Geometric Optics: Crash Course Physics #38

Crash Course: Physics
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===== Introduction (0:00) =====

Sunlight, moonlight, torchlight, and flashlight. They all come from different places, but they're all the very same thing: light! It's what makes it possible for us to see the world around us, so it's worth a close, hard look.

For instance, how does light travel? When you flip that switch in the bathroom to brush your teeth, how does light move from the light bulb, to the mirror, and into your eyes? And if you're one of many people who wear glasses, how do those lenses turn a blurry world into a high-definition experience?

Whether it's glasses, microscopes, or telescopes, it's all about bending light to our will. How do we go about this grand task of controlling the very thing that helps us see? Well, let's take a look!

[theme music]

===== The Ray Model of Light (0:50) =====

No matter where light comes from, we generally talk about it in the same way, and make the same assumptions about how it travels. Say you're lying on the beach, basking in a ray of sunshine. One of the first assumptions we make is that the light is traveling from the sun to you in a straight line. This way of thinking about light is called the ray model, and the core tenant of the model is that light travels in straight-line paths called rays.

But each individual ray is really just a graphical representation of actual light. A light source may be emitting an infinite number of rays, but we only draw a few to get the point across. Now, let's say we have a flashlight that's emitting rays of light. If we point the flashlight at a reflective surface, like a calm pool of water, we can trace the rays as lines that leave the flashlight, reflect off the water and continue on as a straight line. Note that the rays on top of the flash light are now on the bottom, and vice versa. This makes sense, because if you're viewing something in a reflection, you see its image reversed.

===== Laws of Reflection and Refraction (1:39) =====

Another important observation is that rays leave the reflected surface at the same angle at which they struck it. So if I point the flashlight at a 30 degree angle - an angle that we call the angle of incidence - it would leave at a 30 degree angle in the other direction. So we'd say that the angle of reflection is equal to the angle of incidence. And the fact that these two angles equal each other is called the law of reflection.

Now, the way I described the light hitting the pool of water was oversimplified, wasn't it? Because, in reality, some of the incident light will reflect off the water's surface, while the rest of it will go into the water. And, an interesting phenomenon happens whe light rays change from one medium to another, such as going from air into water.

Have you ever looked at a straw sitting in a cup of water and noticed how the submerged part of the straw looks bent? Of course the straw itself isn't bent, but the light is, when it passes between the water and the air. This phenomenon, of light rays changing direction at the interface between media, is called refraction.

When a ray moves from air into water, the ray's angle after passing into the water will be less than the incident angle. So, the straw looks bent because the rays coming from the straw into your eyes don't travel in a straight path. They become bent, so the bottom of the straw appears to be in a place where it's not.

The angle of a light ray after it passes from one medium to another is called the angle of refraction, and it's related to the angle of incidence by Snell's Law. Snell's Law says that the angles of refraction are determined by the index of refraction for each medium and the angle of incidence.

The incidence of refraction for a certain medium is the ratio of the speed of light in a vacuum versus the speed in that medium. And when a ray enters a medium with an increased index of refraction, the angle of refraction decreases. In other words, the higher the index of refraction, the smaller the angle.

And refraction occurs when light leaves a medium, too. Say you have a flat piece of glass standing on end, and a light ray enters the glass at an incident angle of theta one. The angle of refraction inside the glass would be less than theta one, since the index of refraction of glass is greater.

But, once the ray reaches the interface between the glass and the air on the other side, it refracts again, and now the angle of refraction is equal to that first incident angle. So, if you look from the right side of the glass, your eyes see an object that appears to be lower than it actually is.

Now, when you observe an object through refracted light like this, what you're seeing is an image, a visually reproduced copy of an object. And not all images are the same.

===== Real and Virtul Images (3:50) =====

An image is considered to be a real image if the rays from an object converge at some location, such as your eye or on some other surface, like a film. Real images can be projected onto screens, because the light rays from an object are actually traveling there.

But the alternative is a virtual image - an image where the light rays don't actually converge, so your eyes construct an image as if the diverging rays originated from a single point. When you look in the mirror, for example, it looks like you're standing on the other side of the mirror. But you aren't. You're seeing a virtual image, because the light rays that make up your reflection aren't actually converging to form an image of you.

Now, what if we take that plate of glass and re-form both sides so they're no longer flat? How does that change the law of reflection? It desn't! Refraction still occurs. It's just that the normal line, which is the imaginary line that the angles are relative to, changes. Warped pieces of material that form images of objects are lenses, and they're the most critical tool in the field of optics.

===== Lenses (4:43) =====

Say we have a lens that has a spherical face on both sides, known as a convex lens. As light rays enter the lens the turn slightly towards the axis of the , the imaginary line that runs through the centre, perpendicular to its face. As they leave the lens and run back through the air the rays are angled slightly more towards the central axis due to the lenses' curvature. The rays on the top and bottom are bent at a larger angle towards to central axis than the rays near the centre which stay almost parallel and they all eventually converge at a single point, called the focal point.

Think of a magnifying glass. If you hold it just right in the sunlight, you can concentrate the sun's rays into a single very hot point. That works because you've taken a bunch of incoming parallel rays and placed your target of choice at the focal length of the magnifying glass. That's the distance between the lens and its focal point.

And one measure of a lens is its power, which is expressed simply as one over the focal length. But a lens the causes light waves to converge in this way is known as the converging lens. And when you look through a converging lens, you can see real images from objects that are beyond the focal point.

This is because light rays from those objects actually converge after passing through the lens. And remember, when rays converge at a point, that means a real image has been formed. Let's show this using a ray diagram, which tells us about the position and size of images as seen through a lens.

Let's take a candle that's some distance from the lens, which we'll call the object distance. We'll use the object distance and the focal length of the lens to find the image distance, the location where the image forms on the other side of the lens. Lenses have the same focal length on both sides, so we'll label the focal point on the side opposite of the object as F, and the point on the same side as the object as F prime (F').

Now, we know that the ray traveling parallel to the axis will pass through the focal point on the other side, so let's draw a ray from the top of the candle, refracting through the lens and then passing straight through the focal point F. Since the focal length is the same on both sides, we draw a second ray from the top of the candle through the F' focal point, which then refracts through the lens and travels parallel to the axis. The third ray travels straight through the center of the lens.

We draw this line because if we assume a thin lens, then we can draw a straight line through the center and disregard the slight offset that would occur due to refraction. With these three rays in place, we see that they intersect at single point, representing the top of the candle in the newly formed image. You might notice that the image is upside down, which will always be the case for convex lenses. And the image is formed by light rays that actually originated from the object, so a real image is formed.

The distance between the image and the lens is the image distance, and it's related to the object distance and the focal length by a very important equation. This is the thin lens equation, which is derived from ray diagram geometry. For a single converging lens the focal length and the object distance will always be positive. The image distance will be positive if the image is on the opposite side of the light source.

This equation holds true for converging lenses, as well as their opposite- diverging lenses. Diverging lenses have a concave shape and do the opposite of a converging lens, causing rays of light to diverge away from the lens' axis. When we're looking at an object through a diverging lens, our eyes imagine that the diverging rays originate from a location where the rays don't actually begin, so the lens generates a virtual image.

And when we construct a ray diagram for a diverging lens, there are a few key differences. First of all, the focal point F is on the same side as the object, and F' is on the opposite side. While a single ray of light still goes through the very center of the lens, the other two rays take slightly different, resulting in a virtual image forming on the same side as the object itself.

For a diverging lens, the thin lens equation is still true, but the focal length is now a negative value. Another important equation that's true for both converging and diverging lenses is the magnification equation. Magnification is the ratio of the image height to the height of the actual object. When the image is upside down like in our converging lens, then the height is a negative value and the ratio of the image distance to the object distance is also negative.

===== Conclusion (8:34) =====

But all of these ideas taken in whole give you a good understanding of optics, the fundamental rules that explain how we can observe particles to small to see with our eyes as well as objects that are millions of light years away. Today we learned about the ray model of light and the laws of reflection and refraction. We learned about how refraction works with converging and diverging lenses. Finally, we built ray diagrams to discover how objects are viewed through different kinds of lenses at different points.

===== Credits (9:00) =====

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This episode of Crash Course was filmed in the Dr. Cheryl C. Kinney Crash Course Studio with the help of these amazing people and our equally amazing graphics team is Thought Cafe.