Instructor
You’re back! Good. That means you’ve completed your work on friction, aced the quiz, and you’re ready to study the next type of force and the motion that goes with it.

Let’s start with a demonstration. I have here an action figure in a cup on a swinging platform. Watch what happens when I swing the platform in a circle. Why doesn’t the action figure fall out of the cup when the cup is upside down? Surely the force of gravity is still working. And why doesn’t the cup leave the platform and keep going in a straight line? Aren’t Newton’s Laws of Motion still valid? Yes, they are.

And in this part of the program we’ll use them to help us describe motion in a circle and the force that causes circular motion.

VO
Many objects do not move in straight lines, but rather in a circular motion. If we swing a ball at the end of a rope in a circular path, the force of the rope on the ball is perpendicular to the direction of the ball at that instant.

In order for any object to move in a circular path at uniform speed, an inward perpendicular force is necessary. This inward force is known as centripetal force.

If the rope were to break, the ball would fly off in a straight line because a centripetal force would no longer be acting on it. As an object moves in a circular path, its speed may or may not be constant, but its direction is constantly changing. In other words, an object in circular motion is constantly accelerating. According to Newton’s second law, in order for an object to accelerate, a force must be acting on it. In circular motion, that force is centripetal force. As the ball moves around, it is the rope that is exerting centripetal force on the ball.

Instructor
When I whirl this stopper around in a circle, I feel the string pulling away from my hand. But that’s only what I feel. The tension in the string goes both ways. The string pulls outward on my hand, but the other half of the action-reaction pair is that I’m pulling the stopper toward the center of the circle. That’s the centripetal force.

VO
Centripetal force is abbreviated “F_c.”
Actually centripetal force is not a new kind of force at all. It’s any force that is directed toward the center.

Instructor
It can be the force of gravity, which hold the moon in orbit, or an electric force, which keeps electrons revolving around the nucleus. Or it can be as simple as the tension on a string.
Like projectile motion, circular motion is two-dimensional. This ball is traveling in a clockwise circle. Watch what happens when we eliminate the centripetal force by letting go of the string.

When we let the ball go at the twelve o’clock position, it moves to the right in a straight line.

And when we let it go at the three o’clock position, it moves in a straight line toward the bottom of the screen.

A vector diagram helps us see the two components of the ball’s motion. Draw it with me.

First, look at the ball in the twelve o’clock position on its circular path. When we let go of the string, the ball’s inertia keeps it moving in a straight line to the right. So we draw a velocity vector to the right.

This is the uniform component of the ball’s motion. The other component is caused by the tension on the string pulling the ball toward the center of the circle. This force would cause the ball to accelerate toward the center. Draw this vector inward at a right angle to the straight-line component. Now we draw the resultant of the two components like this.

When the string was released at the three o’clock position, the ball went in a straight line toward the bottom of the screen. Draw this vector. Again the string pulled it inward, and the resultant is in this direction. This is repeated in every position and the result is circular motion, clockwise.

Where circular motion is involved, people often misinterpret what they observe or experience. Listen to this example of something we’ve all experienced and see if you can find the error in Roger’s thinking.

Roger and Edna are in his brand new car. Roger has his seat belt fastened and is holding on to the steering wheel, but Edna doesn’t have her seat belt on. Edna is not too bright!!! When the car goes around a sharp curve to the left, Edna feels pushed to the right and slams into door. Roger says, “Edna, there’s a strong centrifugal force pushing you to the outside of the circle. You’d better slide over here next to me so I can put my arm around you and help you resist the force the next time we turn left.” Roger is a lover, not a physics student!

Here’s your challenge. Tell what’s wrong with Roger’s explanation. What really caused Edna to move toward the door? Talk it over and tell your teacher. Come back when you’ve finished.

I hope you used what you already know to figure this out. Did anyone think about riding in a car when the car stops suddenly? You feel as if you are being pushed forward. But it is not a force pushing you, it’s actually your own inertia that keeps you moving forward as the car stops. The same thing happened to Edna when the car turned left. Edna’s own inertia made her continue to move in a
straight line as the car turned left. Inertia is often misinterpreted as a force. In this case, it’s even
given the name, centrifugal force. But there is no such force. When Edna hit the door, it pushed her
inward and supplied the centripetal force needed to make her go in a circle with the car and with
Roger. Without the door, Edna’s inertia would keep her going in a straight line right out of the car.

Now sometimes that can be a good thing. For instance, the holes in the spinning tub of a washing
machine allows the water to keep going straight and escape, while the sides of the tub exert a
centripetal force on the clothes to keep them going in a circle.

And have you ever wondered how this fabric softener ball works in a washing machine? You put the
softener in here, pop the heavy stopper in place and throw it in the machine. How does it know when
to open and release the liquid? It does it during the first spin cycle. Watch and listen.

(popping noise)

Did you hear the stopper pop? And did you notice that I said that the stopper was heavy? That means
it has lots of inertia, which made it go in a straight line while the rest of the ball stayed with the
spinning tub. You can explain so many of life’s mysteries with a little physics!!

(amusement park ride on screen)

VO
Your body can’t sense uniform motion, but it can feel any acceleration, like an elevator slowing down
or a car speeding up. Even though this amusement park ride is moving at constant speed, the students
riding it can sense the fact that their motion is accelerated. How can motion be accelerated when
speed is constant? Tell your teacher.

Instructor
Did you say that velocity involves both speed and direction and that during circular motion, direction
is always changing? That means velocity is changing. According to Newton’s 2nd Law, acceleration
requires a net force. And that’s the centripetal force.

Now there are four variables that could affect each other when objects, like the students on the
amusement park ride, move in a circle. We’re going to study these factors in an experiment involving
this apparatus. The stopper is the object that will be moving in a circle. Watch as I put it in motion
and see if you can figure out the four quantities we can measure or calculate and then vary to see how
they affect each other.

I’ll hang this weight from the bottom of the string and hold the string here to get started. And with
my other hand, I’ll manipulate the tube to make the stopper move in a horizontal circle over my head.
After it starts moving, I’ll let go of the string. Watch what happens to the circle as the stopper moves
faster and slower. The hardest part of the experiment is stopping without hitting myself in the head.
I’ve learned the hard way to pull down on the bottom of the string as I stop the motion.

Now your teacher will pause the tape so that you can list the four factors that could affect the motion
of the stopper.

(Pause Tape Now graphic)

(diagram on screen)

VO
Here are the four factors we’ll be varying. The first is the mass of the object. We’ll vary this by
using two different stoppers in two trials.

The second factor will be the radius of the circle, which is the distance from the tube to the center of the stopper. To control the radius, we’ll attach a clip one centimeter below the tube to serve as a guide. The trick is not letting the clip touch the bottom of the tube since that would mess up the results. If it gets too close, the student will pull down on the string and then adjust the speed to get the clip back in place.

The third factor is the centripetal force that pulls the stopper toward the center of the circle. We’re using gravity to do this, and we’re changing the direction from downward to horizontal by using the top of the tube as a pulley. So the weight of our hanging mass will serve as the centripetal force.

The last variable is the velocity of the stopper. We’ll keep the speed of the stopper constant and will calculate it using the formula, “velocity equals distance over time.” In the experiment we’ll measure the time it takes the stopper to make 20 revolutions. The distance will be 20 times the circumference of the circle, which you should know is \(2\pi r\).

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**(table on screen)**

**VO**

To record the data, you’ll need to copy this data table. Your teacher will put it on the board or overhead for you and give you time to make your own. You can go ahead and fill in some of the data since we’ll be manipulating the mass, radius, and centripetal force used in the experiment.

Local teachers, please turn off the tape and give students this data table from the facilitator's guide.

**(Pause Tape Now graphic)**

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**(students on screen)**

**VO**

Now we’re ready to perform the experiment and record data. In the first trial, a stopper with a mass of 0.016 kg is used and the radius of the circle is set at 0.50 m. A hooked mass that weighs 1.0 N is hung from the string.

The time it takes to make 20 revolutions is found to be 11 seconds.

In trial two, the same stopper and the same hanging mass are used and only the radius of the circle is changed. This time the radius is set at 0.75 m. When the experiment is repeated with the new radius, the time for 20 revolutions is 16 seconds.

In trial three the same stopper as before is used, and we go back to the same radius used in trial one, 0.5 m. This time the centripetal force is varied by hanging a 2.0 N weight from the string. When the experiment is repeated with the new centripetal force, the time for 20 revolutions is only 8 seconds.

In trial four, we go back to the 1.0 N centripetal force and change to a stopper with a mass of 0.036 kg. When the experiment is repeated with the mass, the time for 20 revolutions is 17 seconds.
In this lab, we studied three variables, mass, centripetal force, and radius, to see how they affected the velocity of an object in circular motion. Notice that in trials one and two, we kept mass and force constant while we varied the radius. In trials one and three, we varied only the centripetal force, and in trials one and four, we varied only the mass of the stopper.

Now, all that’s left to do is to use the radius for each trial to calculate the distance the stopper traveled in twenty revolutions and to use the distance and time to calculate velocity. Then you’ll make some conclusions based on your results and answer some questions. Local teachers, these lab questions can be found in unit five of the facilitator's guide.

Instructor
Come on! Get in there. Oh, you’re back! I’m sure you’ve probably tried one of these puzzles. It seems so easy to get both balls in these holes, but it’s really harder than it looks. Come on you little … Oh well … While I’m working this puzzle I think everyone should complete your lab calculations, conclusions, and questions. When you come back, we’ll discuss your lab conclusions. And maybe I’ll have mastered this little puzzle by then. See you later.

Instructor
I finally figured this puzzle out. Did you? At first, I tried to use my fine motor skills to get the job done. But apparently my motor skills weren’t fine enough. So I decided to use my brain. Don’t laugh! Since we’re studying circular motion, I used the old noggin’ to figure out the solution. I knew it must have something to do with making the balls move in a circle.

And as soon as I gave the toy a spin, I had it. At the outside of the circle, the balls’ inertia made them try to go in a straight line, but the sides of the box furnished the centripetal force needed to keep them going in a circle and settle into the holes.

Now, where were we before I got so involved with this darn thing? Oh, yes. You were analyzing the lab data we collected during the last program. We varied the mass of the whirling stopper, the radius of the circular path, and the centripetal force, one at a time, and saw what happened to the velocity of the stopper.

You were supposed to calculate the distance traveled by the stopper during its twenty revolutions and then determine its velocity. Then you had some conclusions to make and some questions to answer, based on those conclusions. Let’s look at the final data first.

VO
The first conclusion you were asked to make was the relationship between radius and velocity. For that, you should have looked at trials one and two because the mass and force were held constant, and only the radius was changed. Notice that when the radius doubled, the velocity increased, but it didn’t double. That should have led you conclude that radius is directly proportional to velocity in some form. Did you try squaring the velocity? You can see that when the radius is doubled, velocity squared also doubles. So radius is directly proportional to velocity squared. Write that down.
Next, we need to look at trials one and three to see the relationship between centripetal force and velocity. The force is doubled, and you can see that velocity squared also doubles. So centripetal force is directly proportional to velocity squared. Write that down, too.

Finally, we look at trials one and four to see the relationship between mass and velocity. We doubled our mass and the velocity decreased, so we know we’re looking at an inverse proportion. But the velocity was not cut in half, so we look at velocity squared. Within bounds of experimental error, “v squared” was cut in half. So mass is inversely proportional to velocity squared. Write it down.

**Instructor**

Let’s turn these three proportions into one equation. Don’t write anything down until we’re finished. You’ve learned that when variables are directly proportional, they are on opposite sides of the equals. So we’ll put “r” on the left and “v^2” on the right. And “F_c” needs to be on the left. Since mass is inversely proportional to velocity squared, we’ll put “m” on the same side as “v^2.” You usually don’t see the equation in this form, so we’ll rearrange it by dividing both sides by “r.”

(green chalkboard on screen)

**VO**

This is the equation for calculating centripetal force. It’s a special case of Newton’s Second Law, “F equals m a.”

So centripetal acceleration equals velocity squared over radius.

**Instructor**

You may have worried that we didn’t insert a constant when we changed the proportion into an equation. We don’t need one in this situation, since the units cancel out. If you want to check this for yourself, use the kilogram meters per second squared for the newton and try it.

Now, how will we use this equation? We could do a lot of plugging and chugging, but we won’t this time. Instead, we’ll ask you questions like the one your teacher will put on the board or overhead. Then we’ll show you an easy way to solve this kind of problem.

(text on screen)

**VO**

Local Teachers: Turn off tape and give students problem set number one from facilitator’s guide.

(Pause Tape Now graphic)

(text on screen)

**VO**

Here’s an easy way to solve this kind of problem. We call it the “one’s method.” Just take the equation and make every constant and variable a one. Of course, exponents have to remain in the equation, since they affect the answer. So our centripetal force equation becomes “one equals one times one squared over one.” Now all we do is exactly what our problems tells us to do. In this example, we are told to triple the mass, so we change the one to a three. And we need to cut the radius in half, so we’ll do that. Now, we just do the math and we see that the centripetal force is multiplied times six.
In the next problem, we’re told to double mass, radius and velocity. Now don’t forget that velocity is squared, so you must square whatever you do to “v”. The result is “two times two squared divided by two.” The centripetal force must be multiplied by four to keep this object moving in a circle.

**Instructor**

Let’s talk about some practical applications of our equation. What do you think furnishes the centripetal force required to keep your car going in a circle when the road curves? Tell your teacher.

If you said the tires, you’re close. The tires push outward on the road and the road pushes inward on the car. And, to be even more specific, it’s the friction between the road and tires that furnishes the centripetal force when the road is flat.

*(race car on screen)*

**VO**

Race car tires are wide to maximize contact with the road. On a flat track, the tires have to be changed frequently because the outside wears out from pushing outward on the road.

But what have you noticed about many curves on racetracks and on newer roads?

The road is often banked. How does that help?

*(diagram of car on screen)*

**VO**

When a car goes around a banked curve, it presses on the road, perpendicular to the hill.

And the hill presses back. Action-reaction, remember? This **normal** force can be resolved into vertical and horizontal components.

Since the horizontal component is directed toward the center of the circle, it furnishes a centripetal force to change the car’s direction. This is in addition to the friction between the road and tires. The result is a much greater centripetal force than on unbanked curves.

**Instructor**

Now use what you’ve learned so far to answer this question. Let’s say that you see this sign on the highway telling you that you need to slow down to twenty miles per hour to make an upcoming curve. You know that the mass of the car is constant and so is the maximum centripetal force that the bank of the road and friction between the road tires can produce.

*(road sign and text on screen)*

**VO**

What if you decide to take the curve at 60 miles per hour? What will happen to the radius of the circle your car will make? Use your “one’s method” to decide.

Your teacher will pause the tape until everyone has an answer.

*(Pause Tape Now graphic)*
VO
We’ll keep the mass and centripetal force constant and triple the velocity. Since we’ve gone from 20 to 60 miles per hour. Since velocity is squared, that means the radius of the circle will be multiplied by nine.

Instructor
You should have learned more than just physics on this last example. The mass of your car is constant, and the centripetal force the road can exert depends on the bank of the road and the condition of the road and tires for friction. So all you can control is the velocity of your car. It turns out that velocity is the most important factor since it’s squared. So a small increase in velocity makes the radius of the circle much larger.
In our example, the radius is nine times greater. Our car couldn’t stay on the road at that speed. So the moral is, “To stay on the road, keep your speed down.” This is especially true when weather conditions are bad because the centripetal force will be even less than on dry days. Now you can impress your Driver Education teacher with a little physics knowledge.

(instructor whirling cup on screen)
VO
Let’s finish our study of centripetal force like we started it, with the whirling cup of water demonstration. When the cup is at the top of the circle, why doesn’t the water fall? Isn’t the force of gravity acting on it? The answer is: “Yes, the force of gravity is pulling the water down and yes, it is falling.” But there’s more to the story. When the apparatus is at the 12 o’clock position, I don’t feel any tension in the string. Try it for yourself and you’ll see what I mean.

At that point, I’m not pulling down at all because gravity is doing the job for me. The force of gravity is pulling everything, water included, downward and toward the center of the circle.

At the same time, the inertia of everything, including the water, makes it tend to go in a straight line. The result is that the water goes in a circle instead of falling out of the cup.

Instructor
And speaking of gravity, that will be the last force we study during this unit. And who will help us understand some of the mysteries of our planet and the rest of the universe? None other than Sir Isaac Newton. It’ll be nice to hear from him again, won’t it? I’ll see you later.