Traveling Waves: Crash Course Physics #17

Crash Course: Physics
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(PBS Digital Studios Intro)

Here we have an ordinary piece of rope. It's not one of those magician's ropes that can mysteriously be put back together once its been cut in half, and it's not particularly strong or durable, but you might say that it does have special powers, because it's gonna demonstrate for us the physics of traveling waves.

Ropes and strings are really good for this kind of thing, because when you move them back and forth, the movement of your hand travels through the rope as a wave. By observing what happens to this rope when we try different things with it, we'll be able to see how waves behave, including how those waves sometimes disappear completely. How's that for a magic trick?

(Intro)

This is a typical wave, and waves form whenever there's a disturbance of some kind. Often, when something about the physical world changes, the information about that disturbance gradually moves outwards, away from the source in every direction, and as the information travels, it makes a wave shape. Think about the disturbance you cause, for example, when you jump on a trampoline. When you hit the trampoline, the downward push that you create moves the material next to it down a little bit too, and the same goes for the material next to that, and so on. And while that information is traveling outward, the spot where your feet first hit the trampoline is already recovering, moving upward again, because of the tension force in the trampoline, and that moves the area next to it upward, too. This up and down motion gradually ripples outward, covering more and more of the trampoline, and the ripples take the shape of a wave.

Waves are made up of peaks with crests, the bumps on the top, and troughs, the bumps on the bottom. They have an amplitude, which is the distance from the peaks to the middle of the wave. They also have a wavelength, which is the distance between crests, a full cycle of the wave, and a frequency, which is how many of those cycles pass through a given point every second. Multiply the wavelength by the frequency and you get the wave's speed, how fast it's going, and the wave's speed only depends on the medium it's traveling through. That's why the speed of sound, which is a wave, doesn't depend on the sound itself.

It doesn't matter how loud or quiet it is, it just depends on whether the sound is traveling through, say, air or water. Now, there are four main kinds of waves. We can use our rope to show the difference between some of them. A pulse wave is what happens when you move the end of the rope back and forth just one time. One lonely crest travels through the rope. That's the pulse. Then, there's the continuous wave, which is what happens when you keep moving the rope back and forth. In that case, your hand is acting as an oscillator. Anything that causes an oscillation or vibration can create a continuous wave. Now, things that cause simple harmonic oscillation move in such a way that they create sinusoidal waves, meaning that if you plotted the waves on a graph, they'd look a lot like the graph of sin(x). But the waves we've mainly been talking about so far are transverse waves, ones in which the oscillation is perpendicular to the direction that the wave is traveling in. When a wave travels along this rope, for example, the peaks are perpendicular to the rope's length. The same thing was mostly true for the waves you made on the trampoline. The waves were traveling along the surface horizontally, but the peaks were vertical. But there's also longitudinal waves, where the oscillations happen in the same direction as the wave is moving. In the case of a longitudinal wave, the back and forth motion is more of a compression and expansion. These are the kinds of waves that you get by compressing and stretching a spring, and they're also the kinds by which sound travels, which we'll talk about more next time, but all waves, no matter what kind they are, have something in common: they transport energy as they travel. At a microscopic level, waves occur when the movement at one particle affects the particle next to it, and to make that next particle start moving, there has to be an energy transfer. But how can you tell how much energy a wave has? Well, remember that an object in simple harmonic motion has a total energy of 1/2 times the spring constant times the amplitude of the motion squared, which means for a wave caused by simple harmonic motion, every particle in the wave will also have the same total energy of half k a squared. All of this together tells us that a wave's energy is proportional to its amplitude squared.

In other words, if you double the wave's amplitude, you get four times the energy, triple the amplitude and you get nine times the energy. So why is the relationship between amplitude and energy transport so important? Well, the intensity of a wave is related to the energy it transports. More specifically, its intensity is equal to its power divided by the area it's spread over and power is energy over time, so changing the amplitude of a wave can change its energy and therefore its intensity by the square of the change in amplitude, and this relationship is extremely important for things like figuring out how much damage can be caused by the shockwaves from an earthquake.

But waves also get weaker as they spread out, because they're distributed over more area. A spherical wave, for example, one that ripples outwards in all directions will be spread over the surface area of a sphere that gets bigger and bigger the further the wave travels. The surface area of a sphere is equal to four times pi times its radius squared. So as a spherical wave moves further from its source, its intensity will decrease by the square of the distance from it. Two meters away from the source, and the intensity of the wave will be four times less than if you were one meter away. Three meters away, and it will be nine times less. That's why being just a little bit further away from the source of an earthquake can sometimes make a huge difference.

Now let's go back to the waves we were making with the rope. Suppose you attach one end of the rope to a ring that's free to move up and down on a rod. Then, with your hand, you send a pulse in the form of crest rippling along it. When the pulse gets to the end of the rope, the rope slides along the rod, but then, it slides back to where it was. That motion, the sliding back, reflects the wave back along the road, again, as a crest. There's something totally different happens if you attach the end of the rope so it's fixed and can't move. Now, if you send a pulse along the rope, it will still be reflected, but this time as a trough. The wave was inverted. That's because when the pulse reached the fixed end of the rope, it was trying to slide the end of the rope upward, but it couldn't, because the end of the rope was fixed, so instead, the rope got yanked downwards, and the momentum from that downward movement carried the rope below the fixed end, inverting the wave.

Now, sometimes multiple waves can combine. For example, say you send two identical pulses, both crests, along a rope, one from each end. When the two pulses overlap, they combine to make one crest with a higher amplitude than the original ones. That's called constructive interference, the waves build on each other. Now, let's say you do the same thing again, this time, both waves have the same amplitude, but one's a crest and the other is a trough, and when they overlap, the rope will be flat. It looks like the wave's just disappeared. That's called destructive interference, when the waves cancel each other out.

Constructive and destructive interference happen with all kinds of waves, pulse or continuous, transverse or longitudinal, and sometimes, we can use the effects to our advantage. Noise cancelling headphones, for example, work by analyzing the noise

around you and generating a sound wave that destructively interferes with the sound waves from that noise, cancelling it out. There's a lot more to talk about when it comes to the physics of sound, but we'll save that for next time.

Today, you learned about traveling waves and how their frequency wavelength and speed are all connected. We also talked about different types of waves, including pulse, continuous, transverse, and longitudinal waves and how they all transport energy. Finally, we discussed reflection and interference.

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