Light Is Waves: Crash Course Physics #39

Crash Course: Physics
https://youtube.com/watch?v=IRBfpBPELmE
https://nerdfighteria.info/v/IRBfpBPELmE

Here's a question for you: If you shine a light on a coin that's hanging in mid-air, what do you think its shadow will look like? Do you think its shadow would have a bright spot of light right in the middle of it? Because it would! It might be counter intuitive, and 19th-century physicists thought so too, when they tried this experiment. But that little spot in the middle of the coin's shadow helps prove one of the most important discoveries ever made in physics - light is a wave.

In the seventeenth and eighteenth centuries, most physicists thought that light was a particle because it often behaved like one. But over the years, some scientists began to think that it might actually be a wave. They did experiments to test this idea, and slowly, evidence started to build. We now know that light is both a particle and a wave- a strange sounding concept that we'll explore more later on.

But the point is, light is a wave, and we know this because waves behave in very specific and sometimes weird ways. One of the most important reasons that light acts the way it does is known as Huygens' principle. Christian Huygens was a seventeenth-century Dutch physicist who believed light acted as a wave. He came up with a way to predict how a wave will spread out, and we still use his method today.

Huygens' Principle says that you can predict a wave's position in the future by analyzing its current position. All you have to do is think of each point on the wave as a source of its own tinier wave. See, Huygens knew that when you multiply the velocity of something by the amount of time it's traveled, you can figure out how far it went. And he figured that this would also be true for each individual point on a wave.

Let's say you have a wave that's traveling ten centimeters per second, and you want to know what the wave will look like after two seconds.

To use Huygens' Principle, you first draw a bunch of little points along the wave. Then you a half circle around each point in front of the wave, with a radius equal to the wave's velocity multiplied y time - so, twenty centimeters. Each of those little half circles is called a wavelet. Finally, you draw a curve that's tangent to each wavelet, meaning that it touches each half circle at exactly one point. That line shows the location of the wave after two seconds!

So, a two-dimensional wave traveling through empty space will look pretty simple - it's basically an expanding circle.

But things get a little more complicated when a wave hits an obstacle. For example, let's apply Huygens' Principle to a wave that moves past the edge of a flat object. When the wave hits the obstacle, part of it gets blocked. But the part that isn't blocked keeps moving past the edge, and it follows Huygens' Principle, forming wavelets. The wavelets from the part of the wave near the edge will curve behind the edge. And when you draw a line to connect all the wavelets, you end up with a line that bends around the edge.

In the same way, when a wave moves through a slit that's roughly the sane width as its wavelength, it travels past the slit in a circular curve that spreads outward. When waves are re-shaped by obstacles, that's called diffraction. And it's very different from what a stream of particles would do.

For example, if you rolled a bunch of marbles straight through a doorway, you'd expect them all to hit the far wall opposite the doorway. They wouldn't hit the wall in places to the right or left of the door. But when waves diffract, they often spread outward behind obstacles. Diffraction is one of the reasons there's a bright spot in the middle of the shadow when you shine a light on a round object.

The other reason is interference. In our lesson on traveling waves, we described what happens when waves run into each other: they interfere in one of two ways. Waves constantly interfere constructively when the crests of both waves end up in the same spot and so for their troughs. The waves essentially combine into one wave that has a larger amplitude - with higher crests and lower troughs - than either of the two waves did before.

But waves interfere destructively when one wave's crest run into the other wave's through, and vice versa. In that case, the combined wave has a lower amplitude than either of the waves did before. With perfectly destructive interference, the waves actually disappear completely; they flatten out.

Together, diffraction and interference help explain the results of the famous double-slit experiment conducted by English physicist Thomas Young in 1801. Young covered a window so that only a very narrow stream of sunlight passed through a slit into the room. Then he positioned a plate with two more tiny slits cut into it, spaced very close together so that the single beam of sunlight passed through them. Finally, he placed a screen behind the slits. If light were just a stream of particles, you'd expect to see two bright lines on the screen behind the two slits. But that's not what Young saw. His screen had many lines on it. There was a bright line in the middle, then more bright lines above and below it. This pattern is called a diffraction pattern, and it comes from the diffraction and interference of light waves. Light waves interfere constructively when they're lined up exactly right.

For example, to form that line on the screen between the two slits the waves from each slit travel exactly the same distance. So they line up, interfere constructively, which increases their amplitude to create a bright spot. But in other places on the screen, there's a difference between the distances traveled by each wave. This is called the Path Difference. So, light waves will interfere either constructively or destructively, depending on the size of this path difference. When the waves are an exact number of wavelengths apart, the crests ad troughs will line up - creating constructive interference and a bright line. But when the waves are shifted by exactly half a wavelength - or by 1.5 wavelengths, or 2.5, and so on - light rays will interfere destructively.

By using trigonometry, you can calculate the path difference in a slit experiment. It's equal to the distance between the center of each slit, d, multiplied by the side of the angle between the point on the screen and the straight line between the slits and the screen.

Now, since light is a wave, it has the same properties as other waves. Intensity, for example, is the energy transported by the light per unit area over time. Essentially, intensity is the brightness of the light. As fro other waves, intensity is proportional to the amplitude squared. So if you double the amplitudes of a wave's peaks, it gets four times as bright. If you triple the amplitude, it gets nine times as bright.

When light passes through two slits like in the double-slit experiment, the line in the center will be the most intense. And the further the lines get from the center, the less intense, and therefor, the less bright they'll be. Like other waves, light also has a frequency and wavelength. These determine whether light is visible, and if so, what it's color is. Light with a higher frequency, and therefore a shorter wavelength, is on the bluer side of the spectrum. Light with a lower frequency and linger wavelength is on the redder side of the spectrum. White light, like from sunlight, is actually all of the different colors of light combined.

When white light passes though the two slits in the experiment, they interfere in a way that allows you to see this rainbow of lines on the screen. But the double slit experiment isn't the only situation where light created a diffraction pattern. Diffraction will happen when light passes though a single slot, too, producing a pattern that looks like a series of lines that get dimmer the farther you get from the center.

The light will be brightest on the part of the screen that's opposite the middle of the slit. That bright light is created by the rays that go straight through the slit, perpendicular to the plate. They have a path difference of zero. But to reach the other points on the screen, different rays of light travel different distances, depending on their angle going through the slit. And again, whether the light interface constructively or destructively depends on how the rays line up.

For a single slit, the path difference is between the light coming from the very top of the slit and the light coming from the very bottom of the slit. If the path difference is one wavelength long, then the path difference between the light from the top of the slit and the light from the center of the slit is only half a wavelength. The same holds true for the path difference between the light from the center of the slit and the bottom. So a total path difference a full wavelength means that for each light ray coming through the slit at that angle, there's a corresponding light ray that's shifted by half a wavelength.

And remember: when waves of light are shifted by half a wavelength, that means one wave's crests line up with the other's trough, causing destructive interface.So, for a single slit, when the total path difference is equal to a full wavelength, you end up with pairs that cancel each other out and make a dark line.

Now, constructive interference through a single slit works a little differently. When the path difference between the top and bottom of the slit is equal to 1/5 wavelengths - or 2.5 wavelengths, and so on - there will be a bright line. That's where the rays interfere constructively. As with the previous example, this also has to do with the path difference between individual rays passing through the single slit. Say the light is angled so that the total path difference between the top and bottom of the slit is 1.5 wavelengths. The rays passing through the middle third and bottom third of the slit will be a half a wavelength apart, so they'll cancel each other out. But that top third won't cancel with anything - instead, it will reach the screen, creating a bright line.

So, how do diffraction and interference create the phenomenon we see in the shadow of the coin? Diffraction makes the light waves curve around the coin's edges. When these diffracted waves run into each other, they interfere. The places where the waves interfere destructively become shadows. That's what makes those little ripples spreading outward from the circular shadow. But the places where the waves interfere constructively become bright spots. That's why there's a bright spot right in the middle of the coins shadow! At that point, the waves of light that diffracted around the edges of the coin have all traveled the same distance. So the crests of different light waves combine, and so do the troughs, forming one wave with a higher amplitude. And a bright spot!

Today, you learned about the wave theory of light. We talked about Huygens' Principle, and described how diffraction and interface lead to the results of the double-slit experiment. We also explored the diffraction pattern from a single slit. Finally, we explained the diffraction pattern for a disk.

Crash Course Physics is produced in association with PBS Digital Studios.