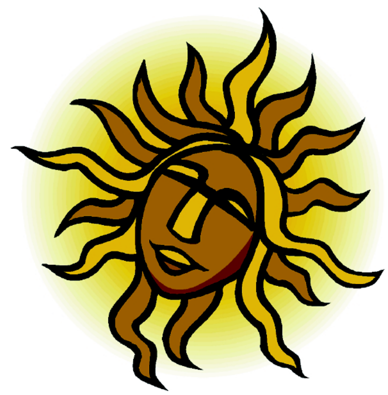
Optics

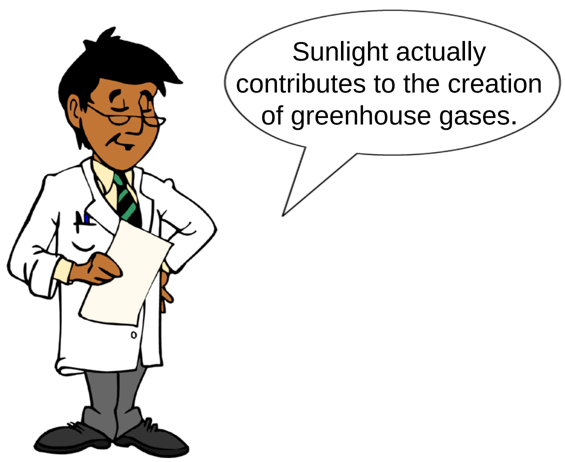
Optics: ʻäp-tiks (noun), 1579
a science that deals with the genesis and propagation of light, the changes that it undergoes and produces, and other phenomena closely associated with it



What is optics?

We wake up in the morning and Grandmother Sun shines down on us. Her light isvery important to every living creature on the planet. Without light, we could not see. More importantly, without it we could not survive, because in the great circle of life, Grandmother Sun's light provides food and energy for the plants which nourish us and all other animals.

What is the name of the process through which plants convert sunlight into food?



Some scientists - biologists, ecologists, botanists, chemists and environmental engineers - study light for its role in photosynthesis and other chemical reactions. But other scientists - physicists, communication engineers and optometrists - study light to learn more about the way it behaves. The study of the behaviour of light is called optics.

A little more about light

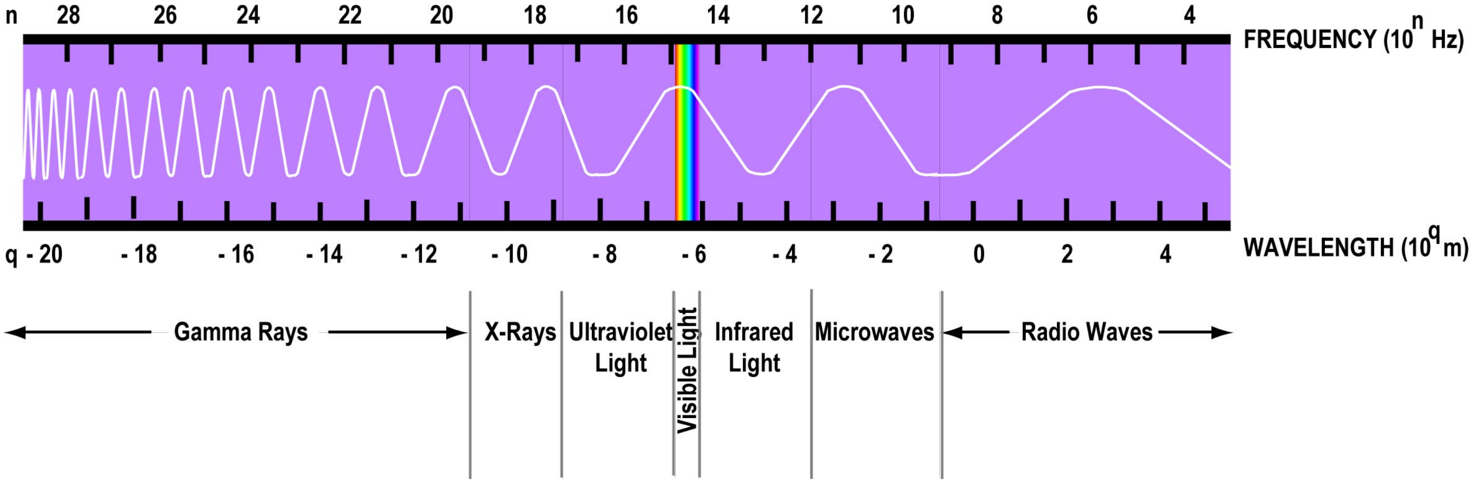
Light is a form of energy which travels in waves.

More specifically, it is the form of electromagnetic (EM) radiation visible to the human eye. There are different types of EM radiation - gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation and radio waves. Together they are known as the electromagnetic spectrum.

You probably know more about the electromagnetic spectrum than you think. What can you guess about the different types of EM radiations just from their names?

Each type of EM radiation consists of streams of massless particles, called photons. These streams of photons move (for the most part) like waves. Each photon moves at exactly the same speed - almost 300,000 km/s, also known as the speed of light. The difference between photons - and the different types of EM radiation - is the amount of energy each carries; some photons carry more energy than others.

The amount of energy carried by a photon is related mathematically to the wavelength and frequency of the wave carrying it. Long waves, like radio waves, have low frequency and low energy. Short waves, like, gamma waves, have high frequency and high energy.



Visible light falls in the middle of the EM spectrum. Its wavelength varies from $1x10^{-8}$m to $4x10^{-7}$m; its frequency varies from $4x10^{14}$Hz to $7.5x10^{14}$Hz; and, its energy from $3x10^{-19}$J to $5x10^{-19}$J.

The speed of light

If you have ever watched Star Trek or seen a Star Wars movie, you've heard some character refer to Light Speed. That's because light travels faster than anything else we know. And, as far as we know, the speed of light in the vacuum of space is as fast as anything can ever or will ever go. In a vacuum, light travels at 299,792,458 m/s. Scientifically the speed of light in space is represented by the letter c.

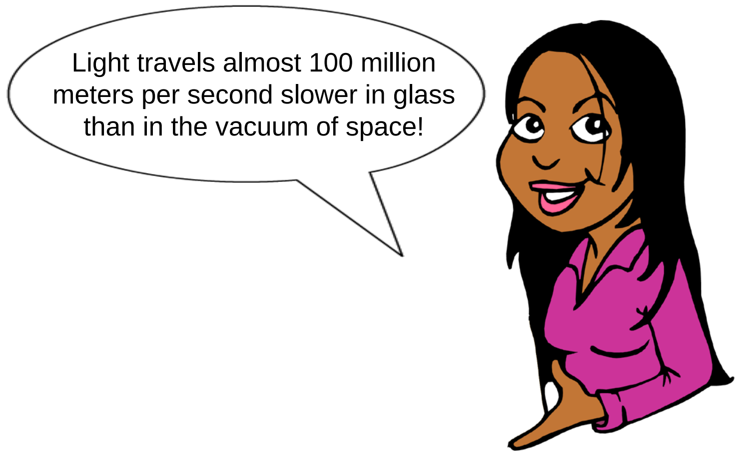
Imagine you're going swimming with friends. You run down from the shore and into the water.

What happens?

Well, the deeper you get into the water the slower you will go. Water is much denser than air and so it is harder for you to run through. A similar thing happens with light. As light moves from a substance which is less optically dense to one which is more optically dense it slows down.

Scientists have been able to measure the speed of light in different substances.

Substance	Speed of Light, m/s
Vacuum	299 792 458
Air	299 702 547
Ice	228 849 204
Water	225 407 863
Glass	199 861 638



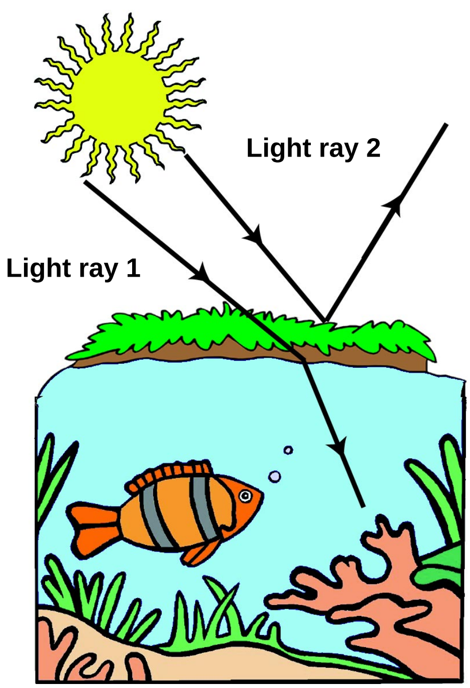
How light behaves

Light travels in straight lines, called light rays, until it hits something. When a light ray hits something, it acts in one of two ways.

Do you have any idea what these two ways are?

The way light behaves depends on the substance it hits. Transparent substances like air, water, some plastics, and vacuum, allow light to travel through them; opaque substances like wood, soil, brick and leather, do not.

If a light ray is moving from one transparent substance to another transparent substance it gets bent or refracted, but basically keeps going in a straight line. In the picture, light ray 1 gets refracted as it moves from air to water.



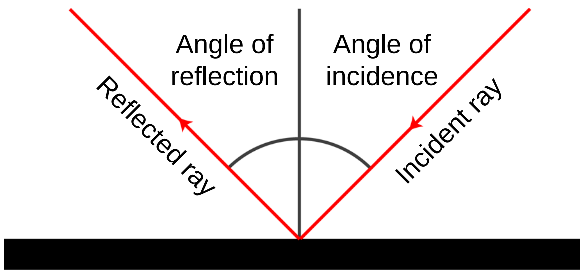
If a light ray hits an opaque substance it gets bounced off the object and reflected back in the general direction from which it came. In the picture, light ray 2 gets reflected back into the air after it hits the ground.

There are some fairly straight forward rules about how light reflects and refracts which let us do all sorts of neat things.

Reflection

We see objects because light reflects off of them into our eyes. To understand how light reflects off an object think of a pool table.

If you hit a ball from one side of the pool table to the bumper on the other side, what happens when the ball hits the bumper?



The pool ball bounces off the bumper at exactly the same angle at which it hit the bumper. Scientifically we say that the angle of incidence is equal to the angle of reflection. Exactly the same thing happens with light. A light ray moves in a straight line, hits an object and then reflects off the object at exactly the same angle.

Most objects - your shoes, your face, your grandfather's hunting jacket - are not very smooth, and so light hits them and reflects off of them in many different directions at the same time. Really smooth surfaces, such as polished metal or mirrors, are much better reflectors; light bounces oof them in predictable ways.

What materials have you seen your reflection in?

Plane Mirrors

Mirrors made from flat surfaces are called plane mirrors. Plane mirrors are the kind you use at home to make sure you don't cut yourself when shaving, or that you look good before going out on a date. The reflection we see behind the mirror is called an image.

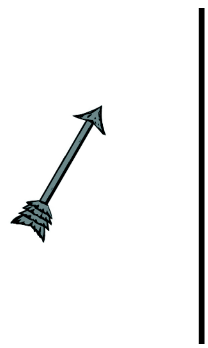
Imagine you are looking at an image of some object in a mirror. A light ray from the object travels to the mirror and reflects off of it. The mirror is such a good reflector, that to you, it appears as if the reflected light is actually coming from an object somewhere behind the mirror.

Knowing this, and remembering that:

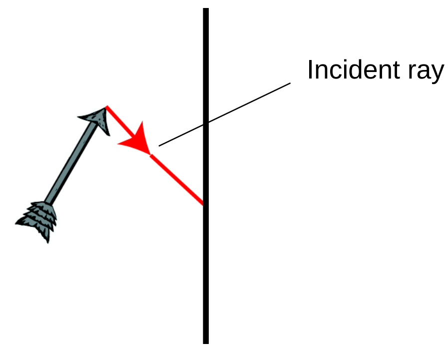
- light is being reflected off all points of the object;
- the angle of incidence is equal to the angle of reflection;

there is a simple way to figure out where an image appears behind a plane mirror using geometry.

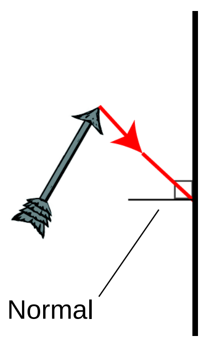
1. Imagine your object is an arrow in front of a mirror.



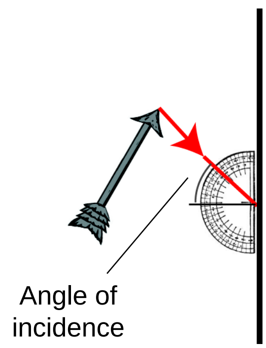
2. You begin by drawing a line from the top of the arrow to the mirror. This line is the incident ray.



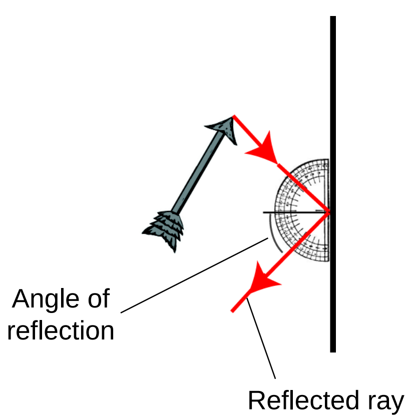
3. At the point where the incident ray hits the mirror, draw a line which makes an angle of 90° with the mirror. This line is called the normal.



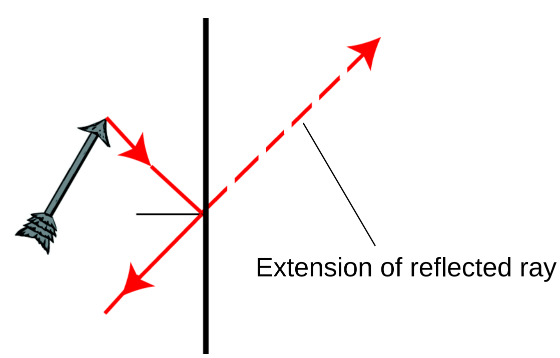
4. Measure the angle between the normal and the incident ray. This angle is the angle of incidence.



5. Mark an angle the same number of degrees on the other side of the normal. This angle is the angle of reflection. From the point where the normal meets the mirror, draw a line through the mark for your angle of reflection. This line is the reflected ray.



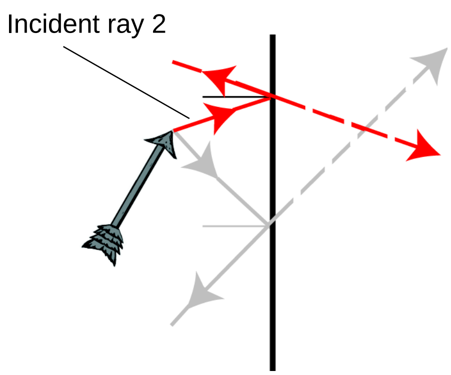
6. Now extend your reflected ray back behind the mirror.



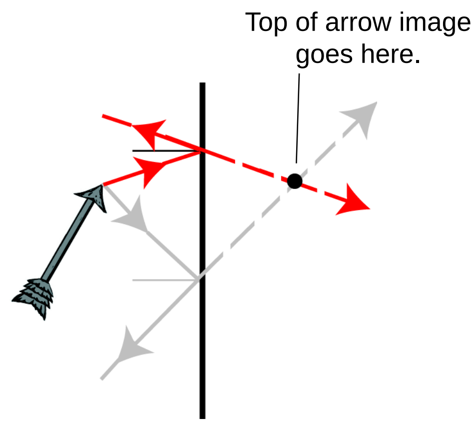
What can you tell from your drawing at this point?

At this point, you can't really get much information from your drawing.

7. In order to determine where part of the image will lie, you need to repeat the process by drawing another line from the top of the arrow. The second incident ray should hit the mirror at a different angle from the first.



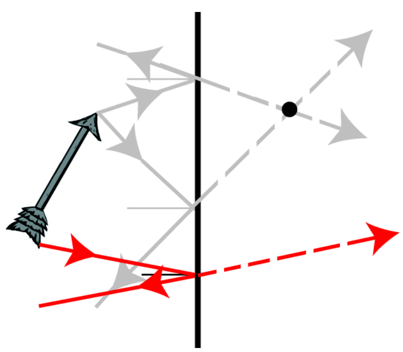
8. Once you have drawn the extension for the second reflected ray, you can tell where the top of the arrow's image will be; it will lie at the point where the two extended lines cross each other.



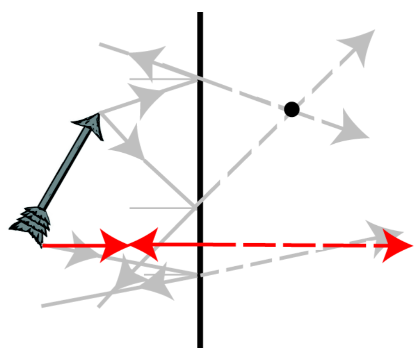
How do you think you find the bottom point for the image?

You find the bottom points of the image in exactly the same way you found the top point.

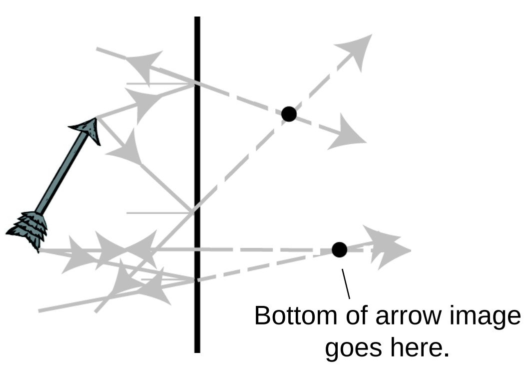
9. You draw an incident ray from the bottom of the arrow, with its reflection. Extend the reflected ray behind the mirror.



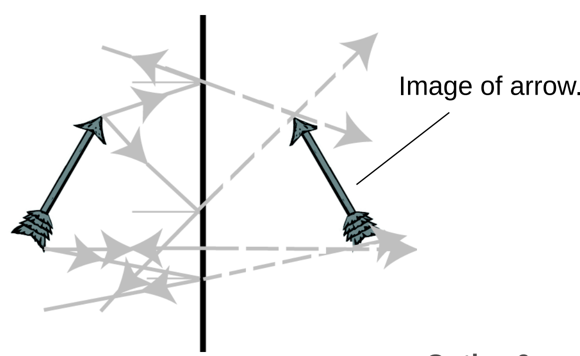
10. You then draw a second incident ray from the bottom of the arrow, so that it hits the mirror at a diffrent angle than the first.



11. The bottom of the arrow's image will lie at the point where the two extended lines cross each other.



12. Now you can draw the image of the arrow in betwwen its top and bottom points.



Curved mirrors

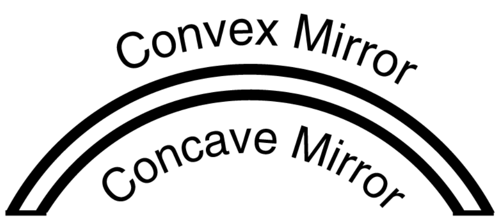
Images in a plane mirror are always exactly the same size as the real object they reflect. They also appear to be exactly the same distance behind the mirror as the object they reflect is in front of the mirror.If you have ever been to a carnival or amusement park fun house, you may have stood in front of mirrors which have completely distorted your reflection.

Where else have you seen distorted images of your reflection?

By adding curves to mirrors (or other reflective surfaces) your reflection can be made to look shorter, taller, fatter or thinner than the real you. Mirrors that are curved in very precise ways are really important to scientists and engineers.

There are two types of curved mirrors: concave and convex. Imagine a ball with mirrored surfaces on the inside and outside surfaces. Now make a cut through the ball in a straight line.

The convex mirror would be the one formed by the outside of the ball.



The concave mirror would be the one formed by the inside of the ball.

Convex Mirrors

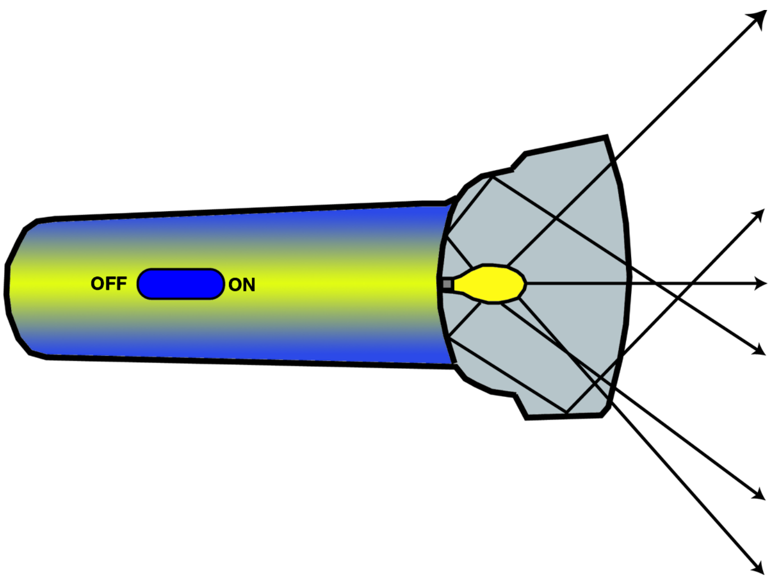
On the sideview and rearview mirrors of some cars it says,
"Objects in mirror are closer than they appear."
Do you know why?

The mirrors used for rearview and sideview mirrors on vehicles, like cars and snowmobiles, are convex mirrors. Convex mirrors give you a larger field of view than plane mirrors (they let you see more), but in doing so they distort the image. Images in convex mirrors are smaller than the real object they reflect. Images in convex mirrors are also further behind the mirror than the object they reflect. So, if a truck seems uncomfortably close when you look in the rearview mirror of your car, it's even closer than you think.

Concave Mirrors

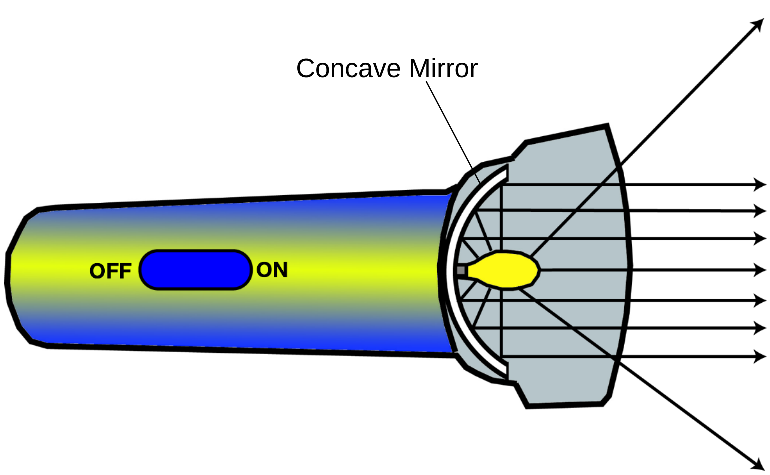
Without concave mirrors your flashlight and car headlights wouldn't be nearly as effective.

If you had a light bulb sitting in a flashlight casing, the light rays from it would spread out in all directions.



With no mirror behind the light bulb, the light rays go in all directions.

A concave mirror placed behind the bulbs acts like a reflector. The light rays which hit the mirror are reflected so that when they leave the mirror they are all parallel. What we see coming out of a flashlight or headlight is a uniform beam of light made up of all those individual parallels rays.



The concave mirror behind the light bulb reflects nearly all the light rays in the same direction, so we see a uniform beam of light.

Scientists and engineers develop curved mirrors for every day uses in things like cars and flashlights, but they also use them for conducting science. Highly polished curved mirrors are used in instruments like the Hubble telescope to let us see and study stars, planets and events in space many light years away.

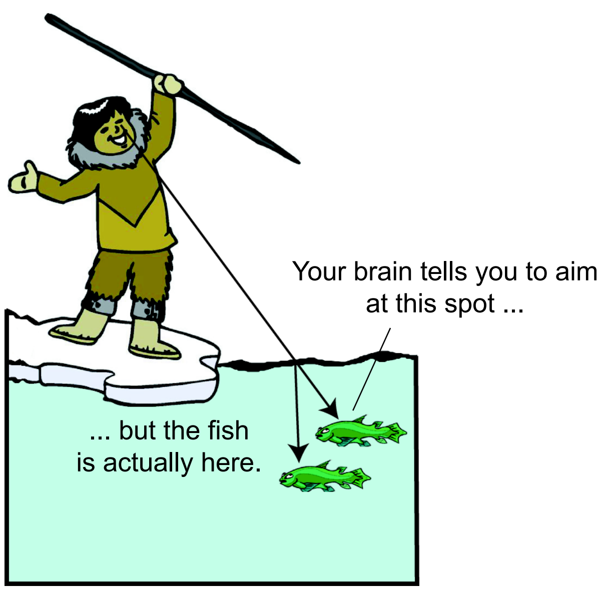
Refraction

You have probably seen a straw in a drinking glass or a reed sticking out of the water near the shore. Below the surface of the water, both will seem to bend, but if you pull the reed or straw out of the water they'll both be straight.

Do you know why?

When light travels between two transparent substances of different densities, its velocity changes and it bends. Scientists call the bending of light refraction.

Have you ever been spear fishing?
What happened the first few times you tried to hit the fish?



Spear fishing is all about understanding refraction. When you look down at the fish you want for dinner, your eye tells you that the fish is at the end of a straight line running between it and the fish. In reality, because the light bends when it hits the water, the fish is actually a bit lower than where you see it, and closer to you.

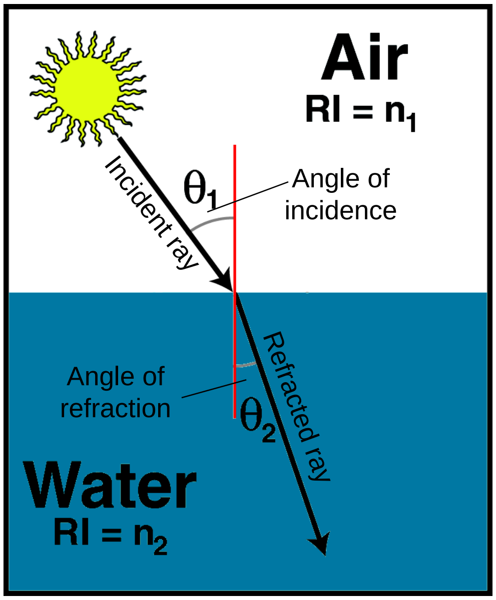
How do you figure out where to aim?

Often experience is the best teacher. Over time, with practice and a bit of help from your grandparents or parents you'll figure out that you have to aim lower and slightly closer to you in order to get your dinner.

What birds of prey hunt fish near your community?
Do you think they have to figure out refraction before they can catch fish?

The Refractive Index

Scientists have discovered a mathematical relationship for what your grandparents know about the bending of light; when light moves from one substance to another it bends in predictable ways.



Imagine a light ray travelling through the air hits the surface of a lake. It makes a certain angle (angle of incidence) with a line normal to the lake's surface. When the light ray enters the water, its velocity changes and it bends. The refracted ray makes a different angle (angle of refraction) with the normal. If the air is substance 1 and the water is substance 2, the mathematical relationship which describes the relationship between the two angles is,

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

where n1 is the refractive index (RI) for substance 1, and
n2 is the refractive index for substance 2.

The refractive index is a ratio between the speed of light in vacuum and the speed of light in a particular substance. You can figure out the refractive index for any material by using the following formula:

$$n_{material} = \frac{c}{v_{material}}$$

where c is the speed of light in a c=vacuum and
$v_{material}$ is the speed of light in that material.

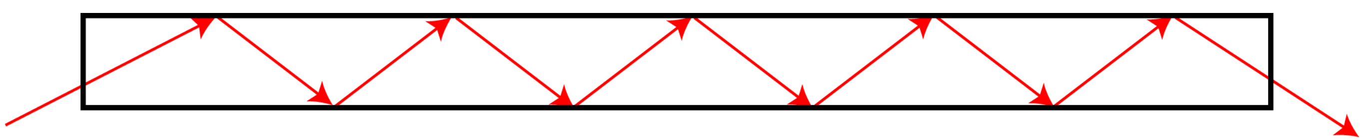
Substance	Refractive Index
Vacuum	1
Air	1.003
Ice	1.31
Water	1.333
Glass	1.44 - 1.9
Ruby	1.76
Diamond	2.417

Glasses and Communications: Some practical uses for optics

People who wear glasses or contact lenses benefit from scientific knowledge about refraction every day. By knowing how light bends when it enters glass or plastic lenses, optometrists and opthamologists can bend and focus light rays in ways which help people with vision problems to read or to see far away. Similar types of precise lenses are used in microscopes, telescopes, cameras and projectors, often in combination with curved and plane mirrors.

Our understanding of optics has also lead to the revolution in communications technologies; light is now used to send information all over the world. The copper wire cable that used to be used for land-based communication is now being replaced by fibre-optic cable made from glass. In fibre-optic cables the sound of your voice or the text from your email is converted into light. The light signal enters a glass cable and travels to its destination. The light rays enter the fibre optic cable at such an angle that they will not cross the boundary between the glass and surrounding air.

Light travelling through fibre optic cable.



You know that refraction is the bending of light. Well, when a light ray is moving from a higher refractive index substance towards a lower refractive substance at a large enough angle of incidence, the angle of refraction may be more than 90^{o}. In other words, the ray of light acts almost as if it were being reflected off a mirror. Scientists actually call this total internal reflection. In fibre optics, a light ray enters the glass fibre at such an angle that it travels along the cable by reflecting off one surface then the other.

Do you know of any place where total internal reflection occurs?

If you live in an town served by fibre optics, you can send signals using the power of light; much as your ancestors may have used the power of light in signal fires.

References

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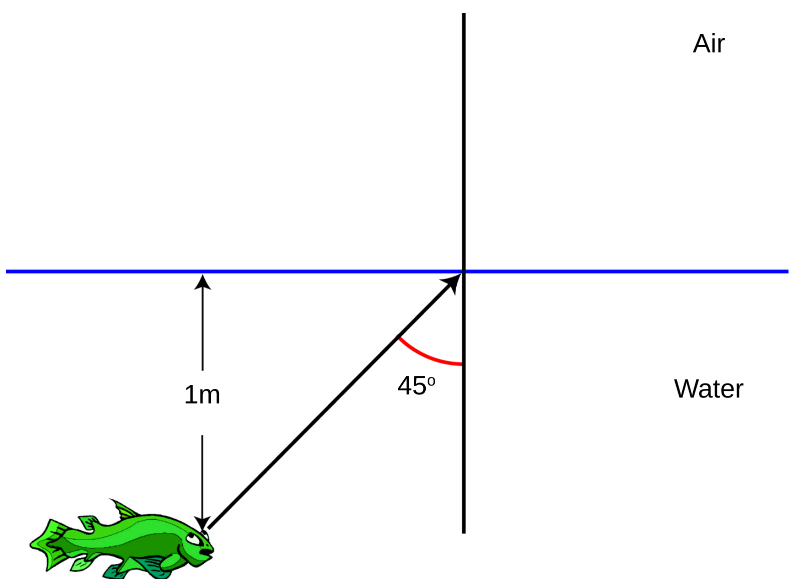
Connecting to Math

You will need to refer to the worksheet for some of the information you need to answer these questions.

1. Your class receives a visit from an engineer who works at the Ekati diamond mine in the Northwest Territories. In part of her presentation, she explains that diamonds are cut so that there is a certain amount of internal reflection. "That's what makes them sparkle," she says. "Some of the light which enters the diamond light from the air has to bounce off several surfaces in side the diamond before it can escape back into the air. When light travels around inside the diamond, it's travelling really fast." She asks if anyone knows how fast light travels inside a diamond. After a few minutes you raise your hand. What do you tell her?

2. You go fishing with your grandfather for the first time. You can easily see the fish in the water. You raise your spear, throw it and miss the fish. You try again and again and still miss. Meanwhile your grandfather has caught two fish. You ask him how he has managed to do it when his eyesight is much worse than yours. He smiles and tells you that sometimes things aren't exactly as you see them; the fish isn't really where you are aiming but closer to you. "It's a gift from Grandmother Sun to the fish that gives it a fair chance of getting away," he explains. You think about this for a second and ask your grandfather, "If I see the fish in the wrong place, does it see me in the wrong place too?" "Yes it does," he says.

   The fish in the picture below is watching you stand at the edge of the water. Assume its eyes are 1m below the surface and it is looking up at the top of your head from a 45^o angle. You are 1.5m tall.



a) Where does the fish see the top of your head?
b) Where are you actually standing?

You will need a calculator to figure out the answers.

ISSN 1494-4944