NEWTON'S PARTICLE THEORY OF LIGHT

Light is made up of little particles.

They obey the same laws of physics as other masses like baseballs and planets.

They are tiny so the particles in two intersecting beams do not scatter off each other.

In 1704 Newton published his treatise *Opticks*, this was 17 years after his great work *Principia*. He had waited until Robert Hook died, since he had become so sensitive to criticism, especially from Hook. *Opticks* was written in English, not the latin of *Principia*, and moreover, was much easier to read. It was very popular and he revised it three times.

Newton proposed that light consists of little masses. This means that a horizontal beam of light near the earth is undergoing projectile motion, and forms a parabola. The straight line we observe is due to the fact that the speed of the particles is so great. In one microsecond, light travels 300 m. In that time it should fall a distance $y = 1/2gt^2 = 5*10^{-12}$ m, much too small to be seen.

Many known properties of light could be explained easily by a particle model. For example it was known that when light reflects from a smooth surface, the angle of incidence is equal to the angle of reflection. This is also how an elastic, frictionless ball bounces from a smooth surface.

As we shall see, a key property for the particle theory is refraction.

PARTICLE THEORY OF REFRACTION

A light particle deep within a medium experiences no net force.

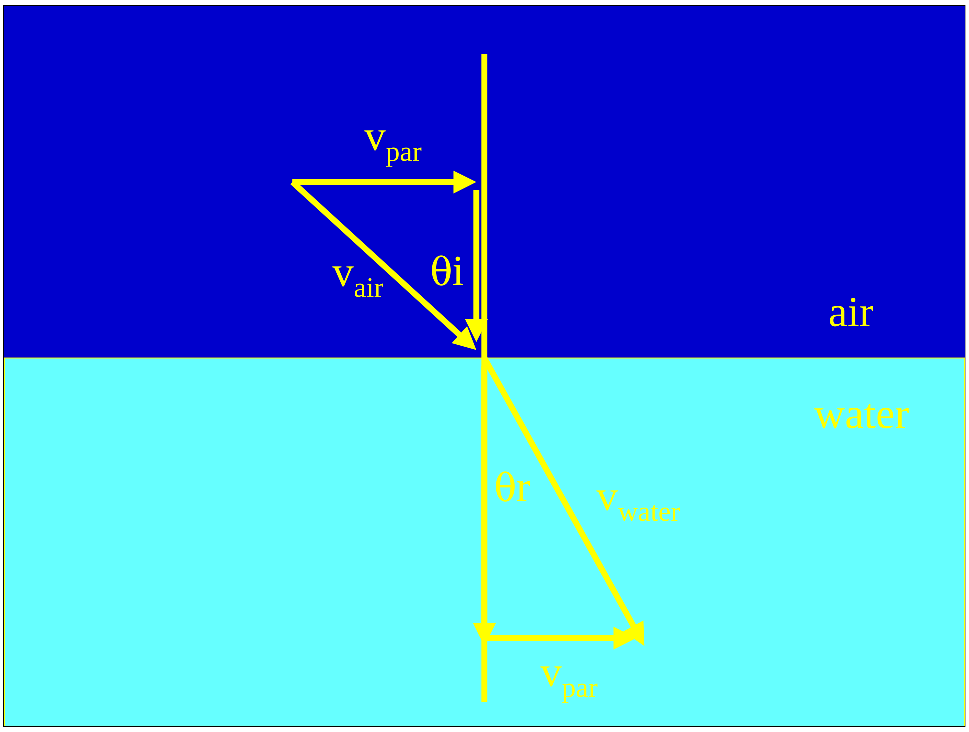
Near an interface, e.g. between air and water, light particles experience an attractive force towards the water.

Could this be the cause of refraction?

Newton imagined that matter is made of particles of some kind (today we would call them molecules or atoms). When a light particle is deep within a medium, such as water or glass, it is surrounded on all sides by equal numbers of these particles. Suppose there is an attractive force between the light particles and the matter particles. Then deep within a medium, these forces cancel each other out and there is no net force on the light particle.

Then, according to Newton's first law, the light particle will continue moving in a straight line since no net force acts on it.

Near an interface the situation is different. Now there are more matter particles on one side than the other, and the light particle can experience a net force. It would experience a brief attractive force towards the medium with more matter particles.



As the light particle moves into the water, it experiences a brief attractive force towards the water. This increases the vertical component of its velocity. Since it did not experience any net horizontal force, its horizontal velocity remains the same.

This brief vertical force speeds the light particle up, and deflects its velocity towards the surface normal, which is what is observed.

As we have seen, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for a given pair of materials.

We can evaluate the sines of the two angles from the above diagram in terms of the velocity of the light particle in air and in water.

From the diagram on the previous slide we can immediately evaluate the sines of the angles of incidence and refraction. In a right triangle the sine of an angle is equal to the ratio of the side opposite the angle to the hypotenuse. This is equal to the component of the light particle's velocity parallel to the surface divided by the magnitude of the velocity in each medium.

Since the light particle's velocity parallel to the surface does not change, since there is a force on the particle only perpendicular to the surface, this simplifies the ratio of the two sines. We see that the ratio of sines, which is just equal to the index of refraction, is equal to the ratio of the speed of the light particle in water to that in air.

This immediately explains why each pair of materials has a different value for the index of refraction. All Newton needed to do was to claim that the speed of light is different in different transparent materials. This is a simple explanation of Snell's law. Newton regarded it as one of his triumphs. He concluded his discussion of this in his book *Opticks* with the words "I take this to be a very convincing argument of the full truth of this proposition."

OTHER PROPERTIES

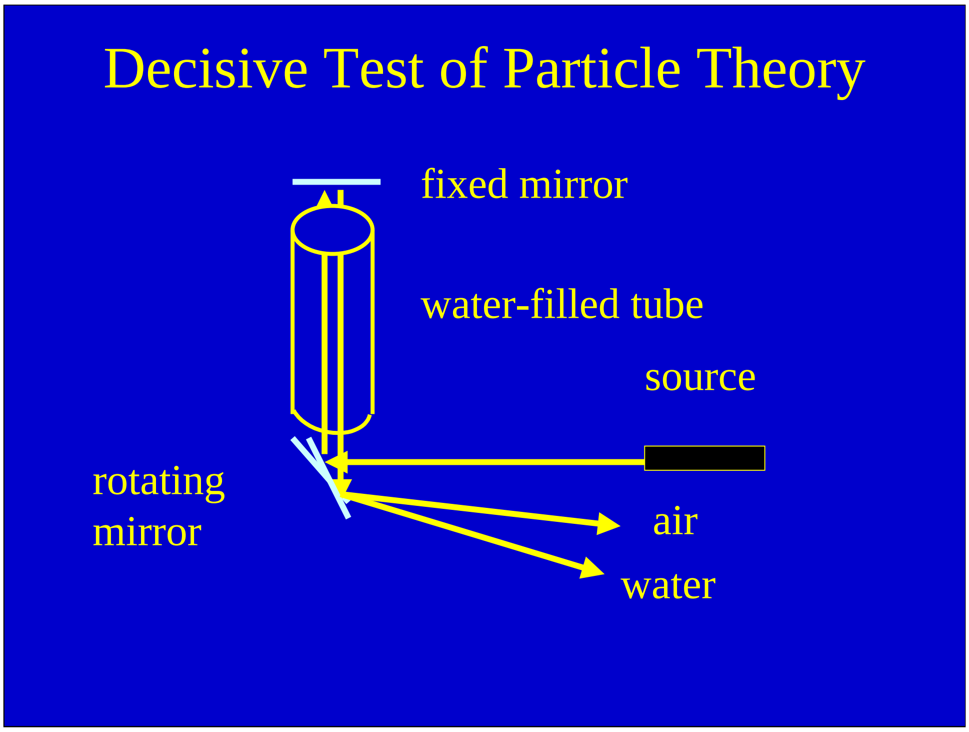
Colors

Polarization

What about other properties of light such as the list of observations we compiled? Can Newton’s particle model account for all of these?

His explanation for the fact that a prism separates a beam of white light into the colors of the rainbow was simple. We have seen that red light refracts least, and violet light most. Newton stated that the mass of the light particle varied with color. Red light particles have more mass than violet, consequently they will be deflected less upon crossing an interface between materials. He assumed all light particles experience the same force on crossing an interface. What differs among them is their inertia. Red light particles with more inertia will be deflected less by the same force than violet light particles.

What about polarization? When we observe the intensity of light transmitted by two sheets of polaroid plastic we find it varies from a maximum to zero and back to a maximum again as the second polarizer is rotated. If the light particles were spherical, this could not happen. Newton stated that the light particles are not spherical, but have “sides”. Perhaps they are platelike, or rectangular. Visualizing a precise shape for the light particles is difficult. Clearly something other than a sphere is needed.



We have seen that Roemer used observations of the eclipses of Io to measure the speed of light in a vacuum. By 1850 the technology became available to do so in a laboratory. Foucault, in France, used a small steam turbine to spin a mirror at the rate of 800 rotations/sec(!). A light beam was reflected from it to another mirror 9m away. When it returned, 60 ns later, the mirror had rotated a little, causing the return beam to be deflected a little below the source. When the mirror is at any other angle, the light beam is reflected elsewhere in the room and lost.

Then what Foucault did was introduce a 3m long tube of water in the vertical light path. If Newton was right, and the light speed in water was greater than in air, then the return light beam would arrive in less than 60 ns, and its path would be deflected closer to the source.

What Foucault found was that introducing the water-filled tube caused the light path to be deflected farther from the source. This showed that light travels more slowly in water than in air. This experiment was decisive. There was no way to save Newton’s particle theory of light.

This is a compelling example of how quickly a grand theoretical structure can collapse. All it takes is one decisive experiment like this one. If there is no way to modify the theory to account for the new result, the theory must be abandoned.

WAVE MOTION

A wave is a pattern, or shape, or disturbance, traveling through a medium.

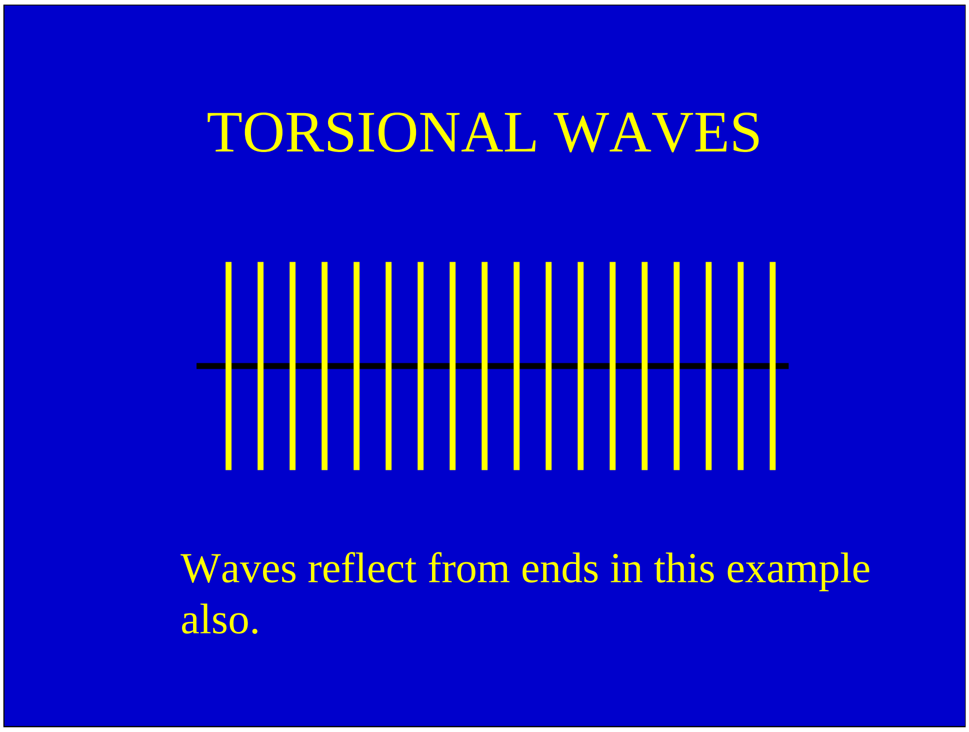
Examples:

- Sound is a pressure wave in air.
- Sideways vibration of stretched string.
- Football stadium “wave”.

As great as Newton was, his particle theory of light has failed. We must find a new model or theory. One other possibility is that light is a wave traveling through space.

Sound consists of waves traveling through air or another mechanical medium. What is waving when we hear sound? It consists of air pressure vibrations: What is waving is the air pressure. To create sound a vibrating object is needed. In an acoustic guitar the vibrating strings cause the guitar body to vibrate, transmitting the vibrations to the surrounding air.

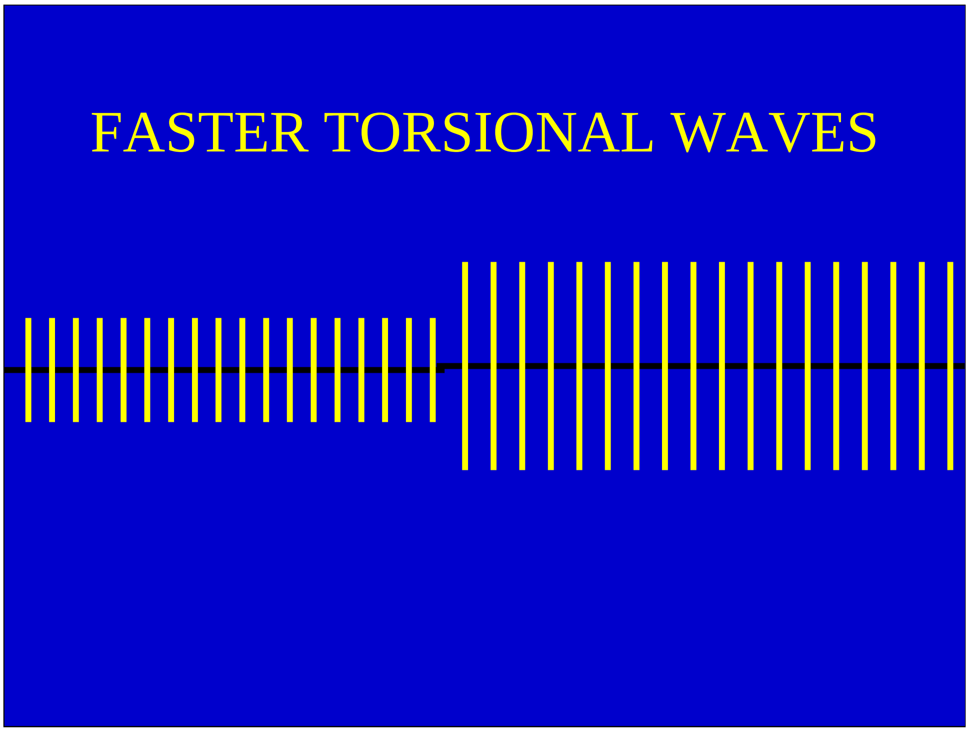
The guitar strings vibrate because of the tension in the strings. The vibration then travels along the string. SHOW long stretched spring. Note how the wave shape reflects from the fixed end of the spring.



This torsional wave apparatus looks like a crudely drawn fish skeleton. The backbone is a steel wire. When a crossbar at one end is rotated up and back down, the steel wire is twisted and transmits the rotational motion to the next crossbar. This process is repeated, and so the disturbance is transmitted along the steel backbone in a wavelike manner.

SHOW Torsion wave demo.

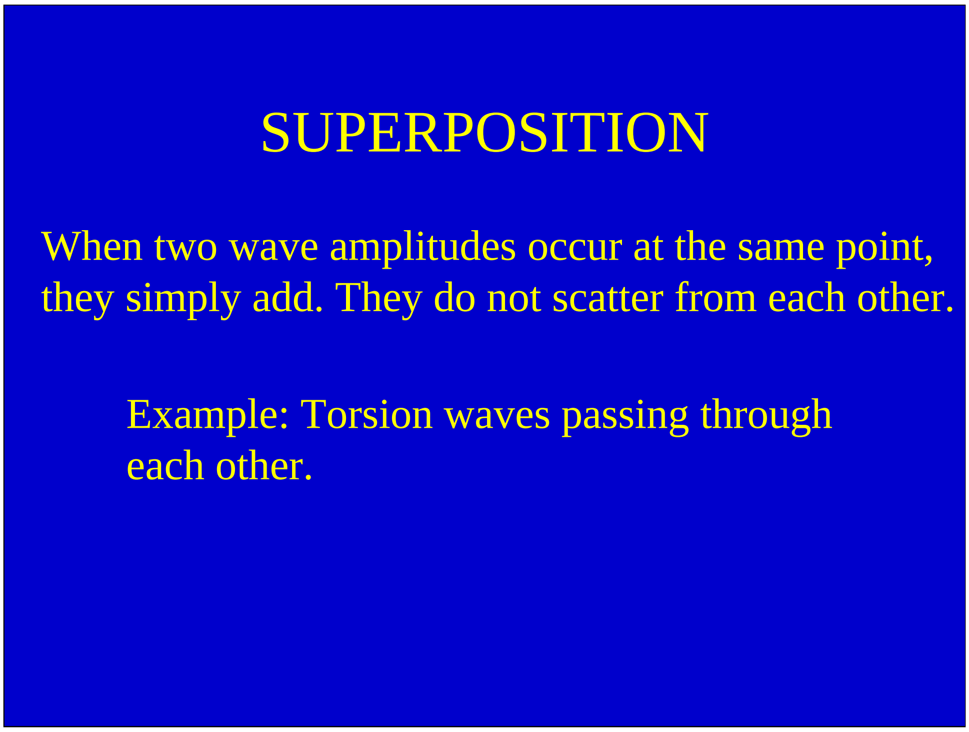
We see that the wave reflects from the ends of the structure, similarly to the example of the stretched spring. Reflection of waves from a sudden change in the medium seems to be a common feature.



A torsion wave apparatus with shorter bars produces a faster wave propagation. The shorter bars have less inertia and so respond more quickly to the twist of the steel wire.

Now if we join together an apparatus with long bars and one with short bars what will happen when we create a wave at one end? SHOW connected torsion wave demo. We see that the wave is partially transmitted to the second skeleton, and partially reflected back towards the origin. This happens whichever side the wave comes from.

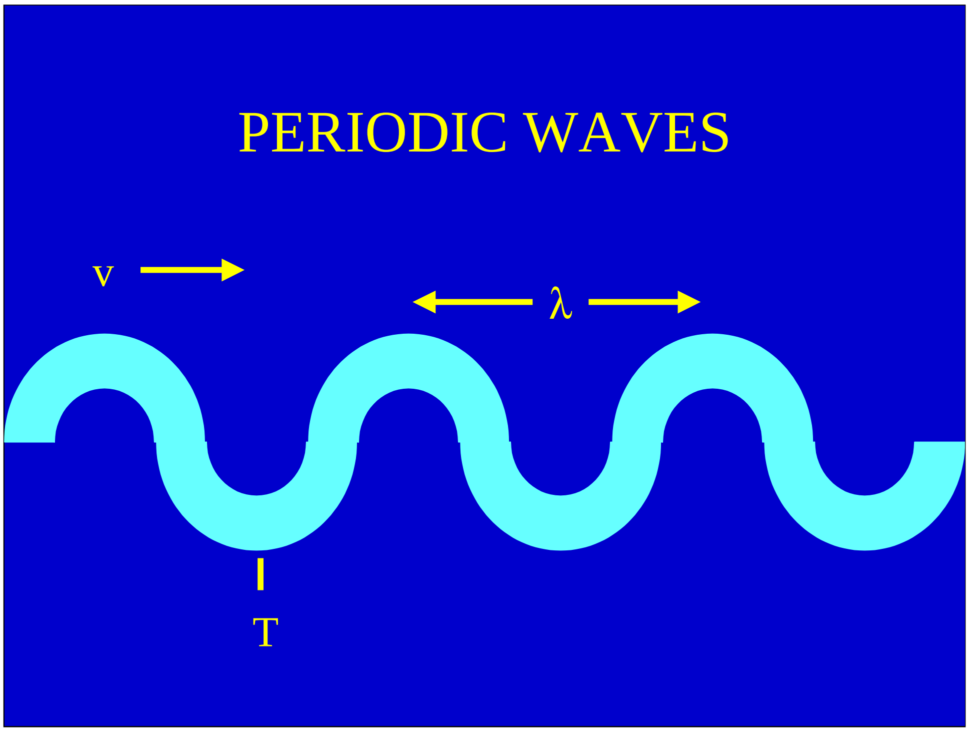
This is a general feature of wave propagation. That when a wave encounters an interface between two media in which the wave speed differs, part of the wave energy is transmitted, and part is reflected. This reminds us of an air-glass or air-water interface for light.



Two waves can occupy the same place at the same time. The total amplitude is simply the sum of the individual amplitudes. The two waves do not scatter from each other. In this way waves are completely different than material particles like billiard balls.

SHOW negative and positive wave crests passing through each other on the torsion wave demo.

SHOW standing periodic waves on torsion wave demo and on stretched rope.



If waves are created on a stretched spring by regularly shaking one end up and down, then a continuous wave train will be formed. The waves propagate to the right with a speed v. Standard language for the description of such waves is: The distance between wave crests is called the wavelength and denoted by the greek letter λ. Iφ ψου αρε λοχατεδ ατ α φιξεδ ποιντ ανδ οβσερϖε τηε ωαϖεσ πασσινγ βψ, τηε τιμε βετωεεν συχχεσσιϖε χρεστσ ισ τηε περιοδ T.

PERIODIC WAVE SPEED

T = period of rope motion. f = frequency = 1/T

v = wave speed

Wavelength = λ = distance between wave crests

Basic relation: v = distance moved/time = $\lambda/T = f\lambda$

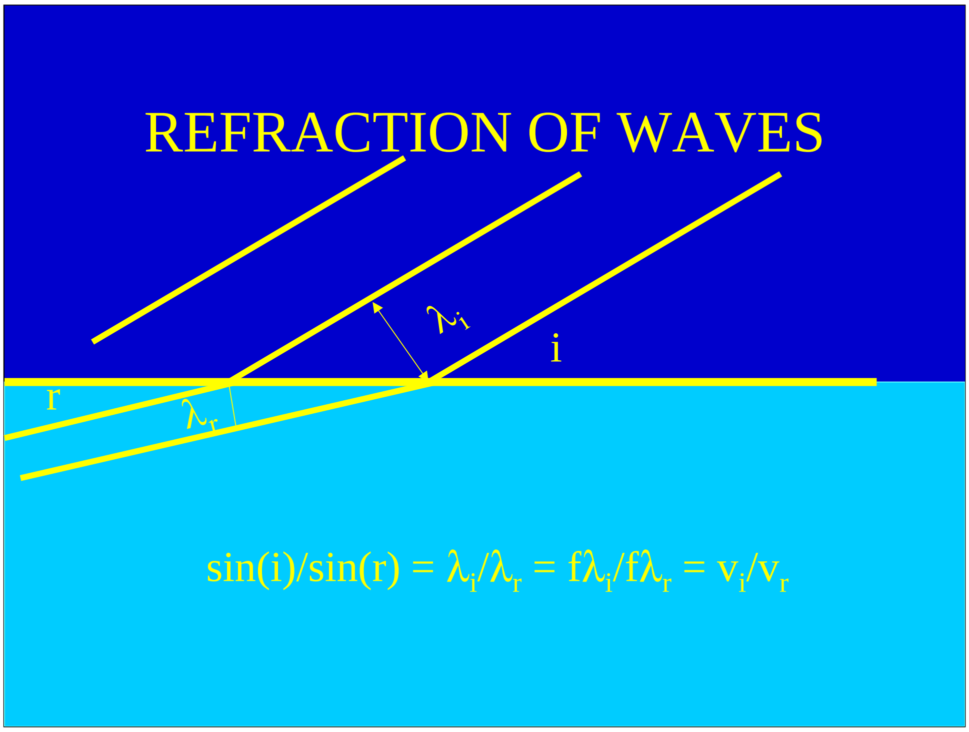
Example: WTJU frequency = 91 MHz.
$\lambda = c/f = 3*10^8/0.9*10^8 = 3.3\text{m}$

At any point along the stretched rope, the rope moves up and down repeatedly with period T. Then f = 1/T is the frequency, telling us how many times per second it moves up and down. This is like a piece of wood floating on water with waves: The piece of wood bobs up and down.

How fast does the wave move along the rope? In a time of one period, it moves along by one wavelength, which is the distance between wave crests. This gives us a relation between wave speed, frequency, and wavelength.

This relation holds for any type of periodic wave. Any wave whose motion repeats regularly.

As an example, the wavelength of WTJU's broadcast signal is given by this relation as 3.3m.



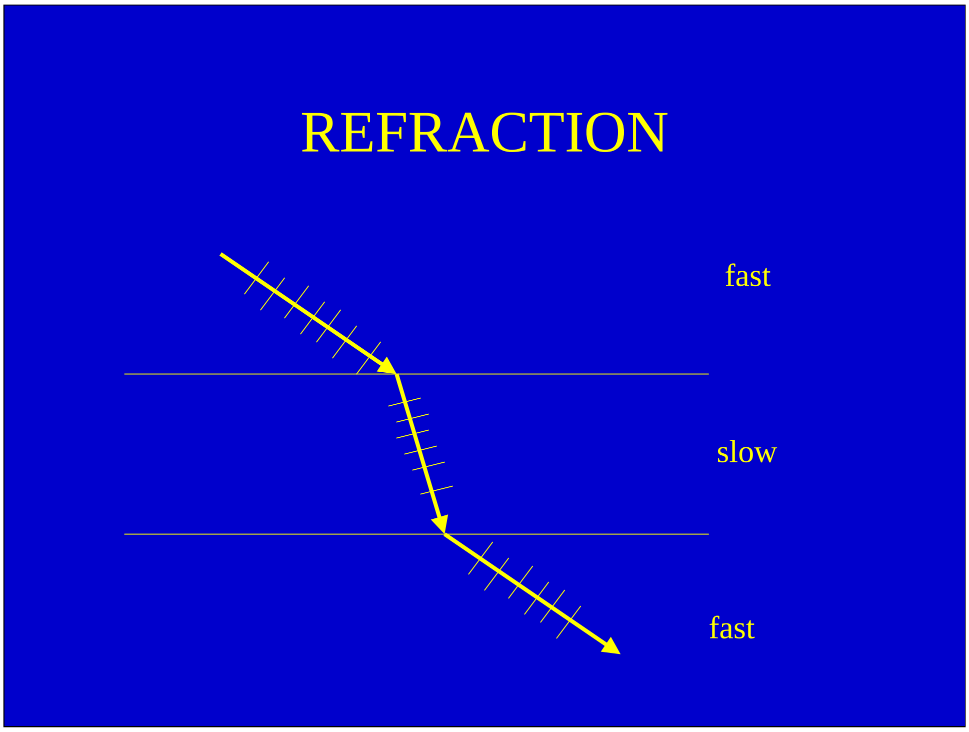
How do waves refract when they travel from a medium with one speed of propagation to another? The diagram above shows waves incident from above on a horizontal interface between two media. The wave speed is smaller in the lower medium. What happens is the wavelength is shorter in the slower medium: The wave does not travel as far in one period.

What is shown in the diagram are the wave crests of the incident waves. The wave crests line up along the interface, and the only way they can do this is if their direction changes. Here i is the angle of incidence, equal to the angle between the wave crest and the interface between the two media. The letter r is the angle of refraction.

Using the two triangles shown at the interface, we see that the ratio of sines is equal to the ratio of wave speeds in the two media, and is independent of the value of i as observed.

Interestingly, this ratio of sines is just the inverse of that obtained using Newton's particle theory of light.

Measurements for the air-water interface give a ratio of sines of 1.33. In 1883 Albert Michelson measured the speed of light in water and found it was slower than for air by precisely this factor. (Foucault, who measured it earlier, did not give a value for the ratio). This is excellent support for the wave theory of light.



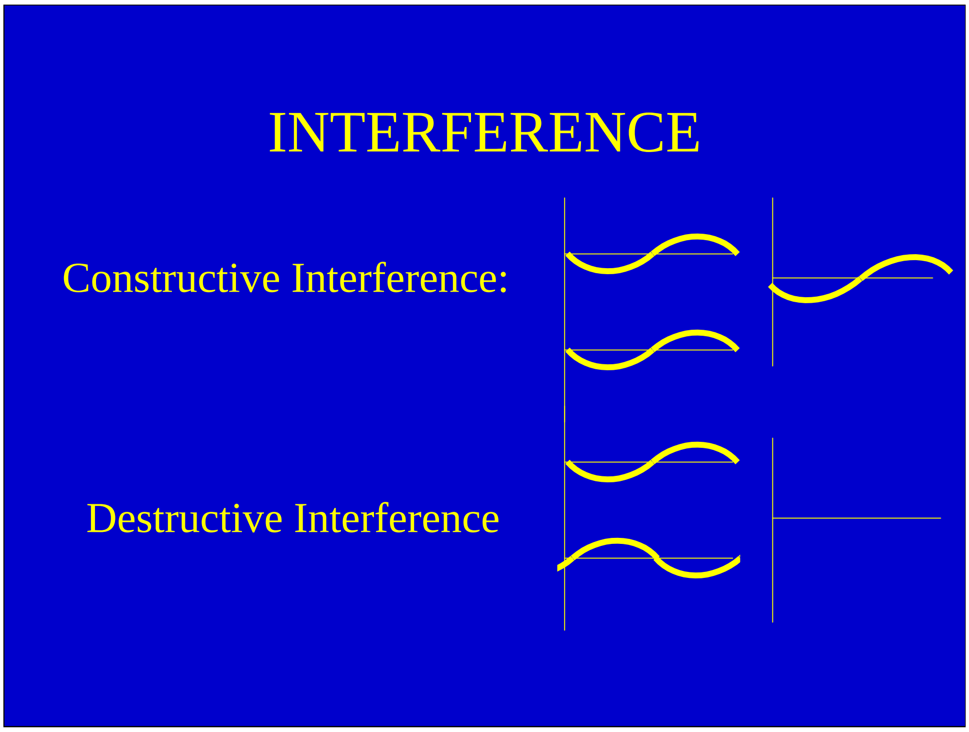
The diagram above shows a wave making two transitions. First it enters a slower medium from a faster one, then re-enters the faster medium. This is like a beam of light going from air to glass and back to air as in through a window.

The beam is refracted towards the surface normal as it enters the slower medium.

Some wave crests are shown. Note that they are perpendicular to the direction of propagation of the wave in both media.

In the example of the wave on a stretched rope, the motion of the rope was perpendicular to the direction of propagation of the wave. Such a wave is called transverse. Sound on the other hand is a longitudinal wave, with the vibrations of air in the same direction as the propagation of the wave.

In a football stadium, “the wave” is transverse. Its medium is people. For light we have yet to discuss what it is that “waves” and whether it is transverse or longitudinal, and whether there is a medium.

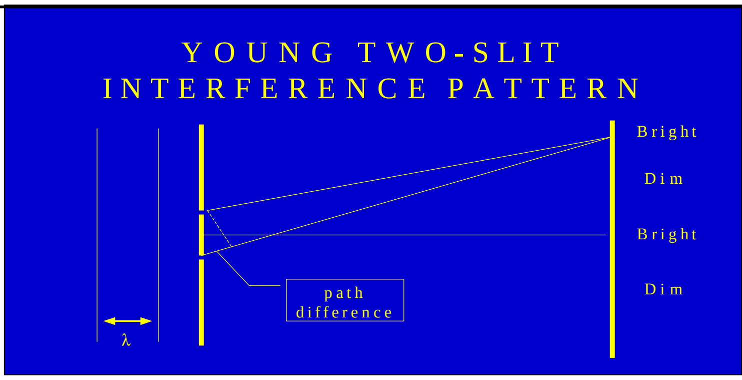


Interference refers to the superposition property of waves. If waves from two sources are brought together so the crest of one wave occurs at the same position as the crest of another, then the result is a larger amplitude wave. This is called constructive interference.

When two waves are brought together so the crest of one is at the same place as the trough of the other, then destructive interference occurs.

If light is a wave phenomenon, then it must exhibit interference. For different kinds of waves, we need to create special situations to make wave interference observable. Water waves, sound waves, and light waves each require different circumstances to bring out interference effects.

One way to do this with light is to separate a beam into two parts traveling different paths, then bring them back together again. If the two path lengths differ by ½ wavelength, the crests of one wave will line up with the troughs of the other, and we will see destructive interference. On the other hand, if the two paths differ by a multiple of a wavelength, then we will see constructive interference.



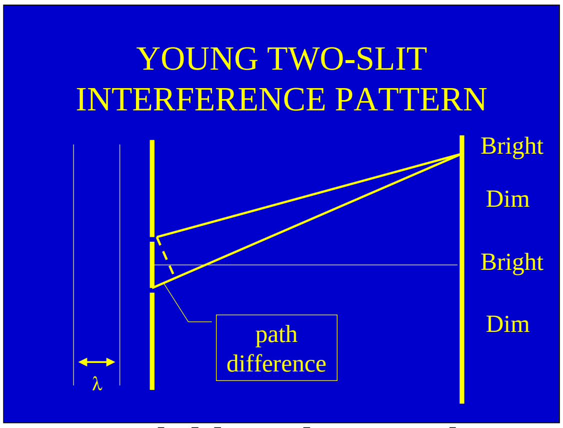
All during the 1700's Newton's particle model of light held sway. Huygens had proposed a wave model, but it was incomplete. There was no serious competition for Newton's model until Thomas Young discovered interference of light in 1801.

The Young two-slit geometry is simple, easy to understand, and still one of the best demonstrations of light interference. Imagine two parallel slits cut into an opaque screen. Light of wavelength lambda from a distant source falls on the screen from the left as shown above. The only light to get past the screen comes through the two slits. The two slits act like sources of light that is "in phase", i.e. the wave crests and troughs line up. If the slits are narrow enough, the light will spread. You can see this qualitatively by looking at a small bright object through the gap between two fingers at arms length, and squeezing the fingers until they nearly touch.

Behind the screen to the right is a white surface. What we want to observe is where on that surface light appears. Where does constructive interference from the two sources occur on the screen? First, it occurs in the center directly behind the two slits. The path lengths from the two slits are equal, and since the light waves were in phase as they came through the slits, they remain in phase after traveling equal distances. We see a bright stripe.

As we move upwards on the white surface, the path to the lower slit becomes longer than that to the upper slit. At some point this path difference becomes equal to ½ wavelength. Then destructive interference occurs: the wave crests from one slit line up with the troughs from the other. We see a dim stripe.

When the path difference equals one wavelength, we again see a bright stripe, and so on. A large number of bright and dim parallel stripes are seen. SHOW Single-slit and Young two-slit pattern.



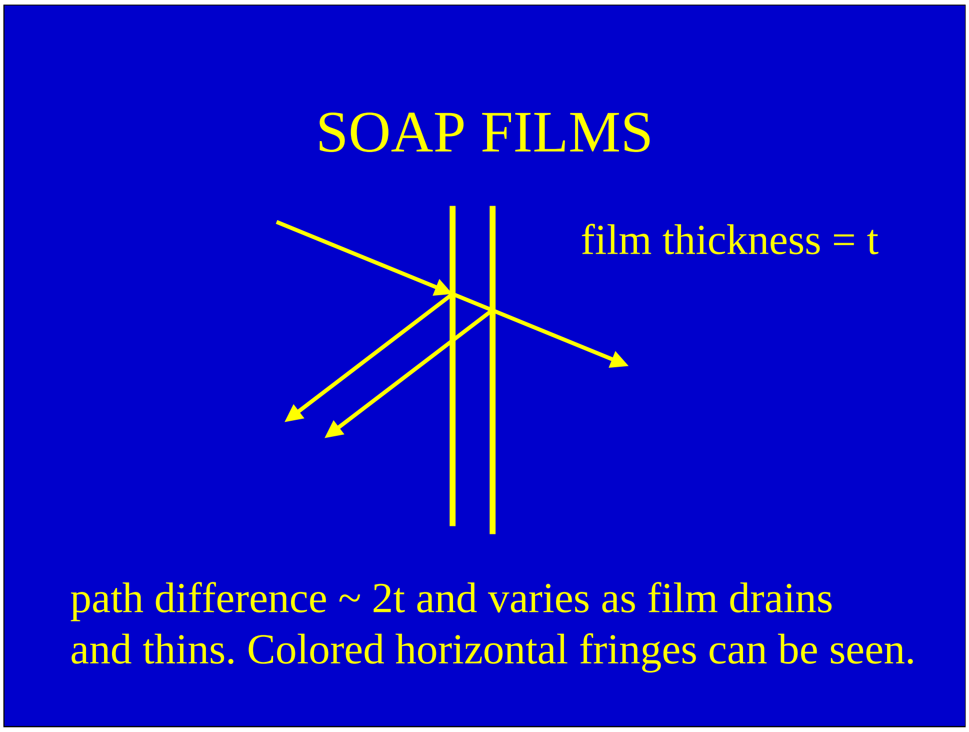
Thomas Young was a child prodigy. He began reading at age two and by 16 knew a dozen languages. He studied medicine and right away discovered how the eye focuses on objects at different distances. He explained that muscles around the lens in the eye contract or relax, making it more or less convex, and changing its focal length. For an object a certain distance away, a particular focal length is needed to produce a sharp image on the retina.

Young helped translate the Rosetta stone, found in Egypt by the French in 1799. It contains the same text in three languages, Greek, Egyptian demotic (used for books and deeds), and Egyptian hieroglyphics (with so many bird symbols).

Young knew the content of Newton's *Opticks* thoroughly. At one point he realized he could explain some of the experiments if he assumed that light was some kind of periodic wave, and that they obeyed the principle of superposition. Interpreting some of Newton's data in this way, he concluded that the wavelength of red light is 650 nm, and that of violet is 440 nm. Both numbers are close to modern values.

This is remarkable. It speaks very will for Newton's experimental skill and the accuracy of his descriptions of results he did not at the time understand.

So in the early 1800's Newton's particle theory and Young's wave theory of light coexisted. Newton's model could not account for the interference effects seen by Young, but his reputation was so strong that the particle model retained adherents for many years. As we have seen, in 1850, Foucault measured the speed of light in water and found it to be less than in air, so the wave theory triumphed. This still does not tell us, of course, what the wave consists of.



If we create a soap film and view it in reflected white light, we see horizontal bands of color. Why does this occur?

About 2% of the light beam is reflected at the air-water interface. So 98% continues on through, and 2% of this reflects from the back surface of the film. These two reflected beams emerge parallel to each other. They differ in distance traveled from the front surface by about twice the thickness of the film.

If this path difference equals a multiple of a wavelength of light, then we will see constructive interference. It will be destructive if the path difference is half a wavelength.

Different colors of light have different wavelengths. We started with white light, which, as Newton showed, contains all colors, hence all wavelengths.

The soap film thins with time by draining and evaporating. As water flows downward, the top becomes thin, and the film becomes slightly wedge-shaped. This is the reason for the horizontal bands of color. When the film thickness produces a path difference equal to a multiple of the wavelength of red light, we see red, and the same for other colors.

SHOW soap film in reflected light.

COLOR AND WAVELENGTH

Color	Wavelength (nm)
Red	650
Yellow	580
Green	540
Blue	470
Violet	440

This table shows a rough correspondence between the colors of the rainbow or produced by a prism and the wavelength of light involved.

Colors used in decoration or by artists are more complex. What is called color above is referred to more generally as hue. A second color quality is called saturation. When we see green leaves on trees close up, they are pure green and close to the above wavelength in the spring. When seen from a distance however, scattering of the light between us and the trees adds a white haze to the green. The green is the same hue, but now less saturated.

When seen from even greater distances, a blue is added due to the blue light from the sky scattering into our eyes. This is how the Blue Ridge got its name.

So our perception of color is not just a simple matter of the wavelength of the light involved. Most outdoor colors are due to several contributions.