Light

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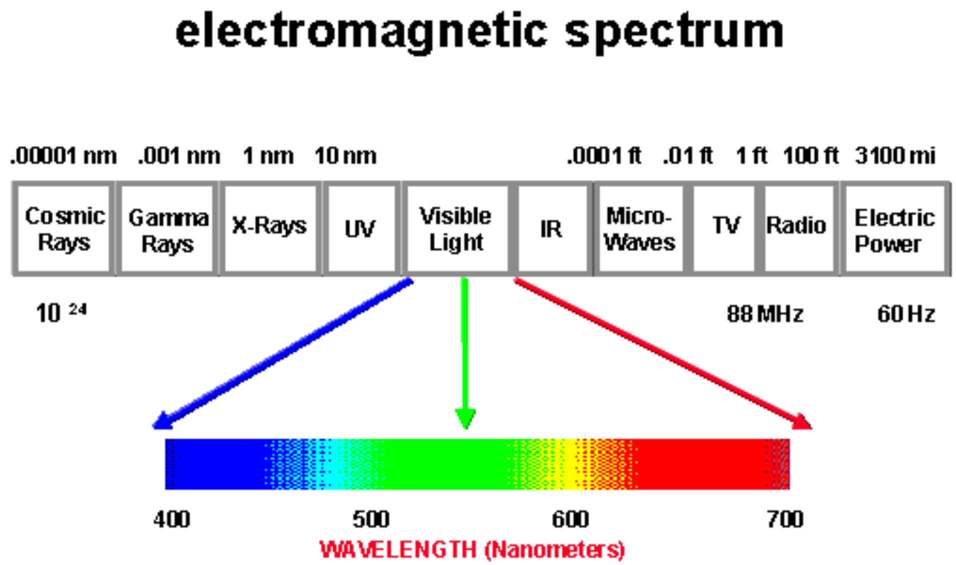
Wave or particles?

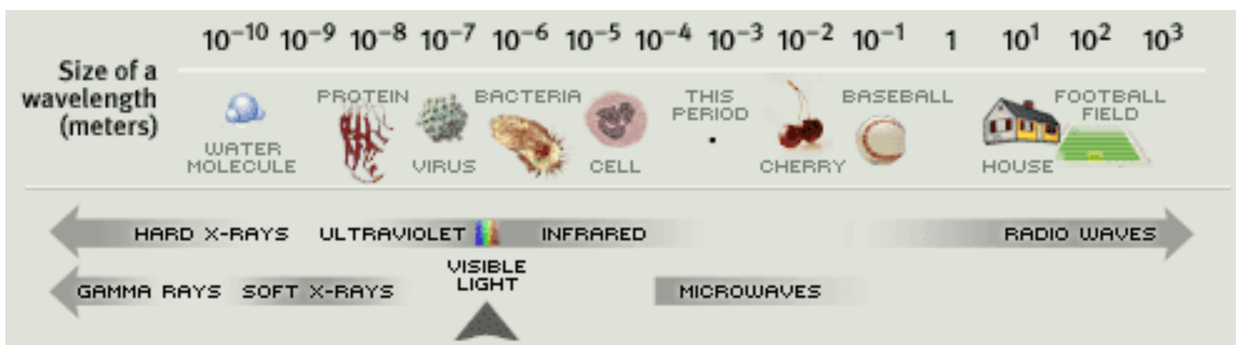
- Socrates & Plato: streamers emitted by the eyes and making contact with objects
- Most Greek philosophers: Light is made of tiny particles that travel in straight lines?
- Empedocles, then Huygens, and scientists of the 19th century: Light is a wave (shown in diffraction).
- Einstein (1905): Light is photons (mass-less bundles of electromagnetic energy)
  - Other "invisible" forms of electromagnetic waves include radio waves, microwaves, X-rays.
- De Broglie: Matter can be viewed as a wave

Spectrum of electromagnetic waves

Approximate frequency in Hertz (oscillations per second)

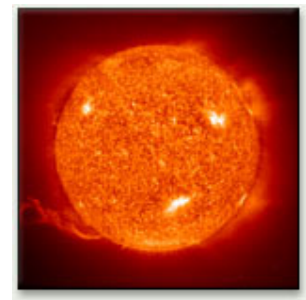
- Radio waves: 10^4
- Micro waves: 10^8
- Infrared: 10^{12}
- Light: 10^{14}
  - red (wavelength = 700nm)
  - orange
  - yellow
  - green (wavelength = 545nm)
  - blue (= 440nm)
  - violet (= 400nm)
- Ultraviolet: 10^{16}
- X-rays: 10^{17}
- Gamma rays: 10^{18}





Light sources

- Fire: Color changes with temperature:
  - black, red, orange, yellow, white, and bluish white
  - Hottest part of the flame is light blue = 1400 °C
  - The red portion is around 800 °C



- Sun
  - The emission from the 5700°C temperature of the surface of the sun gives us our definition of white
  - Visible light from the sun begins as high energy gamma rays. The Sun's energy output (3386 billion billion megawatts) is produced by nuclear fusion reactions.

- Light bulb
  - Thomas Edison (1879)

http://webexhibits.org/causesofcolor

History of color

- Newton (1704) used a prism to show that sunlight was composed of light with all colors in the rainbow. He defined it as the **spectrum**.

Black and white

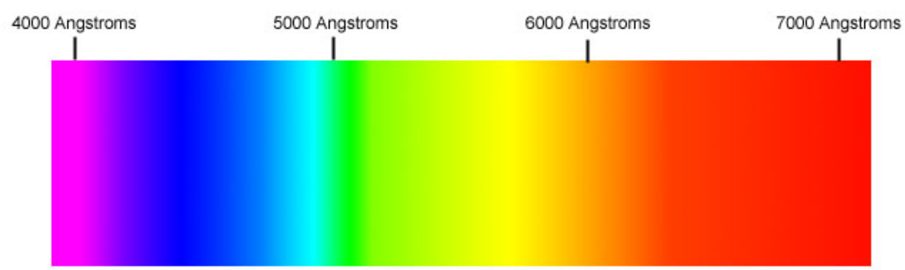
- Light combining intensity of all frequencies is called **white light.**
- Sun light is white light. It preserves the color of objects.
- **Black** is the absence of light, not a color. Object that appear black (such as carbon soot) absorb light of all visible frequencies.
- Stacked razor blades seen head-on appear black because incident light gets trapped and makes many bounces (absorptions) before emerging.
- **Achromatic** light has no color, but may vary in **intensity**, also called **luminance** (physical concept), which is perceived as **brightness** (psychological term) or level of grey.
  - We can represent it by a scalar between 0 (black) and 1 (white)

Gamma correction

- Mapping the intensity levels in [0,1] linearly to 256 levels of brightness will produce a ramp that **appears non-linear**, because the eye is sensitive to ratios of intensities, not to absolute intensity values.
  - The differences between 0.10 and 0.11 and between 0.50 and 0.55 appear the same
- Solution: use a **logarithmic** scale
  - and compensate for nonlinearities in your monitor

The color of light

- The brightness of a light source is usually **unevenly** distributed through a frequency spectrum.
- **Candlelight** lacks high frequencies. It emits **yellowish** light.
- **Incandescent** light emits light at all visible frequencies, but is richer towards the low frequencies and hence enhances the **reds**.
- **Fluorescent** light is richer in high frequencies and enhances **blues**.
- **Sunlight** has all frequencies but they have an uneven distribution: the mid-range (**yellow, green**) are stronger.
  - Since humans evolved in sunlight, we are most **sensitive** to yellow green.



HLS model of chromatic light

Color perception may be discussed in terms of:

- **Hue**: red versus green versus blue
- **Saturation** (also **chroma**): vivid red versus pastel greyish pink
- **Lightness** (also **value**): perceived intensity reflected by object
  - The term **Brightness** is used for emitters: light-bulbs

Artists discuss color in terms of

- **Tint**: the amount of white added to pure pigment to decrease saturation
  - Fully saturated (pure) color contains no white
- **Shade:** the amount of black added to decrease lightness
- **Tone:** the amount of black and white added to a pure pigment (a given hue)

Perception of color

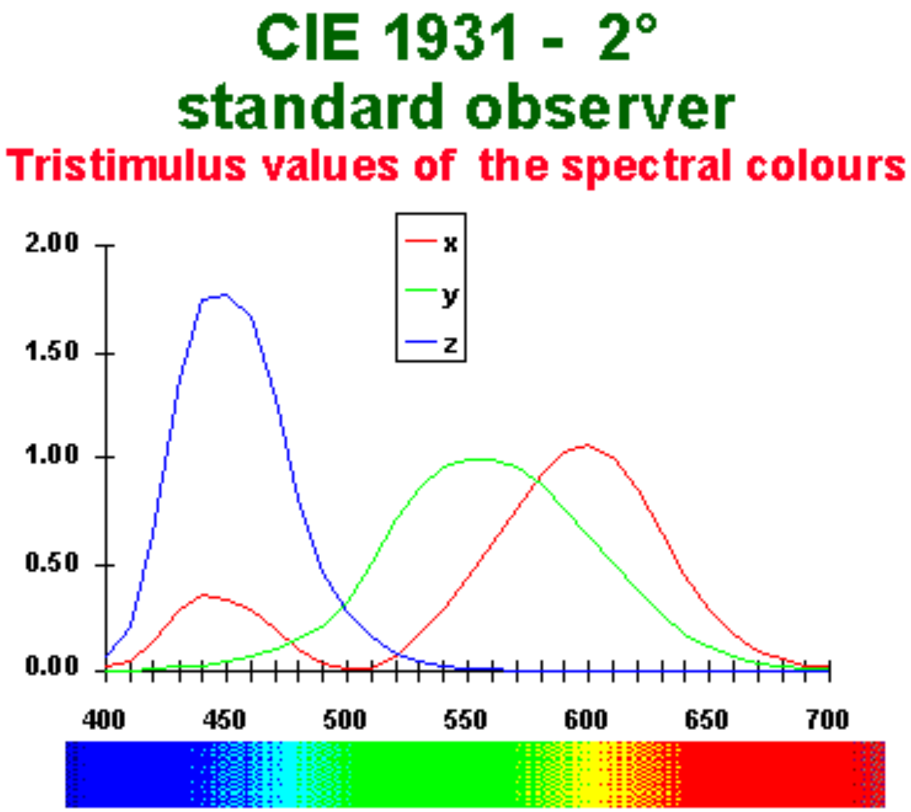
- Humans can distinguish hundreds of thousands of different colors
- Tristimulus theory (Young-Helmholtz): Humans have 3 receptors
  - red (peak response at wavelength = 580nm)
  - green (peak response at wavelength = 545nm)
  - blue (peak response at wavelength = 440nm)
- The eye's is **10x less sensitive to blue** than to the other two
  - It absorbs less energy in the blue range
- A human can distinguish about ***28** fully saturated **hues***
  - At the center of the spectrum, we can distinguish hues separated by 2nm
  - At the ends of the spectrum, hues separated by less than 10nm cannot be distinguished
  - The eye is less sensitive to hue changes in less saturated colors
- Humans can distinguish ***23** different **levels of saturation*** for a fixed hue and lightness at the extremes of the spectrum. This drops to **16 levels** at the center of the spectrum.

CIE color measures

X,Y, Z value-wavelength functions were developed by the Commission Internationale de l'Eclairage to codify color.

- Y matches the luminous-efficiency function for the human eye which plots the eye's response to light of constance luminance as the wavelength is varied.
- X and Z are modified functions that measure the amount of red and blue
- z=Z/(X+Y+Z) measures the luminance
- Color chromaticity is defined by its (x,y) coordinates in the CIE chromatic diagram, where x=X/(X+Y+Z) and y=y/(X+Y+Z)

CIE graph

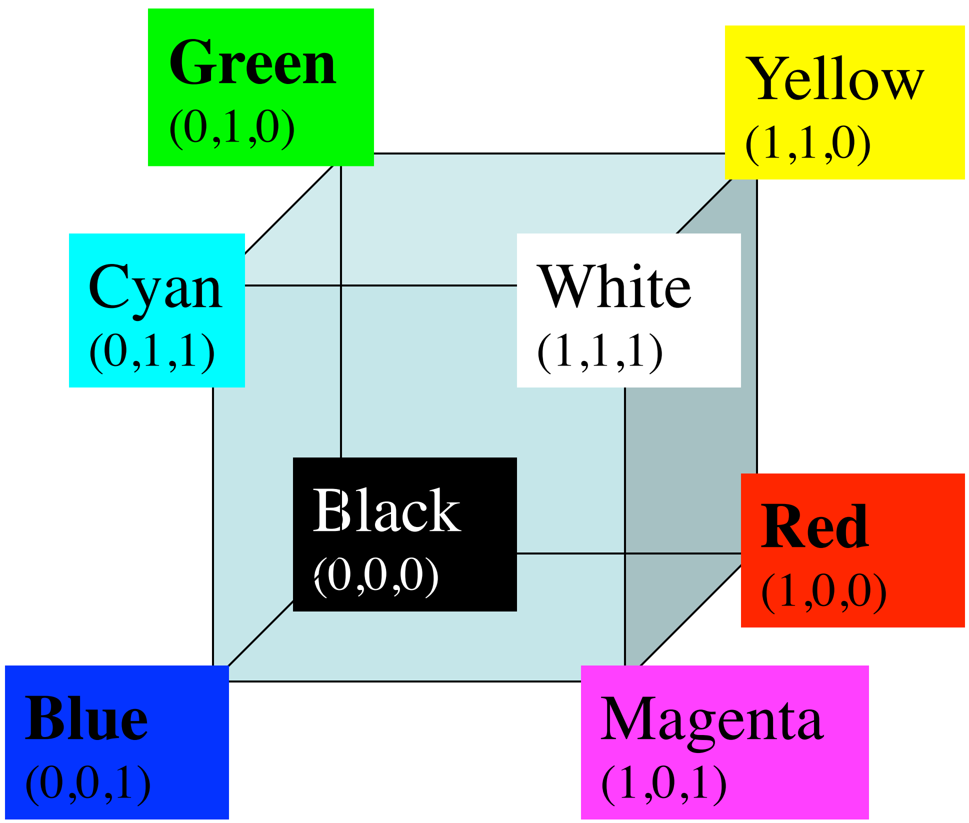


CIE 1931 - 2°
standard observer
Tristimulus values of the spectral colours
x
y
z
2.00
1.50
1.00
0.50
0.00
400
450
500
550
600
650
700

Primary additive colors: RGB

- We can divide the frequency domain of visible light into 3 regions: low frequency (red), middle frequency (green), and high frequency (blue).
- Humans have filters for measuring the amount of received energy in each region, i.e. the number of photons arriving with the frequency in the corresponding range.
- We say that red, green, and blue are the primary **additive** colors.
- Light containing equal intensities off all three appears white.
- Many other colors (hues) can be obtained by combining these three with different intensities.
  - Yellow: low (red)+middle (green)
  - Magenta: low (red) + high (blue)
  - Cyan: middle (green) + high (blue)
- We will measure the quantities of red, green, and blue as numbers between 0 and 1.

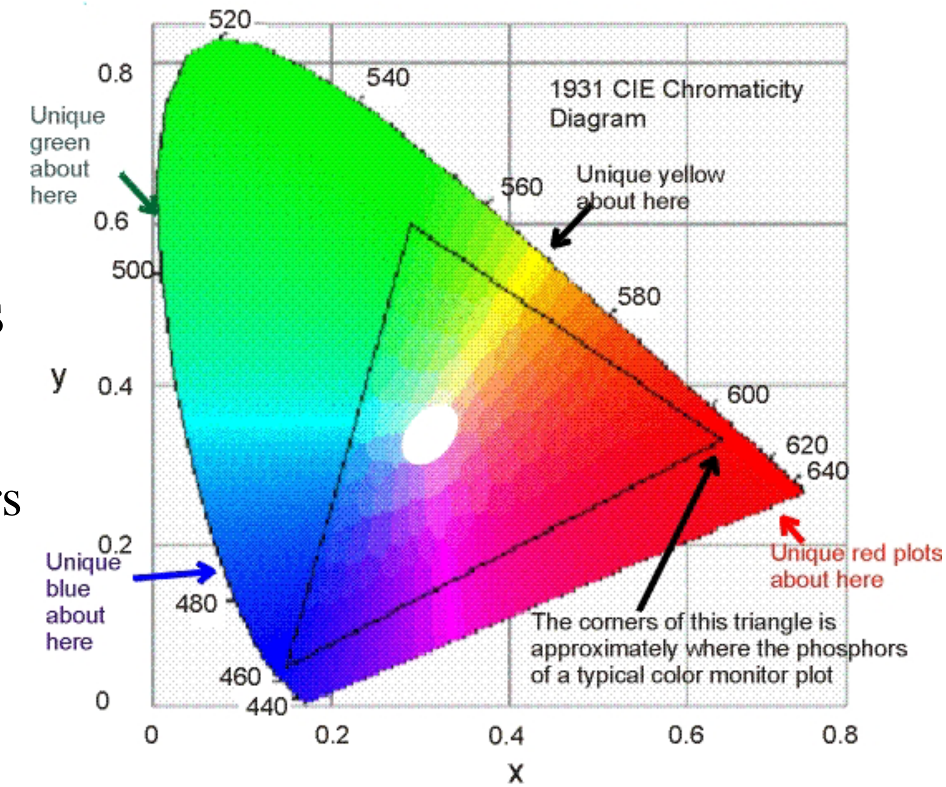
The 3D space of additive colors



Where does the gray appear?

Color Gamut

- Range of colors that may be produced by an output device/ process
- CRT has a limited gamut that does not cover all visible colors
  - It uses phosphors to emit photons of given length
  - Would need to find new phosphors to expand it
- How to render colors that are not in the gamut?
  - Use mapping that distorts the desired color range into the gamut
  - For each desired color, find the closest one in the gamut



Complementary of additive colors

- A and B are complementary colors when A+B is white
- For examples: Yellow and blue are complementary
- ComplementaryOf(R,G,B)=(1.0–R, 1.0–G, 1.0–B)
  - Cyan = 1–Red
  - Magenta = 1–Green
  - Yellow = 1–Blue

Transmitted/reflected colors

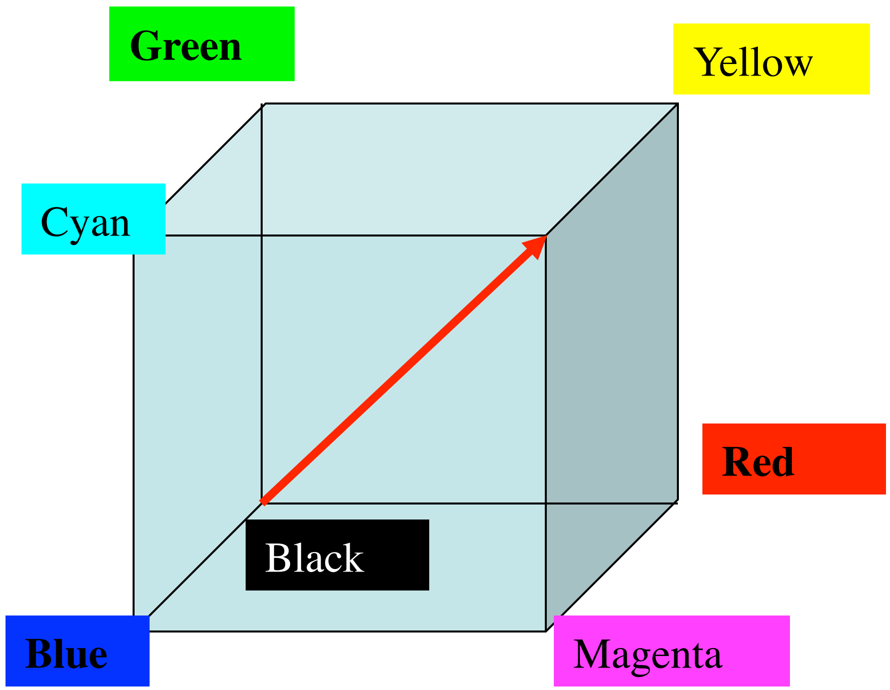
- A red **glass** appears red because it **transmit red** light but absorbs all other colors.
- Red **paint reflects red** and absorbs the other colors.
- The material that absorbs a particular color is called a **pigment**.
- Paint and dyes contain tiny solid particles of some pigments, they usually reflect a wide rage of frequencies (mixture of colors) and absorb the rest.
  - Cyan pigments absorb red

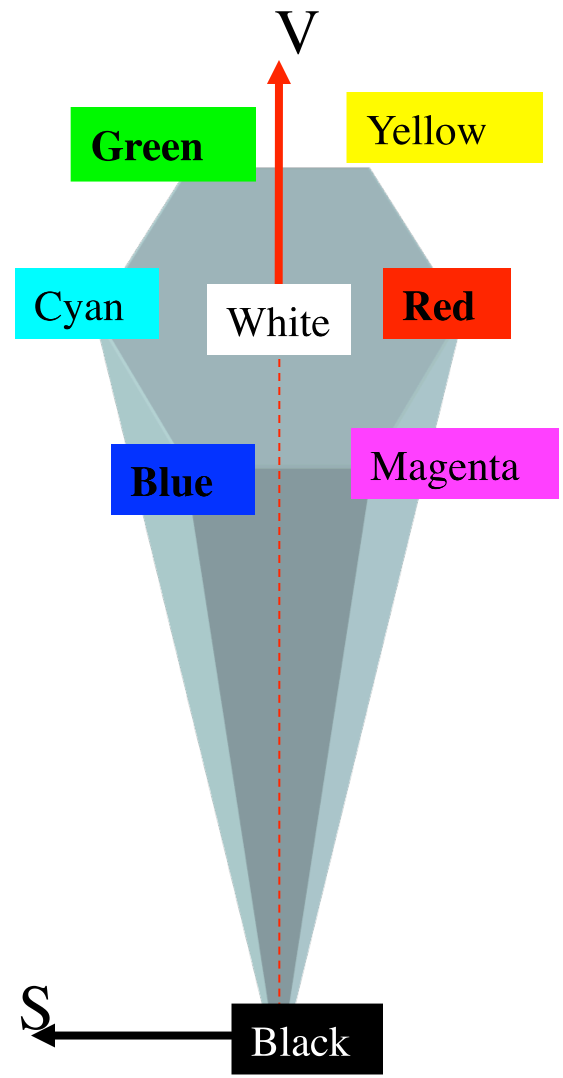
Subtractive color mixing

- **Dyes** can be mixed to combine their absorbing powers
  - Blue paint reflects blue, violet, green, but absorbs red, orange, yellow
  - Yellow paint reflects, red, orange, yellow, green, but absorbs blue, violet
  - When mixed, they reflect only green
- This is called **color mixing by subtraction**
- Primary subtractive colors: magenta, yellow, and cyan
  - The 3 most useful colors in subtractive mixing
- Color printing uses 4 successive passes with different inks:
    - magenta, yellow, cyan and black

HSV color coding

- **Hue**: cyclic [0,360] R-Y-G-C-B-M
- **Saturation**: pure color
- **Value**: Luminance or Brightness





Why is the sky blue?

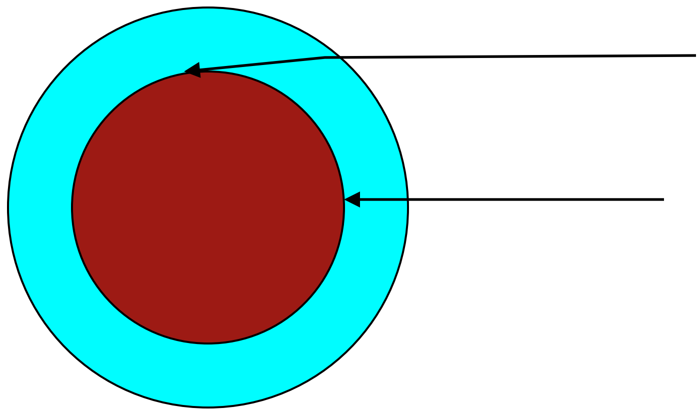
- Light is **scattered** in all directions **by** the **atmosphere** when it hits **atoms** that **resonate to** its **frequency**.
- The **tinier** the particle, the **higher** is the frequency of light that it will scatter.
- The atmosphere contains tiny **nitrogen** and **oxygen** particles.
- Most of the **ultraviolet** light of the sun is **absorbed** by the protective layer of **ozone** gaz in the upper atmosphere.
- Of the remaining visible light that passes through, **violet** is **scattered the most by the atmosphere**, **followed by blue**.
- But **our eyes are more sensitive to blue** than violet.
- When there is **dust** in the atmosphere (larger particles), the **lower frequency** light is **scattered more**, making the sky **whiter**.

Why are clouds bright white?

- They carry **water droplets** of **different sizes**, responding to **different light frequencies** throughout the visible spectrum.
- The **electrons** of a droplet **vibrate together**, scattering a greater amount of energy than the electrons of individual atoms.

Why are sunsets red?

- Low frequencies (**red**) are **scattered the least** by nitrogen and oxygen molecules.
- At **sunset**, the **light travels through a thicker atmosphere**.
- **Only** the **red passes** through.



What happens under water?

- **Red** is **absorbed by water**,
- After 30 ms, **red looks black** and **things appear green/blue**

The color of atoms

- When atoms are **far** enough **apart** (gaseous state), they **emit** their **true color** (their vibrations do not interfere).
  - Neon gas glows a brilliant red
  - Mercury vapors glows violet
  - Helium glows pink
- In **solids**, atoms are crowded together their **colors** are **combined** to produce a **continuous spectrum**.
- The light emitted from each different element produces a **different graph of light intensities as a function of frequency**.

How does light move through space?

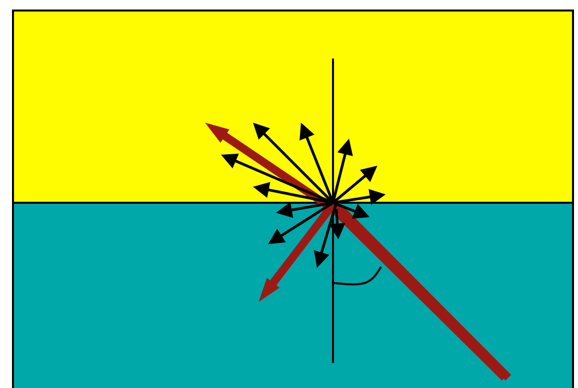
- **Radiance**: measures intensity L(**d**,**p**,w) of light (density of photons) of a wavelength w traveling through a point **p** in direction **d**
  - measured in watt/(sr m^2): as power per unit area and per unit solid angle
- Our eyes and cameras measure radiance at point **p** for a set of directions **d**
- Knowing radiance everywhere describes light completely
- Radiance along an unblocked ray is constant!
  - Why is this true? Energy falls off as $1/r^2$
- We only worry about what happens when photons hit a surface.
  - Reflected radiance is proportional to incoming radiance
- Other measures
  - **Total radiance**: Integral of spectrum radiance over all frequencies
  - **Irradiance**: Total power per unit area incident onto a surface, in watt/m^2
  - **Radiosity**: in watt/m^2
  - **Intensity**: in watt/sr

Material response to light

- **Electrons vibrate** when submitted to a light wave
- How they respond depends on the **light frequency** and the **natural frequency** of the material (how strongly the electron is attached to the nearby nucleus)
- Electrons excited at their natural **resonance** frequency develop a large vibration with respect to their atomic nucleus.
- Vibrating atoms can pass this energy to neighbors (collision) or remit it as light. But when they keep resonating, they heat up and absorb light.

What happens to light hitting a surface?

- Some of it is **reflected** (bounces back)
- Some of it is **refracted** (goes inside the material)
- Some of it is **absorbed** (heat, vibration)
- The proportion of reflected, refracted, and absorbed light depend on the medium and may be different for each frequency of light.
- For a given frequency, the amount of light reflected and refracted in a given direction by an isotropic surface separating two media depends on the speed of light in both media and on the angle between the direction of incident light and the surface normal.
- Light may also be **scattered**
  - by the medium it traverses



Why does light pass through glass?

- Electrons in glass have a natural frequency in the ultraviolet range, so glass is not transparent to ultra-violet.
- But the **lower frequency** of visible light does **not** make them **resonate**. Electron vibrations have smaller amplitude and atoms do not collide as much. Instead of heat, they re-emit all the energy as light to neighboring atoms.
- Light **propagates** through the glass. Glass appears transparent.
- However, there is a **delay** between absorption and re-emission: **Light slows down** in glass.
- Glass blocks ultraviolet and infrared.

Reflective surfaces

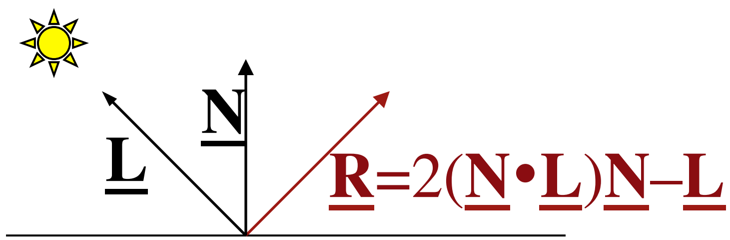
- Metals are opaque.
- The **outer electrons** of atoms in metal have very **weak connections** to the nucleus and are free to wander through the material. (That is why metal is a good electric and heat conductor.)
- When light shines on metal, it **sets the free electrons into vibration**, their **energy** is not turned into kinetic energy (vibration with the nucleus) but is instead **re-emitted as visible light** (shiny reflection).

Reflected color

- If a material is **opaque to light at a particular frequency**, it reflects the light back to the external medium. If not, it absorbs it or transmits it through to the other side.
- Different materials have different natural frequencies for absorbing and reflecting light.
- If a material absorbs light at most frequencies but reflects red, it appears red.
- White material reflect lights at all visible frequencies and appears to take the color of the light that shines upon it.
- Cells that contain **chlorophyll absorb all but green** frequencies.
- Most objects reflect a spread of frequencies, but they can only reflect the frequencies present in the incident light.

Mirror reflection

- Light that bounces from a surface back into the medium it was coming from is reflected
  - A metal surface reflects light with almost full intensity for almost all frequencies (sliver can be used for mirrors)
- **Law of reflection**
  - Reflected direction **R** is computed from direction **L** to the light source and the surface normal **N**.



- The image of a scene with a **mirror** can be computed by considering a virtual mirror copy of the scene that could be seen through the mirror.

Speed of Light

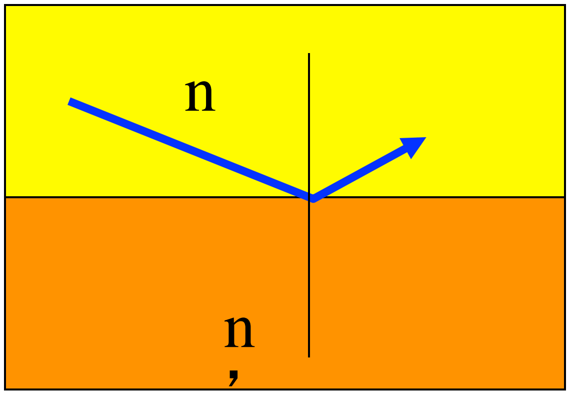
- Galileo tried to measure it but could not
- Roemer (1675) measured that the moon, Io, seems to revolve slower around Jupiter when the earth is moving away from it.
- Huygens concluded that light travels at 300,000km/s
- Michelson (1880) measured it as 299,920km/s by adjusting the speed of a spinning mirror 35 kms away from the source.
  - He got the Nobel prize for this.
- Light travels at **c=300,000km/s** in the vacuum.
  - It travels at **0.75c** in **water**, at 0.67c in glass and at 0.40c in diamond.
  - Light can make 7.5 trips around earth in one second.
  - Light takes 8 minutes to travel from the sun to earth and 4 years from the next nearest star (Alpha Centauri).
  - Our galaxy has a diameter of 100,000 light years.

How much light is reflected

- Assume that c is the speed of light in the vacuum and that kc is the speed of light in medium M
- The **index of refraction** of medium M is: n=1/k

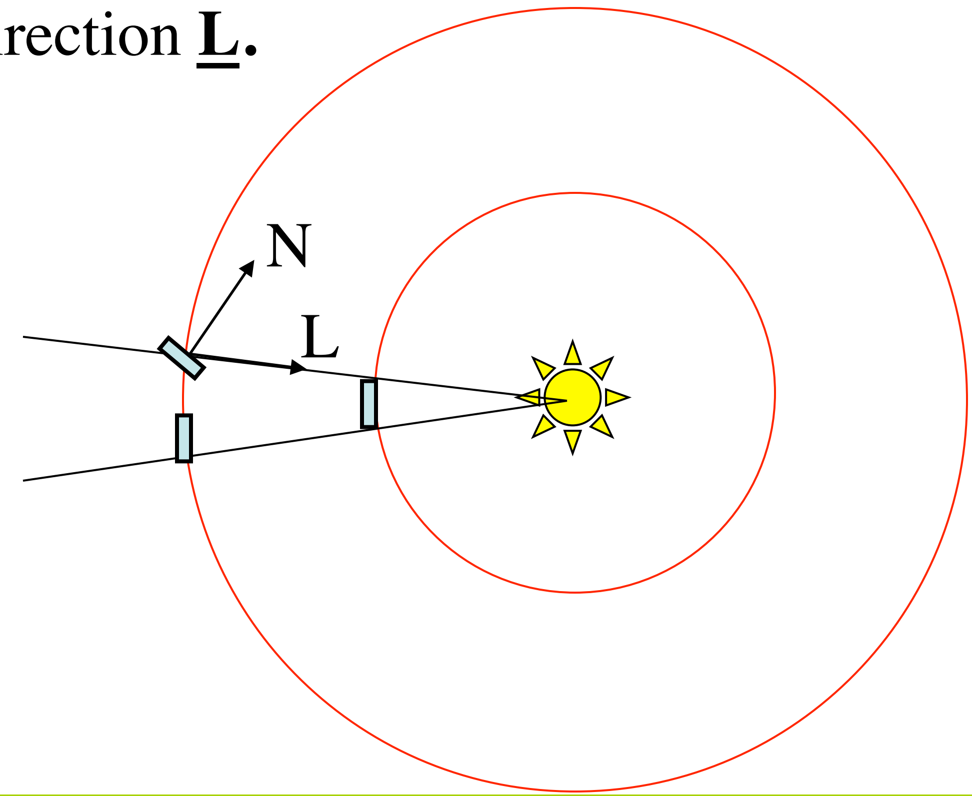
- The proportion of light arriving from medium with index n that is reflected by the surface separating it from a medium of index n' is:

$(n'-n)^2/(n'+n)^2$



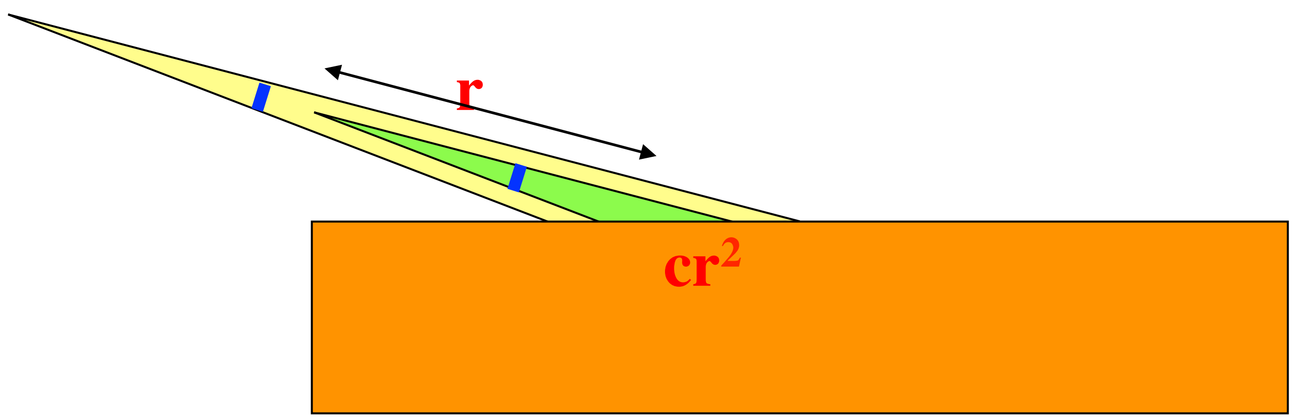
Incident energy depends on distance from source

- The light (**energy received**) by a unit differential surface area is proportional to $1/r^2$, where r is the distance from the **light source**.
- Thus, the **light received** by a surface unit differential area with normal **N** is $\mathbf{N}\bullet\mathbf{L}/r^2$, and hence **depends on the distance from the light source** in direction **L.**



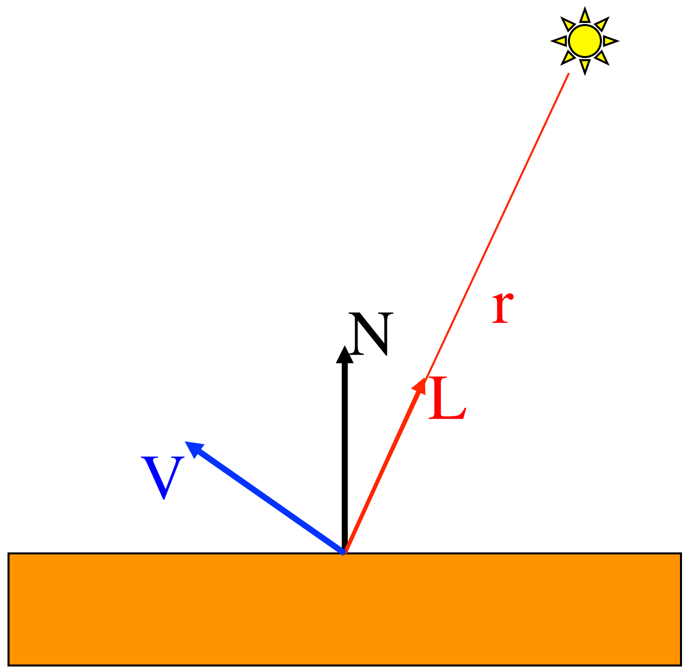
Reflection is independent of distance to viewer

- The intensity of **light reflected** by a **Lambertian surface** towards the viewer that goes through a unit area (screen pixel) is **not dependent on distance r between surface and viewer**
  - The $1/r^2$ attenuation of the energy of reflected light emitted by surface elements is **compensated** by the fact that the amount of surface **seen in the cone is proportional to r^2.**
- Hence, in graphics, we assume that the amount of **light that travels along an unobstructed ray is constant**
  - Ignore atmospheric attenuation and specular reflections.



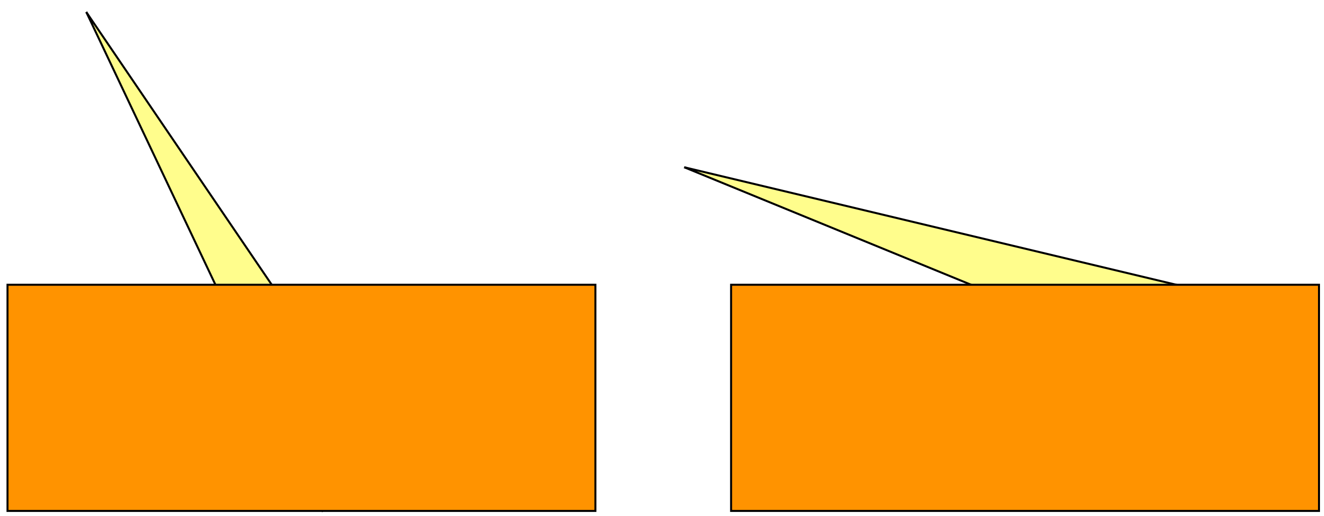
Diffuse reflection

- Light incident upon a (rough, matte, chalk-like) "**Lambertian**" surface is reflected in all directions.
  - Because rays hit facets in different orientations
- **Lambert's law**: The amount of light **reflected** by a unit differential area of a Lambertian surface in the direction V is **proportional** to N•V



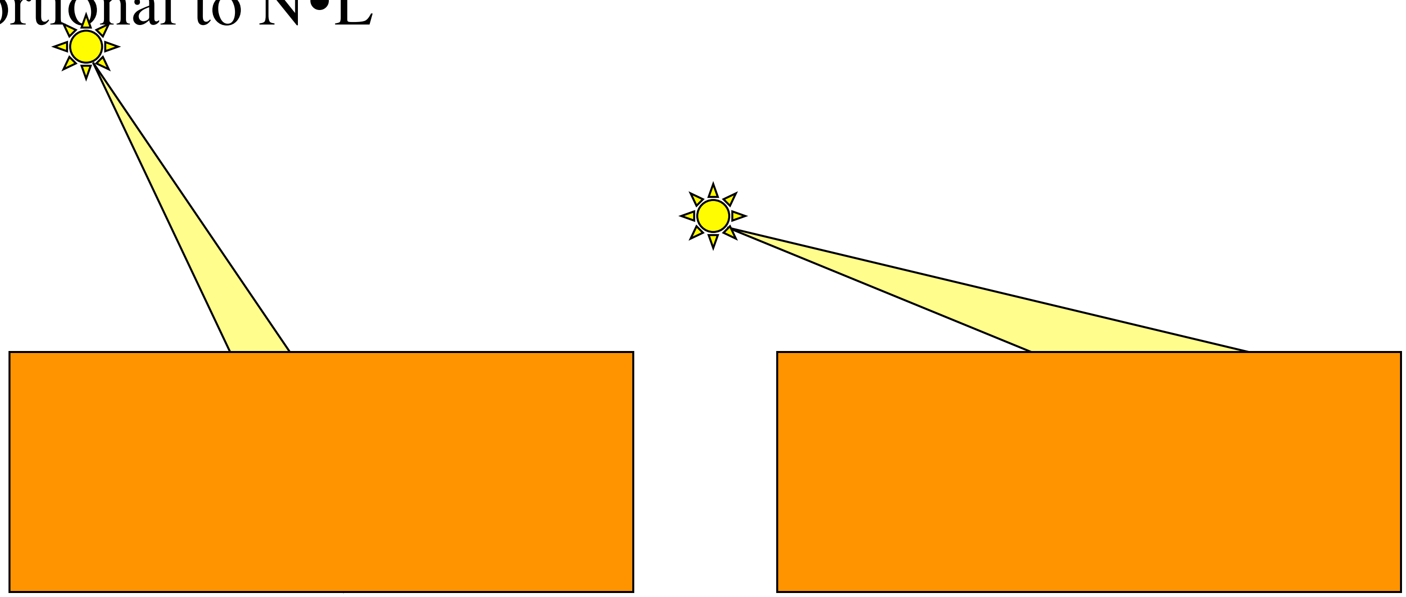
Lambertian reflection is uniform

- **Lambert's law**: The amount of light reflected by a unit differential area of a Lambertian surface in the direction V is **proportional** to N•V
- The amount of surface area seen from direction V is **inversely proportional** to N•V
- The latter two cancel out: **A Lambertian surface appears equally bright from all viewing angles.**



Arriving energy is proportional to N•L

- **Beam** of light with unit differential solid angle arriving from a point light source located at direction L upon a locally flat Lambertian surface with normal N covers an **area** inversely proportional to N•L
- If a light source emits equal amounts of energy in all directions, then the energy arriving upon a differential unit surface will be proportional to N•L



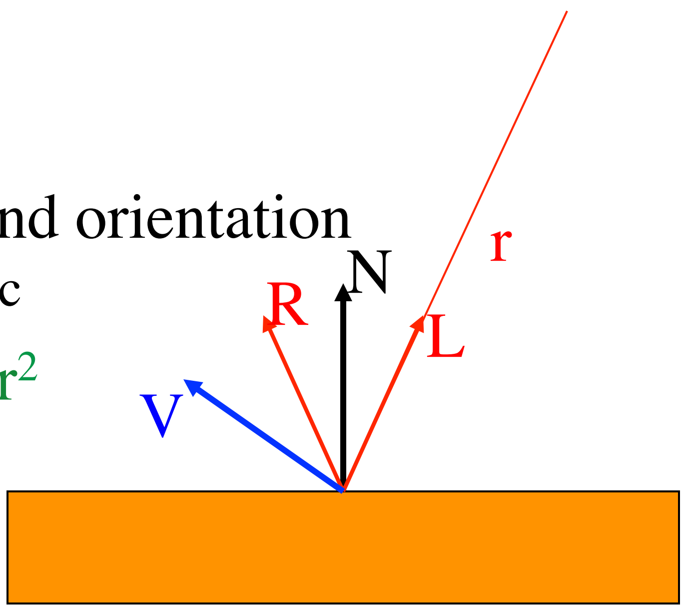
Specular reflection

- A shiny (polished) surface is called **specular**
- A surface may be specular for some frequencies and (lambertian) for others.
  - If the surface elevation varies by less than 1/8th of the wavelength of the light, it is considered polished.
  - An antenna made of wires may seem polished for long radio waves.
- **Highlights** in shiny surfaces
  - Highlights reflected by waxed or shiny plastics reflect the colors of the incident light and are not affected by the color of the material.
  - The highlight is most visible in areas where the viewer would see a mirror reflection of the light source (assuming a perfect mirror).
  - As the angle between the direction of the reflected ray R and the direction V to the viewer increases, the highlight decreases rapidly. The fall-off curve depends on the surface property.
  - **Phong** approximated it by $(V \bullet R)^n$

Reflection model

- k_a = **ambient** light reflection coefficient
- Distance attenuation of incident light: I/r^2
  - I = Intensity of point light source at distance d in direction L
  - The attenuation effect is often softened to $\max(I/(ar^2+br+c),I)$
- **Diffuse** (Lambertian) reflection: $k_d(N \bullet L)$
  - k_d = diffuse reflection coefficient
- **Specular** (Phong) reflection: $k_s(V \bullet R)^n$
  - k_s = specular reflection coefficient
  - n = specular reflection exponent
- k_a, k_d, k_s, & n may vary with frequency and orientation
  - Some surfaces (CD groves) may be anisotropic

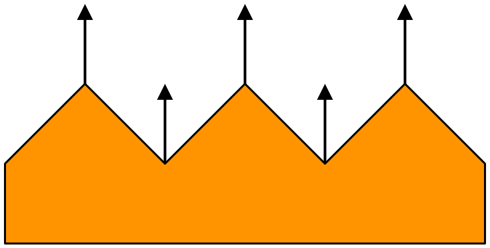
Reflected light: $k_a + (k_s(V \bullet R)^n + k_d(N \bullet L))I/r^2$



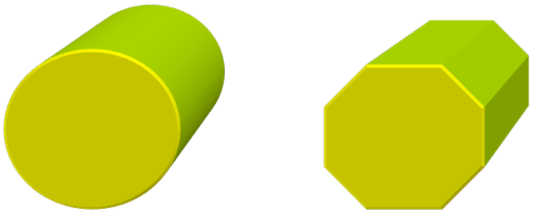
Simplified shading model

- Assume **light is at infinity** in the direction L
- Assume **viewer is at infinity** in the direction V
- Use $k_a + \left(k_s(N \bullet H)^n + k_d(N \bullet L)\right)I$
  - with H=(L+V)/|L+V|
- We can assume that the **shading is constant** over a polygon (flat shading)
- Or we can compute the color of each vertex of a triangle using the shading model and then interpolate the color as a linear function through the triangle
  - First proposed in 1967 by Wylie et al.
  - Generalized to polygons by Gouraud in 1971
- Phong proposed to compute the normal at each vertex and to interpolate its three coordinates over the triangle, normalizing it for each pixel before re-computing the shading (color) of each pixel.

Limitation of shading models

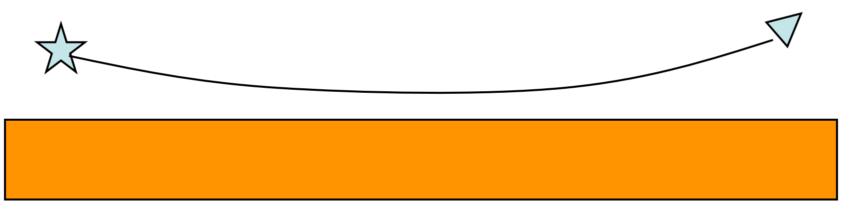


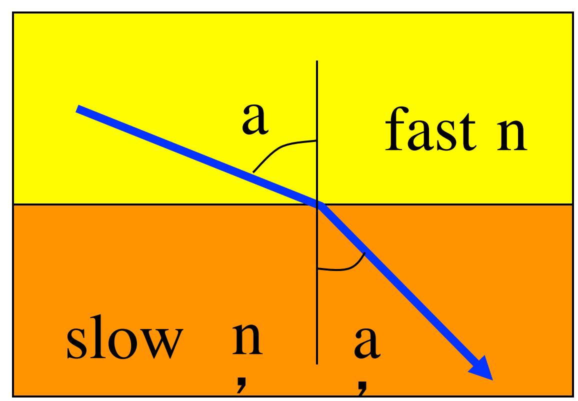
- Smooth shading may hide surface details
  - Wave looks flat when all vertices have same normal
  - Solution: Subdivide
- Silhouettes do not look not smooth
  - Solution: Use adaptive subdivision (modified 4-points)
- When applied to more general polygons (not triangles) the simple interpolation schemes are dependent on the screen orientation.
- Under perspective, a linear interpolation of a value (color, coordinate) does not produce constant differences between one pixel and the next. The correct interpolation involves a division per pixel.
- Some vertices and edges are not smooth, we should use a different normal at each corner).



Refraction

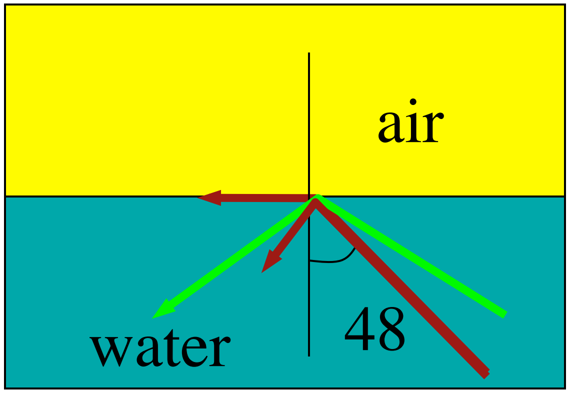
- Light that penetrates the new medium is refracted
- Its trajectory bends inwards when entering a slower medium
  - Think of the right wheel of a cart slowing down first
  - Similarly, sounds bends towards cooler air
- Assume that kc is the speed of light in medium M and k' c is the speed of light in medium M'
- Index of refraction of a material M is: n=1/k
- Snell' s law (1621): sin(a)/k=sin(a')/k'
- A hot road appears wet because light is bending, since light travels faster through the hot air near the ground





Total reflection

- When a light ray in water forms an angle of more than 48 degrees with the surface normal (critical angle), it is completely reflected
- The critical angle for diamond is 24.6
- Optical fibers rely on total reflection to carry information

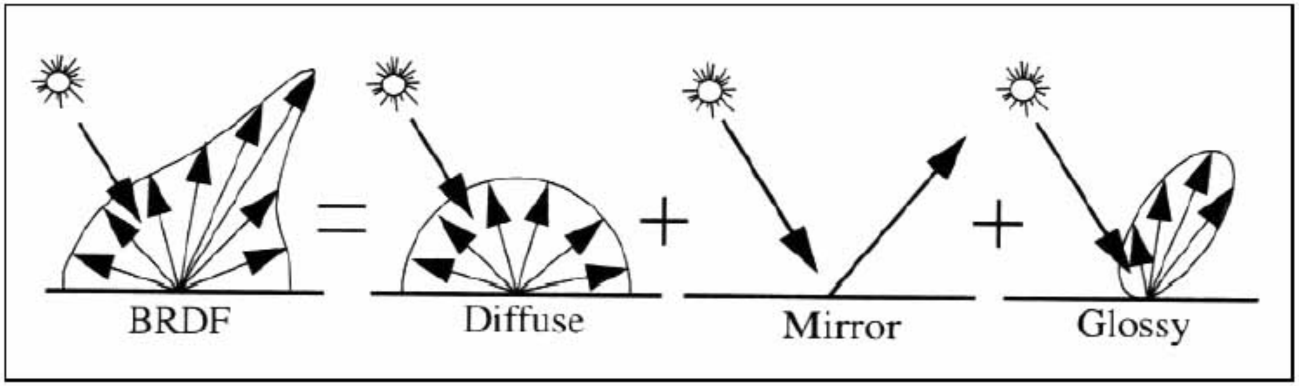


Why do wet things appear darker?

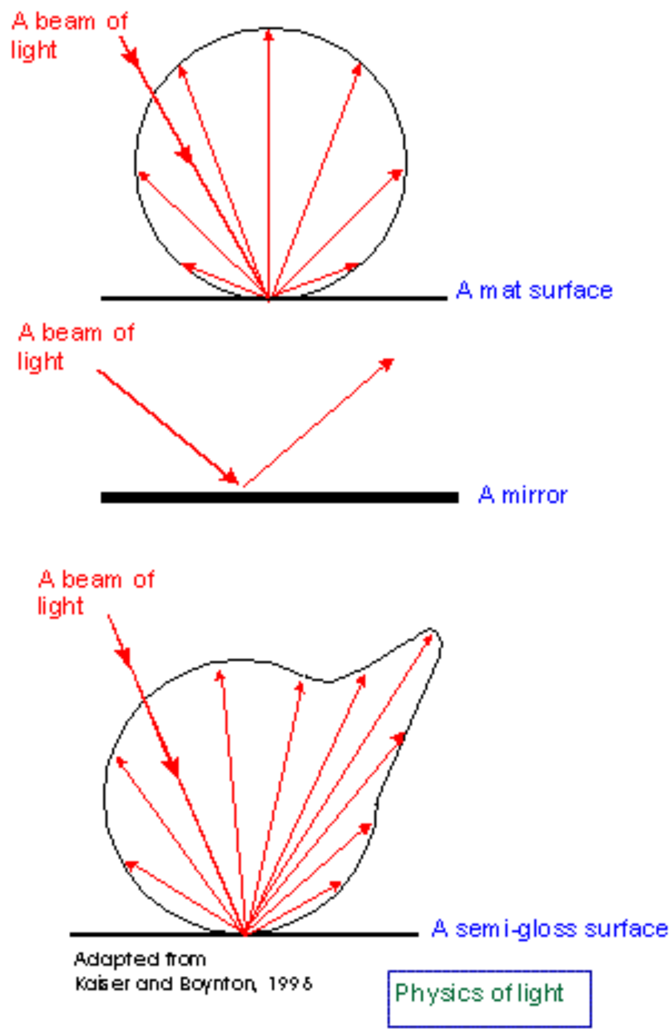
- Light bounces off dry material directly into your eye
- Light incident upon a wet surface bounces several times in the transparent wet layer before leaving for your eye. At each bounce, some light is absorbed and turned into heat.
- Thus wet material appears darker.

Bidirectional Reflectance Distribution Function (BRDF)

- Surface property at a given point which defines the ratio of the outgoing energy in a direction **V** to the incoming energy from a source in a different direction **L**
  - Bi-directional (function of two directions)
  - Depends on the wavelength
- Helmholtz reciprocity principle
  - Revert light direction: the BRDF is the same
- In general, for smooth surfaces, the BRDF is not altered by a rotation of the surface around the normal.
  - Then the BRDF function takes only 3 parameters. For example:
    - ✓**N•L**
    - ✓**V•R**
    - ✓**V•N**
- Units: 1/sr



Mat and glossy reflections

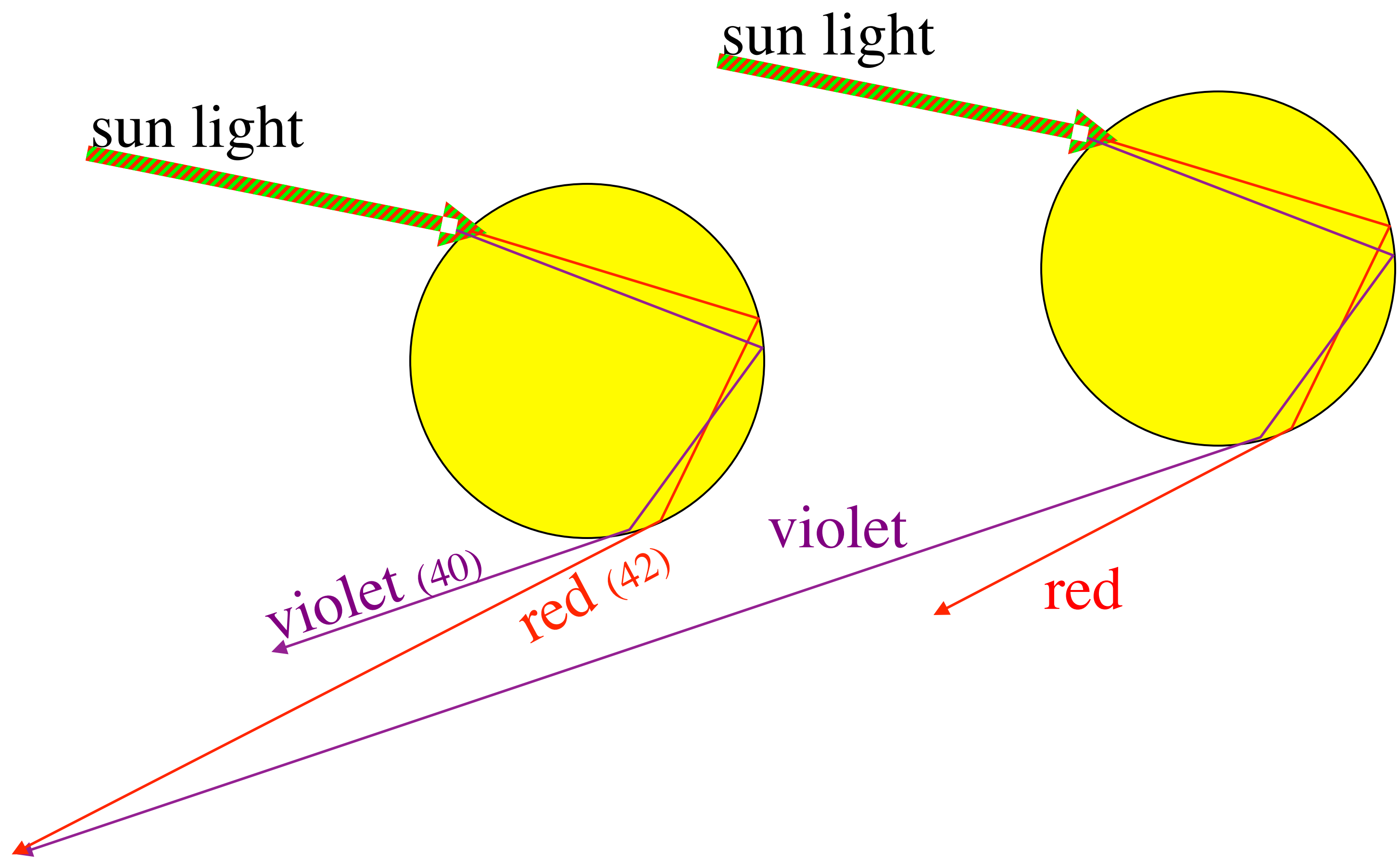


Polarization

- The vibration of a photon is transversal to its direction of propagation (like the waves traveling along a rope).
- A single vibrating electron emits a light wave that vibrates in a single plane (polarized).
- Common light sources are not polarized. Their electrons produce light waves vibrating in random planes.
- A polarizing filter will block all waves except those aligned with the filter's axis.
- When light reflects on a shiny horizontal surface, it is polarized horizontally.
- Polarized glasses have a vertical axis to block the glare from horizontal surfaces.

Dispersion

A droplet of water disperses light into a rainbow



Light rays and shadows

- **Ray** = thin beam of light
- With a single small light source, points that do not see the light because light rays towards them are blocked by an object are in the **shadow**.
- With a larger ("area") light source, the **penumbra** is the set of points that can only see a portion of the light. The **umbra** is the set of points that do not see any.