Torque: Crash Course Physics #12

Crash Course: Physics
https://youtube.com/watch?v=b-HZ1SZPaQw
https://nerdfighteria.info/v/b-HZ1SZPaQw

Shini: You have a box. A ring. And a marble. And they're all at the top of a ramp... because you know how physics loves ramps, especially hypothetical ramps! So, let's say this ramp would allow for static friction, but not kinetic friction. Now, you let go of all of these objects at the same time, so that the box starts sliding, and the ring and marble start rolling, all at once. So, which of them will hit the bottom first? The answer might not be what you'd expect.

I mean, we already know that when you drop two objects from the same height -- in a vacuum at least -- they'll hit the ground at the same time. Even if you tried it with a feather and a bowling ball. So you might think that all of the objects would get to the bottom of the ramp at the same time. But they won't. The reason has to do with how energy is distributed in an object when it's rolling. And in order to understand who wins the ramp-race, and why, we have to investigate some qualities of rotational motion: Specifically, torque, and the moment of inertia.

[Theme Music]

Have you ever tightened a bolt with a wrench? Or pulled a door open? Me too! When we do those things, the wrench and the door's handle do their jobs using torque. That is, they apply a force perpendicular to the axis of rotation, which makes the bolt turn and door swing open. That's what torque does -- it makes things rotate faster or slower. In other words, torque changes an object's angular velocity.

For the first few weeks of this course, we described net forces as changing an object's linear velocity, how fast it moves through space, and in what direction. Torque essentially does the same thing, but for rotational motion. This means that a lot of the relationships and equations that apply to forces will apply to torque in a similar way. But first, let's talk about how to calculate torque, by analyzing what happens when you open a door.

The harder you pull on the handle, the more torque you'll generate, and the more you'll change the door's angular velocity. More net torque then, means the door starts moving faster on its hinges. So, the strength of the force that's applied is one factor that affects torque. Another is the distance between the force and the axis of rotation -- or the radius. A larger radius means more torque. You know this if you've ever tried opening a door with a handle that's too close to the hinge. I'm guessing you haven't tried that, though, because there's a reason doorknobs are generally placed far from the hinges. A door with a handle close to the hinges would be much harder to open, because you get less torque for the same amount of force.

The last factor that affects torque is the ANGLE BETWEEN the applied force and the radius. If you tried to open the door by pulling the handle, say, parallel to the door -- in the direction opposite from the hinges -- the door wouldn't move. Because the only part of the force that affects the door's rotation is the force that's Perpendicular to the radius. To put this idea in mathematical terms, torque -- represented by the Greek letter tau -- is equal to the perpendicular force, times the radius. And, you know how we keep saying that for translational motion, a net force on an object is equal to its acceleration times its mass? Well, something similar applies to rotational motion, too: The net torque on an object is equal to its angular acceleration, times what's known as its moment of inertia.

Now, we've talked about inertia before, at least as it relates to translational motion. Basically, it's an object's tendency to keep doing what it's been doing. An object with lots of inertia is harder to speed up or slow down. And in translational motion, the inertia of an object depends on mass. The MOMENT OF INERTIA works in a somewhat similar way for rotational motion... but the best way to define is mathematically.

Specifically, the moment of inertia is the sum of all the individual points of mass in an object, times the square of their distance from the axis of rotation. So, much in the same way that inertia relates to an object's mass in translational motion, the moment of inertia relates to mass, too, but it depends on how that mass is distributed. The farther away the mass is from the axis of rotation, the higher the object's moment of inertia. It's possible to derive the equation for an object's moment of inertia, by integrating the square of the object's radius over its mass. But those integrals can get complicated.

So this is one of those rare cases where, if you're asked to solve problems using moments of inertia and you don't have access to the equations, it's probably worth memorizing them. Now, there's another thing that torques and forces have in common, and it's going to be the key to figuring out which object wins the race down the ramp. Namely: torques, like forces, have the ability to do work.

As you might remember from our episode on work and energy, the work done by a force is just the integral of that force over a certain distance. In a similar way, the work done by a torque is the integral of that torque over a certain angle. Meaning: the more torque you apply while rotating an object, the more work you do.

We also know that work changes the energy of a system. For example, it can change its kinetic energy, which is the energy of its motion. In the case of objects that move without rotating, all of that kinetic energy goes into translational motion. In this case, keep in mind that -- as we've gone over before -- the kinetic energy of translational motion is equal to half of the object's mass, times its velocity squared. But when an object is ROTATING, some of its kinetic energy is also taking the form of Rotational Motion. And calculating the kinetic energy of rotational motion is pretty easy. Because, first, the moment of inertia affects rotational motion in the same way that mass affects translational motion. And second, rotating objects have angular velocity, just as translating objects have linear velocity. So, the kinetic energy of an object's rotational motion is just half of its moment of inertia, times its angular velocity squared.

OK, there's just one final factor we have to consider, before we finally get back to the box, the marble, and the ring racing down the ramp: And that factor is angular momentum. We've talked about linear momentum -- and how it's equal to an object's mass times its velocity. Well, there's also angular momentum, which is equal to an object's moment of inertia times its angular velocity. And, like linear momentum, angular momentum is always conserved. That's another one of those super-fundamental principles of physics: You can't create or destroy angular momentum. It always has to go somewhere.

So, now, let's get back to The Great Crash Course Physics Ramp Race. All three objects -- the box, the marble, and the ring -- are covering the same distance. And what we want to know is, how fast do they cover that distance? The answer has to do with what happens to each object's energy as it moves down the ramp. When they're at the top of the ramp, all the energy of each object takes the form of gravitational potential energy, which is equal to the object's mass, times small g, times the height of the ramp. As they move down the ramp, all of that potential energy gradually gets converted into kinetic energy.

In the case of the box, all of its potential energy will be converted to translational kinetic energy, because that's the only kind of motion it has. So the object that gets to the bottom of the ramp first is... the box! Because, for both the marble and the ring, some of their potential energy gets converted into rotational kinetic energy. And energy that goes into their rotation isn't being used to make them move faster down the ramp. So really, anything that slides -- at

least on our hypothetical ramp with no kinetic friction -- will reach the bottom before anything that rolls. And the masses of the objects don't even matter, because the energy of an object with more or less mass will increase or decrease accordingly.

So, the box wins. But what's the runner-up? Does the ring reach the bottom next, or does the marble? That question is a little more complicated, but it turns out that the marble reaches the bottom before the ring, because it has a lower moment of inertia. The marble is a solid sphere, so its mass is distributed closer to its center. But the ring's mass is distributed in... well, a ring -- so its mass is distributed far from its center, giving it a higher moment of inertia. What does that mean for the marble's speed versus the ring's? Well, since the marble has a smaller moment of inertia, its velocity can take up a larger proportion of its kinetic energy -- which means it moves faster down the ramp. So, the final results of the race? The box wins, the marble comes in second, and the ring finishes last.

Today, you learned about torque, and how it relates to an object's angular acceleration and its moment of inertia. We also talked about how to calculate moments of inertia, angular momentum, and the fact that torques can do work. Finally, we figured out what would happen if you let a box, marble, and ring move down a ramp.

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