“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
What's Wrong with this Color Scale?

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

Source: Scientific American, June 2000

Not a bad choice of color scale, but the Dynamic Range needs some work
Good choice of color scale and Dynamic Range (probably a summer-only scale)

Two-color Scale Showing where Americans travel for Thanksgiving
Let’s start with the most important component in a visualization system – You!

How Many Shades of Different Colors Are We Able to Detect?

Sensors in Your Retina

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 types of cones: long (~red), medium (~green), and short (~blue) wavelengths
**Sidebar: How Many Pixels Do You Need?**

A person with 20/20 vision has a visual acuity of:
1 arc-minute = 1/60°

\[ \theta = \frac{1}{60} = 0.00029 \text{rad} \]

Density = \( \frac{1}{D \theta} \)

<table>
<thead>
<tr>
<th>Viewing Distance (inches)</th>
<th>Required Pixel Density (ppi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>95</td>
</tr>
<tr>
<td>31</td>
<td>111</td>
</tr>
<tr>
<td>24</td>
<td>143</td>
</tr>
<tr>
<td>12</td>
<td>286</td>
</tr>
<tr>
<td>9</td>
<td>400</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
</tr>
</tbody>
</table>

If the monitor’s resolution is 1600 x 1200, then its diagonal size would need to be:
- 21”
- 18”
- 14”
- 7”
- 5”
- 3”

---

**Monitors: Additive Colors**

[Diagram showing additive colors and their pixel representation]
Additive Color (RGB)

OpenGL:

glColor3f( r, g, b );

0. ≤ r, g, b ≤ 1.

Plasma Displays use Additive Color

- Gas cell
- Phosphor
- Grid of electrodes

http://electronics.howstuffworks.com
LCD Displays use Additive Color

- Grid of electrodes
- Color filters

http://electronics.howstuffworks.com

Hue-Saturation-Value (HSV):
For many vis applications, a simpler way to specify additive color

float hsv[3], rgb[3];
HsvRgb( hsv, rgb );
glColor3fv( rgb );

0. ≤ s, v, r, g, b ≤ 1.
0. ≤ h ≤ 360.

The HsvRgb function is on the web site
Home Depot uses a form of HSV :-)

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

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

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

Blue: 380 nm  Green: 520 nm  Red: 780 nm

For many vis applications, a simpler way to specify additive color

Hue-Saturation-Value (HSV):
Hue-Saturation-Value:
The OSU ColorPicker Program

ParaView Allows You to Pick Among Several Preset Color Ranges
ParaView Allows You to Sculpt Your Own Color Range

OpenDX Allows you to Sculpt the Transfer Function in HSV
A good way to explore discrete color spaces

Type of data

Color schemes

Ways of restricting the color schemes

Number of discrete colors needed
Subtractive Colors (CMYK)

- R = M + Y
- G = C + Y
- B = C + M

R = M + Y
G = C + Y
B = C + M

Y
M
C
G
B

Subtractive Color (CMYK)
Color Printing

- Uses subtractive colors
- Uses 3 (CMY) or 4 (CMYK) passes
- CMYK printers have a better-looking black
- There is a considerable variation in color gamut between products

How Do Color Separations Work in Color Printing?

Getting the CMYK Colors

CIE Chromaticity Diagram
CIE Chromaticity Diagram

- **White Point**
- **520 nm**
- **780 nm**
- **380 nm**

Points:
- **C**: the color
- **D**: the dominant wavelength
- **C'**: the complementary color

Color Gamut for a Workstation Monitor

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

- Color CRT
- Projected Color Slides
- Slide White
- White Point
- Eye

Color Gamut for a Monitor and Color Printer

- Color CRT
- Color Paper Hardcopy
- Eye
The Perceptually Uniform L-a-b Color Space

White Point

520 nm

780 nm

380 nm

OSU Logo

Color Meters Are Able to Measure L-a-b Coordinates
Some Good Rules of Thumb
When Using Color for Scientific Visualization

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 $\Delta$ Luminance
• Using this also helps if someone makes a grayscale 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

\[ Y = 0.30 \times \text{Red} + 0.59 \times \text{Green} + 0.11 \times \text{Blue} \]
### Luminance Table

<table>
<thead>
<tr>
<th></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

(I use a ΔL* of about 0.40)

<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>
<th>Orange</th>
<th>Yellow</th>
</tr>
</thead>
<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>
<td>0.41</td>
<td>0.60</td>
<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>
<td>0.70</td>
<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>
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<td>Cyan</td>
<td>0.70</td>
<td>0.30</td>
<td>0.40</td>
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<td>0.20</td>
<td>0.29</td>
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<td>0.19</td>
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<td>Magenta</td>
<td>0.41</td>
<td>0.59</td>
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<td>0.30</td>
<td>0.29</td>
<td>0.00</td>
<td>0.19</td>
<td>0.48</td>
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<tr>
<td>Orange</td>
<td>0.60</td>
<td>0.41</td>
<td>0.30</td>
<td>0.01</td>
<td>0.49</td>
<td>0.11</td>
<td>0.19</td>
<td>0.00</td>
<td>0.30</td>
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<tr>
<td>Yellow</td>
<td>0.89</td>
<td>0.11</td>
<td>0.59</td>
<td>0.30</td>
<td>0.78</td>
<td>0.19</td>
<td>0.48</td>
<td>0.30</td>
<td>0.00</td>
</tr>
</tbody>
</table>
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>
<th>White:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop</td>
<td>On</td>
<td>Cool</td>
<td>Neutral</td>
</tr>
<tr>
<td>On</td>
<td>Plants</td>
<td>Safe</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Off</td>
<td>Carbon</td>
<td>Deep</td>
<td></td>
</tr>
<tr>
<td>Dangerous</td>
<td>Moving</td>
<td>Nitrogen</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>Money</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High stress</td>
<td>Money</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow</td>
<td>Money loss</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Visualization, we Use the Concept of a Transfer Function to set Color and Opacity as a Function of Scalar Value

![Graph showing the relationship between scalar value and color](Image)
Use the Right Transfer Function Color Scale to Represent a Range of Scalar Values

- Gray scale
- Intensity Interpolation
- Saturation interpolation
- Two-color interpolation
- Rainbow scale
- Heated object interpolation
- Blue-White-Red

Gray Scale

E.g., x-rays
Intensity and Saturation Color Scales

E.g., data uncertainty

Two-Color Interpolation

E.g., geography
Rainbow Color Scale

Implementation:
$240^\circ \rightarrow 120^\circ \rightarrow 0^\circ$

Heated Object Color Scale

Implementation: add one color component at a time

R+G+B
Blue-White-Red Color Scale

E.g., molecules

Color Scale Contours
A Gallery of Color Scales

Something Different:
A Gallery of Add-One-Component-at-a-Time Color Scales

- R+G+B
- R+B+G
- G+R+B
- G+B+R
- B+R+G
- B+G+R
Something Different – Adding Black Beyond Blue

Visualization by Justin Finn

Something Really Different – The Haxby Color Scale
But, Here’s What’s Really Important:

Given any 2 colors, make it *intuitively obvious* which represents “higher” and which represents “lower”
What in the World was *The Oregonian* Thinking When They Chose This Color Scale?

Source: *The Oregonian*, January 11, 2006

 shouldn't lush-green colors represent wet and sand-colors represent dry?

This is Better …

Source: *The Oregonian*, October 31, 2006
And, one more

Much of the total dynamic range of the color scale is used up in the first small percent of the animation, leaving little for the rest of the animation

Source:
The Oregonian, February 21, 2010
Oregon State
University
Computer Graphics

mjb – March 15, 2019
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 • • •
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”

http://xkcd.com
So, What’s Up with the “Blue Dress” Debate?

It’s part of the Color Constancy effect.

If you see this color, but you expect that the dress is currently in a shadow, you “know” that it must really be this color.

If you see this color, but you expect the dress is currently in bright light, you “know” that it must really be this color.
Beware of Mach Banding

Actual Intensity

Perceived Intensity

Oregon State University
Computer Graphics
Beware of Mach Banding

Think of the Mach Banding problem as being similar to trying to round second base at a 90° angle.
The Ability to Discriminate Colors
Changes with the Size of the Colored Area

The Ability to Discriminate Colors
Changes with the Ambient Light
The Ability to Discriminate Colors Changes with the Age of the Viewer

Be Aware of Color Vision Deficiencies (CVD)

- In general, there is no such thing as total “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

Resources for designing color schemes for people with color recognition deficiencies:

http://colorbrewer2.org
http://colororacle.org/usage.html
http://mkweb.bcgsc.ca/colorblind/
Why are more men affected by CVD than women?

It's because the red-green CVD defect is carried on the X Chromosome

http://www.bio.miami.edu/~cmallery/150/mendel/c7.15.X.Y.jpg

A woman with the defective gene on one X chromosome probably has a dominant non-defective gene on the other. A man with a defect gene on his one X chromosome has no other gene to “fix” it.

Be Aware of CVD:
Code Information Redundantly

Four score and seven years ago, our forefathers brought forth upon this continent a new nation...

Four score and seven years ago, our forefathers brought forth upon this continent a new nation...

Four score and seven years ago, our forefathers brought forth upon this continent a new nation...
Be Aware of CVD:
Code Information Redundantly: Color + …

- Different fonts
- Symbols
- Fill pattern
- Outline pattern
- Outline thickness

This also helps if someone makes a grayscale photocopy of your color hardcopy

Use a Black or White Line as the Boundary Between Colored Regions
Do Not Display Fast-moving or High-detail Items in Color, Especially Blue

Watch the Use of Saturated Reds and Blues Together

Reds and Blues are on opposite ends of the color spectrum. It is hard for your eyes to focus on both.
Be Aware of the Differences Between Color Gamuts –

Adapt by Deciding What is Most Important for Your Visualization

Color Gamut for a Monitor and a Color Printer
Color-Preserving vs. Contrast-Preserving Gamut Mappings

Monitor colors to be printed

White Point

Beware of Gratuitous Color Pollution

Just because you have millions of colors to choose from,

doesn’t mean you must use them all •••
Beware of Lots of Other Stuff
Good Color and Perception References