Energy: E Waves transport energy.

Vibration / oscillation: Something must be vibrating / oscillating in order to create a wave.

Medium: Waves must travel in a medium with one important exception.
Electromagnetic waves are the only type of wave that do not require a medium at all.

Frequency: f Number of vibrations, oscillations, cycles, revolutions, etc. that take place each second.

Period: $T = 1/f$ Time for one complete vibration / oscillation.

Wavelength: λ The length on a single wave. Measure to the same point on the next wave.

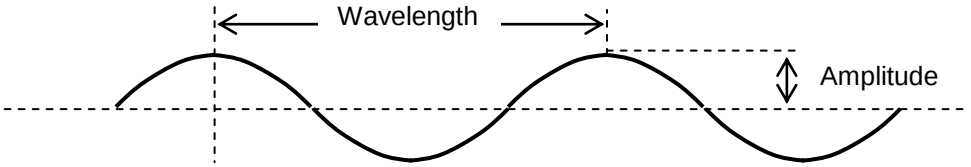
Velocity: $v = f\lambda$ Wave velocity depends on the elasticity of the medium. Sound travels faster in metal than in water and faster in water than in air. Light, however, is unusual. It is fastest in a vacuum and slows slightly in air, and to a greater extent in water.

Amplitude: A Maximum displacement from the equilibrium position (midline on the graph).

Transverse Wave: Particles vibrate in a direction perpendicular to the wave direction & velocity.

Longitudinal Wave: (also Compression, or Shock) Particles vibrate in a direction parallel to wave direction & velocity.

Sinusoidal: When a vibrations displacement is graphed against time a sinusoidal function is plotted. It is the graphical representation for any wave phenomenon, and looks like a transverse wave. However, any wave, even longitudinal waves, follows the same sinusoidal pattern.

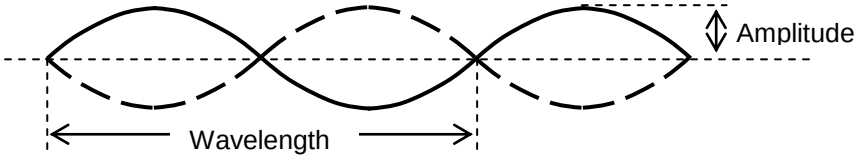


Pulse: A single wave.

Continuous Wave: A series of equal pulses equally spaced moving together.

Standing wave: When a continuous wave strikes a barrier and reflects back on itself it will create an interference pattern (see interference below). If the phase (see phase below) of the reflected wave is exactly opposite to the incoming wave they will superimpose creating a standing wave.

Node: A point on a standing wave that does not move at all.



Speed depends on the mediums elasticity. When a wave travels from one medium to a different medium the speed & wavelength change. However the frequency remains the same.

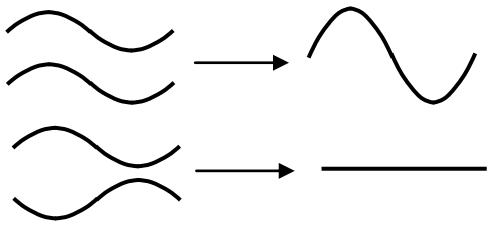
Interference: When two or more wave meet, the amplitudes add.

In phase: Waves are in phase when they have the same wavelength and the crests are aligned.

Out phase: Waves are out of phase when they the crest on one wave aligns with the trough of another.

Constructive Interference: If the waves are in phase you add them to construct a larger amplitude.

Destructive Interference: If the waves are out phase you add them to destroy the amplitude. The waves shown have the same amplitude and wavelength, but any kind of wave can interfere, so different amplitudes and wavelengths can result in many unique new wave functions.

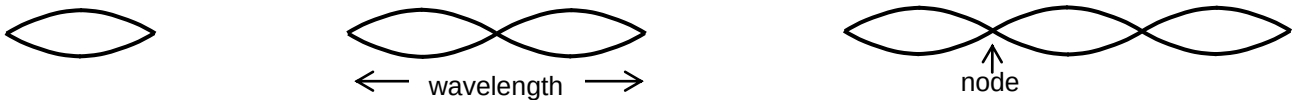


Sound: The speed of sound in air at 25^{o} C is 343 *m/s* (often rounded to 340 *m/s*). The speed of sound changes with temperature since the density and elasticity of air change as temperatures fluctuate.

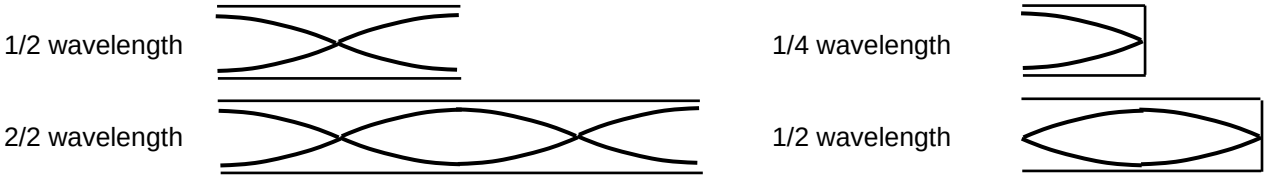
Pitch: Frequency ***Loudness***: Amplitude

Sound waves can originate from vibrating strings or in tubes. This is the basis for musical instruments. There are two types of tubes: those open at both ends & those closed at one end.

Strings: Only multiples of ½ wavelengths can fit on a vibrating string that is held fixed at each end.



Open Tubes: Same as strings, multiples of ½ waves. But the waves look a little different, since the ends aren't fixed.
Closed Tubes: Closed tubes hold multiples of ¼ waves.



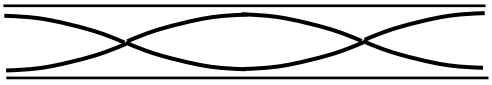
Adjustments to the velocity equation. The simplest case is the minimum number of wavelengths. So we will work with the ***fundamental***, strings or open tubes that have a ½ wavelength, and closed tube holding ¼ wavelength.

Normal wave velocity $\boxed{v = f\lambda}$

Strings: $\boxed{v = f2L}$ If ½ wavelength fits on the string, then $\lambda = 2 \times String\ \ Length = 2L$.

Open tubes: $\boxed{v = f2L}$ If ½ wavelength fits in the tube, then $\lambda = 2 \times Tube\ \ Length = 2L$.

Closed tubes: $\boxed{v = f4L}$ If ¼ wavelength fits in the tube, then $\lambda = 4 \times Tube\ \ Length = 4L$.

To adjust for more than ½ wavelengths in strings & open tubes, and ¼ wavelengths in closed tubes you divide ***L*** by the number of nodes. Example:  This tube contains two nodes. $\boxed{v = f\frac{2L}{n}}$

More on velocity: Sound also follows the normal velocity equation $\boxed{v = d/t}$. You can time the distance to lightening by counting the seconds between the flash and the thunder. But, if you're timing sound that makes a round trip (like an echo, or sonar) you have to divide your final answer by 2.

Resonance: Everything has a natural vibration frequency. If you can match the natural vibration and add more wave energy at the right frequency and wavelength you can shatter the object. Breaking a crystal glass with your voice, or the Tacoma Narrows Bridge are examples.

Light: Travels in packets of energy, called ***Photons***.

Electromagnetic Radiation: It can travel through a vacuum since it is a self-supporting electromagnetic phenomenon. It consists of two perpendicular waves, one electric and one magnetic. The electric field wave generates a magnetic field wave that is perpendicular to it, and the magnetic field wave generates an electric field wave perpendicular to it. After they are emitted by the source they recreate each other and support each other allowing ***EM*** waves to travel through a vacuum free of their original source and without a medium. We see only visible light, which is a very small portion of the entire electromagnetic spectrum. The entire spectrum from weakest to strongest is:

Radio Waves	**Microwaves**	**Infrared (IR)**	**Visible**	**Ultraviolet (UV)**	**X-Rays**	**Gamma Rays**
Long wavelength						Short Wavelength
Low frequency						High frequency
Low energy						High energy

In a vacuum they travel at 3×10^8 *m/s*. When they strike an object they can interact with the object in four principle ways.

Absorb: The wave energy is transferred to the object and its internal energy ***ΔU*** goes up, as the does the temperature.

Scattering: The incoming light can be absorbed briefly, exciting the electrons in the atoms. The excited electrons move to higher energy states, but quickly move down to lower energy levels. The electrons may drop to various intermediate energy levels on their way back to the ground state, thus emitting photons with new frequencies.

Transmit: The waves may pass through an object, like visible light through glass or x-rays through your body.

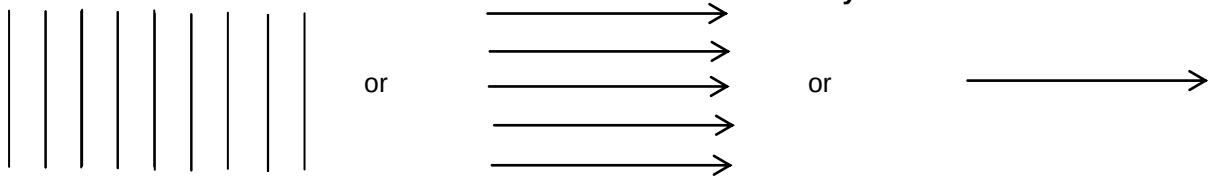
Reflect: They may bounce off of the object.

To see light the waves must be aimed straight into our eyes to excite the photo-receptors at the back of our eyes. The colors we see are the waves of light that reflected off of the object or that were scatted by the object. The colors that are not present are the ones that either passed through the object or were absorbed by the object. Grass is green because it absorbs red and blue light needed for photosynthesis, and it reflects the unnecessary green wavelengths. The sky is blue due to scattering of the white light from the sun by particles in the earth's atmosphere.

Diagramming Waves

Sinusoidal: If you look at a wave from the side you see a sinusoidal pattern.
Wave Front: If you look at waves from above you see the crests moving parallel to each other.
Ray: The easiest method. You use one or more vectors to indicate the direction the waves are moving in.
Even though light radiates radially from a source in rays, light arriving from a distant source arrives very nearly parallel. So for simplicity the waves of light are assumed parallel. A distant source does not need to be very far away for visible light since the wavelengths are measured in nanometers.

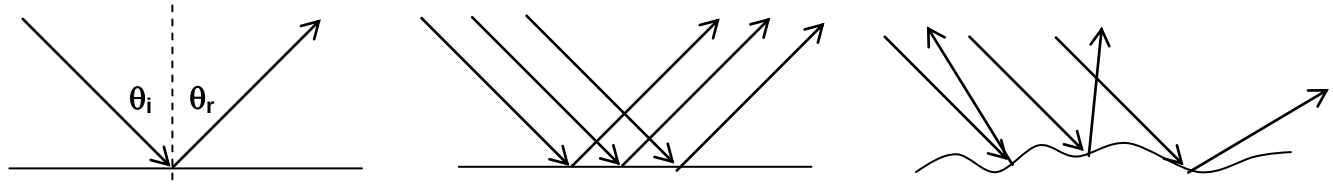
Wave Fronts or **Rays** or



Reflection

Law of reflection $\boxed{\theta_i = \theta_r}$. The angle of incidence and angle of reflection are measured in relation to the normal. A normal is a line perpendicular to the surface (as in Force Normal which is perpendicular to the surface). It is normally shown as a dashed line. To simplify the diagram a single ray of light is shown as opposed to wave fronts of light. Each individual ray follows the law of reflection.

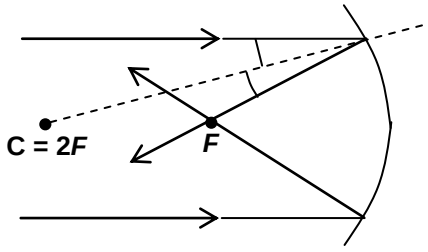
Single Ray, smooth surface **Parallel rays, smooth surface** **Rough surface, *Diffuse* reflection**



On a smooth surface such as a mirror the incident parallel rays of light reflect parallel and the image formed is identical to the object. But on a rough surface the incident parallel rays are sent in all directions and the image may be ***diffuse*** (fuzzy), or not form at all.

Converging Spherical Mirror

The law of reflection holds. You need a normal perpendicular to the surface. A perpendicular line to a sphere will pass through its center. When incident parallel rays arrive from a distant light source the angle of reflection will equal the angle of incidence. The normal bisects this angle. Therefore, the rays of light will ***converge*** on a point half way between the curved surface and the center. The point of convergence is called the ***focus*** or ***focal point***. $\boxed{F = r/2}$ and $\boxed{C = 2F}$



Transmitting Light

The speed of waves is dependent on the medium the wave travels in. Electromagnetic waves are the only waves capable of traveling in a vacuum. And unlike other waves they travel fastest in a vacuum and are slowed by other mediums. The speed of light in a vacuum is $\boxed{c = 3\times10^8\ m/s}$. To compare the speed of light in different mediums an ***Index of refraction*** was devised, $\boxed{n = \frac{c}{v}}$. This index is a comparison value (other comparison values in the course have been the coefficient of friction, coefficient of linear expansion, and resistivity.). If the speed of light in glass is slowed to $2\text{x}10^8$, the index of refraction is 1.5. The index of refraction for light in a vacuum is 1.00. So the index can never be less than one. The index of refraction for air is 1.0003, which rounds to $\boxed{n_{air} = 1.00}$.

Refraction

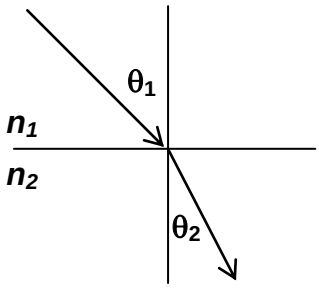
Light Traveling through mediums with different densities $\boxed{v = f\lambda}$

From a less dense to more dense medium
- Light moves ***slower***
- The ***frequency is unchanged***
- So ***wavelength is shorter***
- So light ***bends toward*** the normal

From a more dense to less dense medium
- Light moves ***faster***
- The ***frequency is unchanged***
- So ***wavelength is longer***
- So light ***bends away*** from the normal

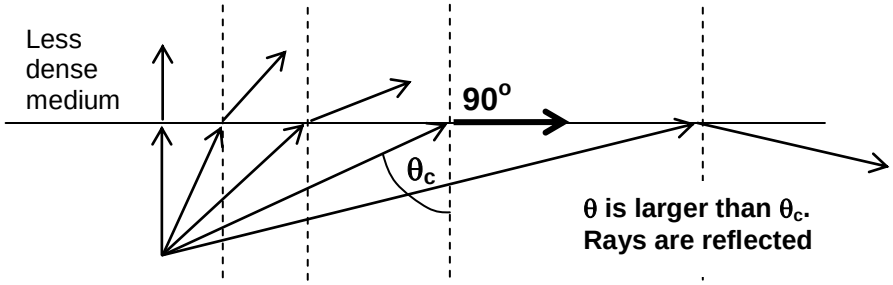
Snell's Law

$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$ Given the speed in one or both mediums the indices of refraction can be determined. Or one or both angles can be determined experimentally. With three pieces of information the fourth can be determined mathematically. The diagram to the right shows light moving from a less dense medium to a more dense medium. ***n_1*** and ***θ_1*** go with the incident medium while ***n_2*** and ***θ_2*** go with the refracted medium.



Total Internal Reflection

A special case of Snell's Law. If the incident angle is of a certain size it will result in a 90° angle of refraction. This incident angle is called the critical angle $\boxed{\theta_c}$. At incident angles larger than the critical angle the light reflects back into the substance. So the light at the critical angle or greater is totally internally reflected.



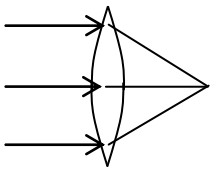
$n_1 \sin\theta_1 = n_2 \sin\theta_2$ If medium one is the incident ray then ***θ_1*** is the critical angle and ***θ_2*** is 90°.

$n_1 \sin\theta_c = n_2 \sin 90^o$ $\quad n_1 \sin\theta_c = n_2$ $\quad \boxed{\sin\theta_c = \frac{n_2}{n_1}}$

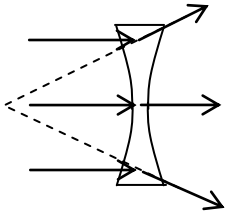
Lenses and Mirrors

Mirrors reflect light and lenses transmit light. They both fall into two main categories. ***Converging*** lenses and mirrors converge parallel rays of light on the focal point. ***Diverging*** lenses and mirrors diverge parallel rays of light away from the focus. The shapes of lenses and mirrors fall into two main categories, ***convex*** and ***concave***. Concave has a cave shape.

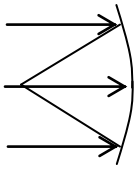
Converging Lense
Convex Lense



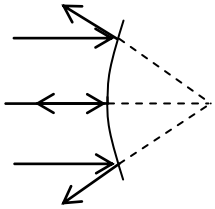
Diverging Lense
Concave Lense



Converging Mirror
Concave Mirror



Diverging Mirror
Convex Mirror



Note: Converging and Diverging are the important terms. The shapes are secondary. The terms converging and diverging dictate the information needed to do the mathematical steps outlined on the next page.

Images*:** Two types of images are formed by light interacting with lenses and mirrors. To find the location and diagram the size of an image you draw the rays of light and look for their intersection. When rays of light converge it is easy. You follow the path of the light, the ***forward ray trace. But, when rays diverge (separate) the forward ray traces will not intersect. So you must draw a ***back ray trace*** to the other focus. The forward trace is drawn as a solid line, while the back ray trace is drawn as a dotted line.

Real Image: Can be projected on a screen. Results from the intersection of ***forward ray traces*** & is always ***inverted***.

Virtual Image: Cannot be projected on a screen. Results from the intersection of ***back ray traces*** & is always ***upright***.

Ray Tracing: See the worksheet on ray tracing for details on all the special cases of the lenses and mirrors. Ray tracing follows a set of rules. There are many variations, but I believe the list below will cover most if not all cases.

Rules for Lenses: Remember light goes through the lens.

- Rays arriving parallel to the midline, either converge on the far focus or diverge from the near focus.
- Rays that go through the center of the lens keep going straight.

Rules for mirrors: Remember light bounces off the mirror.

- Rays arriving parallel to the midline, either converge on the near focus or diverge from the far focus.
- Rays drawn through the object and the focus, go out parallel.
- Rays that go through the center of curvature bounce (***C = 2F***) bounce straight back.

Geometric Optics

$$f = \frac{r}{2}$$ The center of curvature is located at 2***f***. So the focal point is half of the radius.

$$\frac{1}{f} = \frac{1}{s_o} + \frac{1}{s_i}$$ Shows the geometric relationship between the focal length, object distance, image distance.

$$M = \frac{h_i}{h_o} = -\frac{s_i}{s_o}$$ Relates the magnification to the height of the object and image, and the distance to each.

The equations are simply a matter of identifying correct variables and solving. Conversions to base units are not even necessary. In the first equation all variables have the same units and you are merely adding them. The only conversions needed are in cases where you lack unit agreement. In optics centimeters are commonly used. Millimeters may be seen on occasion. In the second equation units cancel providing they are the same.

However, you must know when the variables are positive and when they are negative.

f Converging lenses and mirrors are positive. Diverging lenses and mirrors are negative.

s_o Object is always positive, so the object distance is positive.

s_i Positive if the forward ray traces intersect to create the image. Negative if generated by back ray traces.

h_o Object is always positive, so the object height is positive.

h_i If the image is upright, the image height is positive. If the image is inverted, the image height is negative.

M Plugging in a positive image height into the formula results in positive magnification. Plugging in a negative image height results in negative magnification. Remember negative ***M*** does not mean the image is smaller. It means the image is upside down. 0.5x is a smaller image and upright, while –2.0x is a larger image, but it is inverted.

Real: A real image is formed by positive ray traces. Positive ray traces are where the light goes, so this image can be projected on a screen.

Virtual: A virtual image is formed by back ray traces. It appears on the opposite side of the lens or mirror from the lights path. So it cannot be projected on a screen.

Patterns

A general rule: If the forward light rays touch the focus or image they are positive.

Object distance and height: The object is always positive.

Image height and magnification: Look at the image, up is positive and down is negative.

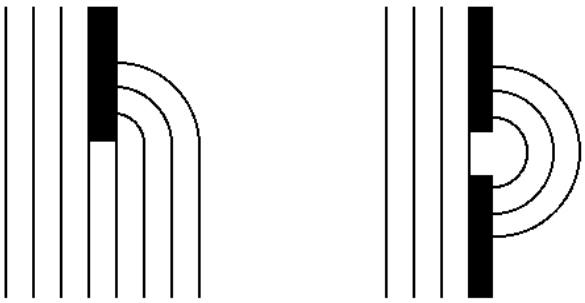
These always go together

Converging	***Real***	***positive s_i***	***inverted***	***negative h_i***	***negative M***
Diverging	***Virtual***	***negative s_i***	***upright***	***positive h_i***	***positive M***

Remember the terms convex and concave are secondary. Focus on the terms converging and diverging. The patterns are based on the nature of the lens or mirror, whether it is converging or diverging.

Diffraction

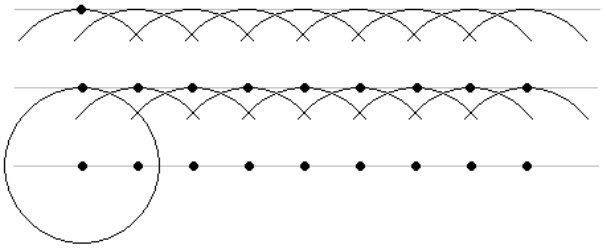
When light hits the edge of a barrier it will bend around it. If the barrier is small compared to the wavelength of light the light will pass the barrier uninterrupted. Like water flowing around a buoy. But, if the barrier is large compared to the wavelength of light the waves will bend around the edge of the barrier in a circular fashion. Imagine water waves hitting the end of a jetty, or going through a hole in a jetty.



Huygen's Principle: Every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The wave front is formed by the constructive interference of the circular wavelets.

So, if the barrier has a hole in it, the particles of the wave create new circular wave fronts when they exit on the other side. This is why you get the circular patterns shown on the previous page.

The particles of light that create this diffraction pattern are the photons. Each photon generates circular wave fronts that constructively interfere to generate linear wavefronts.



Slit Width: If waves move thru an opening or slit the circular wave pattern is more pronounced when the slit is small.

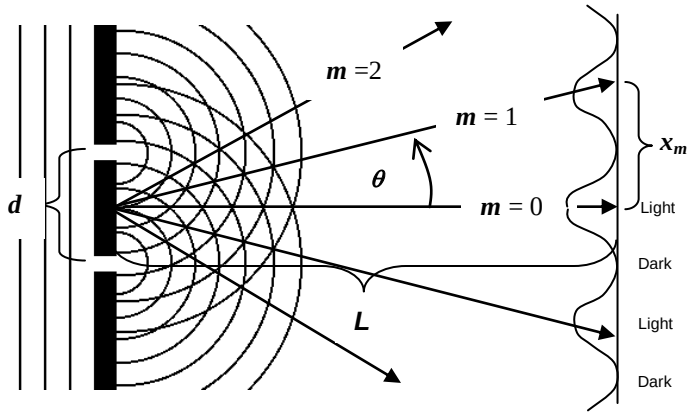
Young's Double Slit Experiment

Uses ***monochromatic*** light source to since white light consisting of all the colors would result in a rainbow refraction.

Light showed the same characteristic pattern as water waves and is ***<u>evidence that light behaves as a wave</u>***.

Light from two slits interferes with each other. As a result you get dark and light bands if the pattern is shown on a screen.

Interference Fringes $d\sin\theta = m\lambda$ $x_m = \frac{m\lambda L}{d}$



d is the distance between the slits.

m is the fringe number. ***m*** = 0 is the central maximum. It is also the ***<u>path difference in wavelengths</u>***.

Whole numbers are used for the bright ***Constructive Interference Fringes***. ***m*** = 0.0, 1.0, 2.0, 3.0, etc.

Half numbers are used for the dark ***Destructicve Interference Fringes***. ***m*** = 0.5, 1.5, 2.5, 3.5, etc.

θ is the angle from the midline (from the middle fringe)

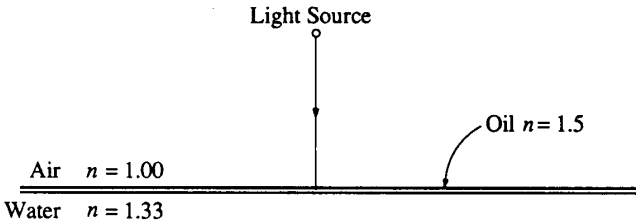
L is the distance from slits to the screen.

x_m is the distance from the midline (center fringe) to the fringe being measured.

Thin Films: Reflection revisited. Most people are familiar with the rainbow effect seen when a thin oil or soap film is floating on top of water. The thickness of the film, and the density of the substances work together to cause this effect.

A reflected ray will change phase by 180^o when going from a medium with a low n to a medium with a high n.

If oil is suspended on water. Light moving from air to oil hits a higher ***n*** and is reflected with a 180^o phase change. Light moving from oil to water hits a smaller ***n*** and its phase is unaltered.



For what wavelengths in the visible spectrum will the intensity be a maximum in the reflected beam?

Maximum intensity occurs when waves reflecting off the oil and those reflecting off the water join and constructively interfere. The waves reflecting off the oil have their phase changed by 180^o. Those reflecting off the water follow the same wave pattern out as they did in. To meet with the rays reflecting off the oil they need to go ½ a wavelength (or a multiple of ½) and then rebound traveling back the same distance. So they must travel a total of 1, 2, or 3, … wavelengths (***m*** wavelengths). So if the film is 1x10^{-7} *m* thick, what wavelengths will results in maximum intensity.

$\lambda = 2(thickness\ \ of\ \ \ film) = 2(1\times10^{-7}) = 2\times10^{-7}m = 200nm$

Any multiple of 200 *nm* will result in maximum intensity.

$m200nm$ where ***m*** is an integer. The rainbow effect depends on where you are standing in relation to the light source. Remember refraction is also happening for the light entering the oil. And the colors are separating with blue bending more. And the oil may not have the exact same thickness everywhere. So a rainbow pattern is seen, which depends on a combination of all these factors.

Reflected rays constructively interfere