Color

Now, honey, you're missing a beautiful sunset out here!

'I'll count to 10, and then... PON!'" "Paw, how come old photographs are always black and white? Didn't they have color film back then?

Sure, they did. In fact, those old photographs are in color. It's just the world was black and white then.

YEP, THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.

THAT'S REALLY WEIRD. WELL, TRUTH IS STRANGER THAN FICTION.

Really?

But... but how could they have painted in color anyway? Wouldn't their paints have been shades of gray back then?

Of course, but they turned colors like everything else did in the '30s.

But then why are old paintings in color? If the world was black and white, wouldn't artists have painted it that way?

Not necessarily. A lot of great artists were insane.

The world is a complicated place, Hobbes. Whenever it seems that way, I take a nap in a tree and wait for dinner.

So why didn't old black and white photos turn color too? Because they were color pictures of black and white, remember?
Piazza

- https://www.youtube.com/watch?v=57dzaMaouXA
Color

Fredo Durand
MIT EECS 6.815/6.865
Motivations
RGB

• Can RGB record all colors?
Different RGBs

- Different coverage of space of all possible colors
RGB

- Can RGB record all colors?  
  - not without negative values!
- How does RGB relate to cone measurements?

\[
s_{\text{RGB}} = \begin{bmatrix}
0.3811, 0.5783, 0.0402 \\
0.1967, 0.7244, 0.0782 \\
0.0241, 0.1288, 0.8444
\end{bmatrix}
\]

  - Why not use cone measurements?
- Are distances meaningful in RGB?  
  - What is the limit of color discrimination?
Perceptually uniform

• In this diagram, 2D distance correspond to human ability to discriminate two colors
• RGB is deformed non linearly

http://upload.wikimedia.org/wikipedia/commons/2/21/Lab_color_space.png
RGB

• Can RGB record all colors?
  – not without negative values!
• How does RGB relate to cone measurements?
  \[ s\text{RGB} = \begin{pmatrix} 0.3811, 0.5783, 0.0402 \\ 0.1967, 0.7244, 0.0782 \\ 0.0241, 0.1288, 0.8444 \end{pmatrix} \]
  – Why not use cone measurements?
• Are distances meaningful in RGB?
  – What is the limit of color discrimination?
• Why are there so many RGBs?
Other color representations

- RGB
- YUV
- Cones LMS
- XYZ
- Lab
- ...

Thursday, September 26, 13
Color space

- Way to encode color as perceived by humans
  - as opposed to physical full-spectrum color
- Usually using 3 numbers (coordinates)
- For example, we have used RGB, YUV, and talked about cone responses

- Many many different color spaces
  - with ways to convert from one to another
Why different color spaces

• Different applications/goals
  – measure color
  – reproduce color
  – predict if colors are visible/different
  – adjust colors (saturation, contrast)

• Legacy
  – info was not available, refinement of definition

• Contradicting objectives and constraints
  – perceptual vs. radiometric
  – linear vs. non-linear
Questions?

Click

Uh oh...

The sky is a deep orange! Calvin's skin is a pale green! Yellow flowers are now blue!

Every color is the opposite of what it should be!

Calvin has been transferred to a color film negative!

His only hope is to be processed by a 1-hour photo finisher! Developer? I need developer!

Doggone it, Calvin! That's another picture ruined! Can't you look pleasant for 1/500th of a second?
How can we reproduce color?

- Good news: we don’t need to reproduce full spectra
  - 3 numbers suffice
- Bad news: reproducing all perceived colors is tough
  - Those 3 numbers might need to get negative
Metamers & color blindness
Cone spectral sensitivity

• Short, Medium and Long wavelength
• Response for a cone

\[ \int \lambda \text{stimulus}(\lambda) \times \text{response}(\lambda) \, d\lambda \]
Cone distribution

- From Fairchild’s book.

Figure 1-5. A representation of the retinal photoreceptor mosaic artificially colored to represent the relative proportions of L (red), M (green), and S (blue) cones in the human retina. Modeled after Williams et al. (1991).
References on different cones

- http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html
Response comparison

- Different wavelength, different intensity
- But different response for different cones
Color blindness

- Classical case: 1 type of cone is missing (e.g. red)
- Makes it impossible to distinguish some spectra
Color blindness – more general

- Dalton
- ~14%% male, 2% female
- Genetic
- Dichromate (2% male)
  - One type of cone missing
    - L (protanope), M (deuteranope), S (tritanope)
- Anomalous trichromat
  - Shifted sensitivity

Color blindness test
Color blindness test

- Maze in subtle intensity contrast
- Visible only to color blinds
- Color contrast overrides intensity otherwise
Questions?

• Links:
  – Vischeck shows you what an image looks like to someone who is colorblind.
  – http://www.vischeck.com/vischeck/
  – Daltonize, changes the red/green variation to brightness and blue/yellow variations.
  – http://www.vischeck.com/daltonize/
Metamers
Metamers

- We are all color blind!
- These two different spectra elicit the same cone responses
- Called metamers
Metamers

• Essentially, we have projected from an infinite-dimensional spectrum to a 3D space: we loose information
There is an infinity of metamers

Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]
Good news: color reproduction

- 3 primaries are (to a first order) enough to reproduce all colors

The dashed line represents daylight reflecting from sunflower petals, while the solid line represents the light emitted by a color CRT display adjusted to match the color of the sunflower.
Recap

• Spectrum: infinite number of values
• projected according to cone spectral response
  => 3 values
• metamers: spectra that induce the same response
  (physically different but look the same)

• Questions?
Metamerism & light source

• Metamers under a given light source
• May not be metamers under a different lamp
Illuminant metamerism example

• Two grey patches in Billmeyer & Saltzman’s book look the same under daylight but different under neon or halogen (& my camera agrees ;-)

Daylight  |  Scan (neon)  |  Hallogen
Bad consequence: cloth matching

- Clothes appear to match in store (e.g. under neon)
- Don’t match outdoor
Recap

• Spectrum is an infinity of numbers
• Projected to 3D cone-response space
  – for each cone, multiply per wavelength and integrate
  – a.k.a. dot product
• Metamerism: infinite-D points projected to the same 3D point
  (different spectrum, same perceived color)
  – affected by illuminant
  – enables color reproduction with only 3 primaries
Questions?

Meryon (a colorblind painter), *Le Vaisseau Fantôme*
Analysis & Synthesis

• Now let’s talk about technology
• We want to measure & reproduce color as seen by humans
• No need for full spectrum
• Only need to match up to metamerism
Analysis & Synthesis

• Focus on additive color synthesis
• We’ll use 3 primaries (e.g. red green and blue) to match all colors

What should those primaries be?
How do we tell the amount of each primary needed to reproduce a given target color?
Additive Synthesis - wrong way

• Take a given stimulus and the corresponding responses s, m, l (here 0.5, 0, 0)
Additive Synthesis - wrong way

- Use it to scale the cone spectra (here 0.5 * S)
- You don’t get the same cone response! (here 0.5, 0.1, 0.1)
What’s going on?

• The three cone responses are not orthogonal
• i.e. they overlap and “pollute” each other
Warning

Tricky thing with spectra & color:
• Spectrum for the stimulus / synthesis
  – Light, monitor, reflectance
• Response curve for receptor / analysis
  – Cones, camera, scanner

They are usually not the same

Because cone responses are not orthogonal
Questions?
CIE color matching
Standard color spaces

• We need a principled color space
• Many possible definition
  – Including cone response (LMS)
  – Unfortunately not really used, (because not known when colorimetry was invented)

• The good news is that color vision is linear and 3-dimensional, so any new color space based on color matching can be obtained using 3x3 matrix
  – But there are also non-linear color spaces (e.g. Hue Saturation Value, Lab)
Overview

• Most standard color space: CIE XYZ
• LMS and the various flavors of RGB are just linear transformations of the XYZ basis
  – 3x3 matrices
Why not measure cone sensitivity?

• Less directly measurable
  – electrode in photoreceptor?
  – not available when color spaces were defined

• Most directly available measurement:
  – notion of metamers & color matching
  – directly in terms of color reproduction: given an input color, how to reproduce it with 3 primary colors?

  – Commission Internationale de l’Eclairage (International Lighting Commission)
  – Circa 1920
CIE color matching

• Given an input color, how to reproduce it with 3 primary colors?
  – (Idea by Maxwell)
CIE color matching

• Primaries (synthesis) at 435.8, 546.1 and 700nm
  – Chosen for robust reproduction, good separation in red-green
  – Don’t worry, we’ll be able to convert it to any other set of primaries (Linear algebra to the rescue!)

• Resulting 3 numbers for each input wavelength are called tristimulus values
Applet

- [http://graphics.stanford.edu/courses/cs178-10/applets/columatching.html](http://graphics.stanford.edu/courses/cs178-10/applets/columatching.html)
Color Matching Problem

• Some colors cannot be produced using only positively weighted primaries
• Solution: add light on the other side!
CIE color matching

• Meaning of these curves: a monochromatic wavelength $\lambda$ can be reproduced with $b(\lambda)$ amount of the 435.8nm primary, $+g(\lambda)$ amount of the 546.1 primary, $+r(\lambda)$ amount of the 700 nm primary

• This fully specifies the color perceived by a human

• Careful: this is not your usual rgb
CIE color matching: what does it mean?

- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)
Relation to cone curves

• Project to the same subspace
  - b, g, and r are linear combinations of S, M and L
• Related by 3x3 matrix.
• Unfortunately unknown at that time. This would have made life a lot easier!

These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.
Recap

- Spectra: infinite dimensional
- Cones: 3 spectral responses
- Metamers: spectra that look the same (same projection onto cone responses)
- CIE measured color response:
  - chose 3 primaries
  - tristimulus curves to reproduce any wavelength

Questions?
How to build a measurement device?

• Idea:
  – Start with light sensor sensitive to all wavelength
  – Use three filters with spectra b, r, g
  – measure 3 numbers

• This is pretty much what the eyes do!
CIE’s problem

• Idea:
  – Start with light sensor sensitive to all wavelength
  – Use three filters with spectra b, r, g
  – measure 3 numbers

• But for those primaries, we need negative spectra
CIE’s problem

• Obvious solution: use cone response!
  – but unknown at the time
• => new set of tristimulus curves
  – linear combinations of b, g, r
  – pretty much add enough b and g until r is positive
CIE XYZ space

• The most standard color space
• Based on tristimulus curves
• Y corresponds to luminance/brightness
• Linear transform compared to RGB or LMS

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
= \begin{bmatrix}
0.8951 & 0.2664 & -0.1614 \\
-0.7502 & 1.7135 & 0.0367 \\
0.0389 & -0.0685 & 1.0296
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]
## XYZ to RGB & back


### sRGB to XYZ

<table>
<thead>
<tr>
<th>XYZ to sRGB</th>
<th>0.412424</th>
<th>0.212656</th>
<th>0.0193324</th>
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<tbody>
<tr>
<td>0.357579</td>
<td>0.715158</td>
<td>0.119193</td>
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<tr>
<td>0.180464</td>
<td>0.0721856</td>
<td>0.950444</td>
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</tbody>
</table>

### Adobe RGB to XYZ

<table>
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<tr>
<th>XYZ to Adobe RGB</th>
<th>0.576700</th>
<th>0.297361</th>
<th>0.0270328</th>
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<tr>
<td>0.185556</td>
<td>0.627355</td>
<td>0.0706879</td>
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<td>0.188212</td>
<td>0.0752847</td>
<td>0.991248</td>
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### NTSC RGB to XYZ

<table>
<thead>
<tr>
<th>XYZ to NTSC RGB</th>
<th>0.606734</th>
<th>0.298839</th>
<th>0.000000</th>
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<tbody>
<tr>
<td>0.173564</td>
<td>0.586811</td>
<td>0.0661196</td>
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<tr>
<td>0.200112</td>
<td>0.114350</td>
<td>1.11491</td>
<td></td>
</tr>
</tbody>
</table>
CIE XYZ space: QUESTIONS?

- The most standard color space
- Based on tristimulus curves
- Y corresponds to luminance/brightness
- Linear transform compared to RGB or LMS

\[
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\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]
Chromaticity diagram
Chromaticity diagrams: motivation

- 3D space are tough to visualize
- Chrominance is our notion of color, as opposed to brightness/luminance
- Recall that our eyes correct for multiplicative scale factors
  - discount light intensity
Chromaticity diagrams

- Project XYZ to 2D
- normalize against by $X + Y + Z$:

$$x = \frac{X}{X + Y + Z}; \quad y = \frac{Y}{X + Y + Z};$$

- equivalent to perspective projection to plane $X + Y + Z = 1$
**Applet**

- [http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html](http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html)
Questions?

- Chromaticity of crayons

**Color gamut**

- Given 3 primaries
- The realisable chromaticities lay in the triangle in xy chromaticity diagram
- Because we can only add light, no negative light
http://graphics.stanford.edu/courses/cs178-10/applets/gamutmapping.html
RGB limitations

- http://dba.med.sc.edu/price/irf/Adobe_tg/manage/images/gamuts.jpg
- http://www.petrvodnakphotography.com/Articles/ColorSpace.htm
Recap

• Metamers enable color reproduction
• CIE defined XYZ using color matching experiments
• Linear transform to/from RGB or LMS
• Chromaticity diagram: 2D version, remove luminance
• Lack of negative numbers makes life hard
Questions?

- Metamers enable color reproduction
- CIE defined XYZ using color matching experiments
- Linear transform to/from RGB or LMS
- Chromaticity diagram: 2D version, remove luminance
- Lack of negative numbers makes life hard
Fundamental problem, bis
Analysis, Synthesis

• Analysis:
  Dot product with 3 matching curves (spectra) gives 3 numbers (color coordinates)
  – e.g. LMS, CIE before positive, CIE after making positive

• Synthesis:
  3 primaries (spectra) are scaled by 3 numbers (color coordinates)
  – e.g. monochromatic primaries, C \( \text{tc.} \)}
Take home message

• Cone spectra are non-orthogonal
• Analysis spectrum (camera, eyes) cannot be the same as synthesis one (display)
• Impossible to encode all possible colors without something negative
  – CIE XYZ only needs positive coordinates, but would need primaries with negative light
  – RGB can use physical (non-negative) primaries, but needs negative coordinates for some colors
More color vision
Remember von Helmholtz

• Colors as relative responses (ratios)

- Violet
- Blue
- Green
- Yellow
- Orange
- Red

Short wavelength receptors
Medium wavelength receptors
Long wavelength receptors

Receptor Responses

Wavelengths (nm)

400 500 600 700

Wavelengths (nm)
Hering 1874: Opponent Colors

- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena
e.g. *Spanish Castle illusion (pset 1)*

- Duplicate layer
- Desaturate bottom layer (ctrl shift U)
- Switch to Lab color mode (don’t flatten)
- Select Lightness channel of 2nd layer
- Fill with 60% grey
- Select all channels and invert (ctrl I)
- Add a black dot in the center
- Potential plus: blur color version, increase saturation

*Spanish Castle illusion (pset 1)*

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*Spanish Castle illusion (pset 1)*

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**Dual Process Theory**

- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green


**Color opponents wiring**

- Sums for brightness
- Differences for color opponents
- At the end, it’s just a 3x3 matrix compared to LMS
Color reparameterization

• The input is LMS
• The output has a different parameterization:
  – Light-dark
  – Blue-yellow
  – Red-green
• A later stage may reparameterize:
  – Brightness or Luminance or Value
  – Hue
  – Saturation

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<table>
<thead>
<tr>
<th>PHYSICS</th>
<th>PSYCHOPHYSICS</th>
<th>PSYCHOLOGY</th>
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<tr>
<td><strong>Light Source</strong></td>
<td><strong>Source x Eye</strong></td>
<td><strong>Color Perception</strong></td>
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<td>Radiant energy</td>
<td>Luminous energy</td>
<td>Dazzling</td>
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<td>Spectral composition</td>
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<td>Brightness</td>
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<td>Aperture</td>
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<td>Illumination</td>
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<td><strong>Characteristics of Radiant Energy</strong></td>
<td><strong>Characteristics of Luminous Energy</strong></td>
<td><strong>Attributes of Color</strong></td>
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<td>Radiant flux</td>
<td>Luminous flux</td>
<td>Brightness</td>
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<td>Radiance</td>
<td>Luminance</td>
<td>Aperture</td>
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<td>Irradiance</td>
<td>Illuminance</td>
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<td>Radiant reflectance</td>
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<td>Radiant transmittance</td>
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<td>Chromaticity</td>
<td>Surface</td>
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<td><em>(Relative spectral composition, quality)</em></td>
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<td>Volume</td>
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<td>Radiant purity</td>
<td>Dominant wavelength (or complementary)</td>
<td>Attributes of modes of appearance:</td>
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<td>Purity</td>
<td>1. Brightness (or lightness)</td>
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<td>2. Hue</td>
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<td>3. Saturation</td>
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<td><img src="image" alt="CIE Illuminant C" /></td>
<td>11. Luster</td>
</tr>
</tbody>
</table>
Color spaces

• color opponent spaces:
  – luminance
  – red-green
  – blue-yellow

• YUV

\[
\begin{bmatrix}
Y' \\
U \\
V
\end{bmatrix} = \begin{bmatrix}
0.299 & 0.587 & 0.114 \\
-0.14713 & -0.28866 & 0.436 \\
0.615 & -0.51499 & -0.10001
\end{bmatrix} \begin{bmatrix}
R' \\
G' \\
B'
\end{bmatrix}
\]

• YcrCb

  – used a lot in image/video compression

\[
Y' = + (0.299 \cdot R'_D) + (0.587 \cdot G'_D) + (0.114 \cdot B'_D)
\]
\[
C_B = 128 - (0.168736 \cdot R'_D) - (0.331264 \cdot G'_D) + (0.5 \cdot B'_D)
\]
\[
C_R = 128 + (0.5 \cdot R'_D) - (0.418688 \cdot G'_D) - (0.081312 \cdot B'_D)
\]
Questions?

http://xkcd.com/964/
Limits of color vision
Limits of human vision

• Color sensitivity
  – Can we tell two colors are different?

• Spatial sensitivity
  – Is a pattern too fine?

  – Is contrast too low?
Perceptual color difference

- Ask subjects if two color patches are the same
- For a given color, draw the colors at the threshold of noticeable difference
- Ellipses in CIE XYZ
- measured by McAdam

Source: [Wyszecki and Stiles ’82]
Perceptual color difference

- In CIE-XYZ, the perceived distance between colors is not equal everywhere
- Same for all linear color spaces (RBG, LMS, etc.)
- We want a color space so that distance are meaningful

Source: [Wyszecki and Stiles ’82]
Perceptually Uniform Space: MacAdam

- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors.
- MacAdam ellipses (areas of unperceptible differences) become circles.
- Non-linear mapping, many solutions have been proposed.

Source: [Wyszecki and Stiles '82]
CIELAB (a.k.a. CIE L*a*b*)

- The reference perceptually uniform color space
- L: lightness
- a and b: color opponents
- Note the cubic roots

- $X_0$, $Y_0$, and $Z_0$ are used to color-balance: they’re the color of the reference white
  - more about white balance next time

Source: [Wyszecki and Stiles '82]
CIELAB (a.k.a. CIE L*a*b*)

- Euclidean distance between two color

\[ \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} \]

- correlates well with ability to discriminate these two colors
  - a human can tell the difference between two colors if their CIE L*a*b* distance is greater than 2
  - called “just noticeable difference”

Source: [Wyszecki and Stiles ’82]
“Well, that’s an interesting bit of trivia — I guess I do only dream in black and white.”
Recap: Color spaces

• LMS: cones
• RGB: displays, but many flavors
• CIE XYZ: color matching, the standard
• YUV, YCrCb: linear color opponents

• CIE Lab: perceptually uniform, color opponent, cubic root
(Non-)linearities

- Raw files are usually linear in sensor color space
- RGB is usually gamma encoded
  - gamma usually 2.2, but 1.8 for ProPhoto RGB
- Lab uses a cubic root
- Some people use log encoding
  - in particular for high-dynamic-range images
Spatial color vision
Contrast Sensitivity

• Sine Wave grating
• What contrast is necessary to make the grating visible?
• How does it change with spatial frequency
Contrast Sensitivity Function (CSF)

Figure 1-18. Spatial contrast sensitivity functions for luminance and chromatic contrast.
Photoshop demo

- Image > Mode > Lab color
- Go to channel panel, select Lightness
- Filter > Blur > Gaussian Blur, e.g. 4 pixel radius
  - very noticeable
- Undo, then select a & b channels
- Filter > Blur > Gaussian Blur, same radius
  - hardly visible effect

Original  Blur Lightness  Blur a & b
Questions?
Opponents and image compression

• JPG, MPG, television
• Color opponents instead of RGB
  – YCrCB, similar to YUV
• Compress color more than luminance
  – downsample by factor of two for jpeg
  – less bandwidth for TV
• Exploit contrast sensitivity function
  – Compress high frequencies more
JPEG Compression

• convert to YCbCr
  – half the resolution for Cr & Cb

• Perform Discrete Cosine Transform to work in frequency space
  – Local DCT, 8x8 pixel blocks

• Use CSF for quantization
  – more bits for frequencies with more sensitivity (medium)

• Other usual coding tricks
  – entropy coding, smart order of blocks
Example

- 800 x 533 image

Low quality JPEG (0 in Photoshop, 172 KB)

High quality JPEG (12 in Photoshop, 460 KB)
Questions?
Selected Bibliography

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by Stephen E. Palmer
760 pages (May 7, 1999)

**Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition**
by Roy S. Berns, Fred W. Billmeyer, Max Saltzman
304 pages 3 edition (March 31, 2000)

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by Margaret Livingstone, David H. Hubel
208 pages (May 2002)
Selected Bibliography

The Reproduction of Color
by R. W. G. Hunt
Fountain Press, 1995

Color Appearance Models
by Mark Fairchild
Addison Wesley, 1998
Questions?

VIII. Philipp Otto Runge, Colour Sphere, 1809, Hamburg Kunsthalle.
Why is green so important

- [http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html](http://hyperphysics.phy-astr.gsu.edu/hbase/vision/rodcone.html)
- CIE brightness
  - sum of 3 cones
- blue is out of focus
Check out the demo applets

- [http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html](http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html](http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/gamutmapping.html](http://graphics.stanford.edu/courses/cs178-10/applets/gamutmapping.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/gamma.html](http://graphics.stanford.edu/courses/cs178-10/applets/gamma.html)