Work, Energy, and Power: Crash Course Physics #9

Crash Course: Physics
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When I say “work,” what’s the first thing that comes to mind? Maybe a cubicle? Or a briefcase? Or that history exam that’s coming up soon? But if you’re a physicist, work has a very specific meaning -- one that has very little to do with spreadsheets or the fall of the Roman Empire.

Today, we’re going to explore that definition -- and how it connects to one of the most important principles in physics: conservation of energy. We’ll also learn what physicists mean when they talk about another concept that comes up a lot in daily life: power. So let’s get to... work.

[Theme Music]

So far in this course, we’ve spent most of our time talking about forces, and the way they make things move. And you need to understand forces before you can understand work. Because work is what happens when you apply a force over a certain distance, to a system -- a system just being whatever section of the universe you happen to be talking about at the time.

For example, if you’re using a rope to drag a box across the floor, we might say that the box is your system, and the force you’re using to pull on it is an external force. So, let’s say you’re pulling on this box-system by dragging it straight behind you, so the rope is parallel to the ground. If you're using the rope to pull the box for one meter, we’d say that you’re doing work on the box. And the amount of work you’re doing is equal to the force you’re using to pull the box, times the distance you moved it.

For example, if you pulled the rope -- and therefore the box -- with a force of 50 Newtons, while you moved it 5 meters, then we’d say that you did 250 Newton-meters of work on the box. More commonly, however, work is expressed in units known as Joules.

Now, sometimes, the force you apply to an object won’t be in exactly the same direction as the direction in which the object is moving. Like, if you tried to drag the box with your hand higher than the box, so that the rope was at an angle to the floor. In that case, the box would move parallel to the floor, but the force would be at an angle to it. And in such an instance, you’d have to use one the tricks we learned back when we first talked about vectors. Specifically, you need to separate the force you’re using on the rope into its component parts: one that’s parallel to the floor, and one that’s perpendicular to it.

To find the part of the force that’s parallel to the floor -- that is, the one that’s actually pulling the box forward -- you just have to multiply the magnitude of the force by the cosine of the rope’s angle to the ground. You’ll remember that we typically designate an angle in a system as theta. So, to calculate the work you did on the box, you just multiply the horizontal component -- or F times the cosine of theta -- by the distance you moved the box.

That’s one way physicists often write the equation for work -- they’ll set it equal to force, times distance, times the cosine of theta. And that equation will fit any scenario that involves a constant force being applied over a certain distance. But what if the force isn’t constant?

What if, say, you started out pulling hard on the box, but then you started to get tired, so the amount of force you exerted on the box got smaller and smaller the farther you dragged it. To calculate the work you did in that case, you’d have to count up the amount of force you applied over each tiny little bit of distance. And if you’ve watched our episodes on calculus, then you know that there’s a faster way to add together infinitely tiny increments: integration.

So, to find the work done by a varying force, you just have to integrate that force relative to the distance the object moved. Which would look like this. But force-times-distance is only one of the ways that physicists measure work. Because, you know how we just said that Joules are the units of work? Well, Joules are often used as the units for something else: energy.

And work uses the same units as energy, because work is just a change in energy. It's what happens when an external force is applied to a system and changes the energy of that system. In fact, that’s one of the ways to define energy -- it’s the ability to do work.

There are all different kinds of energy, but in this episode, we’ll mainly be talking about two of them: kinetic energy and potential energy. Kinetic energy is the energy of motion. When the box was resting on the ground, we’d say that it had no kinetic energy. But once you applied a force and it started moving, it did have kinetic energy. And the energy of the box changed, which means that you did work on it.

More specifically, the kinetic energy of an object is equal to half of its mass, times its velocity squared. If this looks familiar, that’s because it comes from applying both Newton’s second law and the kinematic equations to the idea that work is equal to force times distance. So, if the box has a mass of 20 kilograms, and at some point while you were dragging it, it reached a velocity of 4 meters per second, we’d say that its kinetic energy at that moment was 160 Joules.

Then there’s potential energy, which actually isn’t what it sounds like. Potential energy isn’t potentially energy -- it’s potentially work. In other words, potential energy is energy that could be used to do work. One common type of potential energy is gravitational potential energy - - basically, the potential energy that comes from the fact that gravity exists.

If I hold this book a meter above the ground, we’d say that it has gravitational potential energy. Because if you let it go, then gravity is going to do work on the book. Gravity exerted a force that moved it to the ground. Once the book hits the ground, though, we’d say that its gravitational potential energy is zero, because gravity can’t do work on it anymore.

Calculating gravitational potential energy is easy enough: it’s just the force of gravity on the object -- so, the object’s mass times small g -- multiplied by the object’s height. Or mgh for short. Which means that, just by knowing that this book’s mass is about a kilogram, and that it’s a meter above the ground, we can calculate its potential energy: which is 9.8 Joules.

Another type of potential energy that shows up a lot is spring potential energy. Despite its name, this is not a seasonal thing -- and yes, I really made that joke. Rather, it’s the type of potential energy that’s specific to springs! The force of a spring is equal to the distance by which it’s either compressed or stretched, times a constant that we write as k.

This equation is known as Hooke’s law, after British physicist Robert Hooke, who came up with it in 1660. Now, the constant, k -- also called the spring constant -- is different for each spring, and it’s a measure of the spring’s stiffness. The equation makes sense, if you think about it: The further you push on the spring, and the stiffer it is, the harder it will resist. You even can test this out for yourself by taking apart a clicky pen and playing with the spring inside.

By combining Hooke’s law, with the idea that work equals force times distance, we can find the potential energy from a spring: it’s half times k times the distance squared. For example: if you have a spring with a spring constant of 200 Newton meters, and a block is

compressing it by half a meter, then the potential energy of the block would be 25 Joules. So, when something does work on a system, its energy changes. But how that energy changes depends on the system.

Some systems can lose energy. These are known as a non-conservative systems. Now, that doesn't mean that the energy that's lost is literally disappearing from the universe... And it doesn't have anything to do with the system's personal politics, either. It just relates to one of the most fundamental principles of science: that energy can neither be created or destroyed. But systems can lose energy, like when friction from the box dragging on the floor generates heat.

For non-conservative systems, you can still talk about their kinetic energy or potential energy at any given moment. But conservative systems let you do much more than that. A conservative system is one that doesn't lose energy through work. Say, a simple pendulum. When the pendulum is at the top of its swing, it stops moving for a brief moment as it changes direction -- meaning that its kinetic energy, at that point, is zero. But it has lots of potential energy, because the gravitational force can do work on the pendulum, pulling it down until it reaches the bottom of its swing. At the bottom of the swing, that potential energy becomes zero, because gravity can't pull the pendulum down anymore. But now the pendulum has lots of kinetic energy, because it's moving through the swing.

And it turns out that, at any given point in the pendulum's motion, its kinetic energy and its potential energy will add up to the same number. If its potential energy increases? Its kinetic energy will decrease by the exact same amount, and vice versa.

So, now that we know how to define work, we can use that definition to help explain another common term that physicists have a very specific meaning for: power. Or, more specifically, average power. Average power is defined as work over time, and it's measured in Watts, which is just another way of saying Joules per second. Basically, it's used to measure how much energy is converted from one type to another over time.

So, remember that box you were pulling? We figured out that you did 250 Joules of work on the box when you moved it 5 meters. If it took you 2 seconds to move the box, then your average power output was 125 Watts. You're basically a light bulb! Now, we can also describe power in another way, by putting two different facts together: One, that work is equal to force times distance. And two, that average velocity is equal to distance over time.

Knowing this, we can say that power is the net force applied to something with a particular average velocity. If you moved the box 5 meters in 2 seconds, then its average velocity was 2.5 meters per second. And we already said that you were pulling the box along with a force of 50 Newtons. So, the force you were using to pull the box, times the box's average velocity, would also give you an average power output of 125 Watts.

The two equations for average power are really describing the same relationship; they're just using different qualities to do it. We're going to be talking about power a lot when we discuss electricity in later episodes. It's the best way to calculate how energy moves around in a circuit. But that's a story for another day. For now, our work is done.

Today, you learned the two equations we can use to describe work, and that energy is the ability to do work. We also talked about kinetic and potential energy, and how they play into non-conservative and conservative systems. Finally, we found two different equations for power.

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