

# Light & Color

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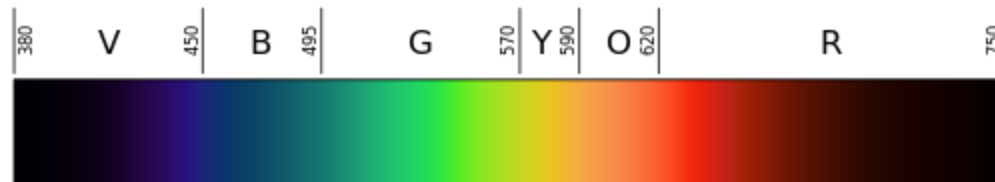
CSE168: Rendering Algorithms

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Light

# Light

- Light is electromagnetic radiation that is visible to the human eye
- Light is emitted and absorbed as photons that have both wave and particle like properties
- Visible light wavelength ranges from around 400 to 700 nanometers



# Photons

- Light is transported as photons
- Each photon has a frequency  $\nu$  and energy  $h\nu$ , where  $h$  is Planck's constant
- The wavelength  $\lambda$  is related to the frequency by:  $\lambda=c/\nu$ , where  $c$  is the speed of light
- For rendering purposes, we're mainly concerned with how photons are *emitted*, *scattered*, and *absorbed* by materials

# Radiance

- *Radiance* is a measure of the quantity of light radiation reflected (and/or emitted) from a surface within a given *solid angle* in a specified direction
- It is measured in units of  $\text{W}/(\text{sr}\cdot\text{m}^2)$  or Watts per steradian meter squared
- It is the property we usually associate as ‘light intensity’ and is what we measure when we are computing the color to display
- Technically, radiance refers to a single wavelength, and *spectral radiance* refers to the radiance across a spectrum
- Spectral radiance is what we associate as the perceived color (including the intensity), and is what we use to determine the pixel color

# Polarization

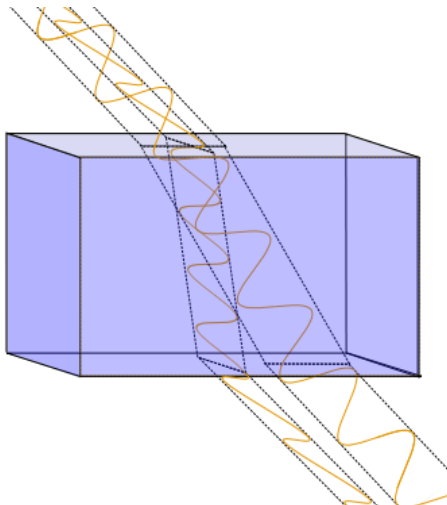
- Light waves are *polarized*, which means that they have an orientation around the axis of propagation
- Most light sources emit circularly polarized light, which is equally distributed across all angles
- Light can be filtered through a polarizing filter that allows passage of only waves oriented in a specific direction
- The effects of polarization are not very noticeable in everyday life, and so it is usually not included in a renderer
- However, there are some effects that can only be achieved by accurate modeling of polarization

# Polarization

- Examples of visual phenomena that require accurate polarization:
  - Use of polarized filters
  - Light scattering in the sky
  - Glare reduction on Fresnel dielectrics (& Brewster's angle)
  - Birefringence of non-orthogonal crystals

# Birefringence

- *Birefringence* is caused by anisotropic arrangement of atoms in a crystal
- Materials like these have two indices of refraction, and light entering a birefringent crystal is split into two rays that take different paths
- The full form of the Fresnel equations includes this property, and this has been included in some ray tracers





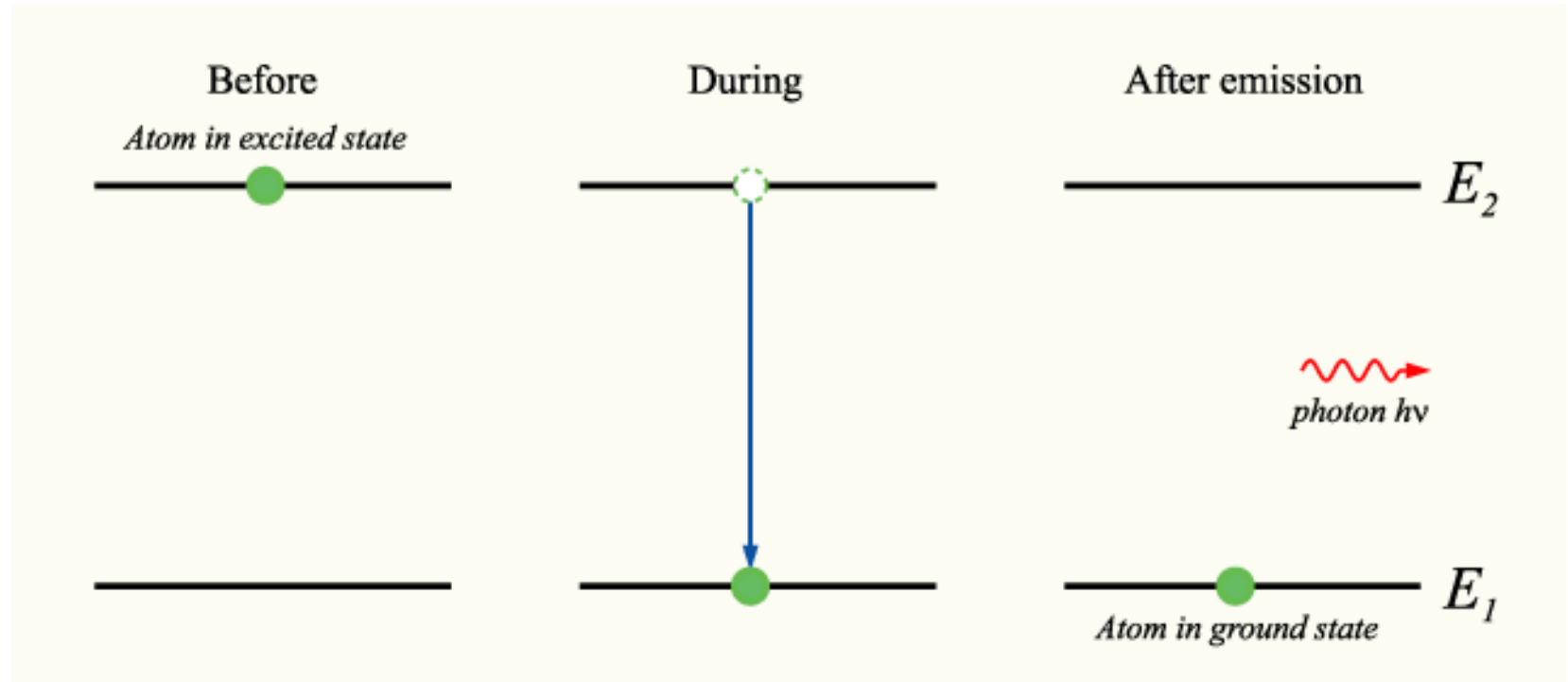
# Light Emission

# Atomic Emission

- When an electron of an atom drops to a lower energy state, a photon is emitted
- The energy of the photon is equal to the difference in energy between the two orbitals
- Because the orbital energy is quantized, atomic emissions can only be on specific wavelengths dependent on the orbitals of the atom
- Neon and sodium vapor lights emit light in this way



# Atomic Emission



# Atomic Emission

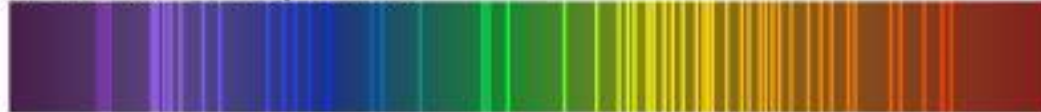
Full white light spectrum



Hydrogen emission spectrum



Neon emission spectrum



Oxygen emission spectrum



Sulphur emission spectrum



# Absorption

- Atoms will also absorb light through the opposite process



# Molecular Emission

- Molecular emission is related to atomic emission, except it results from electrons dropping from one molecular orbital to another
- Molecules have additional degrees of freedom compared to atoms, and therefore will have internal oscillations, leading to non-constant orbital energy levels
- The visible result is that molecular emission lines are spread out over a small range of wavelength, rather than appearing at distinct wavelengths
- The blue core of a Bunsen burner flame is due to molecular emissions
- The colors of pigments result from molecular absorption

# Thermal Emission

- All matter with a temperature greater than absolute zero emits thermal radiation
- Thermal vibrations of atoms and molecules causes electromagnetic radiation continuously across a wide spectrum of energy levels
- All materials start to glow visibly at around 800 K



# Planck's Law

- Planck's law describes the distribution of power for idealized blackbody emission
- Thermal radiation from real materials will closely match this distribution
- The spectral radiance  $L$  for temperature  $T$  at frequency  $\nu$  is:

$$L(T, \nu) = \frac{2h\nu^3}{c^2 \left( e^{\frac{h\nu}{kT}} - 1 \right)}$$

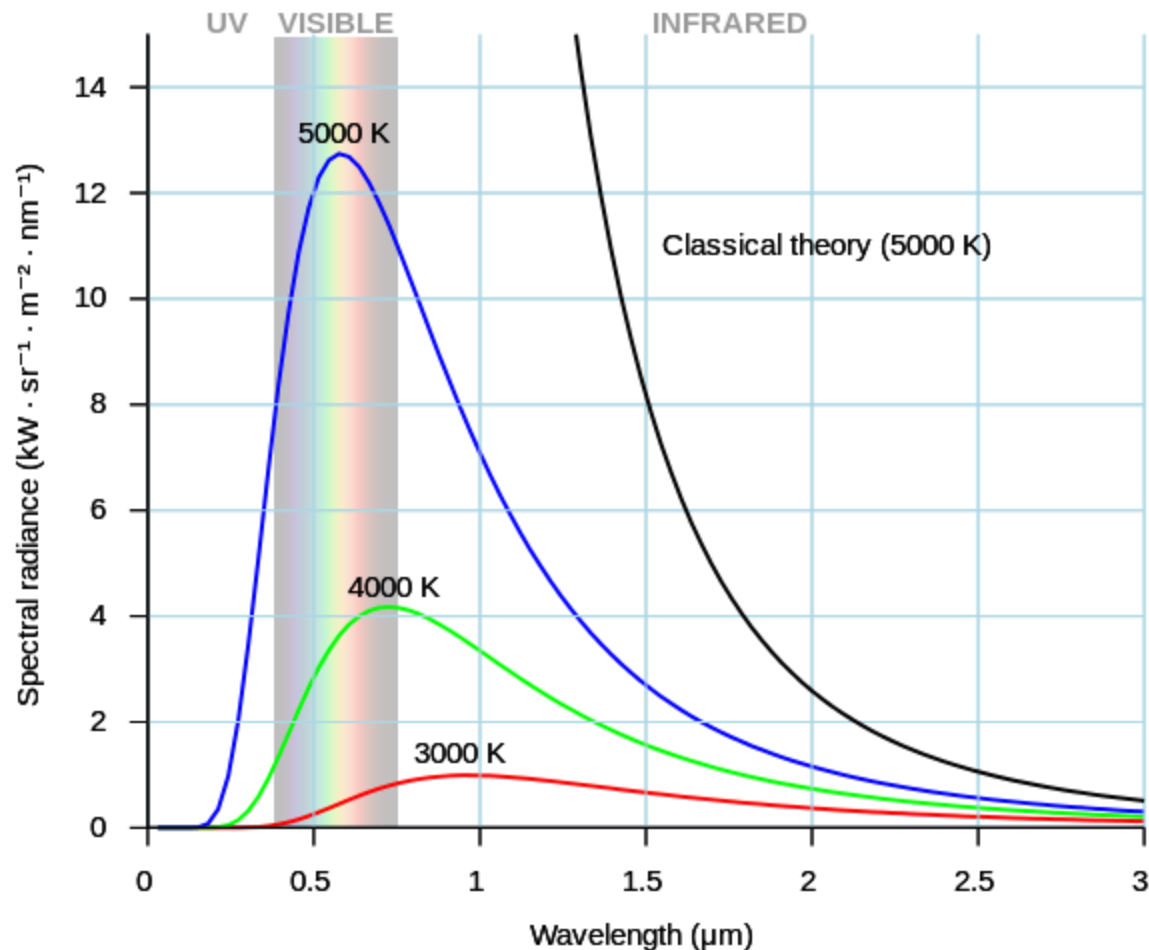
$k$  is Boltzmann's constant  $1.3806488 \times 10^{-23}$  J/K

$h$  is Planck's constant  $6.62606957 \times 10^{-34}$  J·s

$c$  is the speed of light 299,792,458 m/s



# Blackbody Emission



# Incandescence

- Incandescence is the emission of light from a hot object as a result of its temperature
- Incandescent emitters will match the idealized blackbody emission spectrum reasonably well
- Examples of incandescent emitters include:
  - Incandescent light bulbs
  - Lava
  - Sunlight

# Color Temperature

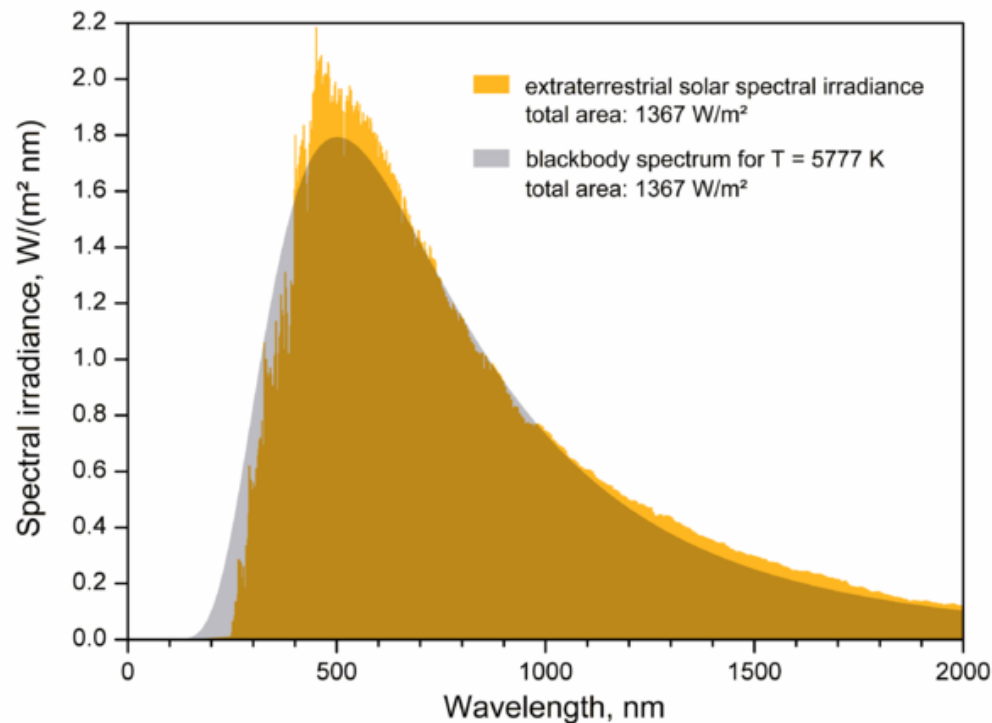
- Light sources are often they are described by their *color temperature* which is the color of a blackbody emitter that matches the appearance of the emitter to the human eye
- For most emitters, the color temperature will be very close to the actual temperature, but there are slight correction factors based on the material type
- Standard tungsten bulbs have a color temperature around 2700 K – 2850 K

# Light Bulbs



# Sunlight

- The surface of the sun emits light effectively as a 5777 K blackbody



# Fire

- The light emission and color of fire is mainly caused by the incandescence of hot carbon soot and closely matches the blackbody spectrum
- In addition, there is some atomic and molecular emission occurring at the actual reaction zone at the core of the flame
- The reaction zone usually appears blue in color, but can vary due to the chemical composition of the fuel source
- 'Physically Based Modeling and Animation of Fire' by Nguyen, Fedkiw, and Jensen (2002) used fluid dynamics to model the behavior of fire and used the temperature results of the simulation to model the light emission for rendering



# Luminescence

- Luminescence is the emission of light by a substance not resulting from heat
- There are many forms of luminescence in nature, but they are generally caused by atomic or molecular emissions triggered by non-thermal causes
- Common types of luminescence include:
  - Fluorescence
  - Phosphorescence
  - Chemiluminescence

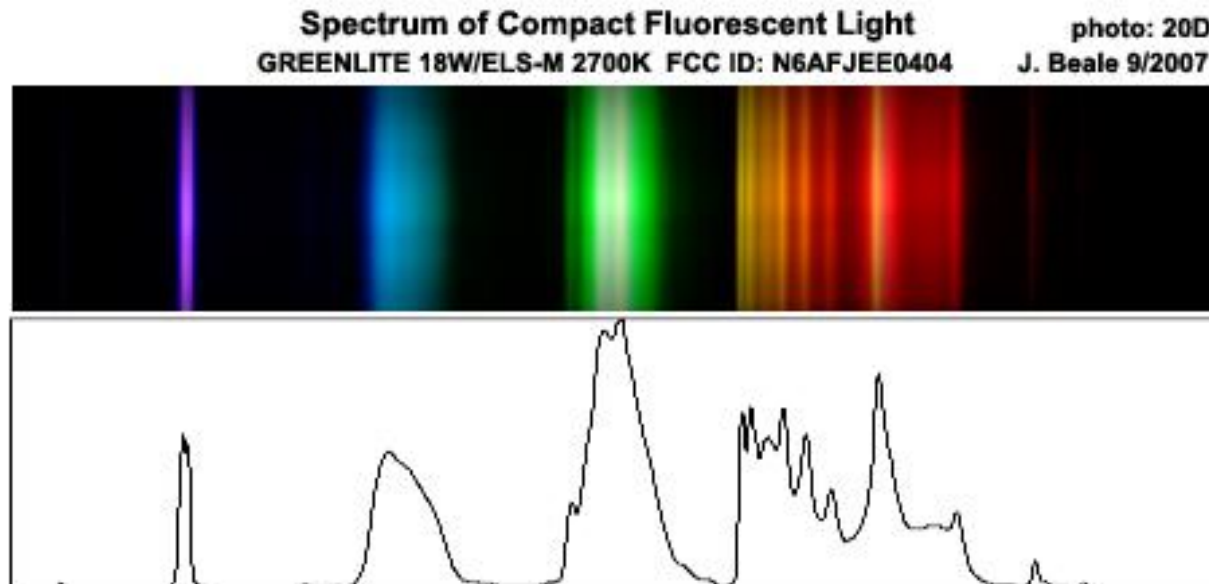
# Fluorescence

- Fluorescence is the emission of light by a material that has absorbed light or other electromagnetic radiation
- For example, an atom might absorb high energy ultraviolet light, which raises electrons up several energy levels
- These then re-emit light in the visible spectrum as they drop down to different levels
- Fluorescent light bulbs use this principle



# Fluorescence

- Fluorescent lights tend to have very irregular spectral distributions



# Phosphorescence

- Phosphorescence is related to fluorescence
- Unlike fluorescence however, the re-emission of light is not immediate and may take a fraction of a second or up to several hours
- Common examples of slow phosphorescence include glow-in-the-dark toys, paint, or clock/watch dials
- The phosphors on CRT monitors are much faster and re-emit light within  $1/60^{\text{th}}$  of a second or so

# Chemiluminescence

- Chemiluminescence is the emission of light resulting from chemical reactions
- Chemical glow-sticks are a common example
- Other examples include the *bioluminescence* of some living organisms like fireflies, glowworms, some squids, several deep sea fish, and some types of plankton and algae

# Scattering

# Absorption

- When light interacts with a material, it is either absorbed or scattered
- Absorption is the opposite of emission and has a symmetric relationship
- Light can be absorbed through atomic, molecular, or thermal absorption, following the same principles as emission
- Absorbed photons can raise the energy level of electrons in atoms or molecules or can contribute to kinetic energy which ultimately is converted to thermal energy

# Scattering

- If light isn't absorbed by the material, it will be scattered away in some direction
- At the atomic scale, this is governed by Maxwell's equations and at the microscopic scale, this is modeled by the Fresnel equations
- At the macroscopic scale, we use BRDF models to produce the complex hemispherical distributions of light scattered off surfaces
- As we've discussed, scattering processes must obey Helmholtz reciprocity and conservation of energy

# Volumetric Scattering

- In a later lecture, we will also look at volumetric scattering where light is scattered in a spherical distribution as it interacts with volumes
- Volumetric scattering is responsible for:
  - The blue light of the sky
  - Lighting of clouds
  - Appearance of smoke and fire
  - Translucent materials

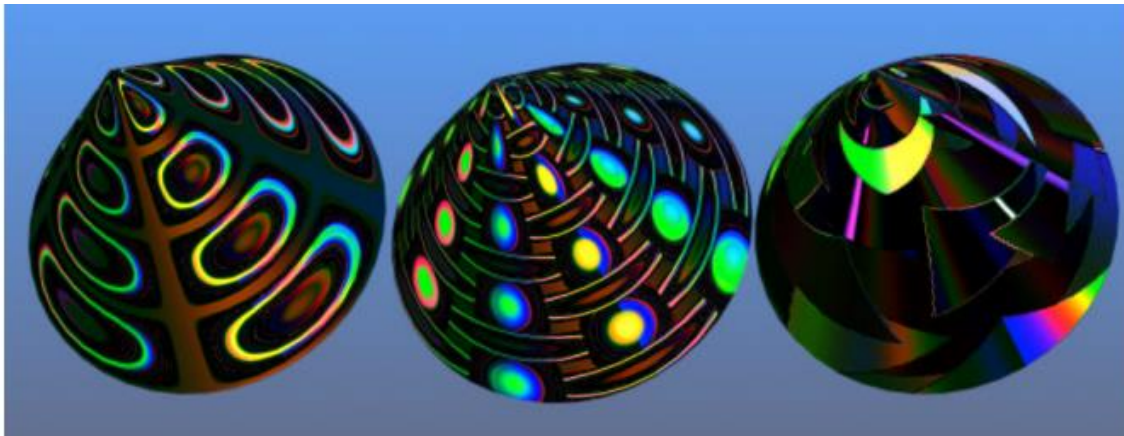
# Color From Scattering

- Most of the color we see in materials comes from molecular absorption of complex pigment molecules just below the surface
- Light enters the material and scatters around. Some is absorbed and some ultimately makes its way back out
- This leads to relatively uniform color in a material that doesn't vary much with the viewing or lighting angles
- Some color phenomena are caused by other processes such as:
  - Interference
  - Diffraction
  - Dispersion
- These tend to generate a variety of colors that can vary based on viewing or lighting angles



# Diffraction

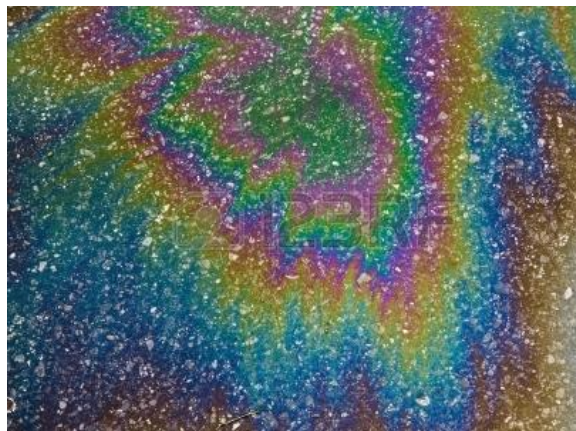
- Diffraction is a complex phenomenon that occurs when light waves interact with objects and requires modeling light as a wave in order to model it accurately in a general way
- The macroscopic effects of diffraction at surfaces can be modeled reasonably well through BRDFs though
- ‘Diffraction Shaders’ by Jos Stam (1999) describes rendering of diffraction at surfaces



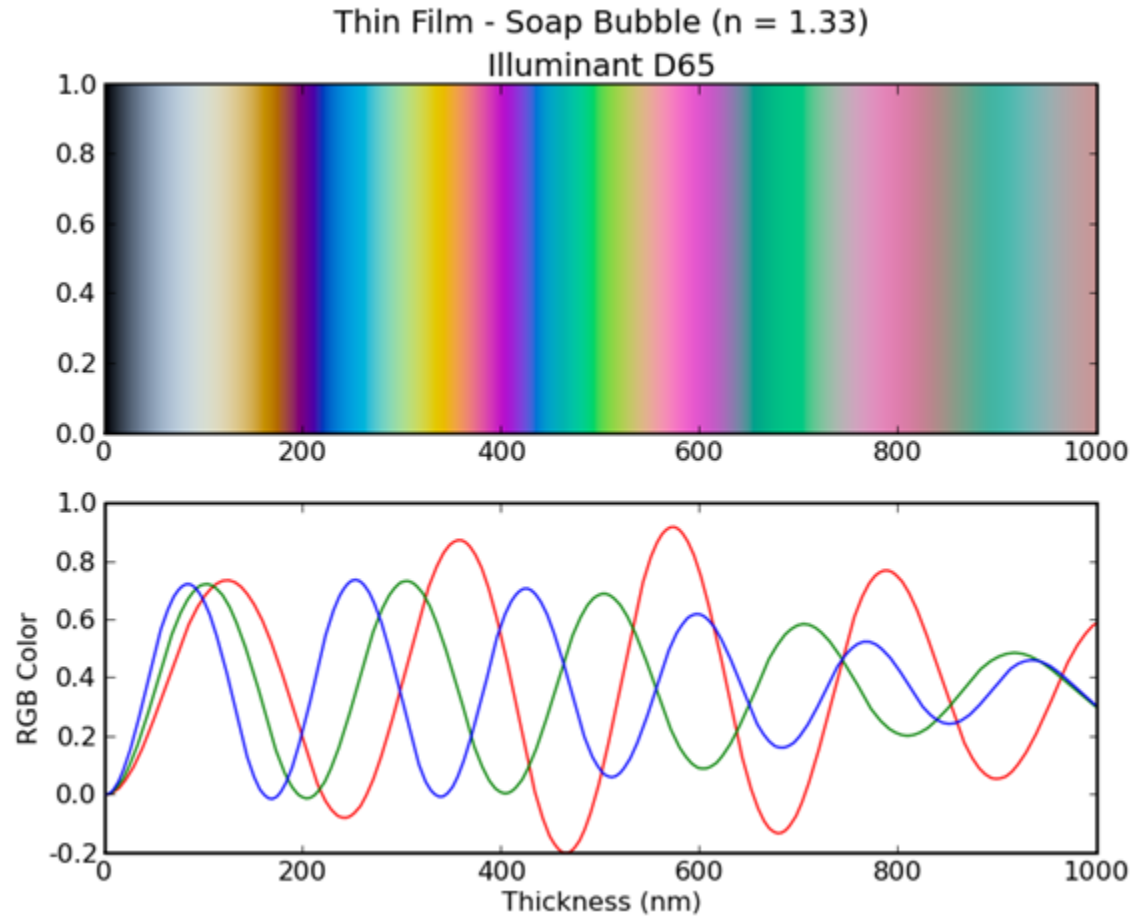
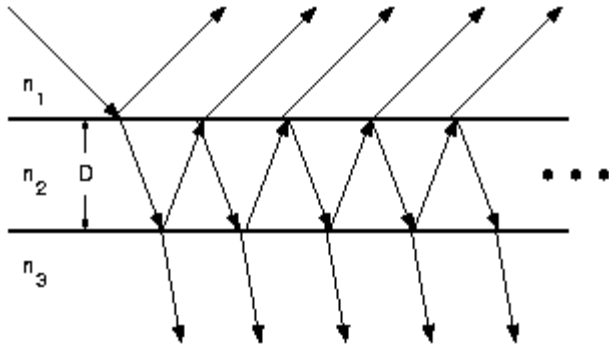
# Interference



- Interference is another wave phenomenon of light, but can be effectively modeled using a simpler particle model of light (as with ray tracing)
- Interference can be seen when light interacts with thin film surfaces such as soap bubbles, oil stains, and lens coatings



# Thin Film Interference



# Dispersion

- The index of refraction of a material varies with the wavelength of light
- This leads to spreading out of the spectrum when light interacts, leading to the colors of rainbows and from prisms
- Within the visible spectrum, index of refraction decreases as wavelength increases, and so red light will bend less than blue



# Cauchy's Equation

- Cauchy's equation is an empirical relationship that models the change in index of refraction  $n$  with wavelength  $\lambda$
- The general form is:

$$n(\lambda) = B + \frac{C}{\lambda^2} + \frac{D}{\lambda^4} + \dots$$

- Usually it is sufficient to limit it to the first two terms:

$$n(\lambda) = B + \frac{C}{\lambda^2}$$

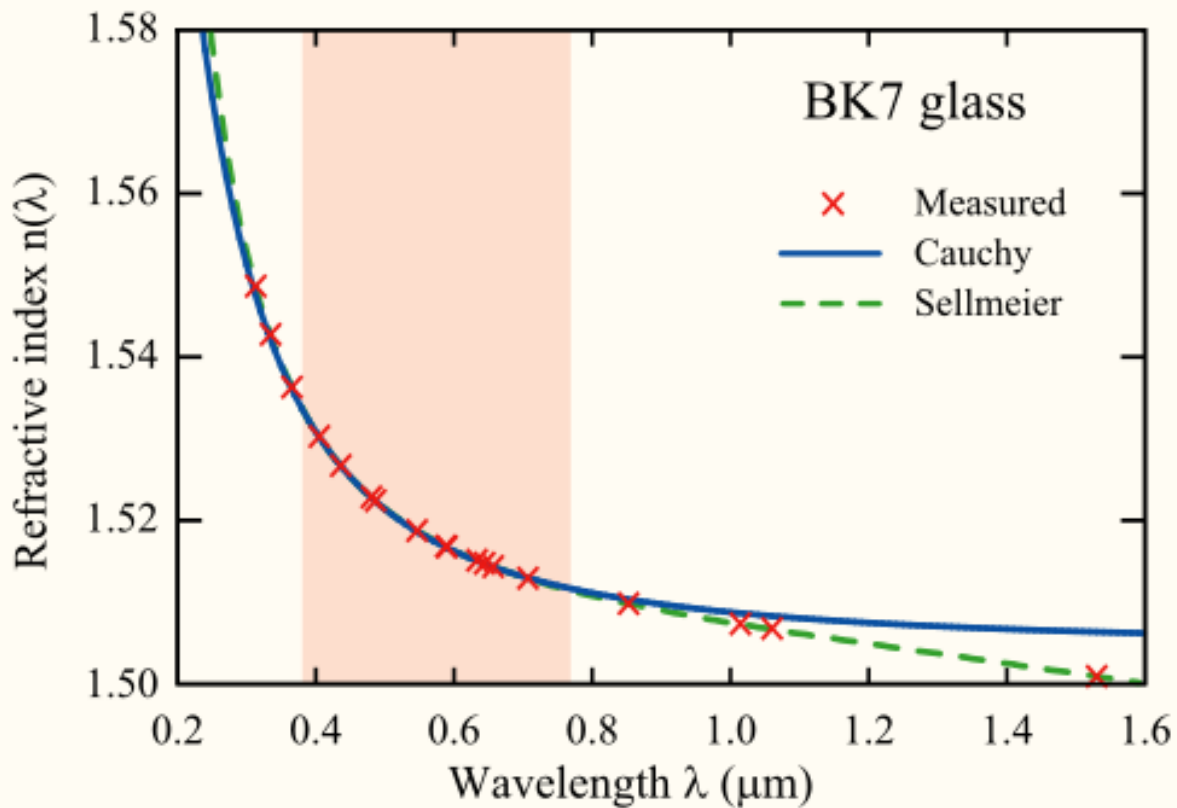
# Cauchy's Equation

$$n(\lambda) = B + \frac{C}{\lambda^2}$$

- The constants for some common optical glasses are:

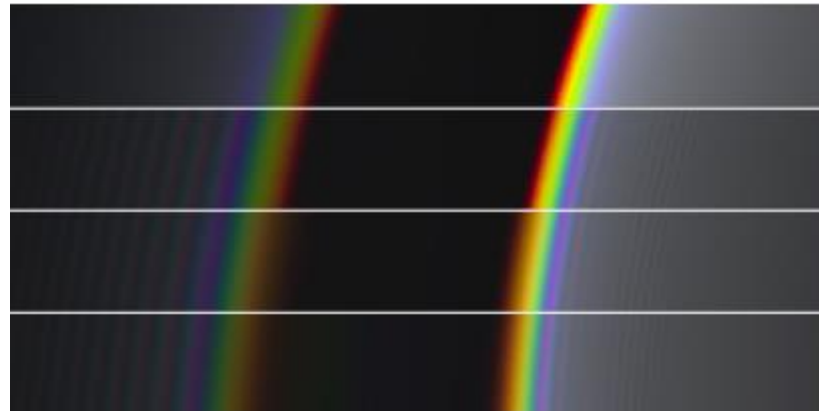
<b>Material</b>	<b>B</b>	<b>C</b>
Fused silica	1.458	0.00354
Hard crown glass	1.522	0.00459
Barium flint glass	1.670	0.00743
Dense flint glass	1.728	0.01342

# Cauchy's Equation



# Rainbows

- Rainbows are primarily caused by dispersion through roughly spherical water droplets
- ‘Physically Based Simulation of Rainbows’ by Sadeghi, Munoz, Laven, Jarosz, Seron, Gutierrez, and Jensen (2011) describes how to accurately render rainbows





# Color Rendering

# Color Rendering

- It is possible to render a wide range of visual phenomena using the standard RGB model of color
- However, there are several reasons to consider using a more sophisticated representation
- One of the more common examples is for rendering dispersion usually associated with prisms and diamonds
- Another reason is to allow more accurate conversion between display formats such as film, monitors, projectors, and color printing

# Color Rendering

- Some other phenomena that are not accurately captured with the simple RGB model are:
  - Light passing through multiple color filters
  - Narrow band effects like lighting from mercury vapor lights
  - Realistic modeling of interactions between different types of light sources and materials

# Spectral Rendering

- A common approach to improving color handling is to represent colors as a spectral distribution across the visible wavelengths
- This is why it is a good idea to use a Color class everywhere where colors are dealt with to allow for easy upgrading to a more sophisticated model
- For example, one might choose to use  $N$  different wavelengths from 400 to 700 nm and represent each color as  $N$  floats ( $N$  is typically around 10, but could be much higher if necessary)
- Only a handful of color operations should be required, such as addition, multiplication by scalar, multiplication by another color, exponent, and conversion to/from RGB

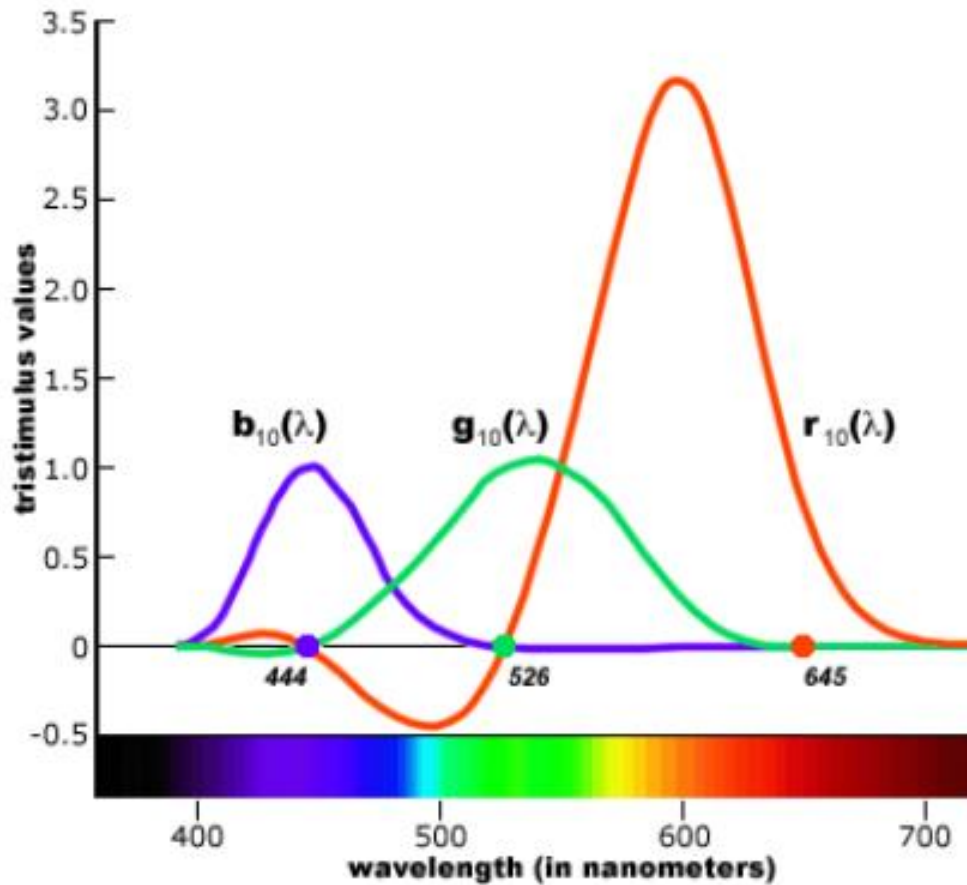
# Spectral Data

- Spectral data is available for many light sources and is actually not too difficult to find
- Good spectral data for material reflections is a lot harder to come by
- Also, commercial paint tools (like Photoshop) generally do not support full spectrum images, so it is difficult to make texture maps containing full spectrum data
- For these reasons, it is still very necessary to support RGB as an input data format for a spectral renderer

# Tristimulus Functions

- The human eye has three different types of color receptor cones that roughly correspond to red, greenish-blue, and blue
- This limits our perception of color so that two different spectral distributions might appear exactly the same color, if they stimulate the receptors equally
- This lets us represent colors by combining three primaries, such as the red, green, and blue primaries used in monitors
- Each of the primaries represents a spectral distribution called a tristimulus function

# Tristimulus Functions



# Conversion From RGB

- To generate a spectral representation of color from an RGB color, just sum up each tristimulus function scaled by the R, G, or B component

$$C(\lambda) = R\bar{r}(\lambda) + G\bar{g}(\lambda) + B\bar{b}(\lambda)$$

- Unfortunately, due to the slightly negative region in the  $\bar{r}()$  function, the results may need to be clamped at 0, leading to some inaccuracy



# Conversion to RGB

$$R = \int_{\Lambda} C(\lambda) \bar{r}(\lambda) d\lambda$$

$$G = \int_{\Lambda} C(\lambda) \bar{g}(\lambda) d\lambda$$

$$B = \int_{\Lambda} C(\lambda) \bar{b}(\lambda) d\lambda$$

# Rendering Dispersion

- To render scenes with dispersion effects, rays start out from the camera the same as they normally would
- If the ray hits a dispersive surface, we would generate a refracted ray for just one wavelength
- We can randomly choose the wavelength using the color spectrum as a probability distribution
- The scattered ray will then be monochromatic and refract according to its wavelength
- The combination of many rays will average out to the desired result. As with other 'smooth' or 'blurry' effects, this may require lots of rays

