Light

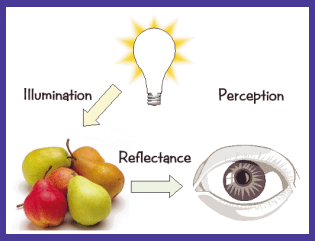
Light
Color
Illumination

10/01/02

Outline

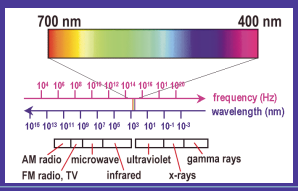
- Real light
- How humans see light
- How computers trick humans into thinking they're seeing light
- Light On Surfaces, the (much too) simple way
- Faking it all with OpenGL

Light Transport



Physics of Light and Color

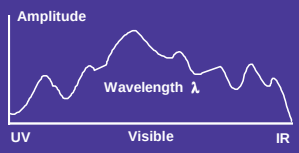
- It's all electromagnetic (EM) radiation
  - Different colors correspond to radiation of different wavelengths λ
  - Intensity of each wavelength specified by amplitude
  - Frequency $\nu = 2\pi / \lambda$
    - » long wavelength is low frequency
    - » short wavelength is high frequency



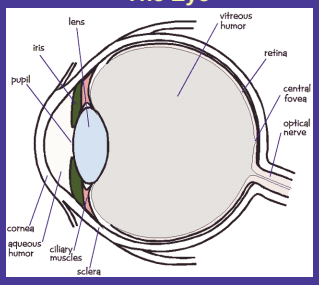
We perceive EM radiation with λ in the 400-700 nm range

Color: What's There vs. What We See

- Human eyes respond to "visible light"
  - tiny piece of spectrum between infra-red and ultraviolet
- Color defined by the emission spectrum of the light source
  - amplitude vs wavelength (or frequency) plot

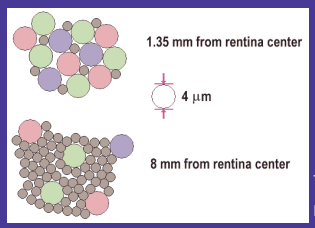


The Eye

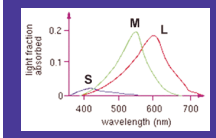


- The image is formed on the *retina*
- Retina contains two types of cells: *rods* and *cones*
- Cones measure color (red, green, blue)
- Rods responsible for monochrome night-vision

The Fovea



Cones are most densely packed within a region of the retina called the *fovea*



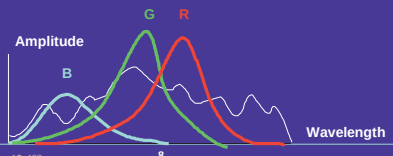
Three types of cones: S,M,L
- Corresponds to 3 visual pigments

Roughly speaking:
- S responds to blue
- M responds to green
- L responds to red

- Note that these are not uniform
  - more sensitive to green than red
- Colorblindness
  - deficiency of one cone/pigment type

Color Filters

- Rods and cones can be thought of as filters
  - Cones detect red, green or blue parts of spectrum
  - Rods detect average intensity across spectrum
- To get the output of a filter
  - Multiply its response curve by the spectrum, integrate over all wavelengths
- A physical spectrum is a complex function of wavelength
  - But what we see can be described by just 3 numbers—the color filter outputs
  - How can we encode a whole function with just 3 numbers?
    - » A: we can't! We can't distinguish certain colors--*metamers*



Your Friend the Photon

- We perceive EM radiation with λ in the 400-700 nm range
- That's really an accident of nature
  - The atmosphere lets through a lot of light in this region
  - It falls in the 1-step excitation band for outer shell electrons
  - It's higher energy than thermal infrared, so heat (and your own body temperature) doesn't swamp it
- These are basically the same reasons why plants are green
- Could/can change range by changing visual pigments
  - Computer graphics images probably look pretty incorrect to animals
- There is no reason why you couldn't do CG with radio, gamma rays, or even sound
  - Transparency and surface properties would change, of course
  - Diffraction depends on wavelength

Vision and Thought are One

- The retina is part of the central nervous system
- 2 million fibers from retina to *LGN*, 10 million from there to brain.
- Primary connection is *Primary Visual Cortex* or *V1*, 2 cm^2 on back of brain
  - Hypothesis: V1 gets used as a sort of image buffer for higher processing in the rest of the brain
- Steps:
  1. Saccade ends
  2. Retina accumulates image
  3. LGN opens connections, image gets written to V1
  4. Rest of brain accesses that info
  5. Meanwhile, a point of interest is being generated for next saccade
  6. Next saccade happens perhaps 250ms later; go back to step 1
- All very automatic; that's why pointing with eyes doesn't work for user interfaces.

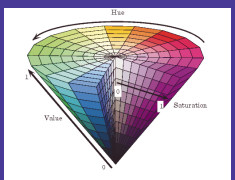
Color Models

- Okay, so our visual system is quite limited
- But maybe this is good news. . .
- We can avoid computing and reproducing the full color spectrum since people only have 3 color channels
  - TV would be much more complex if we perceived the full spectrum
    - » transmission would require much higher bandwidths
    - » display would require much more complex methods
  - real-time color 3D graphics is feasible
  - any scheme for describing color requires only three values
  - lots of different color spaces--related by 3x3 matrix transformations

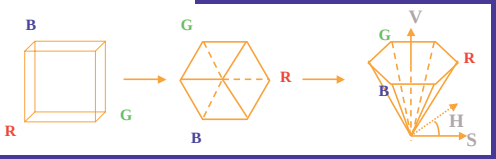
Color Spaces

- There are many ways to describe color
  - Spectrum
    - » allows any radiation (visible or invisible) to be described
    - » usually unnecessary and impractical
  - RGB
    - » convenient for display (CRT uses red, green, and blue phosphors)
    - » not very intuitive
  - HSV
    - » an intuitive color space
    - » H is hue - what color is it? S is saturation or purity - how non-gray is it? V is value - how bright is it?
    - » H is cyclic therefore it is a non-linear transformation of RGB
  - CIE XYZ
    - » a linear transform of RGB used by color scientists

HSV



From mathworks



Additive vs. Subtractive Color

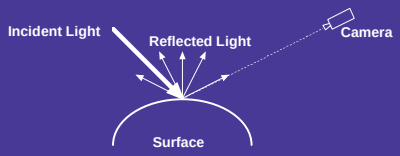
- Working with light: additive primaries
  - Red, green and blue components are added by the superposition property of electromagnetism
  - Conceptually: start with black, primaries add light
- Working with pigments: subtractive primaries
  - Typical inks (CMYK): cyan, magenta, yellow, black
  - Conceptually: start with white, pigments filter out light
  - The pigments remove parts of the spectrum

dye color	absorbs	reflects
cyan	red	blue and green
magenta	green	blue and red
yellow	blue	red and green
black	all	none

  - Inks interact in nonlinear ways--makes converting from monitor color to printer color a challenging problem
  - Black ink (K) used to ensure a high quality black can be printed

Surface Reflection

- When light hits an opaque surface some is absorbed, the rest is reflected (some can be transmitted too--but never mind for now)
- The reflected light is what we see
- Reflection is not simple and varies with material
  - the surface's micro structure define the details of reflection
  - variations produce anything from bright specular reflection (mirrors) to dull matte finish (chalk)



Units of Light and Color

quantity	*dimension*	*units*
solid angle	solid angle	[steradian]
a two-dimensional angle (proportional to area on a sphere)		
power	energy/time	[watt]=[joule/sec]
photons per second; radiance integrated over incoming directions, over a finite area.		
radiance (intensity)	power/(area*solid angle)	[watt/(m^2*steradian)]
how bright is the light reflected by this point along this direction *(reflected light)*		
irradiance (intensity)	power/area	[watt/m^2]
how bright is the light hitting the surface (or image) at this point *(incident light)*		
reflectance	unitless	[1]
what fraction of the light is reflected by a material? typically between 0 and 1.		

The Meaning of "Color"

- What's an image?
  - Irradiance: each pixel measures the incident light at a point on the film
  - Proportional to integral of scene radiance hitting that point
- What's Color?
  - Refers to radiance or irradiance measured at 3 wavelengths
  - Scene color: radiance coming off of surface (for illumination)
  - Image color: irradiance (for rendering)
  - These quantities have different units and should not be confused

Where are we?

- Next time: Shading