Light

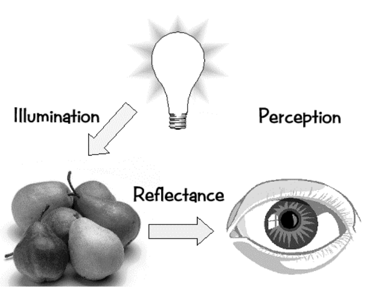
Light
Color
Illumination

Carnegie
Mellon

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

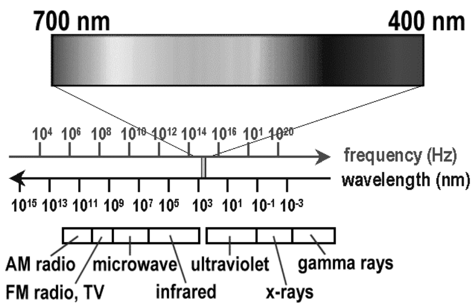


Physics of Light and Color

- 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
- Don't confuse with wavelength/frequencies and spectra in image processing
  - in image processing these refer to spatial values of the signal
  - in image formation these refer to the physical properties of the light
  - Ideally, every image we render should have a full spectrum at every pixel

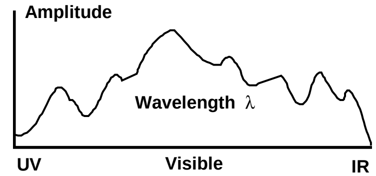
The Visible Spectrum

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



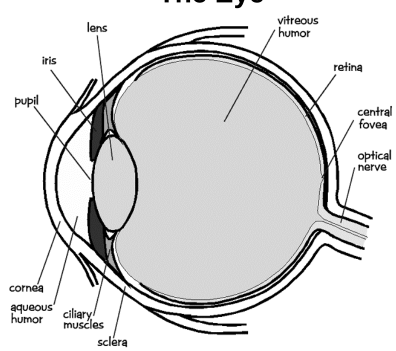
Color: What's There vs What We See

- 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



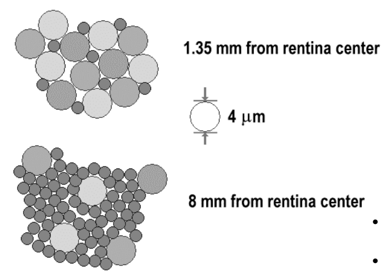
- Sound is a little like this, too. Our ears do a spectrum analysis, so what we hear closely follows what's going on physically.
- Color perception is rather different (alas; it's a bandwidth problem)

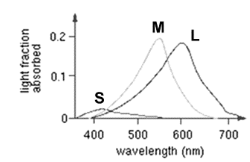
The Eye



- 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



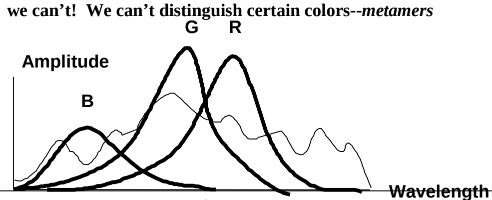


Cones are most densely packed within a region of the retina called the *fovea*

- 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

- **Strange but true, 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

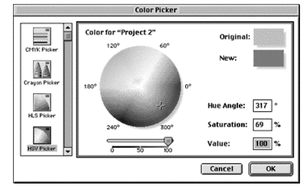
- **Okay, so our visual system is quite limited**
- **But maybe this is good news. . .**
- **We can avoid computing and reproducing the full color spectrum since people only have 3 color channels**
  - **TV would be much more complex if we perceived the full spectrum**
    - » **transmission would require 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**

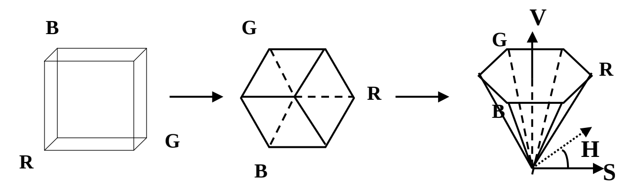
Color Spaces

- 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
- For the very best performance four spectrum samples are used; three is usually enough

HSV

The Apple HSV picker





Additive vs. Subtractive Color

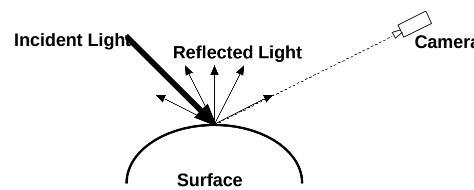
- Working with light: additive primaries
  - Red, green and blue components are added by the superposition property of electromagnetism
  - Conceptually: start with black, primaries add light
- Working with pigments: subtractive primaries
  - Typical inks (CMYK): cyan, magenta, yellow, black
  - Conceptually: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

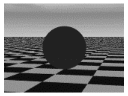
- **What's an image?**
  - **Irradiance: each pixel measures the incident light at a point on the film**
  - **Proportional to integral of scene radiance hitting that point**
- **What's Color?**
  - **Refers to radiance or irradiance measured at 3 wavelengths**
  - **Scene color: radiance coming off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

Illumination

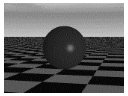
- **Light Sources emit light**
  - **EM spectrum**
  - **Position and direction**
- **Surfaces reflect light**
  - **Reflectance**
  - **Geometry (position, orientation, micro-structure)**
  - **Absorption**
  - **Transmission**
- **Illumination determined by the interactions between light sources and surfaces**

Types of Light Sources

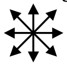
- **Ambient: equal light in all directions**
  - **a hack to model interreflections**

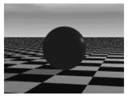


- **Directional: light rays oriented in same direction**
  - **good for distance light sources (sunlight)**

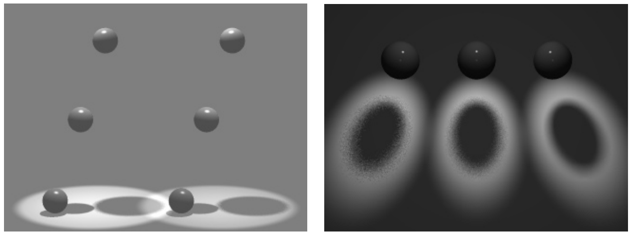


- **Point: light rays diverge from a single point**
  - **approximation to a light bulb**





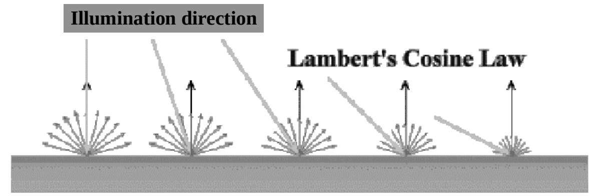
More Light Sources



- **Spotlight:** **point source with directional fall-off**
  - **intensity is maximal along some direction D, falls off away from D**
  - **specified by color, point, direction, fall-off parameters**
- **Area Source:** **Luminous 2D surface**
  - **radiates light from all points on its surface**
  - **generates soft shadows**

Diffuse Reflection

- **Simplest kind of reflector (also known as *Lambertian Reflection*)**
- **Models a matte surface -- rough at the microscopic level**
- **Ideal diffuse reflector**
  - **incoming light is scattered equally in all directions**
  - **viewed brightness does not depend on viewing direction**
  - **brightness *does* depend on direction of illumination**



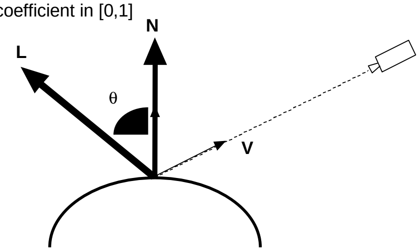
- **Lambert's Law**

$$I_{diffuse} = k_d I_{light} \cos\theta$$
$$= k_d I_{light} (N \bullet L)$$

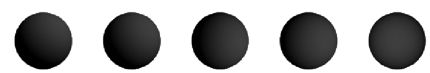
I_{light} : Light Source Intensity

k_d : Surface reflectance coefficient in [0,1]

θ : Light/Normal angle



Examples of Diffuse Illumination



- **Above is the same sphere lit diffusely from different lighting angles**

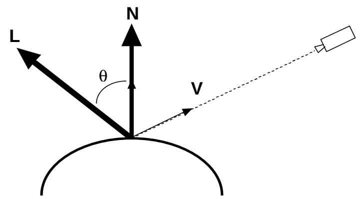
Ambient + Diffuse Reflection

- **CG started using the Lambertian model and the added more terms as extra effects were required**

$$I_{d+a} = k_a I_a + k_d I_{light}(N \bullet L)$$

I_a : Ambient light intensity (global)

k_a : Ambient reflectance (local)



•This is diffuse illumination plus a simple ambient light term

- **a trick to account for a background light level caused by multiple reflections from all objects in the scene**

Further Simple Illumination Effects

•Light attenuation:

- **light intensity falls off with the square of the distance from the source - so we add an extra term for this**

$$I_{d+a} = k_a I_a + f_{att} k_d I_{light}(N \bullet L) \quad \textbf{where} \quad f_{att} = \frac{1}{d^2}$$

with d the light source to surface distance - more complicated formulae are possible (see Foley) and work better

•Colored lights and surfaces:

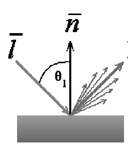
- **just have three separate equations for RGB (or CIE, YIQ, etc.)**

•Atmospheric attenuation:

- **use viewer-to-surface distance to give extra effects**
- **the distance is used to blend the object's radiant color with a "far" color (e.g., a nice hazy gray)**

Specular Reflection

- **Shiny surfaces change appearance when viewpoint is varied**
  - **specularities (highlights) are view-dependent**
  - **caused by surfaces that are microscopically smooth**
- **For shiny surfaces part of the incident light reflects coherently**
  - **an incoming ray is reflected in a single direction (or narrow beam)**
  - **direction is defined by the incoming direction and the surface normal**
- **A mirror is a perfect specular reflector**
  - **approximate specular reflectors give fuzzy highlights**



Phong Illumination

- **One function that approximates specular falloff is called the *Phong Illumination* model**

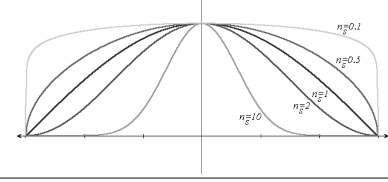
$$I_{specular} = k_s I_{light}(\cos\phi)^{n_{shiny}}$$

- **no physical basis, yet widespread use in computer graphics**

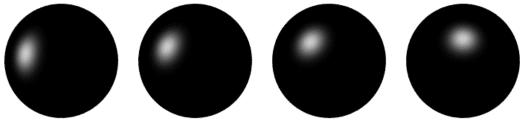
ϕ : 90 - (angle between light source and viewer)

k_s : Specular reflectance

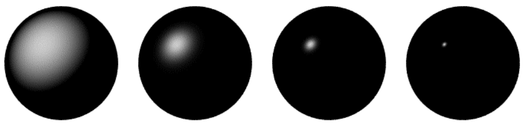
n_{shiny} : Rate of specular falloff



Phong Illumination



Moving the light source



Changing n_{shiny}

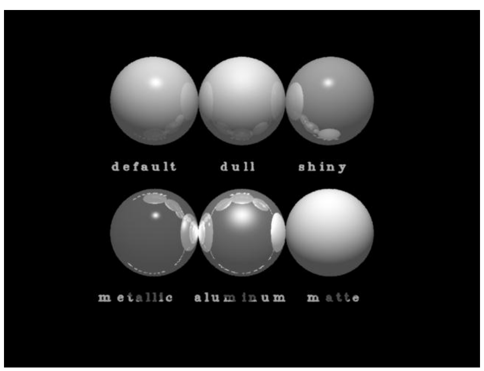
Putting It All Together

- **Combining ambient, diffuse, and specular illumination**

$$I = k_a I_a + f_{att} I_{light}\left[k_d \cos\theta + k_s (\cos\phi)^{n_{shiny}}\right]$$

- **For multiple light sources**
  - **Repeat the diffuse and specular calculations for each light source**
  - **Add the components from all light sources**
  - **The ambient term contributes only once**
- **The different reflectance coefficients can differ.**
  - **Simple "metal": k_a and k_d share material color, k_s is white**
  - **Simple plastic: k_s also includes material color**

Some Examples



OpenGL Materials

```
GLfloat white8[] = {.8, .8, .8, 1.}, white2 = {.2,.2,.2,1.},black={0.,0.,0.};
GLfloat mat_shininess[] = {50.};          /* Phong exponent */

glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT, black);
glMaterialfv(GL_FRONT_AND_BACK, GL_DIFFUSE, white8);
glMaterialfv(GL_FRONT_AND_BACK, GL_SPECULAR, white2);
glMaterialfv(GL_FRONT_AND_BACK, GL_SHININESS, mat_shininess);
```

OpenGL Lighting

```
GLfloat white[] = {1., 1., 1., 1.};
GLfloat light0_position[] = {1., 1., 5., 0.}; /* directional light (w=0) */

glLightfv(GL_LIGHT0, GL_POSITION, light0_position);
glLightfv(GL_LIGHT0, GL_DIFFUSE, white);
glLightfv(GL_LIGHT0, GL_SPECULAR, white);
glEnable(GL_LIGHT0);

glEnable(GL_NORMALIZE);     /* normalize normal vectors */
glLightModeli(GL_LIGHT_MODEL_TWO_SIDE, GL_TRUE);    /* two-sided lighting*/

glEnable(GL_LIGHTING);
```


Index of Refraction

- **Refraction:**
  - **the bending of light due to its different velocities through different materials**
- **Refractive index:**
  - **light travels at speed *c/n* in a material of refractive index *n***
  - ***c* is the speed of light in a vacuum**
  - **varies with wavelength hence rainbows and prisms**

MATERIAL	INDEX OF REFRACTION
Air/Vacuum	1
Water	1.33
Glass	about 1.5
Diamond	2.4

Transmission with Refraction

- **Light bends by the physics *principle of least time*, a consequence of *Huygens' Principle***
  - **light travels from point A to point B by the fastest path**
  - **when passing from a material of index n_1 to one of index n_2 *Snell's law* gives the angle of refraction:**
    $n_1 \sin \theta_1 = n_2 \sin \theta_2$
    where θ_1 and θ_2 are the angles from perpendicular
- **When traveling into a denser material (larger *n*), light bends to be more perpendicular (eg air to water) and vice versa**
  - **light travels further in the faster material**
  - **if the indices are the same the light doesn't bend**
- **When traveling into a less dense material total internal reflection occurs if $\theta_1 > \sin^{-1}(n_2/n_1)$**

Shadows

- **Shadows occur where objects are hidden from a light source**
  - **omit any intensity contribution from hidden light sources**
- **Working out what it hidden is simply a visibility problem**
  - **can the light source see the object?**
  - **use the z-buffer shadow algorithm:**
    - » **run the algorithm from the light source's viewpoint**
    - » **save the z-buffer as the shadow buffer**
    - » **run the real z-buffer algorithm, transforming each point into the light source's coordinates and comparing the z value against the shadow buffer**