Rotating Frames of Reference

The force of gravity acting on any object is due strictly to the other masses in the space around it. On Earth, the gravity we experience is mainly due to Earth itself because of its large mass and the fact that we are on it. There is no device that can make or change gravity. So how can we simulate gravity? The answer is uniform circular motion. Incorporating the principles of uniform circular motion in technology has led to advances in many fields, including medicine, industry, and the space program. For example, while in training, astronauts and jet pilots lie in the compartment at the end of a large centrifuge like the one in **Figure 1**. A **centrifuge** is a device that spins rapidly. The arm of the centrifuge in Figure 1 spins around the centre, and the astronauts and pilots experience large forces that feel like a larger force of gravity pulling on them. Experiencing such forces allows us to better understand how the human body reacts during launches and in space. 🌐 CAREER LINK

centrifuge a rapidly rotating device used to separate substances and simulate the effects of gravity
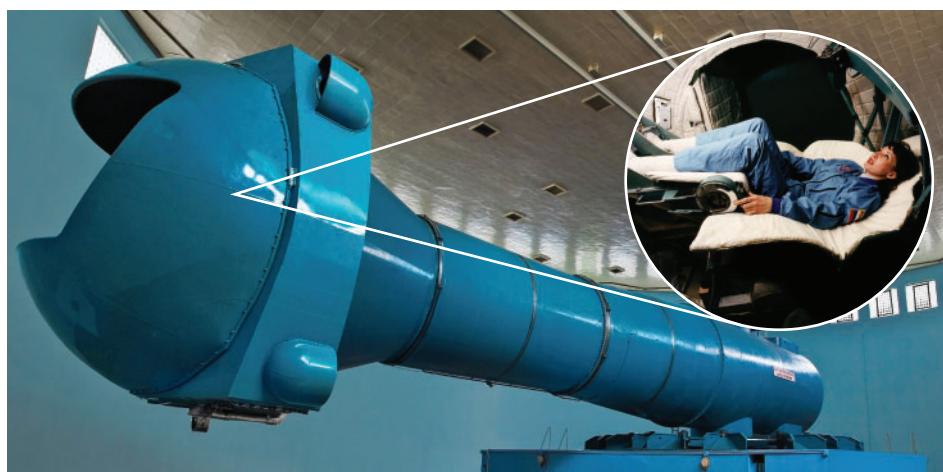

Figure 1 Russian cosmonauts (astronauts) lie in a large centrifuge such as this one as part of their training for space missions.

Centrifugal Force and Rotating Frames of Reference

Before we discuss how circular motion can simulate gravity, we need to look more closely at frames of reference and uniform circular motion. Merry-go-rounds and other rides in which people move in a circle are popular, so we will start with a merry-go-round. When you watch a merry-go-round from your vantage point on the ground, you are observing the motion of the merry-go-round relative to your reference frame on the ground. But the riders sitting on the merry-go-round observe you from a rotating frame of reference.

Now imagine that you are one of the riders sitting on the merry-go-round, leaning against a handrail as it spins. You feel as if the rail is pushing against your body. From Earth's frame of reference (the inertial frame), Newton's first law of motion explains the force that you feel when you tend to maintain your initial velocity in both magnitude and direction. When the merry-go-round turns left, you tend to go straight, but the rail prevents you from going straight. The rail pushes on you toward the centre of the ride and causes you to go in a circular path along with the merry-go-round (**Figure 2** on the next page). The centripetal force acting on your body in this situation is the push from the rail.

centrifugal force the fictitious force in a rotating (accelerating or non-inertial) frame of reference

Consider the same situation from the accelerating frame of reference of the merry-go-round. As it spins, you feel as if you are being pushed to the right toward the outside of the merry-go-round's circle. This force in a rotating frame of reference, acting away from the centre, is a fictitious force called the **centrifugal force** (**Figure 3**).
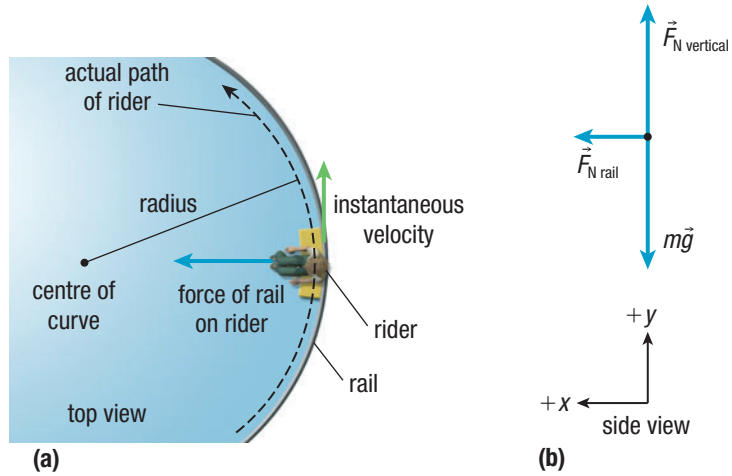

Figure 2 (a) The top view of a rider on a merry-go-round from Earth's frame of reference as the ride turns to the left. (b) The side-view FBD of the rider shows the forces acting on the rider.
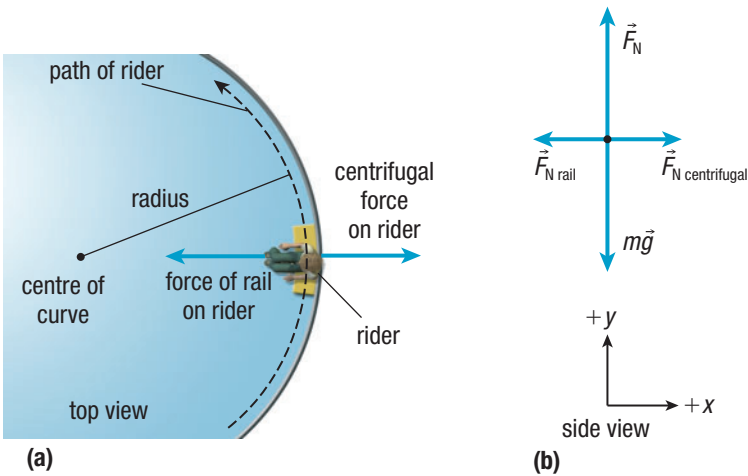

Figure 3 (a) The top view of a rider on a merry-go-round from the merry-go-round's frame of reference as the ride turns to the left. (b) The side-view FBD of the rider shows the (fictitious) centrifugal force in the non-inertial frame of reference.

Centrifugal Force and Centrifuges

Centrifuges are frequently used in medical laboratories to separate blood samples. The centrifuge rotates the test tubes containing blood samples at high speeds. Red blood cells are the densest components of blood. If the red blood cells are near the top of a test tube as the centrifuge starts spinning, centrifugal force will move the cells toward the bottom of the tube. The red blood cells settle on the bottom due to the spinning motion of the centrifuge (**Figure 4**). 🌐 CAREER LINK

Figure 4 A centrifuge rotates at an extremely high rate, producing a large centripetal acceleration for the contents of the test tubes. As a result, the higher-density cells move to the outer end of the tube and separate.

To further clarify how a centrifuge works, consider the single, dense particle in the test tube at A in **Figure 5**. Note that A is near the top of the test tube. To keep the situation as simple as possible, we will disregard the fluid friction acting on this particle. As the centrifuge spins, the particle continues to move at a constant velocity because the net force acting on it is zero. This velocity will carry the particle along in a straight line toward B, near the bottom of the test tube. In the rotating frame of reference of the test tube, the fictitious centrifugal force appears to move the particle toward B. Relative to Earth's frame of reference, the particle moves according to Newton's first law of motion because it is moving in a straight line at a constant velocity while the test tube and the contents accelerate toward the centre of the centrifuge.
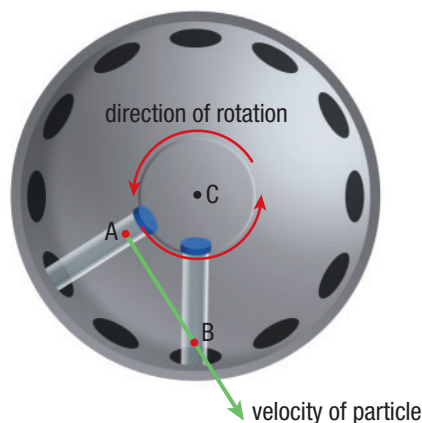

Figure 5 The particle at position A moves according to Newton's first law of motion as the centrifuge spins.

Centrifugal Force and Earth's Surface

Earth's surface is another example of a rotating and, therefore, non-inertial frame of reference. Objects near the surface of Earth are pulled down by gravity toward the centre of Earth by a centripetal force. The rotation of Earth on its axis creates a centrifugal force on objects at Earth's surface, but the effects are very small. If you stand at the equator and drop a rock, the force of gravity pulls the rock straight toward Earth's centre. There is also a centrifugal force directed away from Earth's centre relative to Earth's rotating frame of reference. The net force on the rock you dropped in Earth's rotating frame is less than the force of gravity in a non-rotating frame of reference, as shown in the FBD in **Figure 6**. The rock's acceleration at the equator is about 0.34 % less than the acceleration by gravity alone. At the equator, the magnitude of the centrifugal force is at a maximum. As you move toward the north or the south, the magnitude of the centrifugal force decreases, eventually reaching zero when you reach the poles.
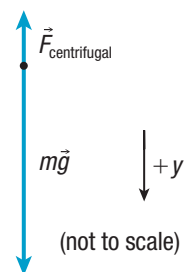
THE CORIOLIS FORCE

When studying the physics of the motion of objects in Earth's rotating frame of reference more closely, we discover another fictitious force. This fictitious force, called the **Coriolis force**, is perpendicular to the velocity of an object in the rotating frame of reference. The Coriolis force, named after the French mathematician Gaspard-Gustave de Coriolis, acts on objects that are in motion relative to the rotating Earth.

The effect of the Coriolis force is not very noticeable on objects moving on Earth's surface. The effect is more noticeable for objects that move for a very long time above Earth's surface. Weather patterns are one example. On the television news, you may see a weather map detailing low-pressure systems that rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. The Coriolis force is responsible for this rotation. ⊕ WEB LINK

Figure 6 A falling rock at the equator experiences a small centrifugal force as well as gravity.

Coriolis force a fictitious force that acts perpendicular to the velocity of an object in a rotating frame of reference

Foucault Pendulum

Skills: Performing, Observing, Analyzing, Communicating

It is difficult to envision Earth as a rotating frame of reference because, standing on its surface, you cannot see Earth move. In 1851, French physicist Jean Foucault designed an experiment to prove that Earth rotates—he strung a weight on a wire over 60 m long above Earth's surface. In this activity, you will work in a group and use a smaller pendulum and a globe to model Foucault's demonstration.

Equipment and Materials: eye protection; globe (or large ball); 50 g mass; wooden splints or straws; string; tape

1. Put on your eye protection. Make a pendulum and attach it to the globe, in a setup similar to that in **Figure 7**.
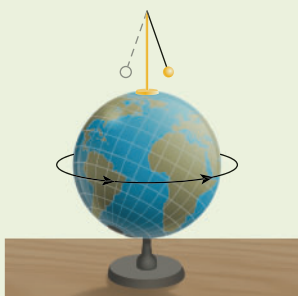
Figure 7

2. Rotate the globe slowly, and observe what happens to the mass. ✋

> ✋ Use caution when spinning the globe to ensure that the pendulum remains securely attached.

3. Rotate the globe more quickly, and observe what happens.

A. How does the rotating globe affect the behaviour of the pendulum mass? T/I

B. How does the period of rotation affect the behaviour of the pendulum mass? What does this imply about the effect of the rotation of Earth on a Foucault pendulum? T/I

C. How would the observed behaviour of a Foucault pendulum at the equator differ from the observed behaviour at your latitude? T/I A

Artificial Gravity

Now that we have had a closer look at frames of reference and uniform circular motion, we are ready to discuss how circular motion can simulate gravity. Have you ever wondered why astronauts and other objects in orbiting spacecraft look as if they are floating? The spacecraft and everything in it are in free fall, and that makes the apparent weight of the spacecraft and all the objects zero.

Over the past several decades, researchers have investigated the effects of extended free fall on the human body. We know that the absence of forces against the human body causes the muscles to become smaller and the bones to lose calcium and become brittle. The heart and blood vessels swell from the buildup of excess body fluids in the upper body. This imbalance of fluids causes the kidneys to release excess urine.

Astronaut-training programs include vigorous exercise programs on space flights to help astronauts reduce these negative effects on their bodies. The problems caused by extended free fall would still be catastrophic if humans travelled in space over the long periods needed to reach Mars and other parts of the solar system. To combat this problem, scientists and engineers are designing interplanetary spacecraft that have **artificial gravity**, which is a situation in which the value of gravity has been changed artificially.

Making a spacecraft rotate constantly can simulate gravity. And, if the spacecraft rotates at the appropriate frequency, the simulated gravity can equal Earth's gravity, making the astronauts' apparent weight equal to their weight on Earth. The following Tutorial illustrates the variables needed to simulate Earth's gravity in space.

artificial gravity a situation in which the value of gravity has been changed artificially to more closely match Earth's gravity

This Tutorial models how to solve problems in which an object moving with uniform circular motion simulates the effects of gravity.

Sample Problem 1: Designing a Space Station

Consider a rotating space station similar to the one in **Figure 8**. The radius of the station is 40.0 m. How many times per minute must the space station rotate to produce a force due to artificial gravity equal to 30.0 % of Earth's gravity?
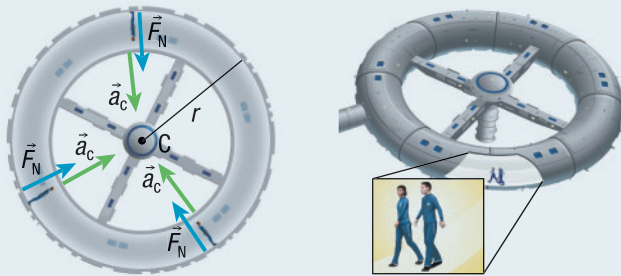

Figure 8

Given: $F_N = 0.30mg$; $r = 40.0$ m; $g = 9.8$ m/s^2

Required: f (revolutions per minute, rpm)

Analysis: The only force acting on the astronauts in Figure 8 is the normal force, and it is directed toward the centre of the station. Therefore, $\Sigma F_c = F_N = \dfrac{mv^2}{r}$. We can use this equation to determine the speed of the space station. Once we have the speed, we can determine the period of rotation, $T = \dfrac{d}{v}$. Then we can use the period, T, to determine the frequency (in revolutions per minute), $f = \dfrac{60\text{ s/min}}{T}$; circumference of a circle $= 2\pi r$.

Solution: $F_N = \dfrac{mv^2}{r}$

$$0.30\,mg = \dfrac{mv^2}{r}$$

$$v = \sqrt{0.30gr}$$

$$= \sqrt{(0.30)(9.8\text{ m/s}^2)(40.0\text{ m})}$$

$$v = 10.8\text{ m/s (one extra digit carried)}$$

$$T = \dfrac{d}{v}$$

$$= \dfrac{2\pi r}{v}$$

$$= \dfrac{2\pi(40.0\text{ m})}{10.8\text{ m/s}}$$

$$T = 23.3\text{ s (one extra digit carried)}$$

$$f = \dfrac{60\text{ s/min}}{T}$$

$$= \dfrac{60\text{ s/min}}{23.3\text{ s}}$$

$$f = 2.6\text{ rpm}$$

Statement: The space station must rotate 2.6 times per minute to produce a force due to artificial gravity equal to 30.0 % of Earth's gravity.

Practice

1. A spacecraft travelling to Mars has an interior diameter of 324 m. The craft rotates around its axis at the rate required to give astronauts along the interior wall an apparent weight equal in magnitude to their weight on Earth. K/U T/I A
   (a) Calculate the speed of the astronauts relative to the centre of the spacecraft. [ans: 39.8 m/s]
   (b) Determine the period of rotation of the spacecraft. [ans: 26 s]

2. Suppose there are two astronauts on the space station in Sample Problem 1. One has a mass of 45 kg, and the other has a mass of 65 kg. Would each astronaut experience artificial gravity equal to about 30.0 % of Earth's gravity? Explain your answer. K/U T/I A

3. Imagine another planet with an acceleration of 10.00 m/s^2 at its equator when ignoring the rotation of the planet. The radius of the planet is 6.2×10^6 m. An object dropped at the equator yields an acceleration of 9.70 m/s^2. Determine the length of one day on this planet. K/U T/I A [ans: 7.9 h]

4. A 56 kg astronaut stands on a bathroom scale inside a rotating circular space station. The radius of the space station is 250 m. The bathroom scale reads 42 kg. At what speed does the space station floor rotate? K/U T/I A [ans: 43 m/s]

5. In theory, if a car went fast enough it could fly off Earth's surface. This is because, at a fast enough speed, Earth's gravity is not strong enough to pull the car in a circle with a radius equal to the radius of Earth. Approximately how fast would a car have to move for this to happen? Refer to Appendix B for Earth's radius. K/U T/I A [ans: 7.9×10^3 m/s]

Summary

- A centrifuge is a device that spins rapidly and is used to separate substances by density, as well as simulate the effects of gravity. A spinning centrifuge applies a centrifugal force to the objects it contains.
- A rotating frame of reference is the frame of reference of any object moving in a circle.
- Centrifugal force is a fictitious force used to explain the outward force observed in a rotating frame of reference.
- Making a spacecraft rotate at the appropriate frequency can simulate gravity equal to Earth's gravity.

Questions

1. When you swing a bucket full of water in a vertical circle at just the right speed, the water stays inside. Explain why. **K/U** **C** **A**

2. Explain how the spin cycle of a washing machine uses circular motion to remove water from clothes. **K/U** **C** **A**

3. You are standing 2.7 m from the centre of a spinning merry-go-round holding one end of a string tied to a 120 g mass. The merry-go-round has a period of 3.9 s. **K/U** **T/I** **C** **A**
   (a) Draw a system diagram of the situation.
   (b) Draw an FBD of the mass in Earth's frame of reference.
   (c) Draw an FBD of the mass in the merry-go-round's rotating frame of reference.
   (d) What angle does the string make with the vertical?
   (e) Determine the magnitude of the tension in the string.

4. Show that the acceleration of an object dropped at the equator is about 0.34 % less than the acceleration due to gravity alone. **K/U** **T/I** **A**

5. In a science fiction movie, a spacecraft has a rotating section to provide artificial gravity for the long voyage. A physicist watches a scene filmed from the interior of the spacecraft and notices that the diameter of the rotating section of the craft is about five times the height of an astronaut walking in that section (or about 10 m). Later, in a scene showing the spacecraft from the exterior, she notices that the living quarters of the ship rotate with a period of about 30 s. Did the movie get the physics right? Compare the centripetal acceleration of a 1.7 m–tall astronaut at his feet to that at his head. Compare these accelerations to g. **T/I** **C** **A**

6. A space station has a radius of 100 m. **K/U** **T/I** **A**
   (a) What period of rotation is needed to provide an artificial gravity of g at the rim?
   (b) At what speed is the rim moving?
   (c) What is your apparent weight if you run along the rim at 4.2 m/s opposite the rotation direction?
   (d) What is your apparent weight if you instead run in the direction of rotation?
   (e) In which direction would you run to get the best workout, with or against the rotation? Or does it matter?

7. An astronaut with a mass of 65 kg is in a rotating space station with a radius of 150 m. She stands on a scale, and the reading is 540 N. **K/U** **T/I** **A**
   (a) At what acceleration do objects fall when dropped near the floor of the space station?
   (b) Calculate the speed of rotation of the outer rim of the space station.
   (c) Calculate the period of rotation of the space station.

8. A centrifuge spins with a frequency of 1.1×10^3 Hz. A particle in a test tube is positioned 3.4 cm from the centre of the centrifuge. **K/U** **T/I** **A**
   (a) Determine the acceleration of the particle at this position from Earth's frame of reference.
   (b) Why do you think centrifuges need such a high frequency?
   (c) Why do you think medical researchers want to separate particles at all?

9. Research large-scale centrifuges. In a format of your choosing, describe how large-scale centrifuges are used in wastewater treatment. **K/U** **T/I** **C** **A**

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