**Course News**

**Assignment 3 (project)**
- Due April 1

**Reading (this week)**
- Chapter 20 (color)

**Reading (this week & next)**
- Chapter 10 (ray tracing)

**Course Topics for the Rest of the Term**

**Color**
- Monday, Today

**Ray-tracing & Global Illumination**
- Friday, next week

**Parametric Curves/Surfaces**
- March 30/April 1
- Taught by Robert Bridson - I will be at a conference

**Overview of current research**
- April 3/6 (Ivo Ihrke - I am still at conference)

**April 8 – Final Q&A (I will be back for that)**

**Electromagnetic Spectrum**

**Light Sources**

**Common light sources differ in the kind of spectrum they emit:**
- Continuous spectrum
  - Energy is emitted at all wavelengths
  - Blackbody radiation
  - Tungsten light bulbs
  - Certain fluorescent lights
  - Sunlight
  - Electrical arcs
- Line spectrum
  - Energy is emitted at certain discrete frequencies

**Blackbody Radiation**

**Black body**
- Dark material, so that reflection can be neglected
- Spectrum of emitted light changes with temperature
  - This is the origin of the term "color temperature"
    - E.g. when setting a white point for your monitor
  - Cold: mostly infrared
  - Hot: redish
  - Very hot: bluish
- Demo:
### Line Spectrum

**Examples:**
- Ionized gases
- Lasers
- Some fluorescent lamps

### Physiology of Vision

**The retina**
- Rods
  - B/w edges
- Cones
  - Color

### Physiology of Vision

**Center of retina is densely packed region called the fovea.**
- Cones much denser here than the periphery

### Color/Lightness Constancy

**Do they match?**

### Color Constancy

- Automatic ‘white balance’ from change in illumination
- Vast amount of processing behind the scenes!
- Colorimetry vs. perception

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*Image courtesy of John McEntee*
**Tristimulus Theory of Color Vision**

- Although light sources can have extremely complex spectra, it was empirically determined that colors could be described by only 3 **primaries**
- Colors that look the same but have different spectra are called **metamers**

**Color Matching Experiments**

**Performed in the 1930s**

- Idea: perceptually based measurement
  - shine given wavelength \( \lambda \) on a screen
  - User must control three pure lights producing three other wavelengths (say \( R=700 \) nm, \( G=546 \) nm, and \( B=438 \) nm)
  - Adjust intensity of RGB until colors are identical

**Negative Lobes**

- **Actually:**
  - Exact target match possible sometimes requires *negative light*
  - Some red has to be added to target color to permit exact match using “knobs” on RGB intensity output
  - Equivalent mathematically to removing red from RGB output

**Color Matching Experiment**

**Results**

- It was found that any color \( S(\lambda) \) could be matched with three suitable primaries \( A(\lambda), B(\lambda), \) and \( C(\lambda) \)
  - Used monochromatic light at 438, 546, and 700 nanometers
  - Also found the space is linear, i.e. if
    \[
    R(\lambda) = S(\lambda)
    \]
    then
    \[
    R(\lambda) + M(\lambda) = S(\lambda) + M(\lambda)
    \]
  and
  \[
  k \cdot R(\lambda) = k \cdot S(\lambda)
  \]

**Determine Matching for Arbitrary Spectra**

**Given**

- Some light spectrum \( s(\lambda) \)

**How do we find \( R, G, B \)?**

- Coefficients to describe color of \( s(\lambda) \) in RGB space
  - i.e. as mixtures of the specific monochromatic colors mentioned!

**Notation**

**Don’t confuse:**

- **Primaries:** the spectra of the three different light sources: \( R, G, B \)
  - For the matching experiments, these were monochromatic (i.e. single wavelength) light!
  - Display primaries usually have a wider spectrum
- **Coefficients \( R, G, B \):**
  - Specify how much of \( R, G, B \) is in a given color
  - Color matching functions: \( r(\lambda), g(\lambda), b(\lambda) \)
  - Specify how much of \( R, G, B \) is needed to produce a color that is a metamer for pure monochromatic light of wavelength \( \lambda \)
Determine Matching for Arbitrary Spectra

**Given**
- Some light spectrum $s(\lambda)$

**How do we find $R$, $G$, $B$?**
- Coefficients to describe color of $s(\lambda)$ in RGB space

**A: Integrate with color matching functions**
- Treat spectra as vector space
- Dot product of $s_1$, $s_2$ defined as
- $R = \int s(\lambda)r(\lambda)d\lambda$
- $G = \int s(\lambda)g(\lambda)d\lambda$
- $B = \int s(\lambda)b(\lambda)d\lambda$

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**Negative Lobes**

**In general:**
- It is **not** possible to find three color primaries (monochromatic or continuous spectrum) that can produce all visible colors with **positive** weights

**Q: How can this be?**
- We only have 3 types of cones, after all?

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**Negative Lobes**

**In general:**
- It is **not** possible to find three color primaries (monochromatic or continuous spectrum) that can produce all visible colors with **positive** weights

**Q: How can this be?**
- We only have 3 types of cones, after all?

**A: the spectral sensitivity curves of cones overlap**
- i.e. the cones span a linear color (vector) space, but this space is not **orthonormal**
- Orthonormalization introduces negative weights...

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**Matching Functions - CIE Color Space**

- CIE defined three "imaginary" lights $X$, $Y$, and $Z$, any wavelength $\lambda$ can be matched perceptually by positive combinations

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**Matching Functions - Measured vs. CIE Color Spaces**

- Measured basis
  - Monochromatic lights
  - Physical observations
  - Negative lobes

- Transformed basis
  - "Imaginary" lights
  - All positive, unit area matching functions
  - $Y$ is luminance, no hue
  - $X,Z$ no luminance
Notation

Don't confuse:
- Synthetic primaries X, Y, Z
  - Contain negative frequencies
  - Do not correspond to visible colors
- Color matching functions x(λ), y(λ), z(λ)
  - Are non-negative everywhere
- Coefficients X, Y, Z
- Normalized chromaticity values

\[ x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}, \quad z = \frac{Z}{X + Y + Z} \]

CIE Gamut and Chromaticity Diagram

3D gamut

Chromaticity diagram
- Hue only, no intensity

Facts about the CIE “Horseshoe” Diagram

- All visible colors lie inside the horseshoe
  - Result from color matching experiments
- Spectral (monochromatic) colors lie around the border
  - The straight line between blue and red contains the purple tones
- Colors combine linearly (i.e. along lines), since the xy-plane is a plane from a linear space

Facts about the CIE “Horseshoe” Diagram (cont.)

A point C can be chosen as a white point corresponding to an illuminant
- Usually this point is of the curve swept out by the black body radiation spectra for different temperatures
- Relative to C, two colors are called complementary if they are located along a line segment through C, but on opposite sides (i.e. C is an affine combination of the two colors)
- The dominant wavelength of the color is found by extending the line from C through the color to the edge of the diagram
- Some colors (i.e. purples) do not have a dominant wavelength, but their complementary color does

CIE Diagram

- Blackbody curve
- Illumination:
  - Candle 2000K
  - Light bulb 3000K (A)
  - Sunlight/
    - Blue 6500K (D)
    - Overcast day 7000K
    - Lightning 32,000K

Color Interpolation, Dominant & Opponent Wavelength

Complementary wavelength
### RGB Color Space (Color Cube)

Define colors with (r, g, b) amounts of red, green, and blue
- Used by OpenGL
- Hardware-centric
- Describes the colors that can be generated with specific RGB light sources

**RGB color cube sits within CIE color space**
- Subset of perceivable colors
- Scaled, rotated, sheared cube

### Device Color Gamuts

Use CIE chromaticity diagram to compare the gamuts of various devices
- X, Y, and Z are hypothetical light sources, not used in real-world applications

### Gamut Mapping

What does this color go to?

### Additive vs. Subtractive Colors

**Additive: light**
- Monitors, LCDs
- RGB model

**Subtractive: pigment**
- Printers
- CMY(K) model

### HSV Color Space

More intuitive color space for people
- H = Hue
- S = Saturation
- V = Value
  - Or brightness B
  - Or intensity i

### Monitors

Monitors have nonlinear response to input
- Characterize by gamma
  - displayedIntensity = a^gamma (maxIntensity)

**Gamma correction**
- displayedIntensity = \( \left( \frac{1}{a} \right)^{\gamma} \) (maxIntensity)
  - a (maxIntensity)

**Gamma for CRTs:**
- Around 2.4
Coming Up...

*Friday, next week:*
- Ray-tracing