LIGHT: OBSERVATIONS

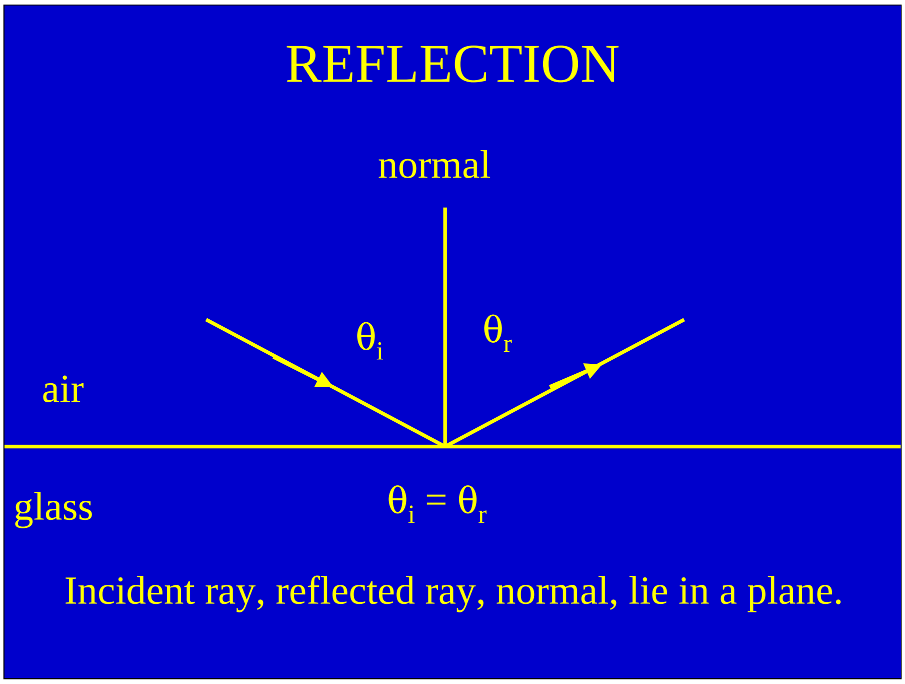
1. Light propagates in straight lines from a source.

   Makes triangulation, surveying, star location, etc. possible.

This property of light was known to the ancients. Without it, our ability to locate objects around us would become much more complex, even impossible.

Try imagining a world in which light travels in curves of some sort. Could we even make sense of such a world? A universe with curved light would likely have other unusual properties as well. It is likely that the kind of long term stability and predictability needed for the evolution of life requires straight line propagation of light.

It is true that near extremely large and dense masses such as black holes, light does curve. But when that curvature is significant, the tidal forces on ordinary sized objects would be so large as to tear them (and us) apart.

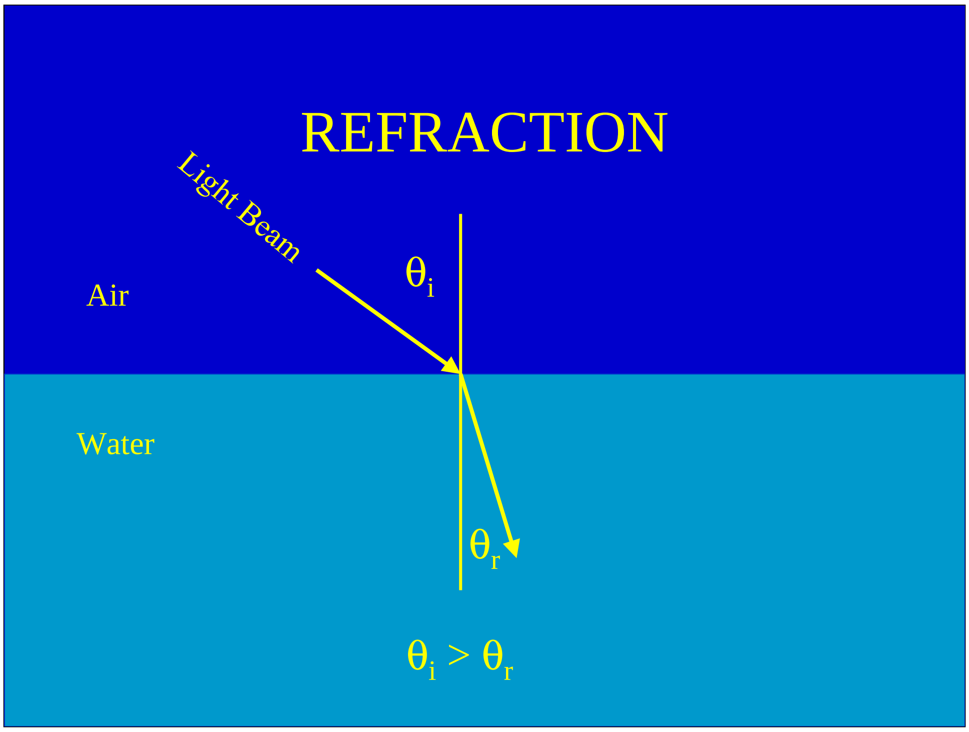


When light encounters an interface between two different materials, its behavior depends first on how smooth the surface is. For an ordinarily rough surface, such as the paint on the walls of this room, the light scatters diffusely from the surface. The paint was manufactured to yield such a result. This produces indirect lighting within the room. Light comes to us from all directions after leaving the lamps in the ceiling and bouncing around.

Now suppose the surface is very smooth. We won't say just yet how smooth is very smooth, but in everyday experience this includes the surface of water in a glass or pond, and polished glass surfaces. In this case, the very simple behavior described above results. By convention we construct a perpendicular to the surface where the light ray lands, and call this the normal direction. Then the direction of the incident ray is indicated by its angle from the normal. The reflected ray is found to make an equal angle with the normal. What has happened is the vertical component of the light ray's motion has been reflected from the surface, and the horizontal component left unchanged.

The angle the incident ray makes with the normal is called the angle of incidence, and for the reflected ray the angle of reflection. These two angles are equal.

Also the incident ray, reflected ray, and the normal to the surface at the point of reflection are all in the same plane.



When light passes from one medium to another, such as from air to water as shown above, its direction changes. The light beam is bent, or refracted, towards a line perpendicular to the interface between the two media. This property had been known since ancient times. In fact Ptolemy's *Almagest* includes a table showing measurements of the angle of incidence and the corresponding angle of refraction for light entering water.

The above diagram shows that the angle of refraction (the angle the light beam makes with the perpendicular to the interface) is smaller than the angle of incidence. Or more properly, the angle in water is smaller than the angle in air. The ray bends towards the normal when entering water from air.

It is found that for both reflection and refraction, the paths taken by light beams are reversible. For example if we place a mirror under the water in the above diagram, so as to reflect the refracted beam back on itself, it would refract at the surface so as to emerge along the line of the incident beam.

How can the particle model account for this? Newton proposed that the denser medium exerts an attractive force on the particles of the beam at the interface. The particles are pulled into the water with a force perpendicular to the surface. This means that the light will be traveling faster in the water than in air. Newton showed that:

$$\text{sine(angle of incidence)/sine(angle of refraction)} = v_{water}/v_{air}$$

VARYING θ_i FOR AIR/WATER

θ_i	θ_r	θ_i/θ_r	$\sin\theta_i/\sin\theta_r$
10	7.5	1.33	1.33
30	22.1	1.36	1.33
60	40.6	1.48	1.33
80	47.8	1.68	1.33

We have seen that the angle of refraction is less than the angle of incidence when light from air enters water. Can we understand this quantitatively? Perhaps the ratio of the angles is a constant. But we see from the above table that this does not describe the data. The ratio starts out nearly constant for small angles, but then increases.

After many tries over the centuries it was found that the ratio of the sines of the angles is a constant, ie is independent of the values of the two angles. The sine of an angle in a right triangle is the ratio of the side opposite the angle to the hypotenuse.

This observation allows us to calculate the angle of refraction for any given angle of incidence as long as we have a calculator with sines available. It is not intuitively obvious why the sines of the angles should be involved. We will return to this question shortly. Here we are just making observations about the behavior of light.

INDEX OF REFRACTION

For light propagating between air and another transparent material,

$$n = \sin\theta_i / \sin\theta_r$$

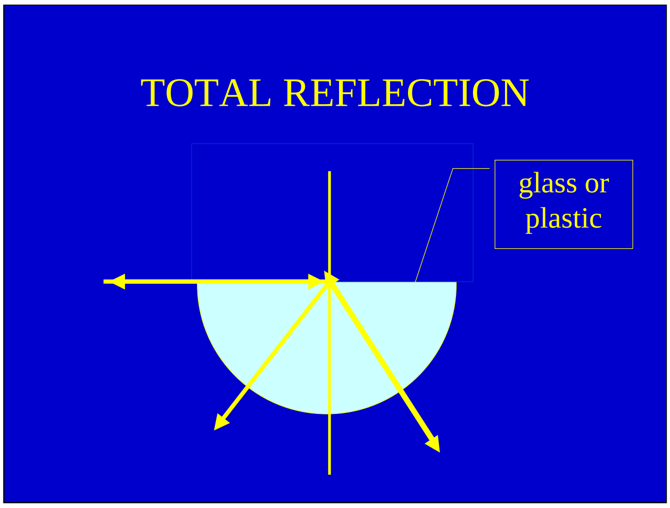
is the index of refraction of the material

The value of n depends on the material:

water: n = 1.33
glass: n = 1.5
diamond: n = 2.4

The ratio of sines is found to be constant for light propagating from air into any other transparent material. The value of the ratio however changes with material. So it makes sense to define a material-dependent quantity equal to this ratio. This is called the index of refraction of the material. The straight line beam "breaks" (fractures) at the interface.

This law of refraction is called Snell's Law after Willebrord Snell who discovered it in 1621. Descartes later discovered this relation and in fact was the first to publish it. In France it is known as Descartes' law. Knowing the index of refraction of component materials and using Snell's law allows complex lens systems to be designed and built.



Say we have a semicircular disc made of plastic or glass with polished surfaces. If we allow an incident light ray to be aimed at the center of the flat upper surface, it will be refracted and enter the material. The angle of incidence can be increased all the way to 90^0, as shown, at which time the angle of refraction will be determined by Snell's Law in the usual way. If the index of refraction of the glass is 1.5, then the angle of refraction will be 42^0 when the angle of incidence is 90^0.

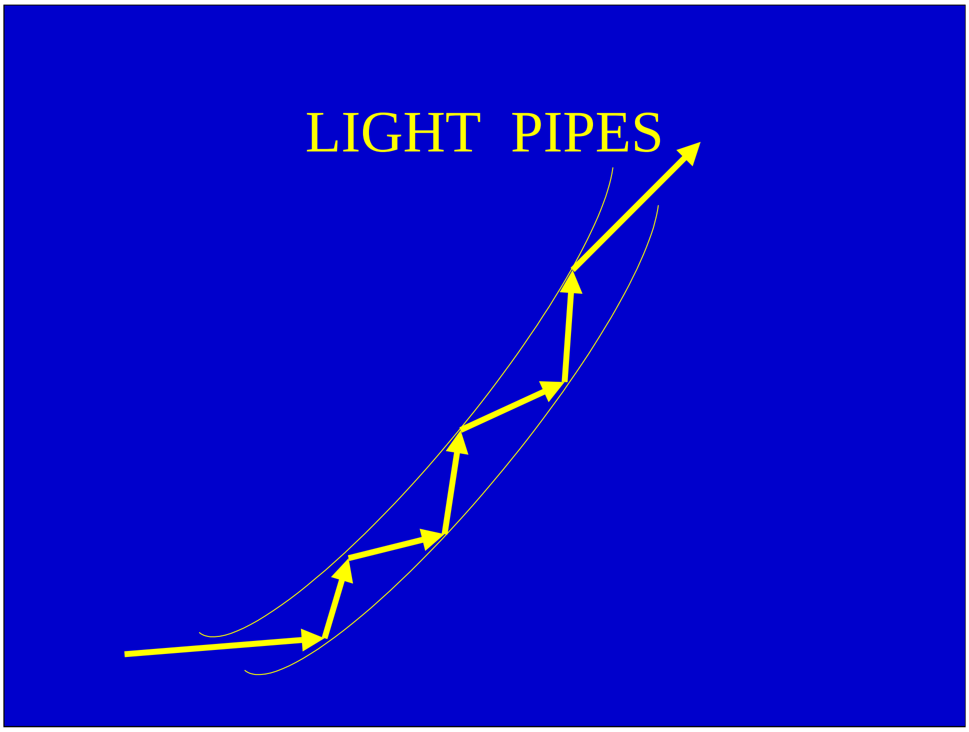
Since we know the paths of light are reversible, we can now imagine sending the light ray from below in the glass. As the angle of incidence inside the glass increases from 0, the angle of refraction increases faster, because its sine is multiplied by 1.5. What happens when we get to an angle of incidence of 42^0? At that angle the angle of refraction in air will be 90^0 and the light beam will emerge into the air in the horizontal direction.

For smaller angles of incidence, the intensity of the light is divided at the interface, with part being refracted, part reflected. As this angle is approached the intensity of the refracted ray decreases, and the intensity of the reflected ray increases. Beyond 42^0, only the reflected ray exists. All the intensity is reflected. This is known as total reflection. It can only occur at an interface where the index of refraction decreases, and so is sometimes known as total internal reflection.

For glass the critical angle for total internal reflection is 42^0. For diamond, with $n = 2.4$, it is 25^0. This is why a properly cut diamond is so sparkly – much of the incident light is reflected back out.

Light pipes, or optical fibers, are solid cylinders of glass. Light entering one end in a nearly parallel beam reflects from the surfaces many times before exiting the other end. As long as the angles of incidence with the walls exceeds the critical angle, the light is totally reflected and contained within the pipe.

SHOW total reflection demonstration.



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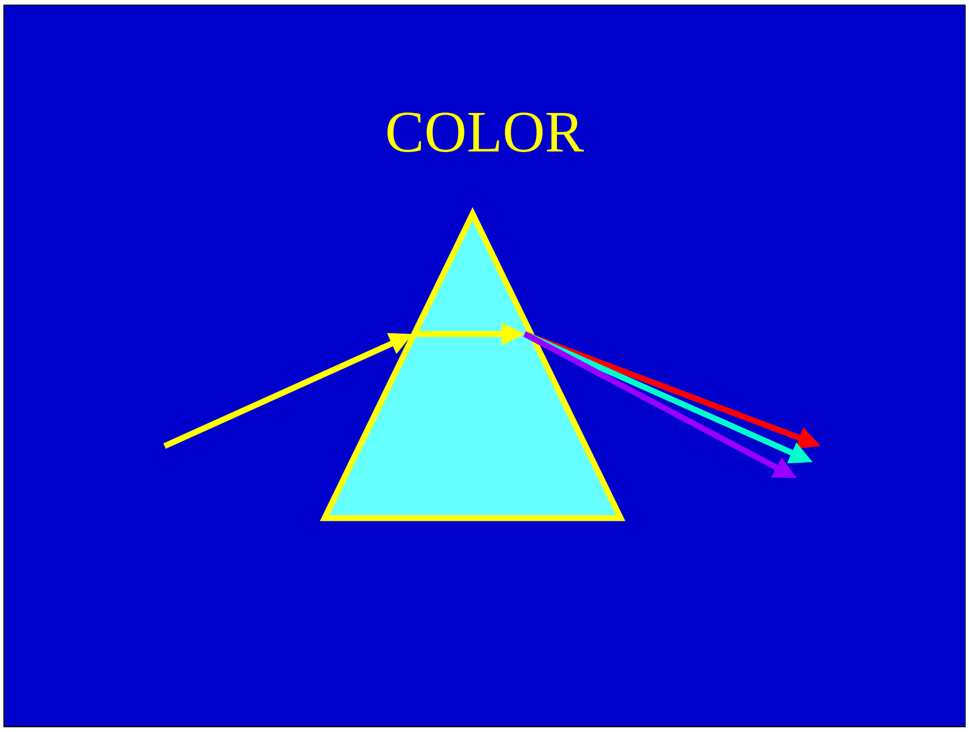
Optical fibers can carry light beams many miles with little intensity decrease. They play a central role in high speed broadband communication.

INTERSECTING BEAMS

- When two light beams intersect, they do not interact with each other at all.

When two light beams cross, they do not collide and bounce off each other. In this way they are completely different from two billiard balls, for example.



Newton discovered that white light, for example from the sun, consisted of all the visible colors together. He found he could separate the colors by means of refraction. Passing a light beam through a prism, he found that the different visible colors refract slightly differently. Red light refracts least, and violet the most, with the other colors in between.

If we now select only the red light and refract it again, it remains red; no additional changes occur. If we place an upside down prism after the one shown above, allowing it to refract all the colors, then once again violet is refracted most, red least, and the colors are recombined, forming a white beam once more.

SHOW prism and colors.

INTERPRETATION

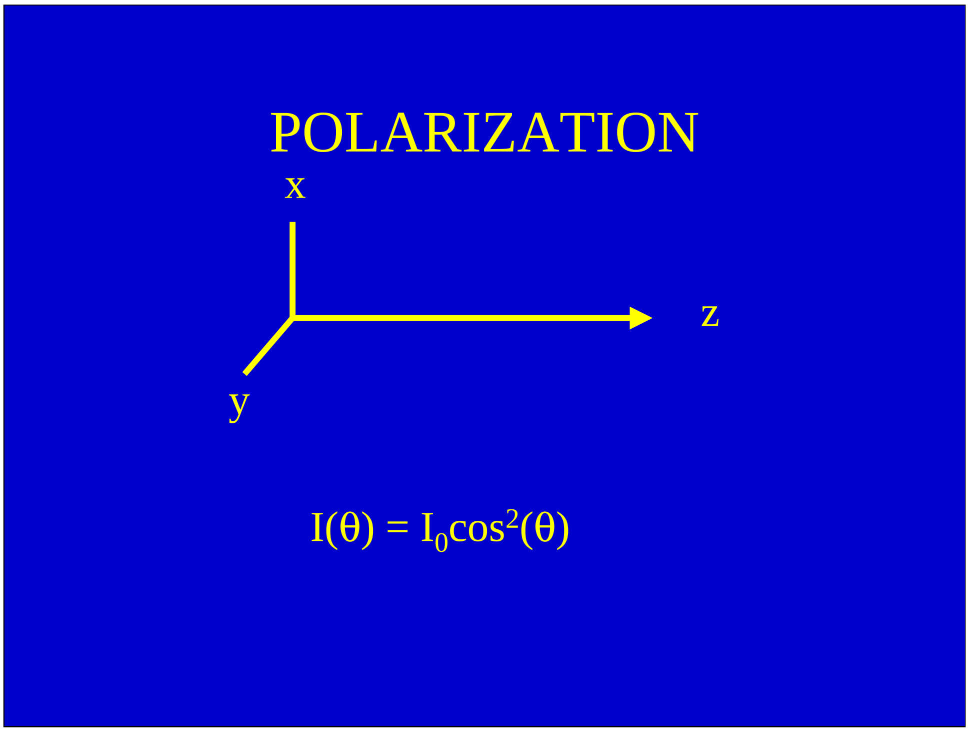
The index of refraction varies with color.

For Glass:

Red:	1.514
Green:	1.520
Violet:	1.529

How do we understand these results about color? Is Snell's law wrong? It is still correct, but it needs modification. The index of refraction of most transparent materials varies with color, with n being slightly larger for violet light than red light.

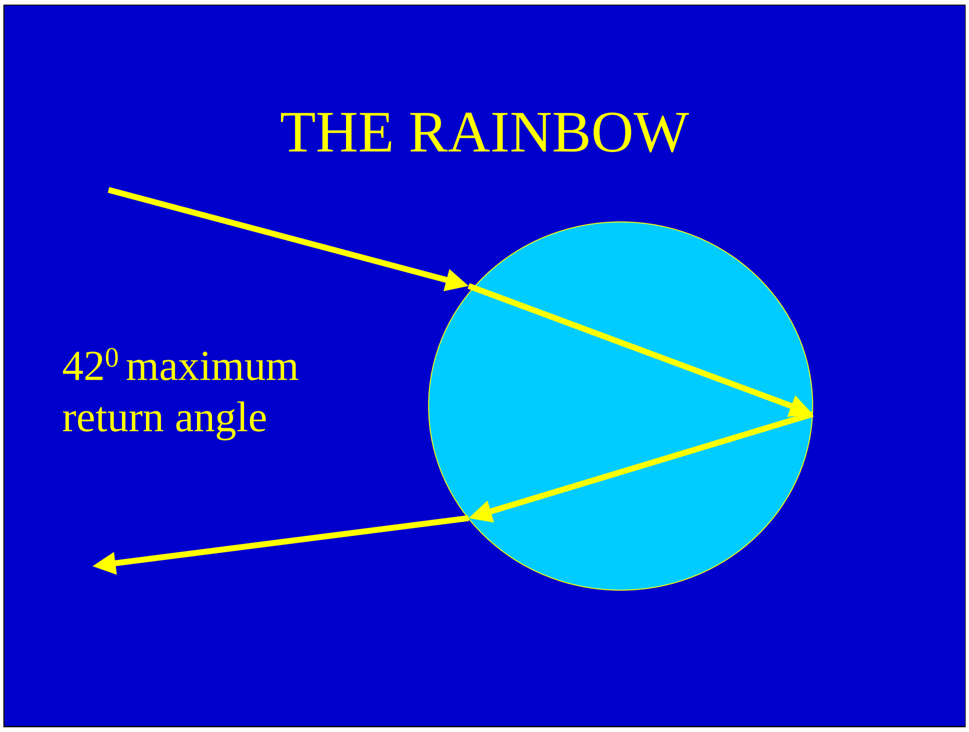
This variation of n with color can be used to produce beautiful displays. It is, however, a nuisance if you want to focus a faithful image of an object. A telescope, for example, will focus the violet light of an object at a different position than that of the red light. This is called chromatic aberration. For Galileo this was a serious problem since he did not know how to take any steps to reduce the effect. Refracting telescopes today can produce images with very little chromatic aberration.



An important property of light is referred to as polarization. What this means is that in the plane perpendicular to the direction of propagation of the light, the light beam can have an orientation. If it is transmitting in the z direction, then it can be polarized in either the x or y directions, or can be a combination of these polarizations. Light coming directly from the sun or a typical light bulb is unpolarized, that is, it consists of equal amounts of both possible polarizations.

A sheet of polaroid plastic consists of long molecules (polyvinyl alcohol) treated so they absorb only one polarization of light, allowing the other to transmit through. Polaroid sun glasses are made of this kind of plastic. Light scattered or reflected from most surfaces at a steep angle tends to be polarized parallel to the surface. So, for example, sunlight reflected into our eyes from a lake, or a distant highway is largely polarized horizontally. Sunglasses that transmit only vertically polarized light will then reduce the glare from such scattered light making it easier to see into the water, or to see cars on the road.

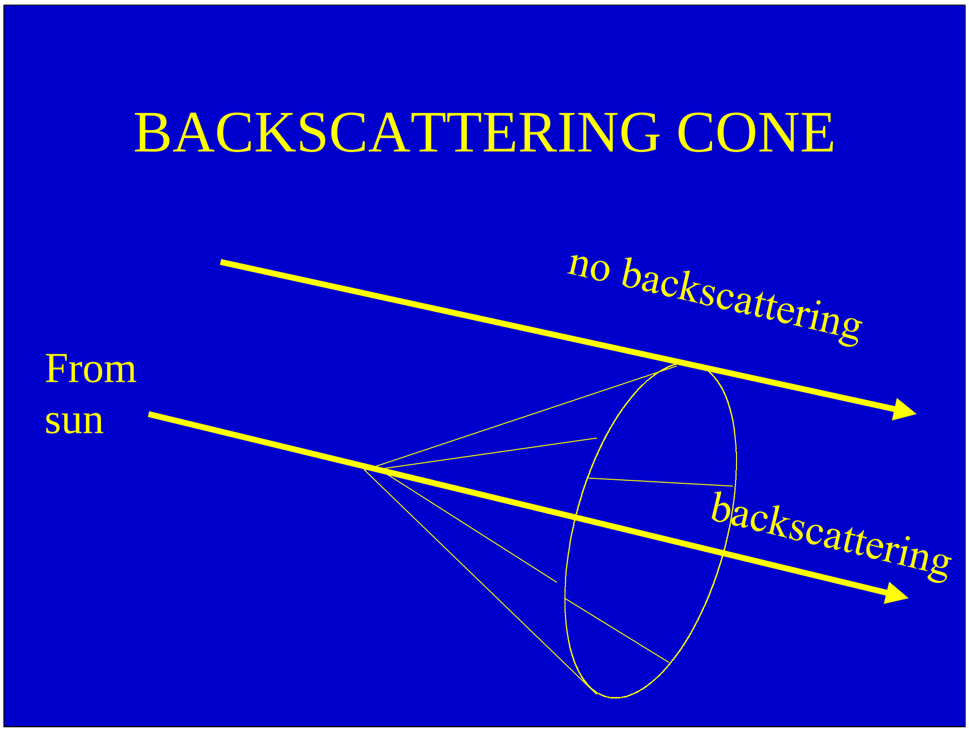
If light is transmitted through one sheet of polarizer it will then be polarized along the transmission axis of the sheet. If another sheet is placed in the beam the amount of light getting through depends on the angle of the second polarizer. When the two axes are aligned, the intensity is a maximum, and it is zero, or nearly so, when the two axes are perpendicular. In between the intensity varies as the square of the cosine of the angle between the two axes.



The rainbow is an atmospheric light event that we have all seen. They can be strikingly beautiful in part because they are unexpected. Why is there a pot of gold at the end of the rainbow? Because you can never get there – it keeps moving away if you try.

The first person to give a satisfactory explanation of the rainbow was Rene Descartes in a paper published in 1637. It had been known for some time that rainbows are somehow caused by sunlight falling on raindrops. Descartes guessed that the size of the drop does not matter, so he used a large spherical glass globe filled with water, and observed how light beams propagated through it. He found he could reproduce rainbow-like effects from rays of light that enter the sphere, reflect from its back surface, and emerge again.

What he showed is that there is a maximum return angle of 42 degrees for light incident on water spheres. He did this by tracing out rays for different entrance positions on the sphere. After Newton developed calculus, he was able to show rigorously that this maximum angle exists

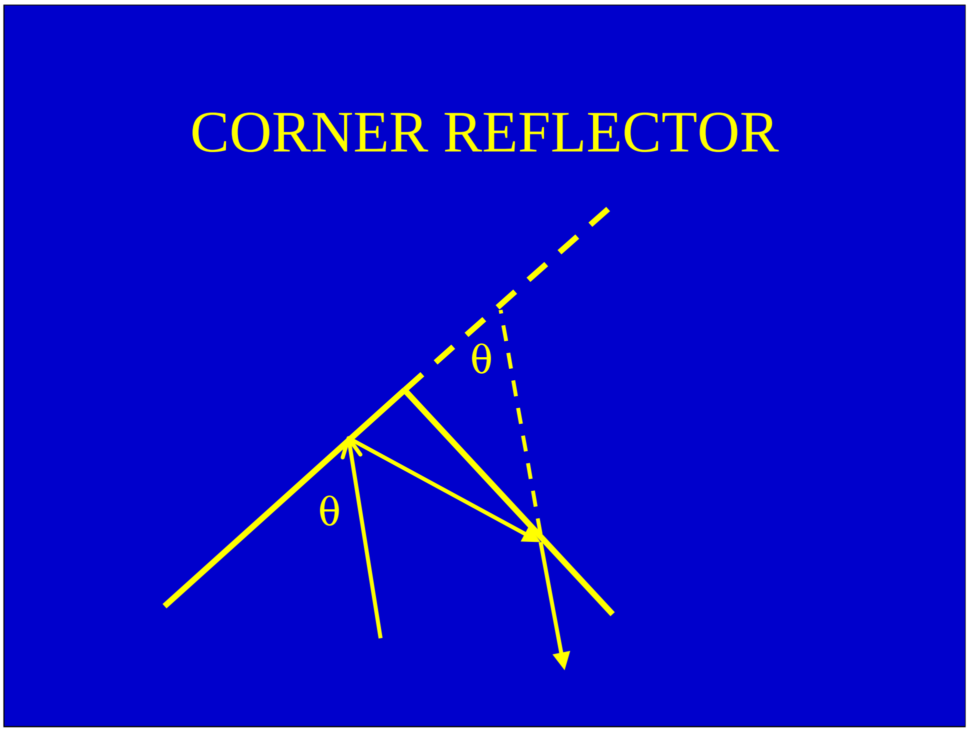


When looking for a rainbow, first find the antisolar point. That is the point opposite the sun from where you are standing, for example the shadow of your head if you can see it. Then the backscattering from any raindrops will occur within a cone of angle 42^0 about the antisolar point. That is the angle where the rainbow appears. When you spread your fingers at arms length, the angle between the tip of your little finger and the tip of your thumb is about 20^0, so the rainbow is located about two hand spans from the antisolar point.

What you will see is white light from the drops within the cone. Then outside the cone, no scattering at all. The cone angle depends on the index of refraction of water, so the angle is slightly different for different colors of light. That is why we see color at the cutoff angle. The cone angle is about 42.5^0 for red light, and 40.8^0 for violet light.

SHOW glass sphere and laser, pictures of rainbows.

Rainbows can be seen in many situations other than a rainstorm. Dewdrops on grass, water drops on a spider web, droplets from a breaking wave or a fountain, a garden sprinkler, are good examples. You will need to position yourself so the drops are 42 degrees from the antisolar point to see the rainbow.

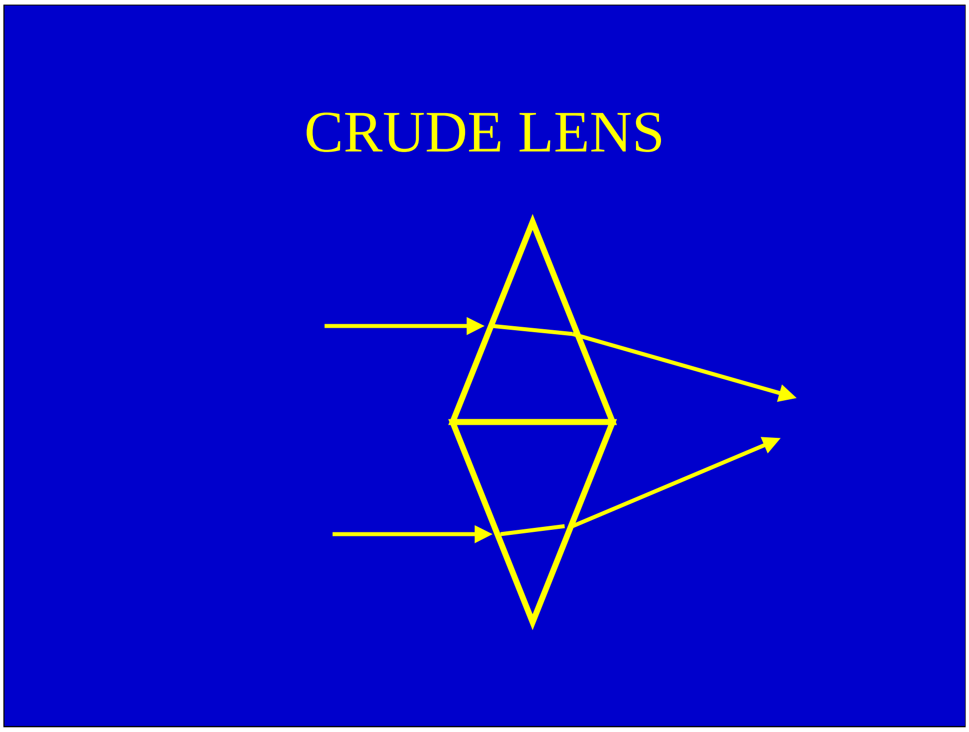


A corner reflector is a prism or set of mirrors that return a beam of light precisely in the direction from which it came, regardless of where that was. Here we see a two dimensional view of such a reflector. The two lines are mirrors or faces of a prism that are perpendicular to each other. A beam of light is incident from an arbitrary direction. It reflects off one of the mirrors. We know the angle of reflection equals the angle of incidence. Call this angle theta. The triangle formed by the reflected beam and the two mirrors is a right triangle, so its other acute angle is 90 – theta. This is also equal to the angle between the outgoing return beam and the second mirror.

Now to see whether this outgoing beam is parallel to the original incoming beam, extend the first mirror as shown by the dashed line, and extend the return beam similarly. The extended return beam forms a right triangle with the second mirror and extended first mirror. Its lower vertex angle is 90 – theta, so its other acute angle is equal to theta. Since the incident and return beams make the same angle, theta, with the first mirror, they are parallel.

Here we see a two-dimensional corner reflector. The same result occurs when we add the third dimension, forming a right angle prism. The incident beam will be returned precisely in the direction from which it came.

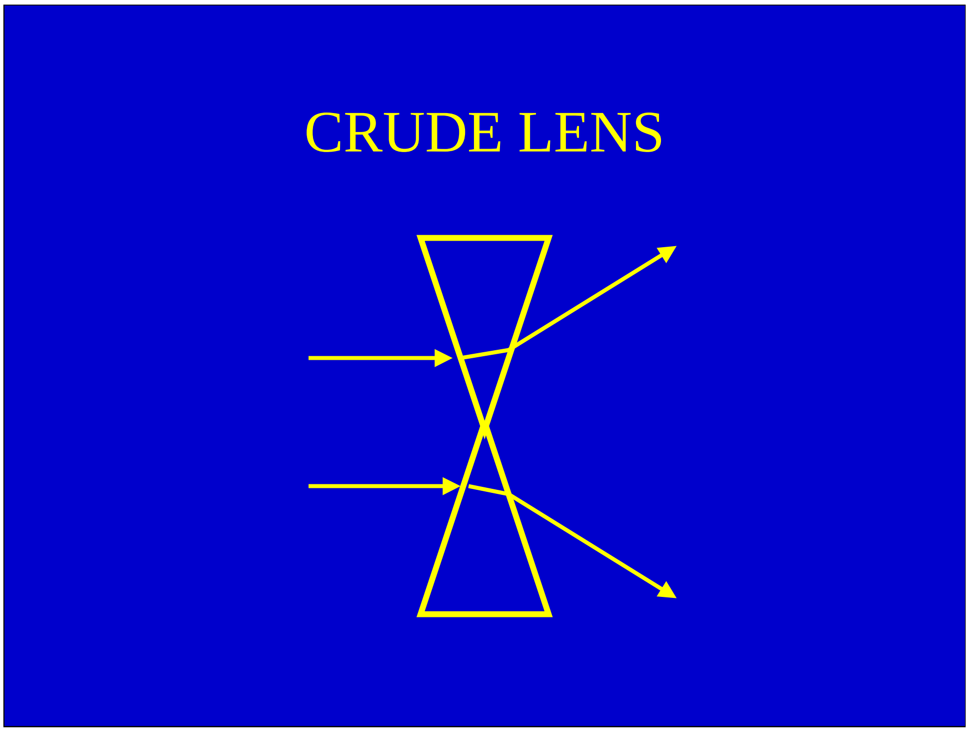
A set of corner reflectors was placed on the Moon years ago by one of the astronaut teams. It has been used since to measure the distance to the moon by timing a reflected laser pulse. The precision of that measurement has improved from about a meter originally to less than a millimeter now.



Here we have placed two glass prisms together at the bases. Two light beams are indicated incident on the prisms horizontally. As they transmit through the prisms, how does refraction alter their paths?

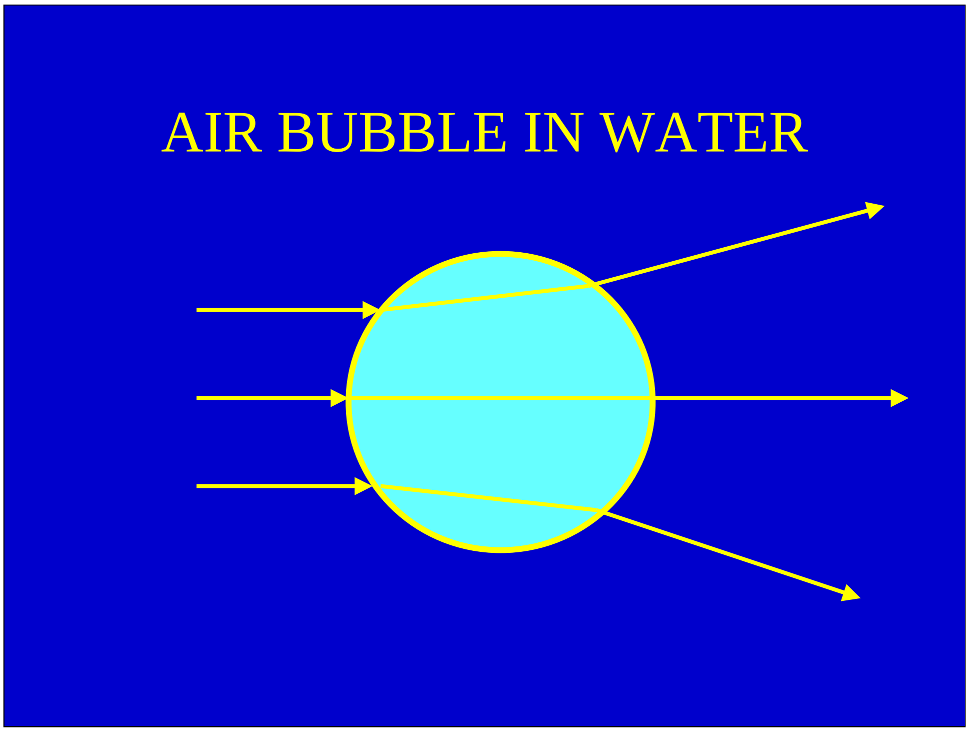
Since the index of refraction increases on going from air to glass, the beams will be bent towards the surface normal at the first interface. This means the upper beam is bent downward. As it leaves the prism, the index of refraction decreases, so the beam is bent away from the surface normal. This means it is bent downward again. The lower beam is bent upward at each interface by the same argument.

The two prisms form a crude convex, or converging, lens.



Here we have placed the two prisms together again, but this time they are joined at the vertices. Two horizontal beams are incident from the left as before. The upper beam is bent upward as it enters the prism since the index of refraction increases, and it bends towards the surface normal. As it leaves, it bends away from the surface normal, and so is deflected upwards again. Similarly with the lower beam, which is bent downward at each interface.

This arrangement of the prisms form a crude convex, or diverging, lens.



How does a spherical bubble in water affect light transmitting through it? Refraction must be taking place since the index of refraction changes at the bubble surface. Here we show three rays incident horizontally from the left. The central ray enters and leaves the bubble normally, i.e. perpendicular to the air-water surface, so the angle of incidence is zero, and there is no change in direction.

The upper ray bends away from the surface normal since the index of refraction decreases. This means it is deflected upward. Upon leaving the bubble, it bends toward the surface normal, and so is deflected upward again. The lower ray is deflected downward at both surfaces by the same argument.

So we see that an air bubble in water acts as a concave, or diverging, lens, even though it's shape is clearly convex.

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.

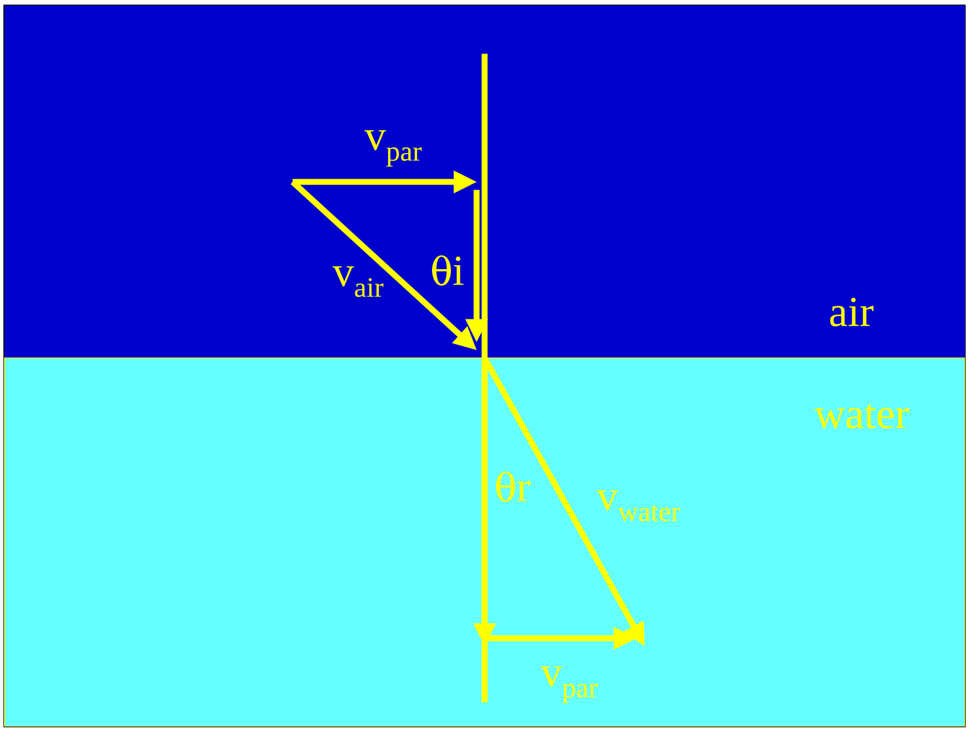
Near an interface, e.g. between air and water, light particles experience an attractive force towards the water.

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.

NEWTON’S EXPLANATION OF SNELL’S LAW

$$\sin(\theta_i) = v_{par}/v_{air}$$

$$\sin(\theta_r) = v_{par}/v_{water}$$

$$\sin(\theta_i)/\sin(\theta_r) = v_{water}/v_{air}$$

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

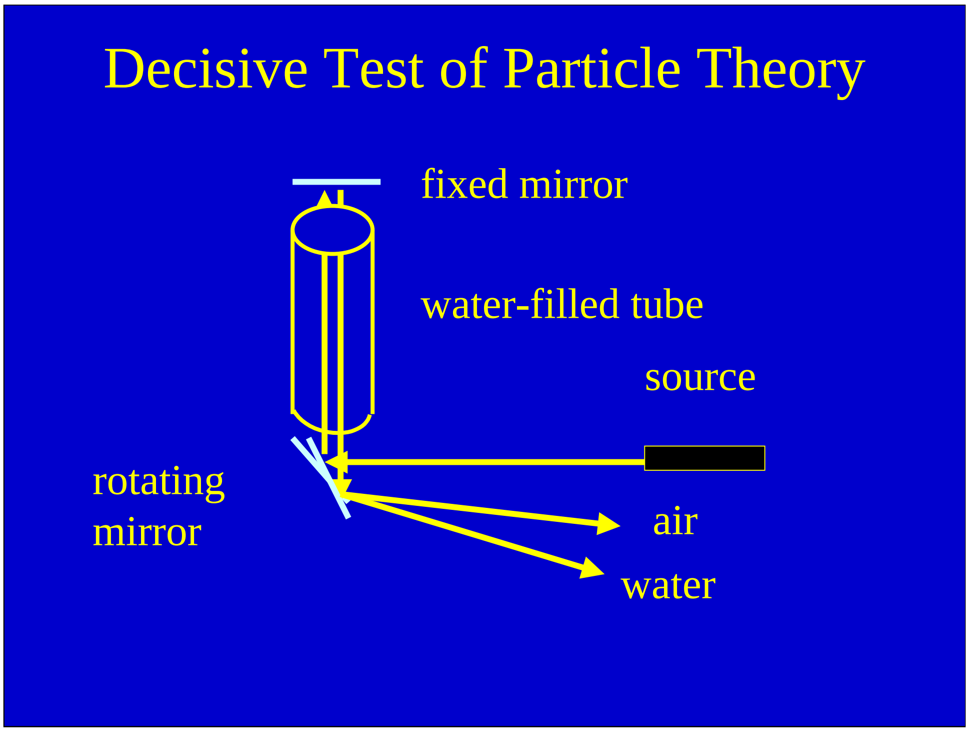
Colors

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.