Your Intensity/Color Sensors

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:
1 arc-minute = 1/60°

\[
\Theta = \frac{1}{60°} = 0.00029^R
\]

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:

```c
glColor3f( r, g, b );
```

0. ≤ r, g, b ≤ 1.
Yes, Our Vision System Really Does Mush Red and Green Together to Make Yellow!
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

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

0. ≤ s, v, r, g, b ≤ 1.
0. ≤ h ≤ 360.

Marching around the Hue color wheel is a nice way to get a range of colors

The HsvRgb( ) function is in your sample code
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

$$Hue = 240 - 240 \cdot \frac{S - S_{min}}{S_{max} - S_{min}}$$
Hue-Saturation-Value: The OSU ColorPicker Program
ParaView Allows You to Pick Among Several Preset Color Ranges

<table>
<thead>
<tr>
<th>Presets</th>
<th>Presets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool to Warm</td>
<td>Cool to Warm (Extended)</td>
</tr>
<tr>
<td>Black-Body Radiation</td>
<td>X Ray</td>
</tr>
<tr>
<td>Inferno (matplotlib)</td>
<td>Black, Blue and White</td>
</tr>
<tr>
<td>Blue Orange (divergent)</td>
<td>Viridis (matplotlib)</td>
</tr>
<tr>
<td>Gray and Red</td>
<td>Linear Green (Gr41)</td>
</tr>
<tr>
<td>Cold and Hot</td>
<td>Blue - Green - Orange</td>
</tr>
<tr>
<td>Rainbow Desaturated</td>
<td>Yellow - Gray - Blue</td>
</tr>
<tr>
<td>Rainbow Uniform</td>
<td>jet</td>
</tr>
</tbody>
</table>

Tip: <click> to select, <double-click> to apply a preset.
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

http://colorbrewer2.org

Number of discrete colors needed

Type of data

Color schemes

Ways of restricting the color schemes
(the colorblind safe option is especially important!)

A good way to explore discrete color spaces
Subtractive Colors (CMYK)

- **R** = Red
- **G** = Green
- **B** = Blue
- **W** = White
- **C** = Cyan
- **M** = Magenta
- **Y** = Yellow
- **K** = Black
Subtractive Colors (CMYK)

\[
\begin{align*}
R &= M + Y \\
G &= C + Y \\
Y &= C \\
M &= B \\
B &= C + M \\
K &= C + M + Y
\end{align*}
\]
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
The CYM Cube

How the Cube is setup:

How it looks when you sight through two faces:
CIE Chromaticity Diagram

White Point

520 nm

380 nm

780 nm
CIE Chromaticity Diagram

White Point

520 nm

380 nm

780 nm

C = the color
D = the dominant wavelength
C’ = the complementary color
Color Gamut for a Workstation Monitor

- Color CRT
- Monitor White
- White Point
- Eye

Graph showing the color gamut for a workstation monitor, with axes labeled x and y, and points indicating the color CRT, monitor white, and white point.
Color Gamut for a Monitor and Color Slides

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

The diagram illustrates the color gamut for a monitor and color slides, comparing the color spaces of a CRT, projected color slides, and the human eye. The graph shows the color coordinates on an xy plane with various white points marked for each type of display.
Color Gamut for a Monitor and Color Printer

![Color Gamut Diagram]

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

520 nm

White Point

380 nm

780 nm

OSU Logo
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!

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!
TUESDAY
MARCH 29
3-4 PM

RSVP to:
http://oregonstate.qualtrics.com/jfe/form/SV_cGCds52191FXirR
Or call: 541.737.0664
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>
</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>
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”
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.
Afterimages
Beware of Mach Banding
Beware of Mach Banding

Actual Intensity

Perceived 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.
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

An XX with the defective gene on one X chromosome probably has a dominant non-defective gene on the other. An XY with a defective gene on one X chromosome has no other gene to “fix” it.
Four score and seven years ago, our fathers brought forth upon this continent a new nation...

Be Aware of CVD: Code Information Redundantly
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.
Beware of Lots of Other Stuff
Good Color and Perception References


