Color Vision

CS 445/645: Intro Graphics 2005
Greg Humphreys (in loco Luebkis)
Why Study Vision at All?

We’re rendering for humans, after all

Efficient rendering

- Don’t compute things we can’t perceive

Effective rendering:

- Eliminate artifacts that change our perception

Just showing the right colors isn’t enough!

What does “right” mean, anyhow?
Human Vision

Eyes and brain

- We know lots about the eye
- But not much about the brain
Physiology of Vision

The center of the retina is a densely packed region called the fovea.

- Cones much denser here than the periphery

![Diagram showing the density of cones at the fovea compared to the periphery.]

1.35 mm from retina center

8 mm from retina center
Photoreceptor Density

![Graph showing photoreceptor density with peaks for rods and cones, with regions labeled for fovea, optic disk, nasal periphery, and temporal periphery.]

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The Electromagnetic Spectrum

<table>
<thead>
<tr>
<th></th>
<th>gamma</th>
<th>X</th>
<th>UV</th>
<th>IR</th>
<th>Radar</th>
<th>FM</th>
<th>TV</th>
<th>Short-wave</th>
<th>AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-14}</td>
<td>10^{-12}</td>
<td>10^{-10}</td>
<td>10^{-8}</td>
<td>10^{-6}</td>
<td>10^{-4}</td>
<td>10^{-2}</td>
<td>10^{0}</td>
<td>10^{2}</td>
<td>10^{4}</td>
</tr>
</tbody>
</table>

Wavelength (meters)

380 nm

780 nm

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Spectral Plot: CIE D6500
Just Noticeable Differences

\[ I + \Delta I \]

\[ I \]
Just Noticeable Differences

Contrast: \[
\frac{\Delta I}{I}
\]

For most intensities, contrast of .02 is just noticeable

We’re sensitive to contrasts, not intensity!
Noise: Original
Noise: 5%
Noise: 10%
Noise: 15%
Noise: 20%
Noise: 25%
Noise: 50%
Noise: 75%
Mach Bands

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Contrast

Inner gray boxes are the *same* intensity
Contrast
Classic Contrast Illusion

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.

Edward H. Adelson
Color Opponency
Color Channels in the Brain

Color transmitted along three channels:

- Achromatic: \( M+L \)
- Red/Green: \( M-L \)
- Blue/Yellow: \( S-M-L = S-A \)

This suggests a 3D color space...
The “Standard Observer”

What does it mean to call a color “green”? Is it some particular wavelength? How will two observers see this wavelength?

- Background illumination
- Target size
- Recent stimuli
- Fatigue
- Age of observer
- Nutrition (!)
- ...

Still, some objective standard would be useful...
CIE Color Matching Experiment

1. Choose three color primaries: “r”, “g”, “b”
2. Show a target color
3. Allow user to mix primaries from +1 to -1
   - Positive: mixed with other primaries
   - Negative: mixed with target
4. Record mixing levels for target spectrum
5. Average over many observers
RGB Matching Curves

![RGB Matching Curves Diagram]

- $\bar{b}(\lambda)$
- $\bar{r}(\lambda)$
- $\bar{g}(\lambda)$

Wavelength, $\lambda$ (nm)

Tristimulus values

435.8 nm

546.1 nm

700.0 nm

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Finite # of Primaries $\rightarrow$ Metamers

Wavelength, $\lambda$ (nm)

Radiant power

$P_{1\lambda}$

$P_{2\lambda}$
Negative Matching is Awkward...

Define hypothetical primaries $X, Y, Z$ with positive matching functions $x(\lambda), y(\lambda), z(\lambda)$

Then given a spectrum $C$, we can write:

$$C(\lambda) = \frac{\lambda}{X} x(\lambda) + \frac{\lambda}{Y} y(\lambda) + \frac{\lambda}{Z} z(\lambda)$$

$$\frac{\lambda}{X} = \int_{380}^{780} C(\lambda) x(\lambda) d\lambda$$

$$\frac{\lambda}{Y} = \int_{380}^{780} C(\lambda) y(\lambda) d\lambda$$

$$\frac{\lambda}{Z} = \int_{380}^{780} C(\lambda) z(\lambda) d\lambda$$
XYZ Matching Functions

![Graph showing XYZ matching functions for 2° and 10° observers. The graph plots wavelength (nm) on the x-axis and a scale ranging from 0 to 2 on the y-axis. The curves for \( \bar{X}(\lambda) \), \( \bar{Y}(\lambda) \), and \( \bar{Z}(\lambda) \) are depicted for both observers.](image)
A Problem With XYZ Colors

If we have two colors C1 and C2, and we add $\Delta C$ to both of them, the differences between the original and new colors will not be perceived to be equal.

This is due to the variation of the just noticeable differences in saturated hues.

XYZ space is not perceptually uniform.

$LUV$ space was created to address this problem.
Spectral Locus

Human perceptual gamut
Chromaticity

Normalize XYZ by dividing by luminance

Project onto $X+Y+Z=1$

\[
x = \frac{X}{X + Y + Z}
\]

\[
y = \frac{Y}{X + Y + Z}
\]

\[
z = \frac{Z}{X + Y + Z} = 1 - x - y
\]
Chromaticity Diagram

Converting from RGB to XYZ is a snap:

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
2.77 & 1.75 & 1.13 \\
1.00 & 4.59 & 0.06 \\
0.00 & 0.57 & 5.59
\end{bmatrix}
\begin{bmatrix}
R_x \\
G_x \\
B_x
\end{bmatrix}
\]

\[
x = \frac{X}{X + Y + Z}
\]

\[
y = \frac{Y}{X + Y + Z}
\]

Given \(x\), \(y\), and \(Y\), we can recover the XYZ coordinates.
Gamuts

CRT Gamut

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How Do Artists Specify Color?

Tints, shades, and tones of saturated (pure) pigments

- **Tint**: Adding white to a pure pigment, decreasing saturation
- **Shade**: Adding black to a pure pigment, decreasing lightness
- **Tone**: Adding white and black to a pure pigment
HSV Color Model

<table>
<thead>
<tr>
<th>H</th>
<th>S</th>
<th>V</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>Red</td>
</tr>
<tr>
<td>120</td>
<td>1.0</td>
<td>1.0</td>
<td>Green</td>
</tr>
<tr>
<td>240</td>
<td>1.0</td>
<td>1.0</td>
<td>Blue</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>1.0</td>
<td>White</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>0.5</td>
<td>Gray</td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>0.0</td>
<td>Black</td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.0</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

Figure 15.16&15.17 from H&B

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Intuitive Color Spaces

HSV is an intuitive color space, corresponding to our perceptual notions of tint, shade, and tone.

Hue (H) is the angle around the vertical axis.

Saturation (S) is a value from 0 to 1 indicating how far from the vertical axis the color lies.

Value (V) is the height of the “hexcone”.
The RGB Color Model

This is the model used in color CRT monitors
RGB are additive primaries
We can represent this space as a unit cube:
More on RGB

RGB color gamut: phosphor chromaticities

Make an image look identical across displays?

- Measure the chromaticities of the phosphors on both displays
- Convert the image to XYZ space
- Convert to the gamut of display #2

One single matrix multiply!
The CMY Color Model

Cyan, magenta, and yellow are the complements of red, green, and blue

- We can use them as filters to subtract from white
- The space is the same as RGB except the origin is white instead of black

This is useful for hardcopy devices like laser printers

- If you put cyan ink on the page, no red light is reflected

\[
\begin{bmatrix}
C \\
M \\
Y \\
\end{bmatrix} = \begin{bmatrix} 1 \\
1 \\
1 \\
\end{bmatrix} - \begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix}
\]
CMYK

Most printers actually add a fourth color, black.
Use black in place of equal amounts of C, M, and Y.

\[
\begin{align*}
K &= \min(C, M, Y) \\
C &= C - K \\
M &= M - K \\
Y &= Y - K
\end{align*}
\]

Why?
The YIQ Color Model

YIQ is used to encode television signals

Y is the CIE Y primary, not yellow

Y is luminance, so I and Q encode the chromaticity of the color

If we just throw I and Q away, we have black and white TV

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.275 & -0.321 \\
0.212 & -0.528 & 0.311
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

This assumes known chromaticities for your monitor

Why?