White Paper
Standardization of Color Palettes for Scientific Visualization

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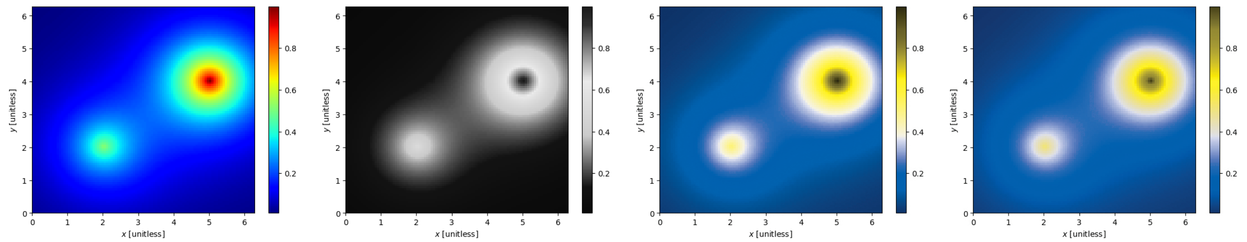
1 Introduction & Motivation

The purpose of this white paper is to demonstrate the importance of color palette choice in scientific visualizations and to promote an effort to convene an interdisciplinary team of researchers to study and recommend color palettes based on intended application(s) and audience(s). Advancing the state of the art in this area is expected to benefit analytic skill set development (improving human-technology interactions), improve coordination and communication among researchers, and reduce errors and biases in decision making.

It is clear that scientific computing (simulation) has become the third pillar of technical research and development (joining theory and experimentation). As such, the applications for scientific computing are ever increasing along with the speed and capabilities of computers. The progress in these areas is leading to a situation where researchers can produce immense amounts of data that must be somehow post-processed and considered by the researcher. To help the researcher identify trends and/or important behaviors, he or she will often use software to visualize the data leading to another technical field that complements scientific computing: scientific visualization, i.e., the visual representation of technical data.

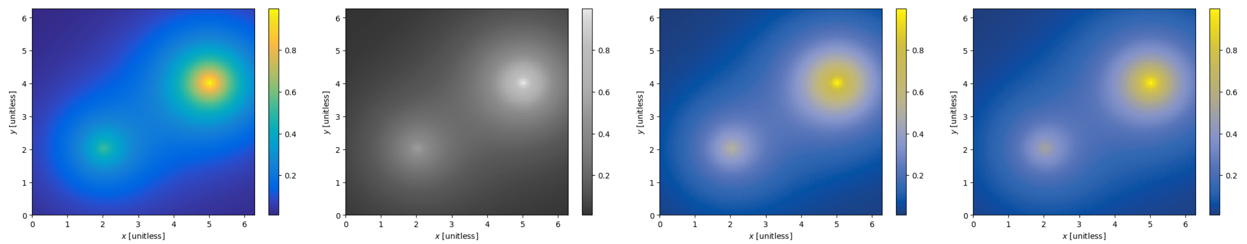
Scientific visualization must clearly, ideally intuitively, convey precise information without biasing the viewer. If scientific visualization fails in this goal, then errors or misunderstandings can result that can lead to inappropriate decision making at both the science/engineering and policy levels. One can argue that historically little attention was paid to the task of selecting an appropriate color palette when displaying data. Throughout time, this has caused researchers to become comfortable with demonstrably inferior color palettes [1] relative to recently developed color palettes. However, because of comfort and familiarity, some researchers are resistant to change. Furthermore, many researchers do not consider color palette choice (often using the default in whatever visualization software is being used) and thus can use a non-ideal color palette that can lead to errors in interpreting the underlying data. All of these factors complicates coordination and communication among researchers.

Much has been written about visualizing data [2, 3, 4] and there have been individual efforts to develop and share best practices (e.g., [5, 6, 7]). While researchers must select the type of figure to most effectively visualize the data under consideration, they must also select the best way to color the data to differentiate data series and to highlight important features. This white paper will go on to demonstrate representative current state-of-the-art color palettes for various types of visualizations. Using the current state as background, work will be proposed for an interdisciplinary team of visualization software developers, visual perception specialists (perhaps cognitive psychologists), and researchers (i.e., end users). The ultimate goal is to study, communicate, and incorporate as default color palettes that serve the broadest audience of researchers and viewers.



(a) Nominal (b) Grayscale (c) Colorblind (Protanopia) (d) Colorblind (Deuteranopia)

Figure 1: "Jet" Color Scheme



(a) Nominal (b) Grayscale (c) Colorblind (Protanopia) (d) Colorblind (Deuteranopia)

Figure 2: "Parula" Color Scheme

2 Current State-of-the-Art

There are three general types of color palettes:

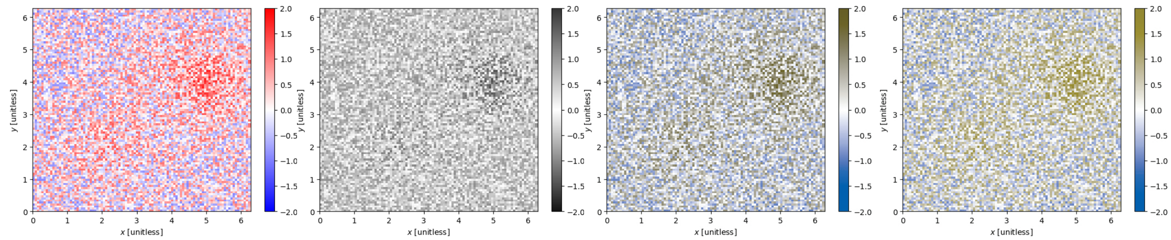
1. Sequential, representing values that exist along a continuum with logically high and low values (e.g., fluid velocity, temperature, material density),
2. Diverging, representing values that logically exist about some nominal median value (e.g., temperature above and below freezing, ratios of results about unity), and
3. Qualitative, which uses color to differentiate between distinct data sets.

Benefits, weaknesses, and areas of study for each type of color palette are discussed in the following subsections.

2.1 Sequential Color Palettes

Sequential color maps are the most common, with perhaps the most common one (historically) shown in Fig. 1a and referred to herein as "Jet". Since the development of Jet and because of its weaknesses [5, 1], both commercial [8, 9, 10, 11] and open source [12] developers have investigated alternate color palettes. An example alternate sequential color palette called "Parula" developed by MathWorks is shown in Fig. 2a. The Parula color palette has several desirable properties relative to Jet:

1. Parula is nearly perceptually uniform (i.e., values correspond to a ramped intensity that follows a logical progression without accentuating particular values along the ramp). Because of being perceptually uniform, no artificial contour bands exist in Parula (compare Figs. 1a and 2a noting that the data is smooth; the apparent yellow-green ring in Jet is a non-physical feature by virtue of applying Jet),



(a) Nominal (b) Grayscale (c) Colorblind (Protanopia) (d) Colorblind (Deuteranopia)

Figure 3: Blue-white-red Diverging Color Palette

2. Parula does not contain colors that challenge color blind viewers (compare the Protanopia and Deuteranopia representations of Jet and Parula in Figs. 1 and 2), and

3. Parula reproduces the sequential gradient when shown using grayscale (note that one cannot distinguish high versus low values with Jet in Fig. 1b).

Because of these traits Parula (or other color palettes like it, e.g., [13]) is more useful to a more inclusive group of viewers in a broader set of circumstances than Jet. Slowly, visualization software products are adopting perceptually uniform color palettes in lieu of traditional spectral palettes like Jet. However, the types of considerations that make Parula superior are often not made by researchers when applying a color palette to work (users will often apply a piece of software's default palette). For this reason, software developers should strive to provide default color palettes that serve the widest audience in the widest set of circumstances. One must ask: are there other considerations such as aesthetic value that define an ideal sequential color palette? What types of considerations do researchers need to make when selecting a color palette and what is the guidance once those factors have been evaluated?

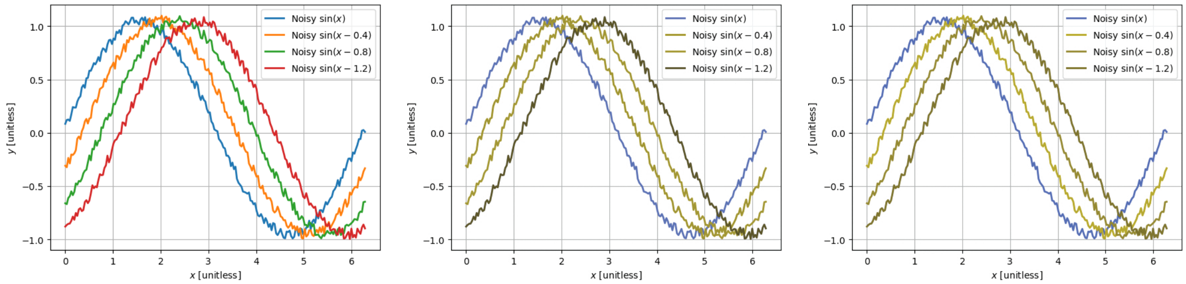
2.2 Diverging Color Palettes

Diverging color maps are often represented by different colors that increase in intensity relative to a central, generally neutral color. Perhaps the most common is a blue-white-red color palette shown in Fig. 3a. Unfortunately, diverging color palettes generally do not display well in grayscale because one cannot distinguish the direction of divergence (both get increasingly dark moving away from the median value). Diverging color palettes can be suitable for colorblind viewers as long as non-conflicting colors (e.g., red and green) are not used to represent the divergence. Arguments have been made that blue-white-red color palettes are suitable as sequential color palettes by indicating minimum, median, and maximum values. Further, a blue-white-red color palette has a relatively high luminance making it suitable for showing detailed shading on three-dimensional surfaces. Because of these benefits and despite the inability to reproduce well in grayscale, it would be valuable to study whether blue-white-red might be a suitable default color map serving both the purposes of showing sequential (in a somewhat unconventional way) and diverging values. Again, one must ask and answer: which color palette makes the best default that serves the widest audience in the widest set of circumstances?

2.3 Qualitative Color Palettes

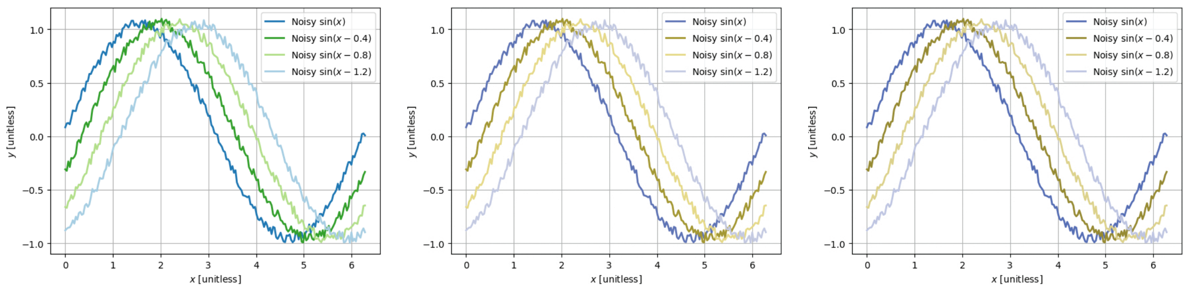
Qualitative color palettes seek to distinguish distinct data sets. Such examples are shown in Figs. 4 and 5.

Grayscale representations are not shown because, for line plots, dashing and dotting can be used to help distinguish data series. Of more subtle concern is a particular color palettes suitability for color blind users.



(a) Nominal (b) Colorblind (Protanopia) (c) Colorblind (Deuteranopia)

Figure 4: Colorblind-insensitive Qualitative Color Palette



(a) Nominal (b) Colorblind (Protanopia) (c) Colorblind (Deuteranopia)

Figure 5: Colorblind-sensitive Color Palette

Note that Fig. 4 contains data series that are difficult to distinguish for colorblind users based on color alone (particularly Fig. 4b). Researchers must be sensitive to this fact and use a combination of colors and plot styles to differentiate data series in a wide variety of circumstances. The question remains: is there a qualitative color palette that is optimum? Under what circumstances is one qualitative color palette ideal or non-ideal relative to another?

3 Conclusion & Proposed Work

This white paper helps the reader understand the importance of color palette choice when generating scientific visualizations and to correspondingly compel the reader to actively manage the color palette for each figure produced. Further, the value of researching, identifying, and disseminating color palettes for scientific visualization software developers to adopt and include is demonstrated.

Using the previously described types of color palettes and questions as starting points, we propose assembling a team of visualization software developers, visual perception specialists (perhaps cognitive psychologists), and researchers (i.e., end users) to study and recommend a set of color palettes appropriate for scientific visualization. While it is likely that there is no single color palette appropriate for all scientific visualization applications, the goal is to identify appropriate color palettes given a set of criteria (and to first identify those criteria for evaluating color palettes). Using the most-general set of criteria, a default color palette should be recommended. It is also hoped that this work would bring together disparate disciplines that have not typically worked together to share and promulgate best practices. Finally, it is hoped that visualization software developers will embrace the recommended default to help researchers universally gain comfort with it, as was inadvertently done with Jet many years ago.

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