Color

Computer Graphics
CMU 15-462/15-662
Why do we need to be able to talk precisely about color?
Starry Night, Van Gogh
What is color?
Light is EM Radiation; Color is Frequency

- Light is oscillating electric & magnetic field
- KEY IDEA: frequency determines color of light
- Q: What is the difference between frequency and wavelength?
Q: Why does your stove turn red when it heats up?
Heat generates light

- One of many ways light is produced:
- Maxwell: motion of charged particles creates EM field
- Thermodynamics: ...particles jiggle around!
- Hence, anything moving generates light
- In other words:
  - every object around you is producing color!
  - frequency determined by temperature
Most light is not visible!

- Frequencies visible by human eyes are called “visible spectrum”
- These frequencies what we normally think of as “color”
Natural light is a mixture of frequencies

- “White” light is really a mixture of all (visible) frequencies
- E.g., the light from our sun

![Spectrum of Solar Radiation (Earth)](image)
Additive vs. Subtractive Models of Light

- Spectrum we just saw for the sun “emission spectrum”
  - How much light is produced (by heat, fusion, etc.)
  - Useful for, e.g., characterizing color of a lightbulb

- Another useful description: “absorbtion spectrum”
  - How much light is absorbed (e.g., turned into heat)
  - Useful for, e.g., characterizing color of paint, ink, etc.
Emission Spectrum
Describes light intensity as a function of frequency

Below: spectrum of various common light sources:

Figure credit:
[Image credit: admesy]
Emission Spectrum—Example

Why so many different kinds of lightbulbs on the market?

“Quality” of light:

Incandescent:
- more sun-like
- power-hungry

CFL:
- “choppy” spectrum
+ power efficient
Absorption Spectrum

- Emission spectrum is intensity as a function of frequency
- Absorption spectrum is fraction absorbed as function of frequency

Q: What color is an object with this absorption spectrum?
This is the fundamental description of color: intensity or absorption as a function of frequency.

Everything else is merely a convenient approximation!
If you remember to use spectral description as a starting point, the issues surrounding color theory/practice will make a lot more sense!
If on the other hand you always think of color in terms of approximate digital encodings (RGB, CMYK) etc., there are certain phenomena you simply cannot explain/understand!
Interaction of emission and reflection

- Toy model for what happens when light gets reflected
  - $\nu$—frequency (Greek “nu”)
  - Light source has emission spectrum $f(\nu)$
  - Surface has reflection spectrum $g(\nu)$
  - Resulting intensity is the product $f(\nu)g(\nu)$
Color reproduction is hard!

- Color clearly starts to get complicated as we start combining emission and absorption/reflection (real-world challenge!)

(What color ink should we use to get the desired appearance?)
...And what about perception?

Q: What color is this dress?
How does electromagnetic radiation (with a given power distribution) end up being perceived by a human as a certain color?
The eye

Image credit: Georgia Retina (http://www.garetina.com/about-the-eye)
The eye (optics)

Image credit: Georgia Retina (http://www.garetina.com/about-the-eye)
Photosensor response (eye, camera, . . .)

- **Photosensor input:** light
  - Electromagnetic power distribution over wavelengths: $\Phi(\lambda)$

- **Photosensor output:** a “response” . . . a number
  - e.g., encoded in electrical signal

- **Spectral response function:** $f(\lambda)$
  - Sensitivity of sensor to light of a given wavelength
  - Greater $f(\lambda)$ corresponds to more efficient sensor (when $f(\lambda)$ is large, a small amount of light at wavelength $\lambda$ will trigger a large sensor response)

- **Total response of photosensor:**

$$R = \int_{\lambda} \Phi(\lambda) f(\lambda) d\lambda$$
The eye’s photoreceptor cells: rods & cones

- Rods are primary receptors under dark viewing conditions (scotopic conditions)
  - Approx. 120 million rods in human eye

- Cones are primary receptors under high-light viewing conditions (photopic conditions, e.g., daylight)
  - Approx. 6-7 million cones in the human eye
  - Each of the three types of cone feature a different spectral response. This will be critical to color vision (much more on this in the coming slides)
Density of rods and cones in the retina

- Highest density of cones is in fovea (best color vision at center of where human is looking)
- Note “blind spot” due to optic nerve
ACTIVITY: Rods vs. Cones

- Grab someone and try it at home!
  - Have them hold up colored markers in peripheral vision
  - All you have to do is say what color it is (easy!)
Spectral response of cones

Three types of cones: S, M, and L cones (corresponding to peak response at short, medium, and long wavelengths)

\[ S = \int_{\lambda} \Phi(\lambda) S(\lambda) d\lambda \]
\[ M = \int_{\lambda} \Phi(\lambda) M(\lambda) d\lambda \]
\[ L = \int_{\lambda} \Phi(\lambda) L(\lambda) d\lambda \]

Response functions for S, M, and L cones

Uneven distribution of cone types in eye
~64% of cones are L cones, ~32% M cones
Response of S,M,L cones to monochromatic light

Figure visualizes cone’s response to monochromatic light (light with energy in a single wavelength) as points in 3D space

(plots value of S, M, L response functions as a point in 3D space)
The human visual system

- Human eye does not directly measure the spectrum of incoming light - i.e., the brain does not receive “a spectrum” from the eye

- The eye measures three response values = (S, M, L). The result of integrating the incoming spectrum against response functions of S, M, L-cones

\[
\Phi(\lambda) = \int f(\lambda) d\lambda
\]

Eye
- Focuses light on retina
- Cones measure light (photopic case)

Brain
- Cone responses (S, M, L) carried along optic nerve
Q: Is it possible for two functions to integrate to the same value?
Metamers

- Metamers = two different spectra that integrate to the same (S,M,L) response!

- The fact that metameters exist is critical to color reproduction: we don’t have to reproduce the exact same spectrum that was present in a real world scene in order to reproduce the perceived color on a monitor (or piece of paper, or paint on a wall)

- …On the other hand, combination of light & paint could still cause trouble—different objects appearing “wrong” under different lighting conditions.
Example: Counterfeit Detection

- Many countries print currency, passports, etc., with special inks that yield different appearance under UV light:
Ok, so color can get pretty complicated!

How do we encode it in a simple(r) way?
Color Spaces and Color Models

- Many ways to specify a color
  - storage
  - convenience
- In general, specify a color from some color space using a color model
- Color space is like artist’s palette: full range of colors we can choose from
- Color model is the way a particular color in a color space is specified:
  - artist’s palette: “yellow ochre”
  - RGB color model: 204, 119, 34
Additive vs. Subtractive Color Models

- Just like we had emission & absorption spectra, we have additive and subtractive* color models
- Additive
  - Used for, e.g., combining colored lights
  - Prototypical example: RGB
- Subtractive
  - Used for, e.g., combining paint colors
  - Prototypical example: CMYK

*A better name than subtractive might be multiplicative, since we multiply to get the final color!
Let’s shed some light on this picture...
Other Common Color Models

- **HSV**
  - hue, saturation, value
  - more intuitive than RGB/CMYK

- **SML**—physiological model
  - corresponds to stimulus of cones
  - not practical for most color work

- **XYZ**—preceptually-driven model
  - Y captures luminance (intensity)
  - X,Z capture chromaticity (color)
  - related to, but different from, SML

- **Lab**—“perceptually uniform” modification of XYZ
CIE LAB color space

- Developed by the International Commission on Illumination (CIE) and widely used in printing, textiles, product design...
- L = lightness from 0 (black) to 100 (white)
- a = position on green (negative) to red (positive) axis
- b = position on blue (negative) to yellow (positive) axis
- Designed to be perceptually uniform, meaning that equal distances in the color space correspond to equal perceptual differences in color.
Practical Encoding of Color Values

- How do colors actually get encoded digitally?
- One common encoding (e.g., HTML): 8bpc hexadecimal values*:

  #1B1F8A

- What does this string mean? Common encoding of RGB.
- Want to store 8-bits per channel (red, green, blue), corresponding to 256 possible values
- Rather than use digits 0-9, use 0, 1,2,3,4,5,6,7,8,9,A,B,C,D,E,F
- Single character now encodes 16 values, two characters encode 16*16 = 256 values
- Q: Roughly what color is #ff6600?

*Upper vs. lowercase letters? Makes absolutely no difference!
Other Ways of Specifying Color?

- Other color specifications not based on continuous color space
- E.g., Pantone Matching System
  - industry standard (proprietary)
  - 1,114 colors
  - Combination of 13 base pigments
- And not to forget…
Why use different color models?

- **Convenience**
  - Is it easy for a user to choose the color they want?

- **Color compositing/processing**
  - Does it matter what color space we interpolate / blend in?

- **Efficiency of encoding**
  - E.g., use more of numerical range for perceptually significant colors
  - Compression!
Example: $Y'CbCr$ color model

- Common for modern digital video
- $Y' =$ luma: perceived luminance (same as $L^*$ in CIELAB)
- $Cb =$ blue-yellow deviation from gray
- $Cr =$ red-cyan deviation from gray
Original picture
Contents of CbCr color channels downsampled by a factor of 20 in each dimension (400x reduction in number of samples)
Full resolution sampling of luma ($Y'$)
Reconstructed result
(looks pretty good)
By the way, how might we reduce this artifact?
Why use different color models? (cont.)

- **Convenience**
  - Is it easy for a user to choose the color they want?

- **Efficiency of encoding**
  - E.g., use more of numerical range for perceptually significant colors
  - Do color images compress well?

- **Gamut**
  - Which colors can be expressed using a given model?
  - Very different for print vs. display
Which raises a very important question:

Which actual colors (i.e., spectra) do these values get mapped to?
CIE 1931* Color Space (different from CIE Lab)

- Standard “reference” color space
- Encompasses all colors visible by “most” human observers
  - associated color model (XYZ) captures perceptual effects
  - e.g., perception of color (“chromaticity”) changes w/ brightness (“luminosity”)
  - different from specifying direct simulation of cones (SML)

*CIE 1931 does not mean anything important: “created in 1931 by the Commission Internationale de l’Éclairage"
Chromaticity Diagrams

- Chromaticity is the intensity-independent component of a color
- Chromaticity diagram used to visualize extent of a color space

A display with primaries with chromacities $P_1$, $P_2$, $P_3$ can create colors that are combinations of these primaries (colors that fall within the triangle)
sRGB Color Space

- CIE 1934 captured all possible human-visible colors
- sRGB (roughly) subset of colors available on displays, printers, ...
- Nonlinear relationship between stored RGB values & intensity
  - Makes better use of limited set of numerical values
Color Acuity (MacAdam Ellipse)

- In addition to range of colors visible, one might be interested in how sensitive people are to changes in color.
- Each ellipse corresponds to a region of “just noticeable differences” of color (chromaticity).
- So, if you want to make two colors distinct, at bare minimum should avoid overlapping ellipses…
Nonstandard Color Vision

- Morphological differences in eye can cause people (and animals) to see different ranges of color (e.g., more/fewer cone types)
- Alternative chromaticity diagrams help visualize color gamut, useful for designing, e.g., widely-accessible interfaces
Color Conversion

- Given a color specified in one model/space (e.g., sRGB), try to find corresponding color in another model (e.g., CMYK)
- In a perfect world: want to match output spectrum
- Even matching perception of color would be terrific (metamers)
- In reality: may not always be possible!
  - Depends on the gamut of the output device
  - E.g., VR headset vs. inkjet printer
- Complicated task!
- Lots of standards & software
  - ICC Profiles
Gamma correction

Old CRT display:

1. Image contains value X
2. CRT display converts digital signal to an electron beam voltage $V(x)$ (linear relationship)
3. Electron beam voltage converted to light: (non-linear relationship)
   $$ Y \propto V^\gamma $$
   Where: $\gamma \approx 2.5$

So if pixels store $Y$, what will the display’s output look like?

Fix: pixels sent to display must store:
$$ Y^{1/2.5} = Y^{0.4} $$

(Doesn’t apply to modern LCD displays, whose luminance output is linearly proportional to input; DOES still apply to other devices, like sensors, etc.)

Image credit: http://creativebits.org/mac_os_x/windows_vs_mac_monitor_gamma
Human Perception—Accommodation Effect
Human Perception—Acommodation Effect
Next time...

- A whole spectrum of things to know about light & color
- In the next few lectures we’ll talk more about
  - radiometry
  - cameras
  - scattering
  - …