Announcements

- HW0 graded
- HW1 has been posted
- See links on web page for reading

Camera parameters

- Issue
  - camera may not be at the origin, looking down the z-axis
    - extrinsic parameters (Rigid Transformation)
    - one unit in camera coordinates may not be the same as one unit in world coordinates
  - intrinsic parameters - focal length, principal point, aspect ratio, angle between axes, etc.

\[
\begin{pmatrix}
U \\
V \\
W
\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}
\]

3 x 3 4 x 4

Lighting

- Special light sources
  - Point sources
  - Distant point sources
  - Strip sources
  - Area sources
- Common to think of lighting at infinity (a function on the sphere, a 2-D space)
- Completely arbitrary lighting can be represented as a function on the 4-D ray space (radiances)

Radiance

- Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle
  \[ I = \frac{P}{(dd\cos\theta)dn} \]
- Units: watts per square meter per steradian: \( w/(m^2sr) \)

Irradiance

- How much light is arriving at a surface?
- Irradiance -- power per unit area: \( W/cm^2 \)
- Total power arriving at the surface is given by adding irradiance over all incoming angles

\[
I = \int \int \int E(x, y, \lambda, t)s(x, y)q(\lambda)dydxdt
\]

Camera’s sensor

- Measured pixel intensity is a function of irradiance integrated over
  - pixel’s area
  - over a range of wavelengths
  - For some time
BRDF

- Bi-directional Reflectance Distribution Function
  \[ \rho(\theta_{in}, \phi_{in} : \theta_{out}, \phi_{out}) \]
- Function of
  - Incoming light direction: \( \theta_{in}, \phi_{in} \)
  - Outgoing light direction: \( \theta_{out}, \phi_{out} \)
- Ratio of incident irradiance to emitted radiance

Lambertian Surface

At image location \((u,v)\), the intensity of a pixel \(x(u,v)\) is:

\[ E(u,v) = \left[ a(u,v) \cdot n(u,v) \right] \cdot s_0 \cdot s \]

where
- \(a(u,v)\) is the albedo of the surface projecting to \((u,v)\).
- \(n(u,v)\) is the direction of the surface normal.
- \(s_0\) is the light source intensity.
- \(s\) is the direction to the light source.

Color Cameras

Eye:

Three types of Cones

- Prism (with 3 sensors)
- Filter mosaic
- Filter wheel
- X3

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”
Color Afterimage: South African Flag

opponent colors
Blue -> yellow
Red -> green
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”.

Light Spectrum

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Color Reflectance

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Illumination Spectra

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides
Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedoes, 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

Not on a computer Screen

Color matching experiment

The color-matching experiment. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test field. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975. Frontiers of Vision, by Brian Ponder, Harvard University, 1999.
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

- "Red" cone
- "Green" cone
- "Blue" cone

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

Color Matching Functions

- 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

Color spaces

- 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. Usually draw x, y, where $x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$

RGB Color Cube

- Block of colours 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)

YIQ Model

- Used by NTSC TV standard
- Separates Hue & Saturation (I,Q) from Luminance (Y)
CIE -XYZ and x-y

\[ X + Y + Z = 1 \]

CIE xyY (Chromaticity Space)

CIE xyY (Chromaticity Space)

HSV Hexcone

Hue, Saturation, Value

AKA: Hue, Saturation, Intensity (HIS)

Hexagon arises from projection of cube onto plane orthogonal to (R,G,B) = (1,1,1)

Metameric Lights

(Metamers)

4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.