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:

\[ \theta = \frac{1}{60} \text{°} \]

<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>

\[ \text{Density} = \frac{1}{\theta} \]

Monitors: Additive Colors

Additive Color (RGB)

\[
\begin{align*}
\text{R} & = \text{Y} + \text{G} + \text{B} \\
\text{G} & = \text{R} + \text{G} + \text{B} \\
\text{B} & = \text{G} + \text{B} \\
\text{M} & = \text{R} + \text{B} \\
\text{C} & = \text{G} + \text{B} \\
\end{align*}
\]

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

0 ≤ r, g, b ≤ 1.

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 is HSV. The HSV model uses three components:

- **Hue (H)**: The color component, ranging from 0 to 360 degrees.
- **Saturation (S)**: The intensity of the color, ranging from 0 to 1.
- **Value (V)**: The brightness of the color, ranging from 0 to 1.

The HsvRgb() function is in your sample code:

```c
float hsv[3], rgb[3];
HsvRgb(hsv, rgb);
glColor3fv(rgb);
```

The 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: 480 nm
- Green: 520 nm
- Red: 780 nm

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

```c
Hue = 240.0 - 240.0 \times \frac{S - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}}
```

ParaView Allows You to Pick Among Several Preset Color Ranges.
OpenDX Allows you to Sculpt the Transfer Function in HSV

http://colorbrewer2.org

A good way to explore discrete color spaces

Subtractive Colors (CMYK)

Y
M
C

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

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

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

Color Gamut for a Workstation Monitor

Color Gamut for a Monitor and Color Slides

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!

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

 brightly publicizes its event.

RISE to:
http://brightlypublicizes.net/
Or call 541.737.5664
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>0.0</td>
</tr>
<tr>
<td>White</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Red</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Green</td>
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<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Blue</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Cyan</td>
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<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Magenta</td>
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<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Orange</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Yellow</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Contrast Table

I use a \( \Delta L^* \) 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.
Afterimages

Beware 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

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 fathers brought forth upon this continent a new nation...

Be Aware of CVD: Code Information Redundantly

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

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

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

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
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