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°

<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>

Monitors: Additive Colors

Additive Color (RGB)

OpenGL: glColor3f( r, g, b );
0 ≤ r, g, b ≤ 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
**Computer Graphics**

**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-

Value-

Black

White

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

Saturation

240º

120º

0º

240º

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

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

**Home Depot uses a form of HSV :-)**

**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

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

---

**The CYM Cube**

How the Cube is setup:

How it looks when you sight through two faces:

---

**CIE Chromaticity Diagram**

- 520 nm
- 780 nm
- 380 nm

- White Point

---

**CIE Chromaticity Diagram**

- 520 nm
- 780 nm
- 380 nm

- 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

---

**Color Gamut for a Monitor and Color Slides**

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

Eye

Color CRT

Color Paper

Hardcopy

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

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>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>White</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Red</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Green</td>
<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Blue</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.00</td>
<td>0.50</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Magenta</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Orange</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Yellow</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Contrast Table**

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

<table>
<thead>
<tr>
<th>Color</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>0.09</td>
<td>0.30</td>
<td>0.59</td>
<td>0.41</td>
<td>0.11</td>
</tr>
<tr>
<td>Red</td>
<td>0.35</td>
<td>0.70</td>
<td>0.00</td>
<td>0.20</td>
<td>0.19</td>
<td>0.40</td>
<td>0.11</td>
<td>0.16</td>
<td>0.01</td>
</tr>
<tr>
<td>Green</td>
<td>0.59</td>
<td>0.41</td>
<td>0.25</td>
<td>0.00</td>
<td>0.40</td>
<td>0.11</td>
<td>0.16</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>0.50</td>
<td>0.30</td>
<td>0.40</td>
<td>0.13</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.76</td>
<td>0.30</td>
<td>0.11</td>
<td>0.00</td>
<td>0.20</td>
<td>0.50</td>
<td>0.11</td>
<td>0.30</td>
<td>0.13</td>
</tr>
<tr>
<td>Magenta</td>
<td>0.41</td>
<td>0.59</td>
<td>0.11</td>
<td>0.18</td>
<td>0.20</td>
<td>0.00</td>
<td>0.50</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>Orange</td>
<td>0.89</td>
<td>0.61</td>
<td>0.50</td>
<td>0.00</td>
<td>0.11</td>
<td>0.19</td>
<td>0.00</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Yellow</td>
<td>0.30</td>
<td>0.11</td>
<td>0.30</td>
<td>0.18</td>
<td>0.10</td>
<td>0.40</td>
<td>0.30</td>
<td>0.04</td>
<td>0.40</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"
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

Actual Intensity

Perceived Intensity

Perceived Intensity

Actual Intensity
Be Aware of Mach Banding

Think of the Mach Banding problem as being similar to trying to round second base at a 90º 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

Be Aware of CVD: Code Information Redundantly

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

Code Information Redundantly: Color + …

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

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

[Pattern of squares]

[Pattern of abstract shapes]

[Pattern of abstract shapes]

[Pattern of abstract shapes]
Good Color and Perception References