Announcements

• Homework 3 will be returned this week
• Homework 4 is due Sat, Dec 5, 11:59 PM
• Please complete TA and course evaluations
• Reading:
  – Chapter 3: Color

The appearance of colors

• Color appearance is strongly affected by (at least):
  – spectrum of lighting striking the retina
  – other nearby colors (space)
  – adaptation to previous views (time)
  – “state of mind”
Talking about colors

1. Spectrum –
   • A positive function over interval 400nm-700nm
   • “Infinite” number of values needed.
2. Names
   • red, harvest gold, cyan, aquamarine, auburn, chestnut
   • A large, discrete set of color names
3. R,G,B values
   • Just 3 numbers

Color Reflectance

Measured color spectrum is a function of the spectrum of the illumination and reflectance
Illumination Spectra

Blue skylight  Tungsten bulb

Measurements of relative spectral power of sunlight, made by J. Parkkinen and P. Silfsten. Relative spectral power is plotted against wavelength in nm. The visible range is about 400nm to 700nm. The color names on the horizontal axis give the color names used for monochromatic light of the corresponding wavelength — the “colors of the rainbow.” Mnemonic is “Richard of York got blisters in Venice.”

Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Fresnel Equation for Polished Copper

Color matching experiment

Color Matching
The principle of trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
    - Exceptional people can match with two or only one primary.
    - This could be caused by a variety of deficiencies.
  - Most people make the same matches.
    - There are some anomalous trichromats, who use three primaries but make different combinations to match.

Color receptors

Response of $k$th cone = $\int \rho_k(\lambda)E(\lambda)d\lambda$

Color matching functions

- Choose primaries, say $P_1(\lambda)$, $P_2(\lambda)$, $P_3(\lambda)$
- For monochromatic (single wavelength) energy function, what amounts of primaries will match it?
- i.e., For each wavelength $\lambda$, determine how much of A, of B, and of C is needed to match light of that wavelength alone.
  $$a(\lambda)$$
  $$b(\lambda)$$
  $$c(\lambda)$$
- These are color matching functions
RGB
RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively.

CIEXYZ
CIEXYZ: Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors).

Three types of cones: R,G,B
Response of kth cone = $\int P_k(\lambda)E(\lambda)d\lambda$

There are three types of cones
S: Short wave lengths (Blue)
M: Mid wave lengths (Green)
L: Long wave lengths (Red)

- Three attributes to a color
- Three numbers to describe a color

Color spaces
- Linear color spaces describe colors as linear combinations of primaries
- Choice of primaries = choice of color matching functions = choice of color space
- Color matching functions, hence color descriptions, are all within linear transformations
- RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively
- CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors).

Example: RGB to YIQ

$\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} = \begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.275 & -0.321 \\
0.212 & -0.532 & 0.311
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}$

- Used by NTSC TV standard
- Separates Hue & Saturation (I,Q) from Luminance (Y)
RGB Color Cube
• Block of colors for (r, g, b) in the range (0-1).
• Convenient to have an upper bound on coefficient of each primary.
• In practice:
  – primaries given by monitor phosphors (phosphors are the materials on the face of the monitor screen that glow when struck by electrons)

CIELAB
• Also referred to as CIE L*a*b*
• Designed to approximate human vision
  – Nonlinear response
• Includes 100% of visible colors
• L is lightness
• A and B are color-opponent dimensions
• Nonlinear conversion to/from CIEXYZ color space
• Human perceptual difference between two colors is the Euclidean distance between the two 3D points in CIELAB space

XYZ Color Space
• Encompasses all color sensations the average person can experience
• Standard reference
  – Many other color space definitions are based on XYZ
• Y is luminance
• Z is quasi-equal to blue stimulation
• X is a linear combination of cone response curves chosen to be nonnegative
• The plane parallel to the XZ plane and that Y lies on contains all possible chromaticities at that luminance

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

CIEExyY (Chromaticity Space)
• Chromaticity coordinates
  – (x, y, z)
  – Usually specified by (x, y)
  – where \( x + y + z = 1 \)

Color Specification: Chromaticity
• Chromaticity coordinates
  – (x, y, z)
  – Usually specified by (x, y)
  – where \( z = 1 - x - y \)
Chromaticities

- Set of chromaticities
  - Red
  - Green
  - Blue
  - White (point)

Standard Illuminants

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Rec. 709 and sRGB
35.9% of visible colors

Adobe RGB
52.1% of visible colors

Wide gamut RGB
77.6% of visible colors

ProPhoto RGB
90% of visible colors

100% of visible colors
Incorrect Image Conversion

Same pixel values stored in files, but with different sets of chromaticities

Chromatic Adaptation

- Estimating the appearance of a sample under a different illuminant
  - Convert between different white points
- LMS color space
  - Response of the three types of cones in the human eye
    - Long, medium, and short wavelengths
- XYZ to LMS
  - Bradford transformation matrix
- Chromatic adaptation
  - Adaptation matrix

Application: Color Transfer

- RGB to XYZ with white point of standard illuminant E (use chromatic adaptation)
- XYZ to Lab
- Map source pixels such that the L*a*b* mean and standard deviations match those of the target image

Nonlinear Encoding

- All of these standards use nonlinear encoding (gamma encoding)
  - Video
    - Recommendation ITU-R BT.601 (standard-definition television (SDTV))
    - SMPTE standard 240M (precursor to Rec. 709)
    - Recommendation ITU-R BT.709 (high-definition television (HDTV))
  - Image
    - sRGB
    - Adobe RGB
    - Wide gamut RGB (or Adobe Wide Gamut RGB)
    - ProPhoto RGB (or reference output medium metric (ROMM) RGB)
- Must convert to linear colorspace first for most color processing

Nonlinear Encoding and Conversion to Linear

- Typical CRT monitors have a transfer function of gamma = 2.2
- Image and video standards were designed to be directly displayed on CRTs
  - Pixel values are encoded to approximate gamma = 2.2
- Nonlinear to linear (floating-point) using a lookup table
- Linear to nonlinear calculation

Nonlinear R’G’B’ Color Space and Linear RGB Color Space

- Example: sRGB
  - Slope of sRGB nonlinear in log-log space
Luminance Y and Luma Y’

- Luminance is calculated from linear RGB
  - Y coordinate of XYZ
- Luma is calculated from nonlinear R’G’B’
- Luminance is different than Luma
- Example: sRGB
  \[
  Y = 0.21263903 \times R + 0.71516871 \times G + 0.072192319 \times B \\
  Y' = 0.21263903 \times R' + 0.71516871 \times G' + 0.072192319 \times B'
  \]

Dialectrics (e.g., plastics)

- Diffuse + specular component
- Specularity is the color of the light source

Motivation: Lambertian Algorithm Applied to Non-Lambertian Surface: Photometric Stereo

Dichromatic Reflection Model

- Diffuse Surface
  - Color depends on light source color and diffuse color

Dichromatic Reflection Model

- Transparent Film
  - Color of light source

Dichromatic Reflection Model

- Dielectric Surface
Image formation: Color Channel $k$

$$I_k = (D_k f_d + S_k f_s(\theta)) \cdot \hat{n}$$

Where $f_d$ and $f_s$ are the diffuse and specular BRDFs.

Data-dependent SUV Color Space

$$[R] S = [1, 0, 0]$$

First row of $R$ is specular color $S$. Other rows are orthogonal to $S$.

Properties of SUV

- Data-dependent.
- Rotational (hence, linear) Transformation.
- The $S$ channel encodes the entire specular component and an unknown amount of diffuse component.
- Shading information is preserved in $u$ and $v$ channels.

$$I_U = r_1 D f_d \cdot \hat{n} \\
I_V = r_2 D f_d \cdot \hat{n}$$

Example

RGB

U

V

Multi-channel Photometric Stereo
Multi-channel Photometric Stereo

\[ J = [I_1, I_2] \]
\[ \mathbf{P} \]: 2-channel color vector under the \( k \)-th light source.
\[ \mathbf{\rho} \]: The \( k \)-th three light source directions.
\[ \mathbf{\rho} \]: 2-channel UV albedo.

\[ J^k = [t_1, t_2]^T = (\mathbf{\rho} \cdot \mathbf{n})^k \]

Shading vector
\[ \mathbf{F} = \begin{bmatrix} f_1 & f_2 & f_3 \end{bmatrix} \]
\[ \mathbf{F} = (\mathbf{P}^T \mathbf{P})^{-1} \mathbf{n} \]

Intensity matrix
\[ \mathbf{n} = \begin{bmatrix} n_1 & n_2 & n_3 \end{bmatrix} \]
\[ \mathbf{F} = \begin{bmatrix} f_1 & f_2 & f_3 \\ f_2 & f_3 & f_4 \\ f_3 & f_4 & f_5 \end{bmatrix}^{-1} \]

The least squares estimate of the shading vector \( \mathbf{F} \) is the principal eigenvector of \( \mathbf{n}^T \mathbf{n} \). Once the shading vector is known, the surface normal is found by solving the matrix equation \( \mathbf{F} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{n} \).

Qualitative Results

Quantitative Results

Next Lecture

- Light field camera
- Human visual system
- Reading:
  - Section 19.3: The Light Field
  - Section 1.1.4: The Human Eye