Uniform Circular Motion: Crash Course Physics #7

Crash Course: Physics
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Ever been in one of those twirly carnival rides? You know the ones where you get into a giant cylinder and then you stand against the wall and then they spin you around like a wet salad?

If you've had that uniquely nauseating experience then you know that the simple act of spinning in a circle can be intense. It also happens to be one of the most misunderstood concepts in Newtonian physics. It's know as uniform circular motion and it's what occurs when anything moves along a circular path in a consistent way. Most of the confusion about this idea has to do with the fact that things accelerate inward as they move in a circle. A kind of acceleration known as centripetal acceleration. But you'll often hear people talking about centrifugal acceleration, pushing things outwards as they move in a circle. That's actually where centrifuges get their name.

And centrifugal acceleration isn't wrong exactly, it's just not real. So to explain how things really accelerate when they move in circles, lets talk about the physics of that ride as it spins you around, assuming you're willing to step inside. I'm getting dizzy just thinking about it.

[Theme Music]

In 1960, NASA was getting ready to send people to space. They knew that a big part of space flight would involve acceleration, so they wanted to test how much acceleration people could handle before they'd black out. Because that's what happens when too much blood is forced away from your brain for too long. So engineers tested potential astronauts by putting them in a human centrifuge -- Basically, a super-powered version of those rides at the fair.

They found that most people could withstand an acceleration of around 98 meters per second squared for 10 minutes -- That's about ten times the acceleration caused by gravity that you'd feel just by jumping in the air. With that in mind, let's say we've been asked to calculate the safety of one of those carnival rides -- which means we'll need to figure out how much acceleration riders would experience.

There are equations we can use to do that, because just like with all the other kinds of motion we've talked about so far, uniform circular motion has four main qualities: position, velocity, acceleration, and time. And they're all related to each other. When it comes to uniform circular motion, position is the most obvious quality: there's an object, and it's on a circular path. But velocity is a little less intuitive.

At any given moment, velocity tells you how fast the object's going, and in what direction. And that direction... is NOT along the path of the circle. It's actually perpendicular to the radius of the circle -- along what we call a tangent. So if you draw an arrow representing the velocity on the circle, it'll only touch the circle in one spot. OK bear with me here, as this might seem kinda strange, but it's true! One of the nice things about the physics of motion is that often, you can just try it out for yourself and see what happens. So here's a quick way to see tangential velocity in action: All you need is some string, a key -- or some other small object to tie the string to -- and a wide open space so nobody gets hurt when the key's flying around.

Move the string so the key starts twirling around in counterclockwise circle, parallel to the ground. Then, when the key is at the point in the circle that's farthest away from you, let go of the string. The key flies to the left! Here's why: In earlier episodes, we've talked about inertia and the idea that if an object is in motion, it'll remain in that motion unless it's acted upon by a net external force. Which means that something moving in a straight line is going to continue moving in a straight line unless a force -- one that isn't balanced out by other forces -- turns it.

Whenever you see something turning? There's a net external force acting on it. That's why, at any given moment, the velocity of an object moving in a circle will be tangent to it. Without a force to turn it, it just flies in whatever direction it was moving last. Once you let go of the string, you got rid of the force that was making the key turn in circles. So it kept moving with the same velocity that it had at the exact moment you let go -- perpendicular to the string connecting it to your hand, which was the center of the key's circular path.

And now, we can finally talk about the mysterious force that was accelerating the key -- changing the direction of its velocity so that it moved in a circle. That force is the same reason riders on the human centrifuge spin in a circle -- in fact, it's the reason anything moves in a circle. That force is known as the centripetal force, and the acceleration it causes is called centripetal acceleration. And the important thing to remember about centripetal acceleration is that it's always directed toward the center of the circular path.

That makes a lot of sense, if you think about it in terms of how the velocity's changing. The key was only turning in circles because your hand was pulling it toward the center of a circular path. But now think about what it's like to be on one of those centrifuge rides -- or, if you've never subjected yourself to one yourself, what it's like to be in a car that turns sharply. The ride -- or the car -- is turning in a circle, so there must be centripetal acceleration pushing you toward the middle of that circle. Except, it feels like you're being pushed outward. People often attribute this sensation to centrifugal force. But that's not real.

The reason that people confuse the centripetal force with what feels like a centrifugal force comes down to a change in perspective -- what physicists call a frame of reference. From the frame of reference of someone standing outside the human centrifuge, it's easy to see what's actually happening: As the cylinder turns, it forces the people inside it to move in a circle. And the wall is pressing on them to keep them turning -- it's actually pushing them toward the center of the circle! But the person inside the cylinder just sees everything moving around with them. From their frame of reference, it feels like they're just being squashed against the wall -- as though there's a centrifugal force acting on them. But there's nothing there to actually create that force. Which is why physicists call it a fictitious force -- it doesn't really exist.

So! Now that we know how acceleration works when you're moving in a circle, we can finally come up with some ways to connect position, velocity, and acceleration -- and figure out if that centrifuge ride is safe for people. But first, we have to talk about time. When something's moving around a circle in a consistent way -- in other words, its acceleration is constant -- it'll take a certain amount of time to return to its starting conditions. In this case, those starting conditions are a particular point along the circular path. We call that time the period of the motion, and the variable we use to represent it is a capital T. Which isn't too hard to remember, as long as you keep in mind that the period is an amount of time.

From timing the centrifuge ride in action, we know that it takes 2 seconds to spin around once. So we'd say that the period of its motion is 2 seconds. But sometimes it's easier to talk about the same idea in another way -- how many revolutions does the ride make in one second? That's what we'd call the frequency of the motion -- which we write as an f in equations. That's simple enough to figure out: if it takes the ride 2 seconds to make one revolution, then it's making one half of a revolution per second. It's also not too difficult to relate period and frequency with an equation: frequency is just 1, divided by the period.

Now that we've gotten time out of the way, let's talk about position. We generally talk about distance in terms of the circumference of the circle, because that tells us how many times you've gone around the circle. In other words, if a centrifuge rider covers the same distance as one circumference, we know they've made one revolution. And circumference is just 2 times pi times the radius of the circle. So if that human centrifuge has a radius of 5 meters, riders would travel 31.4 meters every revolution.

Now: What about their speed? Well, in our episodes on motion in a straight line, we talked about how average velocity is generally equal to the change in position over the change in time -- which turns out to be a great way to describe the speed of uniform circular motion. When the riders made one revolution around the circle, they've covered a distance equal to 2 times pi times r -- or, in this case, 31.4 meters. That's how far they've traveled. And the amount of time it took was equal to the period of the ride's motion. That is their change in time.

Divide the distance they've traveled by their change in time, and you get the speed equation for uniform circular motion. Using that equation, we can calculate the speed of a rider on the centrifuge -- it's 15.7 meters per second.

Next, getting the equation for the magnitude of centripetal acceleration -- how strong it is, basically -- is a little less straightforward. That magnitude will be equal to the change in velocity over the change in time at any given moment -- in other words, its derivative. Actually calculating the derivative can get complicated, but it turns out to be equal to the speed, squared, divided by the radius of the circle.

This equation makes a lot of sense for a few reasons: First, take a look at the units. Acceleration is measured in meters per second squared, so we already know that whatever the equation for centripetal acceleration is, the units have to work out to meters per second squared. And they do: square the speed, and you end up with units of meters squared per second squared. Just divide those units by meters, and you get meters per second squared.

We can also tell from this equation that if you increase your speed along the circular path or decrease the radius of that path, you should end up with a higher acceleration. And that relationship between acceleration, speed, and radius checks out in real life, too: Try spinning the key on a string faster, or shortening the string but spinning it at the same speed. You'll feel the key pulling harder on your fingers, because it's experiencing more acceleration. And now that we have an equation for the acceleration that riders would experience on the centrifuge, we can finally figure out if that ride is safe.

We already know that their speed would be 15.7 meters per second, and that the radius of the ride is 5 meters. So, according to the equation for acceleration, their acceleration would be 49.3 meters per second squared. That's about half the acceleration that NASA found would make people black out. So the ride is probably safe, at least for a couple of minutes. Whether that much acceleration would be pleasant is a different story -- but hey, we're just here to make sure the ride is safe. We're not responsible for cleaning up the vomit once it's over. Today, you learned that when an object is in uniform circular motion, its velocity is tangent to the circle and its acceleration is pointing inward. We also talked about the difference between centripetal and centrifugal forces, and derived equations for period, frequency, velocity, and acceleration. Crash Course Physics is produced in association with PBS Digital Studios. You can head over to their channel to check out amazing shows like Deep Look, The Good Stuff, and PBS Space Time. This episode of Crash Course was filmed in the Doctor Cheryl C. Kinney Crash Course Studio with the help of these amazing people and our equally amazing graphics team is Thought Cafe.