Collisions: Crash Course Physics #10

Crash Course: Physics
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You and I have explored the rules that govern lots of different moving objects so far. But physics isn't just about dragging blocks up inclines, or astronauts floating in Vomit Comets. There are also collisions! And physics has a lot to say about collisions -- whether it's two billiard balls knocking against each other, or what happens when you fail at a Super Mario level for the 47th time and throw your controller at the floor. Stupid lava sticks!

To figure out what's happening when objects collide, we'll have to take into account two main qualities: momentum and impulse. We'll also discuss what physicists mean when they talk about center of mass, and why that's important. And we'll have our old friend Sir Isaac Newton to help us out along the way.

[Theme Music]

Remember Newton's second law? That's the one that says the net force on an object is equal to its mass, times its acceleration. Except, that's not actually what Newton said. He really said that an object's so-called "quantity of motion" was equal to its mass, times its velocity. And the net force is equal to the change in that mass-times-velocity over time.

In other words, it's the derivative of mass-times-velocity with respect to time. And if you were to calculate that derivative, you'd find that the net force is just equal to mass times acceleration. But putting Newton's second law in terms of mass and velocity introduces an aspect of motion that we haven't talked about yet.

Newton didn't really give this aspect a name, but we will: it's called momentum, and it's one of those things that's easier to see in real life than to describe. Momentum is often described as an object's tendency to remain in motion, but technically, it's an object's mass times its velocity. So, a big bag full of leaves rolling down a hill? It might be going fast, but it doesn't have much mass, so it doesn't have a lot of momentum, and it wouldn't be too hard to stop. But the boulder chasing Indiana Jones? That had a lot of mass -- and therefore lots of momentum. So it would have been much harder to stop.

And momentum is one factor that affects collisions between objects. After all, if a huge boulder crashes into another huge boulder, that's going to be a very different sort of crash than if a bag of leaves crashes into a boulder.

But the other quality of a collision that we often consider is known as impulse, which -- at least in the context of physics -- doesn't actually have anything to do with willpower, or why you throw your game controller when you get stuck on a level. Instead, impulse -- usually represented by a J -- is the integral of the net force on an object over time -- in other words, its change in momentum.

Impulse turns out to be a particularly useful way to describe a crash -- because generally, in collisions, forces change very quickly. So, if a ball smacks into a wall, and over the course of half a second, its force on the wall in Newtons is equal to the time, multiplied by 25, we'd say that its impulse was 3.1 Newton-seconds.

Now, let's consider the different kinds of collisions that we can study. Generally, collisions can be described as either elastic or inelastic. And it's going to be important to figure out which kind you're dealing with, because the math works in very different ways. If elastic collisions sound bouncy, that's because they are. Like the conservative systems we talked about last time, in elastic collisions, kinetic energy is neither created nor destroyed.

For example: let's say you knock a white billiard ball into a second, red one that's sitting on the table, and they hit each other in just the right way. For this to be a true elastic collision, all of the kinetic energy from the white ball would be transferred to the red ball. Meaning, after they hit each other, the white ball would stay put, and the red one would zoom away with all of the kinetic energy -- so, the same speed, basically -- that the white ball used to have.

But you won't come across elastic collisions in real life. Because there's always going to be some energy that's lost somewhere in a collision, generally as heat or sound. And when kinetic energy isn't conserved, that's an inelastic collision. There's one thing that's going to be true about every collision, though, whether or not it's elastic: The momentum of the system will always be conserved. It might be transferred to another object -- it might even be transferred to more than one object -- but the momentum is always going to go somewhere, And we'll be able to use math to figure out where it went.

And we can use what we know about impulse -- and Newton's third law -- to prove it. The third law, of course, is the one that says that every action has an equal and opposite reaction. And that applies to collisions in the sense that, if a ball hits a wall, it'll exert a force on the wall, and the wall will exert an equally strong force on the ball. We can describe each of these forces as impulses, since we know that an impulse is just a change in an object's momentum.

So, the ball's momentum will be decreasing when it hits the wall, but because of Newton's third law, we know that the wall's momentum is going to increase by an equal amount. The change in the wall's momentum might be impossible for us to see, because the wall is connected to the ground, and Earth has lots of mass. But it's there. And that fact -- that momentum is always conserved -- turns out to be super helpful for describing collisions using math. Like in the case where you knocked the white billiard ball into the red one.

Since momentum is conserved, and momentum is mass times velocity, the white ball's mass-times-velocity before the collision has to be equal to its mass-times-velocity, plus the red ball's mass-times-velocity, after the collision. Which is why -- assuming the balls have the same mass -- if the white ball stops moving after the collision, then the red ball must move with the same velocity that the white ball had.

So, now we know about both elastic and inelastic collisions. But there's also such a thing as a perfectly inelastic collision, because... of course there is. And it's easier for me to tell you, first, what it isn't. So, it is not a collision where the objects lose all of their kinetic energy. Instead, a perfectly inelastic collision is what happens when objects stick together. These collisions lose as much kinetic energy as possible to other forms of energy, like heat, sound, or even potential energy... but still, their momentum is conserved.

An example would be if you pushed one magnet toward another -- at just the right angle for them to stick together on contact -- and then they both started sliding together at half the speed of the magnet you pushed. Before the collision, the momentum of one magnet was zero, and the momentum of the one you pushed was its mass times its velocity. Once the magnets collide, the mass is doubled, and the velocity is cut in half. So the total momentum stays the same, but you lose some kinetic energy because there's less speed involved.

So that's the basics of how collisions work, and how they relate to the momentum of motion in a straight line. But there's one more detail we have to explore in order to really understand how objects move, whether they're going to collide or not. And that is: center of mass.

Until now, we've been talking about objects as though they were

little point-particles. And that's worked fine -- for the most part, the objects we've been talking about would act much like a small dot would. But of course, not all objects work that way. If you've ever tried to fling a hammer, for example -- which I do not recommend doing! -- it wouldn't fly through the air the same way a softball would, because the hammer's mass isn't distributed evenly. Likewise, a pendulum with a big ball on the end of a very light string -- called simple pendulum -- would behave very differently from a pendulum that uses a heavier stick -- what's known as a physical pendulum.

In these situations, it's more useful to describe what the center of mass is doing. When you throw the hammer, for example, it'll rotate around its center of mass. So, what is the center of mass? It's basically the average position of all the mass in the system. Say you have a 3 meter long stick -- which we'll pretend is massless -- with a 2-kilogram ball stuck on either end. It's easy to see where the center of mass should be -- the mass is distributed symmetrically, so its center is going to be right in the middle of the stick.

Now, let's say you have another 3 meter stick, and on the left side there's a 2 kilogram ball, but on the right side, there's a 4 kilogram ball. This time, there's twice the mass on the right side of the stick. So when you're trying to calculate the average position of all the mass attached to the stick, you're going to be counting the right-hand side twice as much. That means the center of mass will be two thirds of the way along the stick, closer to the 4 kilogram ball. It's like each piece of mass pulls on the center of mass a little bit, so parts with more mass end up pulling harder and moving it closer.

But if you don't want to calculate this in your head -- and if there are like seven different particles to deal with, you probably won't -- but there's an equation for it! First, pick a starting point to measure from, where x = 0. That can be the end of the stick, the middle of the stick, whatever's easiest. As long as you're consistent. Then, the center of mass will be equal to the sum of each individual mass, times its distance from the starting point, all divided by the total mass in the system.

Let's try it for our stick with the differently-weighted balls. We'll choose the left side of the stick, where the 2 kilogram ball is, as our starting point. The 2 kilogram ball's mass times its position is zero. The 4 kilogram ball's mass times its position -- 3 meters -- is 12 kilogram-meters. And the total mass of the system is 6 kilograms. So, divide 12 kilogram-meters by 6 kilograms, and you get 2 meters. That's the position of the center of mass, which is two thirds of the way along the stick, toward the 4 kilogram ball's side. Exactly what we figured out earlier. I'm telling you all of this now, because from here, we're heading off in a totally new direction. Literally!

But for now, you learned about collisions, and how momentum and impulse can be used to describe them. We also talked about the differences between elastic and inelastic collisions, and how to calculate the center of mass of a system.

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