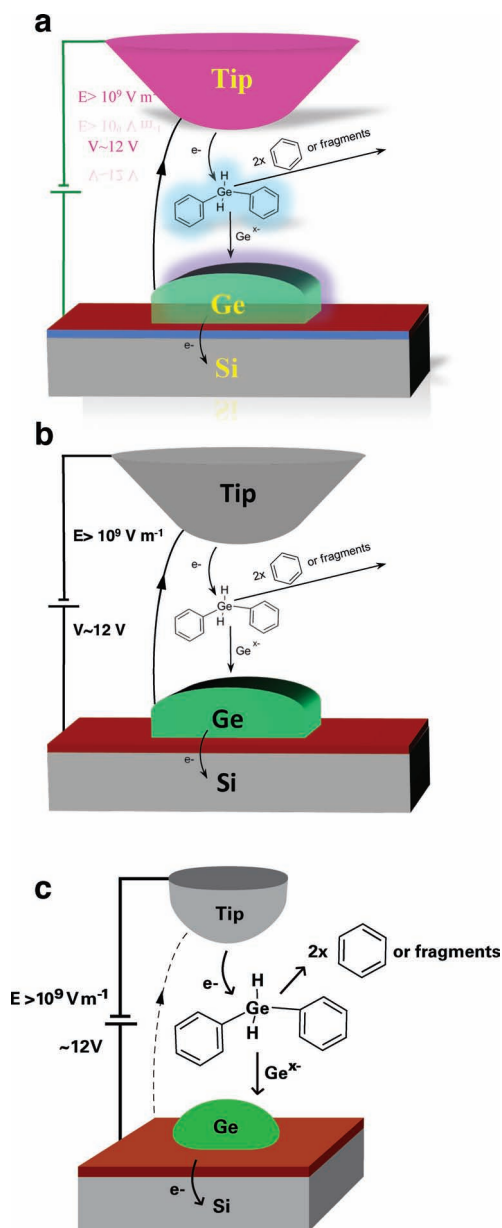


Figure 4. a) A disorganized science graphic, with questionable use of shadows, glows, and other software effects. The text is illegible due to low value contrast. b) A clearer version of (a) designed by one of the authors (M.R.). Reproduced with permission.^[18] c) A version of (b) improved by one of the authors (K.C.). In this redesign, the molecular reaction has been enlarged for greater legibility. Fewer type sizes are used, and components are aligned on an implied grid.

obscures information.^[14] 2) Avoid using too many colors. A limited color palette is often most effective.^[15] Ensure that individual color selections vary in their value, where value refers to the relative lightness or darkness of a color. Value contrast improves the viewer's ability to distinguish between a range of colors. 3) Consider using a limited black-and-white palette rather than full color. High-contrast black and white graphics can be more readable than color.^[16] Black and white graphics are also better for copying and laser printing. When designing in black and white, use different line styles and/or thicknesses,

different shapes, and/or different fills (shades, tints or patterns) for visual contrast. 4) Remove all non-data elements that do not serve a communicative function.^[17] This includes decorative flourishes such as drop shadows, 3D extrusions, unnecessary gradients, etc. (Figure 4).^[18] In graphs, charts, and diagrams, gridlines should be subordinate to the data being displayed. Make supporting tick marks small and guidelines thin or dotted.

3.5. Create Legible and Readable Typography

Text in figures should be clear and readable at a glance. Make sure that the text is readable after the graphic is resized to its final dimensions. To enhance readability: 1) Use sans-serif fonts. Sans-serif typefaces such as Helvetica and Arial are often more legible than serifs when set in small sizes.^[15] Because most publications use serif typefaces for body text, using sans-serif type in graphics provides contrast and avoids confusion. 2) Maximize the contrast between type and background. A 70% contrast of type and background (i.e., white type on a 70% dark gray background) is optimal.^[19] Avoid value combinations below this threshold, especially combinations that pair complementary colors, because this causes visual vibration.^[20] Avoid placing text over a patterned background or photograph, which often renders type illegible (Figure 5). 3) Include scale bars and label the axes. Consider whether the figure needs a legend to label the patterns and symbols used. Direct labeling (text placed directly by points, lines, etc.) is desirable, since it avoids burdening the viewer with back-and-forth legend

Adequate readability due to high value contrast



Inadequate readability due to low value contrast



Inadequate readability due to patterned background



Figure 5. Strive for at least 70% contrast between text and background. Avoid placing text over a patterned background; instead, text should be placed nearby or adjacent to the image or in the legend.

consultation. However, direct labeling is often impossible due to overlap issues and/or space constraints.

4. Outlook

If you think carefully about designing figures, you are already a step ahead in the creative process. As with a manuscript, it is a good idea to ask colleagues, or if you are lucky, a friend with a design background, to review your work. For further reading, there are several excellent guides on designing effective figures, many of which are cited in this essay.

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