“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?"

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?

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

Sensors in Your Retina
Sidebar: How Many Pixels Do You Need?

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

Viewing Distance (inches) | Required Pixel Density (ppi)
--------------------------|---------------------
36                        | 95
31                        | 111
24                        | 143
12                        | 286
9                         | 400
6                         | 600

Density = \( \frac{1}{60°} = 0.00029 R \)
Additive Color (RGB)

\[ R = r, \quad G = g, \quad B = b \]

OpenGL:

\[ \text{glColor3f}( r, g, b ); \]

0. \leq r, g, b \leq 1.

Plasma Displays use Additive Color

- Gas cell
- Phosphor
- Grid of electrodes

http://electronics.howstuffworks.com

Hue-Saturation-Value (HSV):

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

\[ \text{Hue} \quad \text{Saturation} \quad \text{Value} \]

\[ \text{float hsv[3], rgb[3]; HsvRgb( hsv, rgb ); glColor3fv( rgb );} \]

0. \leq s, v, r, g, b \leq 1.

0. \leq h \leq 360.

Home Depot uses a form of HSV :-)

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

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

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

Sheets

CIE Chromaticity Diagram

\[ 0.00 \quad 0.10 \quad 0.20 \quad 0.30 \quad 0.40 \]

\[ 0.00 \quad 0.20 \quad 0.40 \quad 0.60 \quad 0.80 \]

White Point

520 nm

780 nm

Color Gamut for a Workstation Monitor

Color CRT

White Point

Eye

Monitor White
The Perceptually Uniform L-a-b Color Space

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 ∆ 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

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Constrast Table

(I use a \(\Delta L^*\) of about 0.40)

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II-7
Do Not Attempt to Fight Pre-Established Color Meanings

Pre-Established Color Meanings

- **Red:**
  - Stop
  - On
  - Off
  - Dangerous
  - Hot
  - High stress
  - Oxygen
  - Shallow
  - Money loss

- **Green:**
  - On
  - Plants
  - Carbon
  - Moving
  - Money

- **Blue:**
  - Cool
  - Safe
  - Deep
  - Nitrogen

- **White:**
  - Neutral
  - Hydrogen

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

- 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° → 120° → 0°

Heated Object Color Scale

Implementation: add one color component at a time

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

- R+G+B
- R+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”

Obvious:

Not obvious:

What in the World was The Oregonian Thinking When They Chose This Color Scale?

Source: The Oregonian, January 11, 2006

This is Better …

Source: The Oregonian, October 31, 2006

Shouldn’t lush-green colors represent wet and sand-colors represent dry?
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”

mjb – March 3, 2015
Oregon State University
Computer Graphics

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

Beware of Mach Banding

Perceived Intensity

Actual Intensity

Beware of Mach Banding

Perceived Intensity

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

Be Aware of CVD:
Code Information Redundantly:
- 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
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

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