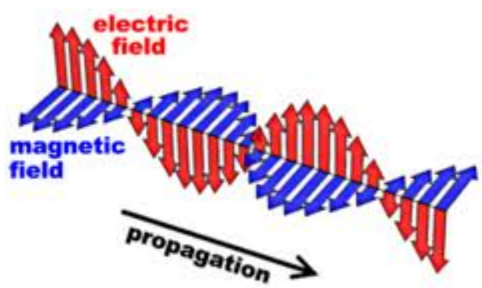
Electromagnetic waves - the wave commonly known as light[1]

An oscillating charge, like the charges in an alternating current, make vibrations in the electric and magnetic field and are called are **electromagnetic (EM) waves**. As compared to mechanical waves, these waves can travel through empty space because they don't require a medium. EM waves are the fastest things in the universe, traveling at the speed of light, represented by the letter c:

$$\mathbf{c = 3.0 \times 10^8\ m/s}$$

For comparison, at that speed a light beam travels 2770 miles from New York to Los Angeles in **0.015 seconds.** Note that this speed is for light traveling in a vacuum and is roughly the same speed for light traveling through air.



Sound vs. Light

Where sound waves are longitudinal waves, EM waves are **transverse waves**, and vibrate in the electric and magnetic fields perpendicular to the axis along which the energy travels. EM waves slow down in anything other than a vacuum.

Though different from longitudinal waves, the wave formula $v= f\lambda$ still holds for them.

The loudness of a sound wave is directly related to the amplitude of a sound wave.
The amplitude for an EM wave is directly related to the intensity or brightness of the wave.

The frequency for a sound wave represents pitch (high pitch means high frequency) whereas for **visible light** frequency denotes color (violet has the largest frequency and red the lowest).

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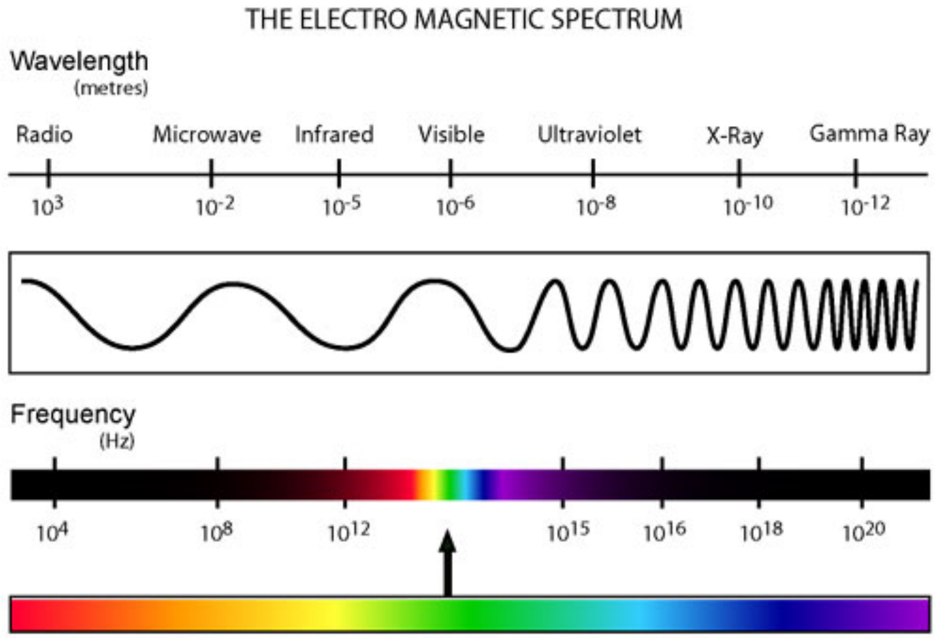
[1] a riff on the music artist Prince who had briefly changed his name to the symbol 
.https://en.wikipedia.org/wiki/Prince_(musician))



Electromagnetic spectrum

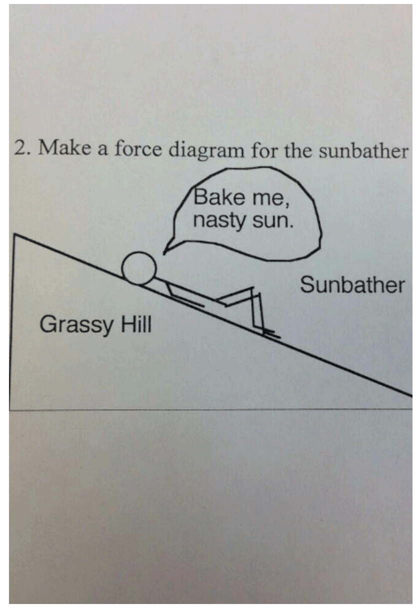
Frequency define the **electromagnetic spectrum** into types of EM waves, which have very different properties. The main frequency ranges, from low to high frequency, are:

1. **radio** (10^6 Hz) – created by alternating current; used for communication.
2. **microwave** (10^8 Hz) – created by alternating currents; observed as the leftover radiation in space from the Big Bang; used for cooking, communication with satellites and cellphones
3. **infrared** (10^{12} Hz) – created by electron transitions in atoms, and detected by your body as heat; used for fiber-optic communication, TV remote controls, some night vision cameras
4. **visible light** (10^{14} Hz) - created by electron transitions in atoms, it is the very narrow part of the spectrum your eyes are tuned to detect. The frequency defines the color of light, with red the lowest, followed by orange, yellow, green blue and violet the highest (ROYGBIV).
5. **ultraviolet** (10^{15} Hz) – created by electron transitions in atoms. These waves carry enough energy to be dangerous to cells, and can cause skin cancer; Used to kill bacteria, and detect/write invisible inks on money
6. **x-rays** (10^{18} Hz) – created by high velocity electrons hitting matter and are commonly found in stars; used for imaging through solid materials; very energetic and dangerous
7. **gamma rays** (> 10^{20} Hz) – emitted by radioactive atoms and nuclear reactions; very dangerous; used to kill cancer tumors.

Stars like the Sun emit EM waves throughout the entire spectrum, but the harmful waves (ultraviolet, x-rays and gamma rays) are **mostly** absorbed by the atmosphere. [2]

Although our eyes can only see in the visible range, we use instruments to make images using other parts of the spectrum, and have computers "map" those images into visible light so we can see them. For example an infrared image of a house tells you where you need insulation in winter. Radar uses microwaves for weather forecasting imagery, to tell where clouds are densest and most full of rain.

[2] You should still wear sunscreen and apply it frequently throughout the day!



Sunbathing and UV protection

Ask the expert[3]: *Does a higher-SPF (sun protection factor) sunscreen always protect your skin better than a lower-SPF sunscreen? How high should I go?*

A: Sunscreens with a higher SPF should offer more protection from the sun's harmful ultraviolet (UV) radiation, which is linked to the vast majority of skin cancers, as well as premature skin aging and eye damage. **But the answer is not that simple.**

UV radiation reaches the earth in the form of UVB and UVA rays. UVB radiation plays a key role in skin cancer, and SPF refers mainly to the amount of UVB protection a sunscreen offers. Thus, higher SPFs can help: An SPF 15 sunscreen blocks 93 percent of UVB radiation, while an SPF 30 sunscreen blocks nearly 97 percent. Furthermore, higher SPF values offer some safety margin, since consumers generally do not apply enough sunscreen. To evaluate SPFs, testers apply two milligrams of sunscreen per square centimeter of skin. **BUT** in everyday life, most people apply from only 0.5 to one milligram per square centimeter of skin. Consequently, the actual SPF they achieve is approximately 1/3 of the labeled value.

Despite these advantages, there are potential downsides to using products with very high SPFs. First, above SPF 50 (which blocks an estimated 98 percent of UVB rays), the increase in UVB protection is minimal. Second, although UVA protection is also important (UVA not only accelerates skin aging, but contributes to and may even initiate skin cancers), SPFs mainly measure UVB protection. Individuals applying high-SPF sunscreens may not burn (UVB is the chief cause of sunburn), but without UVA-screening ingredients they can still receive large amounts of skin-damaging radiation. To avoid such a scenario, regulatory bodies in Europe and Australia have adopted UVA testing guidelines and measurement standards, and capped the SPF of sunscreens at 50+. The US Food and Drug Administration (FDA) may do the same, but hasn't to date.

Products with very high SPFs may also encourage individuals to neglect other photo protective behaviors, like seeking the shade and wearing sun-protective clothing. By preventing sunburn, sunscreens with very high SPFs can create a false sense of security, prompting consumers to stay out in the sun longer. Sun damage (for example, UVA damage) can take place without skin-reddening doses of UV radiation, and even the best sunscreens should be considered just one vital part of a comprehensive sun protection regimen.

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[3] from http://www.skincancer.org/skin-cancer-information/ask-the-experts/does-a-higher-spf-sunscreen-always-protect-your-skin-better

The importance of using both UVB and UVA protection cannot be emphasized enough.

For patients who really wish to know "how high should I go?" **I suggest products with SPFs no lower than 30 and no higher than 50.** In addition to an SPF of 30+, your sunscreen should include some combination of the following UVA-blocking ingredients: zinc oxide, titanium dioxide, avobenzone, ecamsule, and oxybenzone. Sunscreens with both UVA and UVB protection may be labeled multi spectrum, broad spectrum, or UVA/UVB protection.

- Dr. Wang is director of dermatologic surgery and dermatology at Memorial Sloan-Kettering Cancer Center at Basking Ridge, NJ. Dr. Wang is a member of The Skin Cancer Foundation's Photobiology Committee.

Light wave phenomena – polarization and coherence

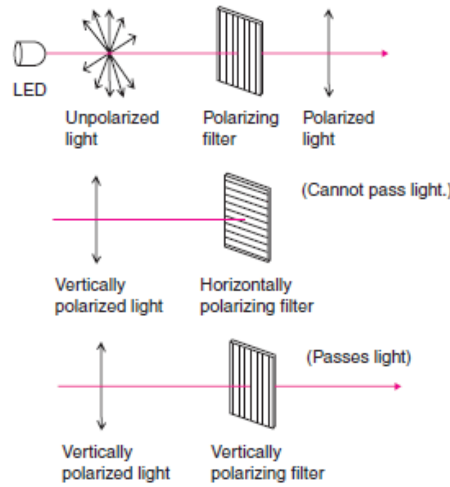
While light waves exhibit all wave behavior we previously studied, two phenomena only happen with electromagnetic waves and not with sound. This is because these require **transverse** vibrations.

Polarization

Most light is made of waves vibrating in all different planes/directions, like the light from the LED in the picture.

When we say light is **polarized,** the light is not vibrating in those directions but only in the same plane. (see figure to the right, image 1)

A **polarizing filter (polarizer)** is a piece of film that only lets waves vibrating in one specific plane pass through, so the light passing through is polarized in the same plane as the filter. If you then pass this polarized light through a second polarizing filter, rotated 90^{o} to the first one, it will block all the light. (figure to the right, image 2)



Remember that sound waves can't be polarized, because they vibrate along the line of travel - a polarizer cannot block them.

Naturally polarized light and applications of polarizers

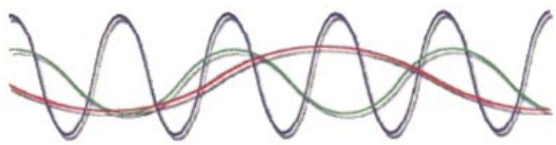
Glare off a shiny surface, like the surface of a lake, is an example of naturally polarized light. People wear polarized sunglasses to block glare off flat surfaces. Photographers use polarizing filters to limit the intensity and directions of light for clearer photos.

with

without

Liquid crystal displays (LCD's) have polarizing filters in them. The characters are displayed when a current makes molecules in the display line up and polarize at 90^{o} to the filter, so that the molecules turn dark.

Coherence – lasers (pew! pew!)[4]



Sunlight (many different colors)

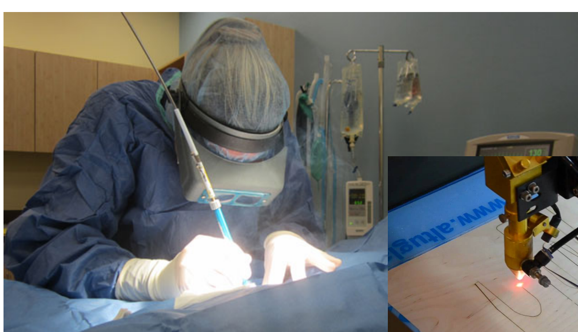
The other phenomenon requiring transverse vibrations is **coherence.** Coherent light (lasers) has two properties:

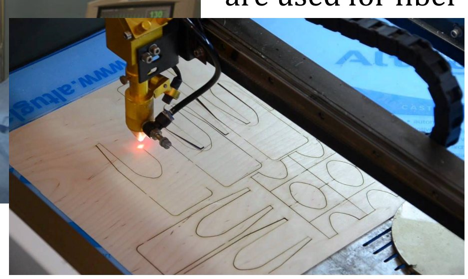
1. the waves are all the **<u>same wavelength</u>** and thus have the same color.
2. These **monochromatic** ("one color") waves have all of their crests lined up and are **<u>"in phase"</u>**.

LED: one color (monochromatic) and waves not in phase (non-coherent)

LASER: One color (monochromatic) and waves in phase (coherent)

As a result, the waves all interfere constructively, resulting in a very large amplitude wave and a very bright intense light with very little power.





Light **A**mplification by **S**timulated **E**mission of **R**adiation, or LASERs, make coherent light and are used for fiber-optic communication, reading and writing CD's and DVD's and for welding, cutting or surgery.

---

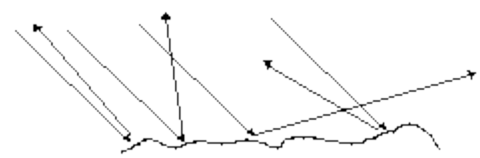
[4] the sound effects of laser blasters make in movies (as seen in Star Wars). Note that this sound is manufactured and not realistic.

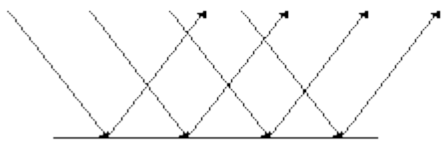
Light reflection

For light, there are two types of reflection. **Specular (or regular) reflection** happens when light rays reflect in a highly organized way to form an image. This only occurs off a mirror-smooth surface, like polished metal or glass.

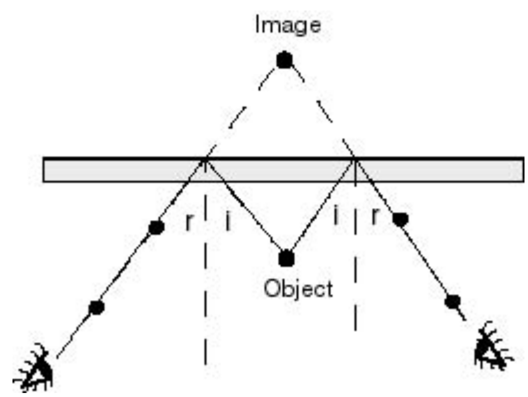
Diffuse reflection is when light is reflected in a scattered way from a surface, without making an image. This is how light reflects off most surfaces, because most smooth surfaces are rough when seen up close. <u>We see objects because of diffuse reflection.</u>

The image below is specular/regular reflection.
The image on the right displays diffuse reflection.





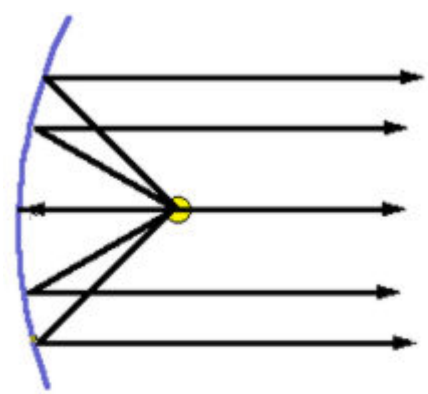
A **plane (or flat) mirror** makes a life-size image. It is called a **virtual image** because it is behind the mirror – no light rays are actually where the image seems to be. The image seems to be the same distance behind the mirror as the object is in front, but is reversed right-to-left. To locate the image of a point in a plane mirror:



1. draw two incident rays from the object to the mirror, and their reflected rays (recall $\theta_i = \theta_r$)
2. trace the reflected rays back behind the mirror until they cross

Your eye assumes all light rays go in straight lines, so your brain traces back the reflected rays you see and assumes there's an object at the point where the reflected rays meet.

A **parabolic reflector** is a mirror whose cross-section is a parabola. Parallel light rays that strike the mirror head-on will all reflect to one focal point, concentrating the light. This is how satellite antennas amplify the weak signal from a satellite.



Behind the headlight of a car has a parabolic reflector like the picture at the right with the light bulb as the yellow circle. The light bulb is at a focal point and all the light rays that hit the mirror reflect straight forward in a parallel, concentrated beam. This accounts for the high intensity of a headlight.

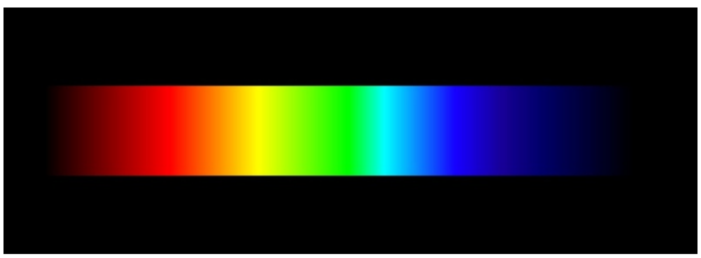
Color – cones

How we perceive color depends on three things:

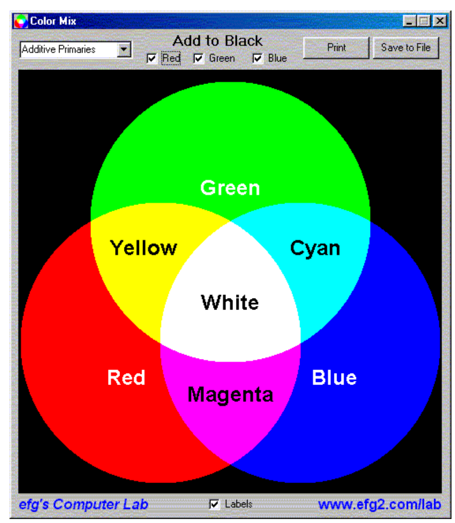
1. The structure of the eye
2. The frequency of the light source
3. The way objects reflect light

The retina of your eye is covered in receptors called **cones**, which are sensitive to color and **rods**, receptors sensitive to light intensity. For this discussion, we'll focus on cones.

In our eyes, are three kinds of cones; ones sensitive to **red**, ones sensitive to **green**, and ones sensitive to **blue**. We see colors other than red, green and blue when the cones are stimulated to different degrees. Your brain mixes the three color signals to give you the sensation of all the different colors. But fundamentally, red, green and blue are the only colors we sense directly.



Since the color of a light beam depends on its frequency, we know light really comes in all the colors of the spectrum: red, orange, yellow, green, blue and violet. **White light** is how we perceive a combination of all the colors of light together, stimulating all three types of cones in the eye. **Black is not a color of light** but rather the absence of light, how we perceive darkness. **Gray** is a "dim white", all the colors of light together but at low intensity.



Since the eye only really senses red, green and blue, we can "trick" the eye into seeing other colors by combing these three **primary colors of light**, which is how a color television works. (Note that the primary colors talked about in art theory are different – that's an older non-scientific term.)

If you overlap spotlights of red, green and blue, they produce white light. Mixing pairs of primary colors produce the **secondary colors** of light: red + blue gives magenta, blue + green gives cyan, and green + red gives yellow. This process is called **additive mixing of light**. Color screens are made up of a tiny matrix of red, green and blue lights (so sometimes called RGB displays), which turn on in various combinations to produce all the different colors. Pixels (picture elements) on a screen can be programmed for specific values of RGB from 0 to 255. Go to the link (or google "RGB color picker") to see what I mean. (https://www.w3schools.com/colors/colors_rgb.asp)

Seeing color - light absorption and reflection

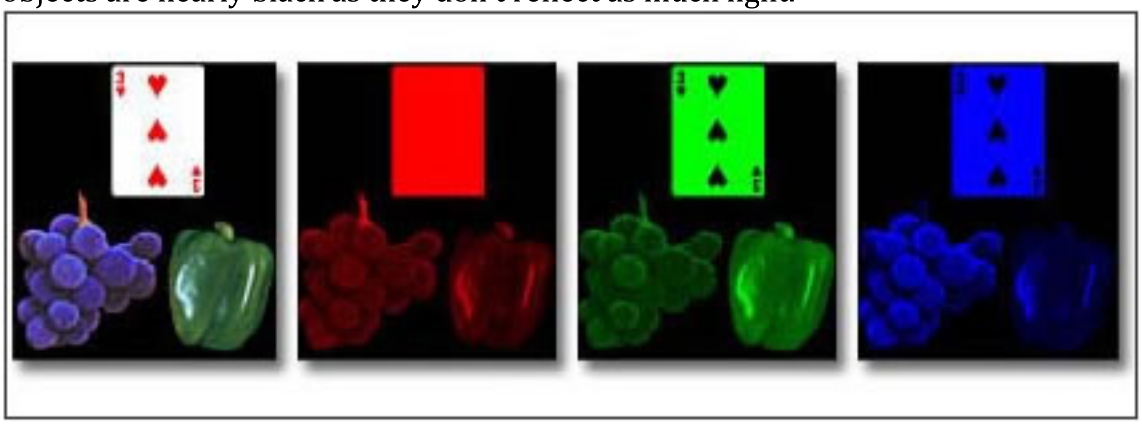
When white light hits an object, the object's color is the color of light its surface reflects. All the other colors of light are absorbed, and become internal energy, warming the object. A red object reflects red light and absorbs most of the other light falling on it.

White objects reflect nearly all the light shining on them, and thus stay cool, while black objects absorb nearly all the light on them and warm quickly. Most objects reflect varying amounts of red, green and blue.

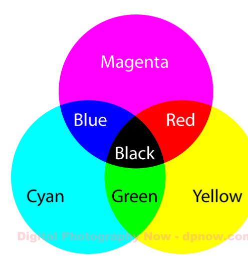
Observing objects under monochromatic light

If you look at an object under monochromatic (one-color) light, then things change. Under a red light, a red object still looks red – but so does a white object. However, a blue object under the red light will look nearly black, since it won't reflect much red. Other colors will be various shades of light to dark red, depending on how much red they reflect.

In the 2nd image below, the playing card is appears fully red under red light as the white parts of the card reflect red as well as the red numbers and hearts. Under red light, the objects are nearly black as they don't reflect as much light.



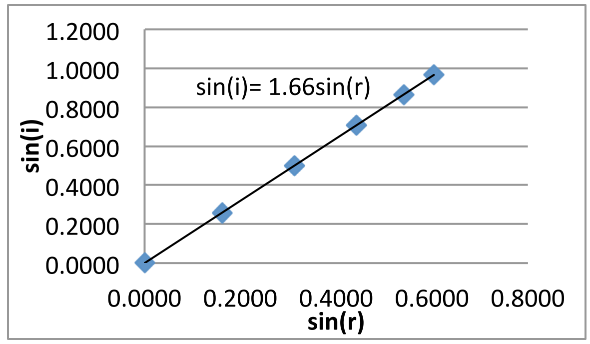
Mixing paint vs. mixing light



Mixing paint or ink to create new colors is not the same as mixing light. Mixing paint is called **subtractive mixing**, because each new color you mix absorbs more light, and the result is always darker.

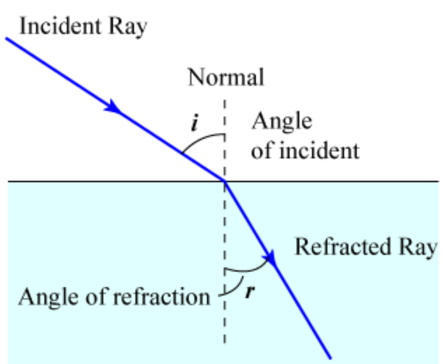
When printing a photograph for example, you start with the **subtractive primary colors**: cyan, magenta and yellow ink. Printing magenta + cyan gives blue, cyan + yellow gives green, and yellow + magenta gives red. All three give black, in theory – in reality they give a dark brown, so printers usually use black ink too. This color printing system is often called **CMYK printing**: Cyan-Magenta-Yellow-Key, where "Key" is an old printing term that refers to the "key plate" which carried the main image in black ink.

Light Refraction and Snell's Law



If you were to shine a laser beam onto a block of glass at an angle, part of the beam would bounce off the boundary (reflect) and part of it would go through the glass (transmit). The transmitted ray bends at a different angle than the angle of incidence, the angle it hits the boundary. When this happens, we say the light is refracted, a form of wave transmission.

If you record the angle of incidence i and the angle of refraction r, and plot of the sines of the angles, the graph will be linear. The slope of the line is called the **index of refraction (n)** of the material, and describes how much that material slows light down. The larger the index (n), the slower the light is moving. The index of a material is simply the ratio of the speed of light in a vacuum to the speed of light in the material. By definition:



$$\mathbf{n = c/v}$$

where $c = 3.0 \times 10^8$ m/s (the speed of light in a vacuum or air) and v is the speed of light in the glass. Since it is a ratio of two velocities, n is a constant no unit.

In a vacuum or air, n=1.0. Then the formula for the data becomes

$$\sin(i) = n \sin(r)$$

Which is a simplification of a scenario when the light starts in air.

Generally, this law becomes **Snell's Law**:

$$\mathbf{n_1 \sin(\theta_1) = n_2 \sin(\theta_2)}$$

where n_1 is the index of the material the light starts in, θ_1 is the angle of incidence, n_2 is the index of the material light ends in, and θ_2 is the angle of refraction in the material. **NOTE THAT THE ANGLE OF INCIDENCE, ANGLE OF REFLECTION AND ANGLE OF REFRACTION ARE ALL MEASURED RELATIVE TO THE NORMAL TO THE BOUNDARY SURFACE.**[5]

---

[5] this is so important that I'm reminding you here again. Angles are measured from the surface's normal line.

Some common indices of refraction are:

air: 1.0 water: 1.33 flint glass: 1.66 diamond: 2.46

<u>Example</u>
A laser beam in water (n=1.33) strikes a flint glass plate (n=1.66) at 30^o from the normal. Find the angle of refraction of the laser in the flint glass.

Find θ_2 *Given*

$n_1 = 1.33$
$\theta_1 = 30^o$
$n_2 = 1.66$

$n_1 sin(\theta_1) = n_2 sin(\theta_2)$

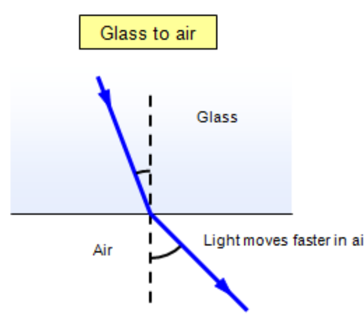
$(1.33)sin(30^o) = (1.66)sin(\theta_2)$
$(1.33/1.66)sin(30^o) = sin(\theta_2)$
$.4006 = sin(\theta_2)$
$\theta_2 = sin^{-1}(.4006) = 23.6 \approx 24^o$

Why and how does light refract / bend in different media?

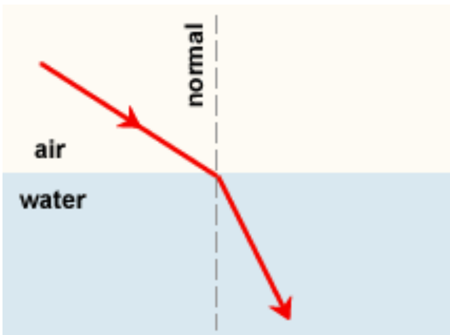
Remember that a wave's speed is determined by the medium. When waves cross a new medium, **the frequency remains the same but changes speed.** This change in speed changes the wavelength and the angle it is moving in the medium.

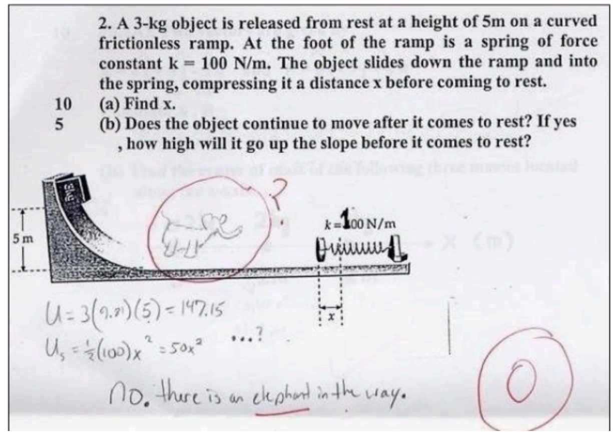
We can observe that when light speeds up (moving from a slower to faster medium), light bends away from the normal. When light slows down (moving from a faster to slower medium) light bends towards the normal. A fun and nice way to remember this behavior is with <u>a really gassy dog</u> and <u>how much you love (hate) science tests</u>.

Spot **S**low
Farts **F**ast
A lot **A**way from the normal



F***ing	**F**ast
Science	**S**low
Test	**T**owards the normal





2. A 3-kg object is released from rest at a height of 5m on a curved frictionless ramp. At the foot of the ramp is a spring of force constant k = 100 N/m. The object slides down the ramp and into the spring, compressing it a distance x before coming to rest.

10 **(a) Find x.**

5 **(b) Does the object continue to move after it comes to rest? If yes , how high will it go up the slope before it comes to rest?**

5 m

$k = 100$ N/m

x

$U = 3(9.81)(5) = 147.15$

$U_s = \frac{1}{2}(100)x^2 = 50x^2$ ...?

no. there is an elephant in the way.

?

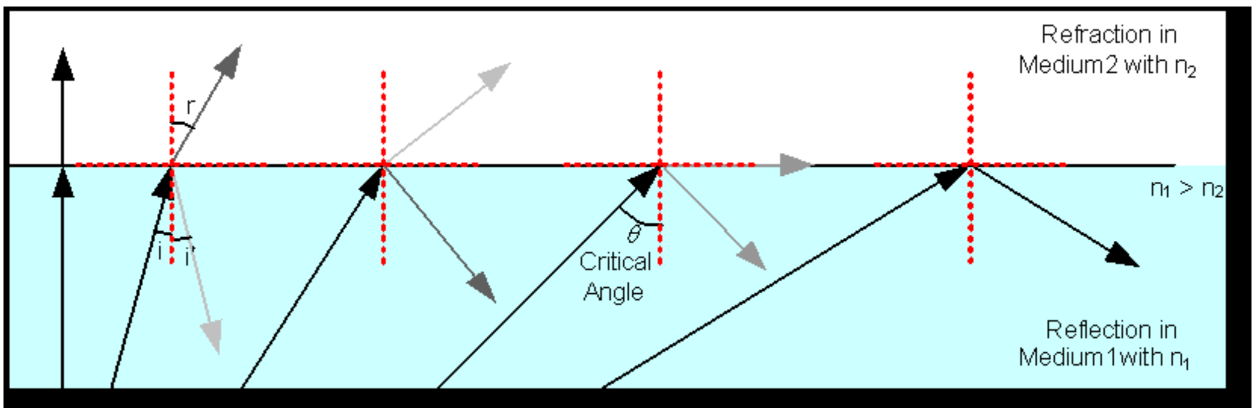
0

Total internal reflection and critical angle

When light enters a less dense medium (speeds up), there is a **critical angle of incidence**, for which the angle of refraction is 90^{o}.

If the angle of incidence is bigger than the critical angle, none of the light is transmitted across the border and hence there is no refraction.

Instead all the light is reflected back from the boundary, a situation called **total internal reflection**. *Total internal reflection only occurs when light goes from a slow medium to a fast medium.*[6]



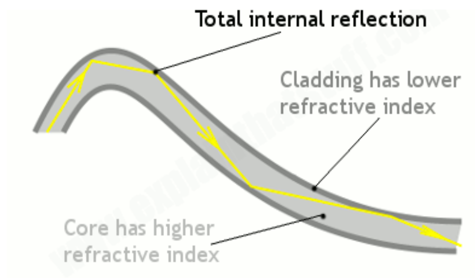
Using Snell's Law, you can solve for the critical angle θ_c by setting the angle that is normally the angle of refraction to $90\,^{o}$.

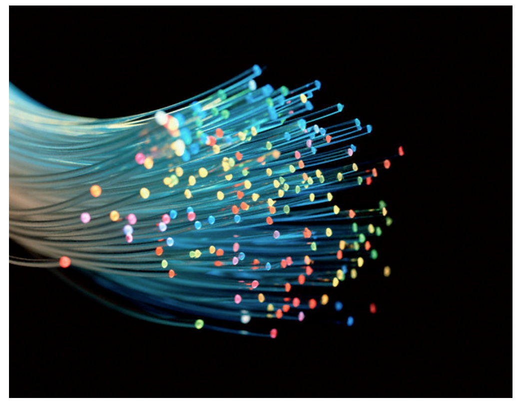
$$n_1\sin(\theta_c)=n_2\sin(90\,^{o})$$
$$n_1\sin(\theta_c)=n_2$$
$$\sin(\theta_c)=n_2/n_1$$
$$\sin^{-1}(\sin(\theta_c))=\sin^{-1}(n_2/n_1)$$
$$\boldsymbol{\theta_c=\sin^{-1}(n_2/n_1)}$$

[6] TIR will not occur for fast to slow transitions

Applications of TIR

Total internal reflection explains why, if you dive under water and look up, the surface of the water looks like a mirror. It also explains how optical fibers (thin strands of glass) can carry laser beams around corners, transmitting phone and internet data. The fibers are so thin that when you bend them, the light still hits the walls of the fiber at such a big angle it bounces back and forth inside the fiber instead of crossing out of the glass.





To learn more about how is data encrypted in light read the supplemental notes on fiber optics.

Example #1

A laser beam in flint glass (n=1.66) strikes water boundary (n=1.33) at 57° from the normal. Find the angle of refraction of the laser in the water.

Find θ_2 *Given*

$n_1 = 1.66$ (starts in flint glass)
$\theta_1 = 57^o$
$n_2 = 1.33$

$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$

$(1.66) \sin(57^o) = (1.33) \sin(\theta_2)$
$1.392 = 1.33 \sin(\theta_2)$
$(1.392/1.33) = \sin(\theta_2)$
$\theta_2 = \sin^{-1}(1.046) =$ ***ERROR***

The angle of refraction results in an error. (the range of sine and cosine is all real numbers 1 to -1, inclusive) This means that the light DOES NOT refract but rather reflects.

Example #2

What is the critical angle for light leaving flint glass and going back into water?

Find θ_c *Given*

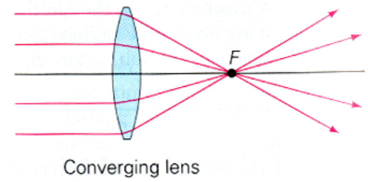
$\theta_2 = \theta_c$
$n_1 = 1.66$ (starts in flint glass)
$\theta_2 = 90^o$ (will not refract)
$n_2 = 1.33$

$n_1 sin(\theta_1)= n_2 sin(\theta_2)$

$(1.66)sin(\theta_c)= (1.33)sin(90^o)$
$(1.66)sin(\theta_c) = 1.33$
$sin(\theta_c) = (1.33/1.66) = 0.8012$
$\theta_c = sin^{-1}(0.8012) =53.24 \approx 53^o$

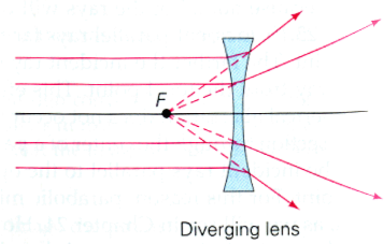
For this boundary, any incident angle larger than 53.24 ^{o} , the critical angle, results in reflection NOT refraction.

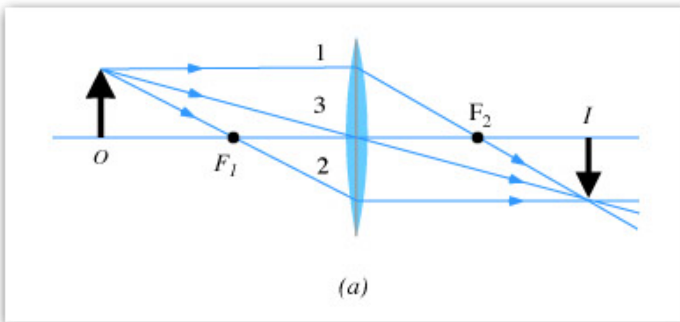
Refraction and Lenses (optional)
but good for studying the SAT 2 Physics Subject Test



Refraction is the bending of light as it changes speed, crossing into and out of the lens material. Convex (converging)lenses cause parallel light to converge, while concave (diverging) lenses cause parallel light rays to diverge.

We use ray-tracing to locate images for lenses, and use an axis perpendicular to the center of the lens as a reference frame. For a convex lens, light rays parallel to the axis all refract through a point on the axis called the focal point, F, on the opposite side of the lens. For a concave lens, light rays parallel to the axis all diverge, as if they had originated from the focal point on the near side of the lens.



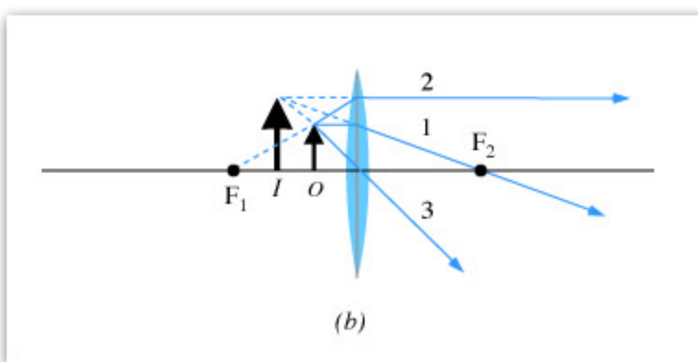


Left is a **convex (converging) lens**, which is always thickest at its center. If an object O is placed on the axis farther back than the focal point F, the lens makes a real image I where the refracted rays cross – but on the other side of the lens. There are three ray-tracing rules for convex lenses, similar to the mirror rules:

1. A ray parallel to the axis refracts through the far focal point
2. A ray through the near focal point refracts parallel to the axis
3. A ray through the center of the lens continues straight on

If the object is further than 2F, the image is smaller than the object. If the object is between F and 2F, the image is larger. An object at 2F creates a life size image, at 2F on the other side. This is how camera lenses, and your eye, work.

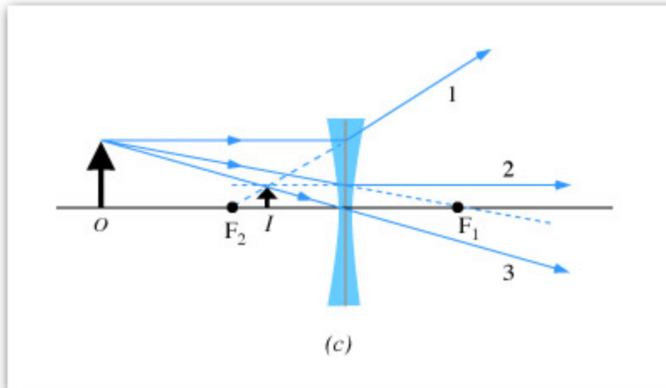
If the object O is placed closer to the lens than the focal point, following the ray tracing rules produces rays that diverge – they don't cross on the far side to form an image. In this case, you trace the refracted rays backwards, to where they form a larger virtual image I on the same side of the



lens as the object. This is how a magnifying glass works.

In contrast, a **concave (or diverging) lens** always makes a smaller virtual image, no matter where the object is placed on the axis. The three ray tracing rules for concave lenses are:

1. A ray parallel to the axis refracts as if it came from the *near* focus (F2)
2. A ray towards the *far* focus (F1) refracts parallel to the axis
3. A ray through the center of the lens doesn't refract



You trace the refracted rays backwards to where they cross to locate the image.

Two problems affect the images made by lenses:

1. **chromatic aberration** – different frequencies (colors) of light refract slightly differently, so they don't all focus at the same point. This can cause a rainbow fringe around light sources and the edges of pictures.
2. **spherical aberration** – Spherical lenses don't focus light perfectly. As with mirrors, lenses really should be shaped like sections of parabolas to bring parallel light rays to a perfect focus.

Diffraction and Young's double-slit experiment (optional)
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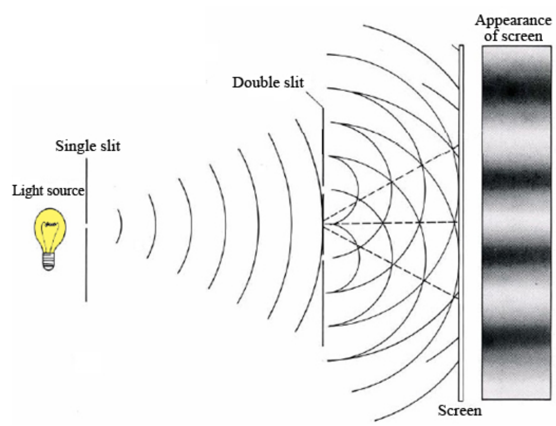
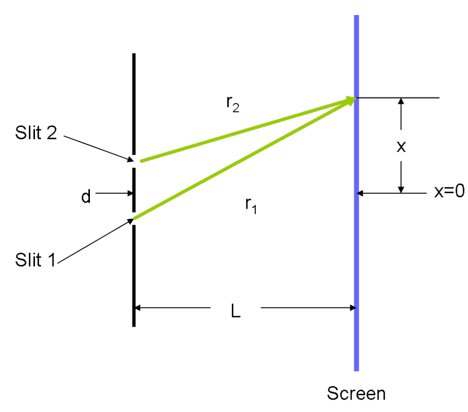
Isaac Newton in the 1600's considered light to be made up tiny particles, and explained how particles could reflect and refract at the boundary of a new medium. Newton did not believe light diffracted around objects, so disagreed with others who thought light was a wave.

In the early 1800's Thomas Young demonstrated that light can diffract, and also produce an interference pattern, strong evidence that light has wave properties. This famous experiment is called the **double-slit experiment**.

- A monochromatic light source is used, so all the waves have the same wavelength.
- The light passes through a single slit, so that all the light rays are in phase to start.
- The light then passes through two parallel slits in a card that are extremely close together (the double slit). Instead of going through the two slits in a straight line, the light diffracts around the two slits (like sound waves from two speakers).
- The two sets of waves overlap and create an interference pattern, again just like sound waves from two speakers. The light shines on a screen, projecting the interference pattern as a pattern of evenly spaced bright lines, the brightest being the **central maximum** across from the two slits.



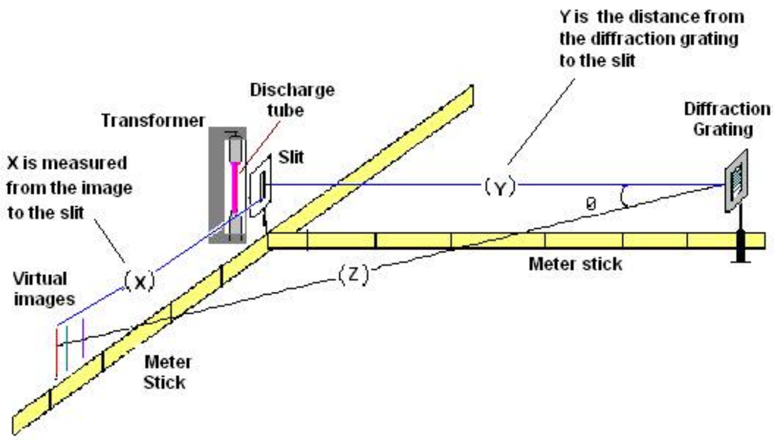
The light beams leaving the double slits start in phase. Both light rays travel the same distance to get to the center of the screen across from the double slit, so they arrive in phase too, meeting in constructive interference – and making the bright central maximum line.



As you move up along the screen, the light from one slit travels further than the other, so the light rays meet out of phase and start cancelling out and getting darker.

But as one light ray travels nearly a full wavelength further than the other, the waves start meeting in phase again, and another bright line forms – the first-order maximum, some distance x up the screen from the central maximum. If the distance from the double-slit to the screen is L and the distance between the slits is d, then the wavelength of the light can be calculated from

$$\lambda = \frac{dx}{L}$$



A **diffraction grating** is a transparent plastic sheet with thousands of parallel lines etched onto it. It **acts like a double slit to produce an interference pattern of light**, and the math is essentially the same as for the double slit, but it produces a much brighter pattern that's easier to see. As well as projecting the light through the grating onto a screen, you can also look directly at the light source through the grating, and see the interference pattern (or spectrum lines) as a virtual image next to the light source. Above is a sample lab setup. The discharge gas tube itself is at the central maximum.

Let **d** the distance between grooves on the diffraction grating, **Y** be the perpendicular distance from the grating to the light source, and **θ** be the angle between the first-order maximum line (the first spectrum line you see) and the gas tube, measured at the diffraction grating. Then the wavelength **λ** measured through a diffraction grating is:

$$\boldsymbol{\lambda = d\ sin\theta}$$

If the angle is hard to measure directly, you can measure the distance **x**, which is perpendicular to Y, from the light source to the first spectrum line, and use trig to calculate θ, since tan(θ) = x/Y.

This is the basis of spectroscopy, analyzing materials by studying their light spectra when they are heated to glowing.

<u>Example</u>
A laser beam passes through a diffraction grating, with a line spacing of 4.0×10^{-5} m. The light falls on a screen 1.5 m behind the diffraction grating, producing an interference pattern of dots spaced 2.0 cm apart. Find the wavelength of the laser light.

Find λ   Given d = 4.0×10^{-5} m Y = 1.5 m   x = 2.0 cm = 0.020 m

$\lambda = d\ sin\theta$ where $\theta = tan^{-1}\left(\frac{x}{Y}\right) = tan^{-1}\left(\frac{.02}{1.5}\right) = 0.764^o$

λ = (4.0×10^{-5} m) sin(.764)

λ = 5.3×10^{-7} m