Colors in Visualization

Adapted from the Slides by Dr. Mike Bailey at Oregon State University
Colors help us break camouflage.
Colors help us break camouflage.

Pre-attentive!!!
“The often scant benefits derived from coloring data indicate that even putting a good color in a good place is a complex matter. Indeed, so difficult and subtle that avoiding catastrophe becomes the first principle in bringing color to information. Above all, do no harm.”

-- Edward Tufte
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey \textit{quantitative} information.
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Color is one of the most effective ways to **encode data defined in two-dimensional space**.
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey quantitative information.

Color is one of the most effective ways to encode data defined in two-dimensional space.

Differences in color can distinguish different categories (for example cropland, forest, or urban areas in a land cover map) or indicate quantity (percent forest cover or population).

We are good at telling relative difference!!!
Is this a good place to use color? Why?

Conflict???
Color selection in data visualization is not merely an aesthetic choice, it is a crucial tool to convey **quantitative** information.

Color is one of the most effective ways to **encode data defined in two-dimensional space**.

**Differences** in color can distinguish different categories (for example, cropland, forest, or urban areas in a land cover map) or indicate quantity (percent forest cover or population).

Properly selected colors convey the underlying data accurately, in contrast to many color schemes commonly used in visualization that **distort relationships** between data values.
What is Wrong with this Color Scale

DEATHS OF WHITE MALES

Age-adjusted mortality per 100,000 population

- Top 10%: 929.7–765.0
- Next Highest 10%: 764.9–724.8
- Middle Highest 20%: 724.7–678.2
- Middle 20%: 678.1–636.4
- Middle Lowest 20%: 636.3–596.0
- Next Lowest 10%: 595.9–564.5
- Bottom 10%: 564.4–440.9
What is Wrong with this Color Scale

Data values vs. Selected colors:  
- **large** vs. **small** colors

Mapping:  
- Incorrect color assignment

Age-adjusted mortality per 100,000 population:
- Top 10%: 929.7–765.0
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Not a bad choice of color scale, but the Dynamic Range needs some work.
Not a bad choice of color scale, but the **Dynamic Range** needs some work.
Let’s start with the most important component in a visualization system – You!
How do we see colors?

Rods
- ~115,000,000
- Concentrated on the periphery of the retina
- Sensitive to intensity
- Most sensitive at 500 nm (~green)

Cones
- ~7,000,000
- Concentrated near the center of the retina
- Sensitive to color
- Three of cones: long (~red), medium (~green), and short (~blue) wavelengths
Visible colors to human eyes

- Increasing Frequency ($\nu$)
- Increasing Wavelength ($\lambda$)

Visible spectrum

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-16}$</td>
<td>$10^{18}$</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>$10^{14}$</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>$10^{10}$</td>
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<tr>
<td>$10^{-8}$</td>
<td>$10^{6}$</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>$10^{4}$</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>$10^{2}$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$10^{0}$</td>
</tr>
<tr>
<td>$10^{0}$</td>
<td>$10^{8}$</td>
</tr>
</tbody>
</table>

- γ rays
- X rays
- UV
- IR
- Microwave
- FM Radio waves
- AM Radio waves
- Long radio waves
We sense different brightness for different color hues
We sense different brightness for different color hues
We sense different brightness for different color hues
We sense different brightness for different color hues
Color Models
Monitors: Additive Colors
Additive Color (RGB)

OpenGL: glColor3f (r, g, b) 0<=r, g, b <=1
What Else are Using Additive Color

- Plasma
- LCD
- Digital film recorder

How plasma displays work
Subtractive Color (CMYK)
Subtractive Color (CMYK)

In contrast to the additive model!!
Color Printing

• Uses subtractive colors
• Uses 3 (CMY) or 4 (CMYK) passes (K stands for Key (Black))
• CMYK printers usually have a better-looking black (with details)
• There is a considerable variation in color gamut between products
CIE Chromaticity Diagram

CIE xyY color space

\[
X = \int_{380}^{780} I(\lambda) \bar{X}(\lambda) \, d\lambda \\
Y = \int_{380}^{780} I(\lambda) \bar{Y}(\lambda) \, d\lambda \\
Z = \int_{380}^{780} I(\lambda) \bar{Z}(\lambda) \, d\lambda
\]

\[
x = \frac{X}{X + Y + Z} \\
y = \frac{Y}{X + Y + Z} \\
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]

White Point

More details please see http://en.wikipedia.org/wiki/CIE_1931_color_space
Color Gamut for a Workstation Monitor

- Color CRT
- White Point
- Monitor White
- Eye
Color Gamut for a Monitor and Color Slides

- Color CRT
- Slide White
- Projected Color Slides
- White Point
- Eye
Color Gamut for a Monitor and Color Printer

Color CRT

Eye

Color Paper Hardcopy
Color Spaces
Red-Green-Blue:
Can be easily represented by displays

OpenGL coloring scheme
Hue-Saturation-Value:
For many VIS applications, **a simpler way to specify additive color**

[Image: Hue disk]

https://en.wikipedia.org/wiki/HSL_and_HSV
Hue-Saturation-Value:
For many VIS applications, a simpler way to specify additive color

Notice that blue-green-red in HSV space corresponds to the visible portion of the electromagnetic spectrum

An example of color transfer function

Turning a scalar value into a hue value when using the Rainbow Color Scale

\[ Hue = 240 - 240 \cdot \frac{S - S_{min}}{S_{max} - S_{min}} \]

Saturation=1
Value=1

HSV color → RGB color
h = hue / 60.;
if ( h >= 6. ) h -= 6.;
if( h < 0. ) h += 6.;

s = saturation;
if( s < 0. ) s = 0.;
if( s > 1. ) s = 1.;

v = value;
if( v < 0. ) v = 0.;
if( v > 1. ) v = 1.;

if( s == 0.0 ) // if saturation=0 it is a gray color
{
    r = g = b = v;
    return;
}

i = floor( h );
f = h - i;
p = v * ( 1. - s );
q = v * ( 1. - s*f );
t = v * ( 1. - ( s * (1.-f) ) );

switch( (int) i ){
    case 0:   r = v; g = t; b = p; break;
    case 1:   r = q; g = v; b = p; break;
    case 2:   r = p; g = v; b = t; break;
    case 3:   r = p; g = q; b = v; break;
    case 4:   r = t; g = p; b = v; break;
    case 5:   r = v; g = p; b = q; break;
}
RGB to HSV

\[
V = M = \max(R, G, B);
\]

\[
m = \min(R, G, B);
\]

\[
S = (M - m)/M;
\]

\[
\text{if (R==M) } h = (G-B)/(M-m);
\]

\[
\text{if (G==M) } h = 2 + (B-R)/(M-m);
\]

\[
\text{if (B==M) } h = 4 + (R-G)/(M-m);
\]

\[
\text{if (h<0) } H = h/6 + 1;
\]

\[
\text{if (h>0) } H = h/6;
\]
Hue-Saturation-Lightness: Similar to HSV but different

- Hue is a degree on the color wheel; 0 (or 360) is red, 120 is green, 240 is blue. Numbers in between reflect different shades.

- Saturation is a percentage value; 100% is the full color.

- Lightness is also a percentage; 0% is dark (black), 100% is light (white), and 50% is the average.

https://en.wikipedia.org/wiki/HSL_and_HSV
CIELab:

- L for luminance
- a for red-green
- b for yellow-blue

https://en.wikipedia.org/wiki/CIELAB_color_space
Use the right **Color Transfer Function** to represent different information

**Hue:** categorical

**Saturation:** ordinal and quantitative

**Luminance:** ordinal and quantitative
Or brightness
Different Types of Color Scales

- Sequential schemes
- Diverging scheme
- Qualitative scheme
Using RGB color space to generate sequential color scheme -- Add-One-Component at a time
Other Sequential Color Schemes

a.
Other Divergence Color Schemes
Other Qualitative Color Schemes
For visualizing quantitative information, Here is What Really Important

Given any 2 colors, make it *intuitively obvious* which color represents “higher” and which represents “lower”
Pay attention to the dynamic range issue.

Much of the total dynamic range of the color scale is used up in the first small percent of the visualization, leaving little for the rest of the visualization.
Issues with some common color schemes

Transitions between some colors, green and red, for example, occur very rapidly, leading to false contrast. Other transitions, especially green, are gradual, and there is a loss of detail. Rainbow palettes have another deficiency: because the overall brightness of the colors increases and decreases over the range of hues there is no natural progression of values.

An alternative is to only use brightness, not color, to encode value, but surrounding tones can significantly alter the perceived values of pixels. Grayscale palettes are best limited to black and white reproductions.

A better approach is to use a color scheme that spirals through a perceptual color space, with each step equally different in hue, saturation, and brightness.
Importance of contrast
Make important features pop up!

by Justin Finn

by Wei Cao
What Makes a Good Contrast?

• Many people think simply adding color onto another color makes a good contrast

• In fact, a better measure is the Δ Luminance

• Using this also helps if someone makes a gray scale photocopy of your color hardcopy
Color Alone Doesn’t Cut It

I sure hope that my life does not depend on being able to read this quickly and accurately!
Luminance Contrast is Crucial

I would prefer that my life depend on being able to read *this* quickly and accurately!
The Luminance Equation

\[ Y = 0.3 \times Red + 0.59 \times Green + 0.11 \times Blue \]
# Luminance Table

<table>
<thead>
<tr>
<th>Color</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>White</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.00</td>
</tr>
<tr>
<td>Red</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Green</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.59</td>
</tr>
<tr>
<td>Blue</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.70</td>
</tr>
<tr>
<td>Magenta</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.41</td>
</tr>
<tr>
<td>Orange</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Yellow</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.89</td>
</tr>
</tbody>
</table>
≅ Contrast Table

<table>
<thead>
<tr>
<th></th>
<th>Black</th>
<th>White</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Cyan</th>
<th>Magenta</th>
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<th>Yellow</th>
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<tbody>
<tr>
<td>Black</td>
<td>0.00</td>
<td>1.00</td>
<td>0.30</td>
<td>0.59</td>
<td>0.11</td>
<td>0.70</td>
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<td>0.89</td>
</tr>
<tr>
<td>White</td>
<td>1.00</td>
<td>0.00</td>
<td>0.70</td>
<td>0.41</td>
<td>0.89</td>
<td>0.30</td>
<td>0.59</td>
<td>0.41</td>
<td>0.11</td>
</tr>
<tr>
<td>Red</td>
<td>0.30</td>
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<td>0.00</td>
<td>0.29</td>
<td>0.19</td>
<td>0.40</td>
<td>0.11</td>
<td>0.30</td>
<td>0.59</td>
</tr>
<tr>
<td>Green</td>
<td>0.59</td>
<td>0.41</td>
<td>0.29</td>
<td>0.00</td>
<td>0.48</td>
<td>0.11</td>
<td>0.18</td>
<td>0.01</td>
<td>0.30</td>
</tr>
<tr>
<td>Blue</td>
<td>0.11</td>
<td>0.89</td>
<td>0.19</td>
<td>0.48</td>
<td>0.00</td>
<td>0.59</td>
<td>0.30</td>
<td>0.49</td>
<td>0.78</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.70</td>
<td>0.30</td>
<td>0.40</td>
<td>0.11</td>
<td>0.59</td>
<td>0.00</td>
<td>0.29</td>
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<td>0.60</td>
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<td>0.19</td>
<td>0.48</td>
<td>0.30</td>
<td>0.00</td>
</tr>
</tbody>
</table>

ΔL* of about 0.40 are highlighted and recommended
Importance of using proper contrast of colors in visualization

Highlighting: make small subset clearly distinct from the rest
Some useful guidelines

• Use more saturated colors for small symbols, thin lines, or small areas (maybe important).

• Use less saturated colors for large areas (background, content...).
Some Good Rules of Thumb
When Using Colors for Scientific Visualization
Do Not Attempt to Fight Pre-Established Color Meanings
# Pre-Established Color Meanings

<table>
<thead>
<tr>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop</td>
<td>On</td>
<td>Cool</td>
</tr>
<tr>
<td>Off</td>
<td>Plants</td>
<td>Safe</td>
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<tr>
<td>Dangerous</td>
<td>Carbon</td>
<td>Deep</td>
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<tr>
<td>Hot</td>
<td>Moving</td>
<td>Nitrogen</td>
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<tr>
<td>High stress</td>
<td>Money</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Money loss</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Limit the Total Number of Colors if viewers are to Discern Information Quickly

Instructions:
1. Press red to logoff normally
2. Press light red to delete all your files, change your password to something random, and logoff

You have 2 seconds • • •
Other Color Facts

In visualization applications, we must be aware that *our perception of color changes* with:

- The surrounding color
- How close two objects are
- How long you have been staring at the color
- Sudden changes in the color intensity
The Ability to Discriminate Colors Changes with Surrounding Color: “Simultaneous Contrast”
The Ability to Discriminate Colors Changes with Surrounding Color: “Simultaneous Contrast”
All colors are equal

... but they are not perceived as the same

Luminance values

Perceived lightness
Beware of Mach Banding
Beware of Mach Banding

We are good at telling the boundaries/border!!!
Beware of Mach Banding
Chromostereopsis

Most people see the red closer than the blue, but some see the opposite effect.

- Red light is refracted less, and is focused toward the ear.
- Blue light is refracted more, and is focused toward the nose.
Easy to read?

Many beginning designers, however, find themselves overwhelmed by the palettes available on most computers, and begin choosing colors for the palette of their designed based on favorites. However, results like that can be disastrous.

Some Aspects of 3D... in Depth!

Single-Source Stereo and Microstereoscopic 3D

Mark Schubin, SchubinCafe.com
Help people make their lives better
Some useful guidelines for Chromostereopsis

• Beware of interactions between some colors (e.g., red/blue)
• Can be useful: for highlighting, creating 3D effect, etc.
• Resolve if unintended by
  • Using colors that are less saturated
  • Surrounding the contrasting colors with a background that moderates the effect of their different wavelengths
  • Separating the contrasting colors
Do different colors affect your mood?

https://www.factmonster.com/color-meanings-and-moods

by David Johnson

Like death and taxes, there is no escaping color. It is ubiquitous. Yet what does it all mean? Why are people more relaxed in green rooms? Why do weightlifters do their best in blue gyms?

Colors often have different meanings in various cultures. And even in Western societies, the meanings of various colors have changed over the years. But today in the U.S., researchers have generally found the following to be accurate.

Black

Black is the color of authority and power. It is popular in fashion because it makes people appear thinner. It is also stylish and timeless. Black also implies submission. Priests wear black to signify submission to God. Some fashion experts say a woman wearing black implies submission to men. Black outfits can also be overpowering, or make the wearer seem aloof or evil. Villains, such as Dracula, often wear black.

White

Brides wear white to symbolize innocence and purity. White reflects light and is considered a summer color. White is popular in decorating and in fashion because it is light, neutral, and goes with everything. However, white shows dirt and is therefore more difficult to keep clean than other colors. Doctors and nurses wear white to imply sterility.

Red

The most emotionally intense color, red stimulates a faster heartbeat and breathing. It is also the color of love. Red clothing gets noticed and makes the wearer appear heavier. Since it is an extreme color, red clothing might not help people in negotiations or confrontations. Red cars are popular targets for thieves. In decorating, red is usually used as an accent.
The Ability to Discriminate Colors Changes with Size of the Colored Area
The Ability to Discriminate Colors Changes with Ambient Light
The Ability to Discriminate Colors Changes with the Age of the Viewer
Be Aware of Color Vision Deficiencies (CVD)

• There is actually no such thing as “color blindness”
• CVD affects ~10% of Caucasian men
• CVD affects ~4% of non-Caucasian men
• CVD affects ~0.5% of women
• The most common type of CVD is red-green
• Blue-yellow also exists
Be Aware of Color Vision Deficiencies (CVD)

- Code Information Redundantly: **Color** + ...
  - Different fonts
  - Symbols
  - Fill pattern
  - Outline pattern
  - Outline thickness

This also helps if someone makes a gray scale photocopy of your color hardcopy
Adding more variations using HSV

<table>
<thead>
<tr>
<th>Hue</th>
<th>Tint</th>
<th>Tone</th>
<th>Shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Colors]</td>
<td>[Colors]</td>
<td>[Colors]</td>
<td>[Colors]</td>
</tr>
<tr>
<td>(Hue + White)</td>
<td>(Hue + Black)</td>
<td>(Hue + Black + White)</td>
<td></td>
</tr>
</tbody>
</table>
Beware of Color Pollution

Just because you have millions of colors to choose from

doesn't mean you must use them all •••
Additional links to the color perception

http://mashable.com/2015/03/26/f8-oculus-optical-illusions/#6493oMF2Hgqg
http://www.weirdoptics.com/melting-colors-optical-illusion/
Additional Reading


• C Ware, *Information Visualization: Perception for design*. Chapters 3-5, 2013.


