Sound: Crash Course Physics #18

Crash Course: Physics
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(PBS Digital Studios Intro)

When you think about it, you probably receive hundreds, even thousands, of cues about what's going on in your environment every day strictly from sound. In addition to things like speech and music, there are other bits of auditory information that shape your day. An ambulance passing by, a baby crying in the next room, and of course, sorry, just got a text. But there's a lot we can learn, not just from what these cues mean, but from how sound itself works.

Studying sound waves has helped doctors learn more about our ears and has allowed engineers to design things like microphones and speakers. Biologists have even used the science of sound to figure out how animals like elephants can communicate over long distances when we can't even hear them doing it. It all comes down to the fact that sound is a wave which travels through a medium like air or water, and knowing that sound is a wave is important, because it means that we can use the physics of waves to describe the qualities of sound.

(Intro)

When you think of a wave, you probably think of the kind you see at the ocean, or the ones you made when we jumped on that trampoline last time. Those waves produced ripples that run perpendicular to the direction that the wave is traveling in. But sound is the other kind of wave. It's a longitudinal wave, meaning that the wave's back and forth motion happens in the same direction in which the wave travels.

Say you get a text message on your phone, and it makes a nice bright little ding sound. What actually happened, like, on a physical level? Your phone's speaker contains a diaphragm, a piece of stiff material usually in the shape of a cone. When you got the message, the electronics inside the speaker made the diaphragm move back and forth, which vibrated the air around your phone. That made the atoms and molecules in the air move back and forth. Then, those moving particles vibrated the air around them, and as the process continued, the sound waves spread outward. Sorry, I'll turn this off now.

Anyway, physicists sometimes describe sound waves in terms of the movement of these particles in the air, in what's known as a displacement wave. But by moving particles in the air, sound waves also do something else: they cause the air to compress and expand, which is why sound waves are sometimes described as pressure waves. As the wave spreads through the air, the particles end up bunching together in some places, and spreading out in others. Together, all that bunching and spreading out causes areas of high pressure and low pressure to form and move through the air. It's useful to describe sound waves as pressure waves, because we can build devices that detect those changes in pressure. That's how some microphones work, for example. They use a diaphragm stretched over a sealed compartment and as sound waves pass by, they create areas of lower or higher pressure in the compartment. The differences in pressure cause the diaphragm to move back and forth, which electronics then translate into audio data, and your eardrums basically work in the same way. As pressure waves pass through, they make your eardrum vibrate. Your brain then interprets those vibrations as sound, but not all sounds are the same.

Even before we knew much about physics, humans were describing sound in terms of certain qualities, mainly by things like loudness and pitch. Our understanding of those qualities helped shape the development of music, which we'll talk about more next time. But there's also a more physics-y side to those qualities of music. Pitch can be high or low, and it corresponds to the frequency of the wave. So air that's vibrating back and forth more times per second will have a higher pitch, and air that's vibrating fewer times per second will have a lower pitch.

Humans hear sounds best when vibrations are somewhere between 20 per second on the low end and 20,000 per second on the high end. As we get older and lose more of the cells that help us to detect sound, we start to lose the ability to hear the higher pitched sounds. Some building security companies will take advantage of this, using devices that emit a high-pitched noise that most people over the age of 25 can't hear. The idea is that since kids and teens can hear it, and it's super annoying to them, they won't hang out near the building. But some sounds are too high or low for any humans to hear. Sounds that are too high in pitch are called ultrasonic, and the sounds that are too low are called infrasonic.

Dog whistles, for example, use an ultrasonic pitch that's too high for us, but is perfectly audible to dogs. Elephants, on the other hand, use infrasonic sound to communicate with each other, across long distances. They can hear these calls from several kilometers away, but we can't hear them at all.

Another aspect that shapes sound is its loudness. When you increase the intensity of a sound, you increase its loudness and vice versa. We've talked about the intensity of a wave before. It's the wave's power over its area, measured in Watts per meter square. We've also said that the intensity of a wave is proportional to the wave's amplitude squared, and the further you are from the source of a wave, the lower its intensity by the square of the distance between you and the source. And just as there's a range of pitches that humans can hear, there's also a range of sound wave intensity that humans can hear comfortably. Generally, people can safely hear sounds from about picowatt per square meter, up to one Watt per square meter, which is about as loud as a rock concert if you're near the speakers. The sound waves coming from a jet plane that's 30 meters away, for example, probably has an intensity of around 100 per meter squared. Now, I don't know if you've ever been that close to a roaring jet plane, but there is a reason why the people that work on the tarmac at airports use those heavy duty headphones. Below one picowatt per square meter, sounds are just too soft for us to detect them, and although we will hear sounds above a watt per square meter, they tend to hurt our ears. But here's a weird thing about loudness and intensity: it's not a linear relationship.

Generally, a sound wave needs to have ten times the intensity to sound twice as loud to us. This relationship holds true as long as the sound is towards the middle of the range of the frequencies we can hear. So instead of directly measuring the loudness of sounds by their intensity, we use units called decibels, which are based on bels. Bels convert a sound wave's intensity to a logarithmic scale, where every notch on the scale is ten times higher than the previous one. The scale starts off with an intensity of one picowatt per square meter, corresponding to zero bels. So a sound that's one bel is ten times as intense as a sound that's zero bels, and a sound that's two bels is ten times as intense as a sound that's one bel, but 100 times as intense as a sound that's zero bels.

Measuring everything in bels can be kind of annoying, because sometimes you want to talk about sounds that are, say, 3.4 bels, without having to deal with decimal points. That's why most of the time, you'll hear the loudness of a sound described using the more familiar decibels unit, a tenth of a bel. To find the loudness of a sound when you know its intensity, you take the base ten logarithm of its intensity over the reference intensity of one picowatt per square meter. Then, you multiply that number by ten to get the sound's decibel level. We can use this equation to convert the intensity of that noisy rock concert, which we said was one Watt per square meter, to decibels.

First, we take the base ten log of one Watt per square meter over one picowatt per square meter. Now, one divided by one times 10 to the -12 is just one times 10 to the 12. So what we really want to do is take the base ten log of one times 10 to the 12, or a trillion Watts per meter squared. What a logarithm asks you to do is find the power that you would need to raise the base to in order to get the number in parentheses. In other words, we're looking for the exponent of ten that would equal one times 10 to the 12, which is just 12. To finish off the calculation of decibels from intensity, we multiply that value, 12, by 10 to get the decibel level of the rock concert where you were standing. 120 decibels. Ow.

You'll notice that as the source of a sound moves closer to you, it gets louder, and as it moves away, it gets softer. That makes sense, as the closer you are to the source of a sound, the greater the intensity of the wave that hits your ear. But have you ever noticed that the pitch of the sound changes, too? It's called the Doppler Effect. As a source of sound moves towards you, the pitch of the sound you hear increase, and as the source moves away, the pitch decreases. To see why, imagine you're standing on the sidewalk, when suddenly you hear an ambulance siren start up. It's coming from down the road and it seems to be moving toward you. The ambulance is continuously emitting sound waves at a certain frequency in the form of that siren, but as that ambulance moves towards you, the ambulance is also moving towards those sound waves.

So the peaks that hit your eardrums are closer together, even though they're moving at the same speed, and you get hit by them more often, which means that you hear a higher pitched sound. At the same time, it keeps emitting more sound, which adds more peaks to those earlier sound waves that were heading your way. What you end up with is a sound wave with a higher frequency than before. That's what hits your eardrums so you hear a sound that's higher in pitch than the one you heard when the ambulance was further away from you. As the ambulance passes you and starts to drive away down the road, the opposite happens. Sound waves are still coming toward you, but the ambulance is driving away from them, so the peaks that hit your eardrum are farther apart and you hear a sound with a lower pitch. The Doppler effect isn't only unique to sound waves; it happens with light, too. Which means we can actually use it to measure the distance of stars, but more on that much later.

For now, you learned about sound waves and how they move particles back and forth to create differences in pressure. We also talked about pitch and how the intensity of a sound wave changes with amplitude and distance. Finally, we covered decibels as well as the Doppler effect.

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