“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. \textit{Above all, do no harm.}”

-- Edward Tufte
What’s Wrong with this Color Scale?

Source:
Scientific American, June 2000
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 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
A person with 20/20 vision has a visual acuity of:
1 arc-minute = 1/60°

$$\Theta = \frac{1}{60} \degree = 0.00029 \text{R}$$

$$\text{Density} = \frac{1}{D\Theta}$$

<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
Additive Color (RGB)

OpenGL:

```
COLOR3f( 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 );
gColor3fv( rgb );
```

The HsvRgb function is in your sample code

0. ≤ s, v, r, g, b ≤ 1.
0. ≤ h ≤ 360.
Home Depot uses a form of HSV  :-)
Hue-Saturation-Value (HSV):
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

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

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

\[ Hue = 240. - 240. \cdot \frac{S - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \]
Hue-Saturation-Value:
The OSU ColorPicker Program
The OpenDX Visualization Software Allows you to Sculpt the Transfer Function in HSV
Subtractive Colors (CMYK)
Subtractive Color (CMYK)

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

C

M

G

R

mjb – March 3, 2015
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

Wax

Toner

Toner

Sheets
CIE Chromaticity Diagram

520 nm

780 nm

380 nm

White Point

White Point
C = the color
D = the dominant wavelength
C' = the complementary color
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

Eye

White Point

Oregon State University
Computer Graphics

mjb – March 3, 2015
Color Gamut for a Monitor and Color Printer

Color CRT

Color Paper

Hardcopy

Eye

0.00 0.20 0.40 0.60 0.80
x

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90
y
The Perceptually Uniform L-a-b Color Space

520 nm

White Point

780 nm

OSU Logo

380 nm
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>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

(I use a $\Delta L^*$ 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>
</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>
<td>0.11</td>
<td>0.19</td>
</tr>
<tr>
<td>Magenta</td>
<td>0.41</td>
<td>0.59</td>
<td>0.11</td>
<td>0.18</td>
<td>0.30</td>
<td>0.29</td>
<td>0.00</td>
<td>0.19</td>
<td>0.48</td>
</tr>
<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>
</tr>
<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
<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 loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Money loss</td>
<td></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
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
Intensity and Saturation Color Scales
Two-Color Interpolation
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
Color Scale Contours
A Gallery of Color Scales
Something Different:
A Gallery of Add-One-Component-at-a-Time Color Scales
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?

Mapping a heck of a lot of rain

This National Weather Service map shows rainfall during the last 14 days ending at 4 a.m. Tuesday in Oregon and Southwest Washington. Some areas on the Oregon Coast received more than 20 inches of rain.

Source: *The Oregonian*, January 11, 2006

Maps from throughout the U.S. can be viewed at: www.srh.noaa.gov/rfcshare/precip_analysis_new.php

Shouldn’t lush-green colors represent wet and sand-colors represent dry?
This is Better …

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

Source:
The Oregonian, February 21, 2010
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
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 • • •
Color Rules

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”
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.
Afterimages
Afterimages
Beware of Mach Banding
Beware of Mach Banding

Perceived Intensity

Actual Intensity
Beware of Mach Banding
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)

- 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
Why are more men affected by CVD than women?

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

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.
<table>
<thead>
<tr>
<th>Four score and seven years ago, our forefathers brought forth upon this continent a new nation...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four score and seven years ago, our forefathers brought forth upon this continent a new nation...</td>
</tr>
<tr>
<td>Four score and seven years ago, our forefathers brought forth upon this continent a new nation...</td>
</tr>
</tbody>
</table>
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 CRT

Color Paper

Hardcopy

Eye

x

y

0.00 0.20 0.40 0.60 0.80

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90

Oregon State University
Computer Graphics

mjb – March 3, 2015
Color-Preserving vs. Contrast-Preserving Gamut Mappings

Monitor colors to be printed

White Point

1 → 3
2 → 3 ?
2 → 4 ?
Some Basic Rules for Using NTSC (Analog) Video

or, Why I’m So Glad We Are in the Twilight of Analog TV…
Understand the Limitations of going from Monitors to NTSC Video

- Use less saturated colors due to color gamut considerations
- Expect an effective resolution of (at best) ~640x480
- Do not use single-pixel thick lines
- Stay away from the edges of the screen
- Some colors have better video resolution than others
### NTSC Cycles-of-Encoding per Scanline

<table>
<thead>
<tr>
<th>What:</th>
<th>Cycles/Scanline:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>267</td>
</tr>
<tr>
<td>Orange-Blue</td>
<td>96</td>
</tr>
<tr>
<td>Purple-Green</td>
<td>35</td>
</tr>
</tbody>
</table>
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


