Color in Computer Graphics

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°

\[ \Theta = \frac{1}{60} \approx 0.0017^\circ \]

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

If the monitor's resolution is 1080 pixels, the diagonal size would need to be:

- 21”
- 18”
- 14”
- 7”
- 5”
- 3”

Monitors: Additive Colors
Additive Color (RGB)

\[ R = \text{Red} \]
\[ G = \text{Green} \]
\[ B = \text{Blue} \]
\[ Y = R + G \]
\[ M = R + B \]
\[ W = R + G + B \]
\[ C = G + B \]

OpenGL:

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

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

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

- Hue
- Saturation
- Value

Black
White

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

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

Home Depot uses a form of HSV :-)
Hue-Saturation-Value: The OSU ColorPicker Program

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
A good way to explore discrete color spaces

Number of discrete colors needed
Type of data
Color schemes
Ways of restricting the color schemes (the colorblind safe option is especially important!)

Subtractive Colors (CMYK)

R = Red
G = Green
B = Blue
W = White
C = Cyan
M = Magenta
Y = Yellow
K = Black

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

White Point

- 380 nm
- 520 nm
- 780 nm
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!
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>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>
</tr>
<tr>
<td>White</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Red</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Green</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Blue</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Magenta</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Orange</td>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Yellow</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Contrast Table

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

<table>
<thead>
<tr>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0.00</td>
<td>1.00</td>
<td>0.30</td>
</tr>
<tr>
<td>White</td>
<td>1.00</td>
<td>0.00</td>
<td>0.70</td>
</tr>
<tr>
<td>Red</td>
<td>0.30</td>
<td>0.70</td>
<td>0.00</td>
</tr>
<tr>
<td>Green</td>
<td>0.59</td>
<td>0.41</td>
<td>0.29</td>
</tr>
<tr>
<td>Blue</td>
<td>0.11</td>
<td>0.89</td>
<td>0.19</td>
</tr>
<tr>
<td>Cyan</td>
<td>0.78</td>
<td>0.30</td>
<td>0.40</td>
</tr>
<tr>
<td>Magenta</td>
<td>0.41</td>
<td>0.59</td>
<td>0.11</td>
</tr>
<tr>
<td>Orange</td>
<td>0.60</td>
<td>0.41</td>
<td>0.30</td>
</tr>
<tr>
<td>Yellow</td>
<td>0.89</td>
<td>0.11</td>
<td>0.59</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

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

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 defective gene on his one X chromosome has no other gene to "fix" it.

Be Aware of CVD:
Code Information Redundantly

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

This also helps if someone makes a grayscale photocopy of your color hardcopy.
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