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

But, are you equally-sensitive to all wavelengths?
Sidebar: How Many Pixels Do You Need?

A person with 20/20 vision has a visual acuity of:

\[ \theta = \frac{1}{60} \text{°} \]

Viewing Distance (inches) | Required Pixel Density (ppi)
--- | ---
23" | 95
18" | 111
14" | 143
7" | 286
3" | 400
3" | 600

Density = \frac{1}{2\theta}

Monitors: Additive Colors

Additive Color (RGB)

\[ R = Y + B \]
\[ M = R + B \]
\[ W = R + G + B \]
\[ Y = R + G \]

OpenGL: `glColor3f( r, g, b );`

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

Yes, Our Vision System Really Does Mix Red and Green Together to Make Yellow!

Color Combinations

Here’s a cool website that shows a lot of different color combinations:


Plasma Displays and LED Displays Emit Color

- Gas cell
- Phosphor
- Grid of electrodes

http://electronics.howstuffworks.com
LCD Displays “Gate” Color

- Grid of electrodes
- Color filters

http://electronics.howstuffworks.com

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

- Hue
- Saturation
- Value

Black
White

float hsv[3], rgb[3];
hsv[0] = something between 0. and 360.
HsvRgb( hsv, rgb );
glColor3fv( rgb );

Saturation

White

0º

240º

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

Hue-Saturation-Value: The OSU ColorPicker Program

ParaView Allows You to Pick Among Several Preset Color Ranges

Home Depot uses a form of HSV :-)

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 using the Rainbow Color Scale

Hue = 240. √ (S − S_min) / S_max − S_min

ParaView Allows You to Pick Among Several Preset Color Ranges

Red, Green, Blue

Hue, Saturation, Value

OSU ColorPicker Program

Preset Color Ranges
- Dark
- Light
- Black
- White
- Blue
- Red
- Green
- Yellow

Preset Color Ranges
- Dark
- Light
- Black
- White
- Blue
- Red
- Green
- Yellow

Preset Color Ranges
- Dark
- Light
- Black
- White
- Blue
- Red
- Green
- Yellow

Preset Color Ranges
- Dark
- Light
- Black
- White
- Blue
- Red
- Green
- Yellow

Preset Color Ranges
- Dark
- Light
- Black
- White
- Blue
- Red
- Green
- Yellow
ParaView Allows You to Sculpt Your Own Color Range

OpenDX Allows you to Sculpt the Transfer Function in HSV

http://colorbrewer2.org

A good way to explore discrete color spaces

Subtractive Colors (CMYK)

Subtractive Colors (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

You See Lots of Color Printing Tests Like This!

CIE Chromaticity Diagram

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

Color Gamut for a Workstation Monitor

- Eye
- Color CRT
- Monitor White
- White Point

Color Gamut for a Monitor and Color Slides

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

The Perceptually Uniform L-a-b Color Space

Color Meters Are Able to Measure L-a-b Coordinates

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 grayscale photocopy of your color hardcopy

Color Alone Doesn’t Cut It!

Luminance Contrast is Crucial!

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

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>
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<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)

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 • • •
The Ability to Discriminate Colors Changes with Surrounding Color: "Simultaneous Contrast"
So, What’s Up with the “Blue Dress” Debate?

It’s all part of the Color Constancy effect.

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

If you see this color, but you think that the dress is currently in bright light, you “know” that it must really be this color.

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Afterimages

Beware of Mach Banding

Actual Intensity

Perceived Intensity

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.

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://coloradvice.org/usages.html
- http://mkweb.berkeley.edu/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

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

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.

Beware of Lots of Other Stuff

Put your computer to sleep because it’s not doing anything!
Good Color and Perception References