Objectives

• Solve problems involving centripetal acceleration.
• Solve problems involving centripetal force.
• Explain how the apparent existence of an outward force in circular motion can be explained as inertia resisting the centripetal force.

Tangential Speed

• The tangential speed \((v_t)\) of an object in circular motion is the object’s speed along an imaginary line drawn tangent to the circular path.
• Tangential speed depends on the distance from the object to the center of the circular path.
• When the tangential speed is constant, the motion is described as uniform circular motion.
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Centripetal Acceleration

- The acceleration of an object moving in a circular path and at constant speed is due to a change in direction.
- An acceleration of this nature is called a centripetal acceleration.

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Centripetal Acceleration, continued

- You have seen that centripetal acceleration results from a change in direction.
- In circular motion, an acceleration due to a change in speed is called tangential acceleration.
- To understand the difference between centripetal and tangential acceleration, consider a car traveling in a circular track.
  - Because the car is moving in a circle, the car has a centripetal component of acceleration.
  - If the car’s speed changes, the car also has a tangential component of acceleration.

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Centripetal Acceleration, continued

- (a) As the particle moves from A to B, the direction of the particle’s velocity vector changes.
- (b) For short time intervals, \( \Delta v \) is directed toward the center of the circle.
- Centripetal acceleration is always directed toward the center of a circle.

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Centripetal Force

- Consider a ball of mass \( m \) that is being whirled in a horizontal circular path of radius \( r \) with
- **Centripetal force** by the string has horizontal and vertical components. The vertical component is equal and opposite to the gravitational force. Thus, the horizontal component is the net force.
- This net force, which is directed toward the center of the circle, is a centripetal force.
Centripetal Force, continued

Newton's second law can be combined with the equation for centripetal acceleration to derive an equation for centripetal force:

• Centripetal force is simply the name given to the net force on an object in uniform circular motion.

• Any type of force or combination of forces can provide this net force.
  – For example, friction between a race car's tires and a circular track is a centripetal force that keeps the car in a circular path.
  – As another example, gravitational force is a centripetal force that keeps the moon in its orbit.

• If the centripetal force vanishes, the object stops moving in a circular path.
  – If the string breaks at the position shown in (a), the ball will move vertically upward in free fall.
  – If the string breaks at the top of the ball's path, as in (b), the ball will move along a parabolic path.

Describing a Rotating System

• To better understand the motion of a rotating system, consider a car traveling at high speed and approaching an exit ramp that curves to the left.

• As the driver makes the sharp left turn, the passenger slides to the right and hits the door.

• What causes the passenger to move toward the door?
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**Describing a Rotating System, continued**
- As the car enters the ramp and travels along a curved path, the passenger, because of inertia, tends to move along the original straight path.
- If a sufficiently large centripetal force acts on the passenger, the person will move along the same curved path that the car does. The origin of the centripetal force is the force of friction between the passenger and the car seat.
- If this frictional force is not sufficient, the passenger slides across the seat as the car turns underneath.

**So what’s centrifugal force?**
- It’s an imposter!
- The term is used when objects moving in a circular path do not experience the centripetal force.
  - Example: A car making a sharp turn throws its passengers to the outside door. Why?
  
  *Because the passenger wants to go in a straight line!*

**Classifying Acceleration**
- The force that causes the acceleration resulting in circular motion is called the **centripetal force**
- Centripetal means “center seeking”. Named because the acceleration points towards the center of the circle

**Practice Problem**
- A ball is swung in a circular path on a string that is 1.5 m long and completes one revolution every 0.5 seconds.
  - Find the tangential velocity of the ball
  - Find the tension force exerted by the string in the ball
Multiple Choice

1. An object moves in a circle at a constant speed. Which of the following is not true of the object?
   A. Its centripetal acceleration is constant.
   B. Its tangential speed is constant.
   C. Its velocity is constant.
   D. A centripetal force acts on the object.

Multiple Choice, continued

2. What is the centripetal acceleration of the car?
   F. $2.4 \times 10^{-2}$ m/s²
   G. 0.60 m/s²
   H. 9.0 m/s²
   J. zero

Use the passage below to answer questions 2–3.

A car traveling at 15 m/s on a flat surface turns in a circle with a radius of 25 m.

3. What is the most direct cause of the car’s centripetal acceleration?

Gravitational Force

- Orbiting objects are in free fall.
- To see how this idea is true, we can use a thought experiment that Newton developed. Consider a cannon sitting on a high mountaintop.

Each successive cannonball has a greater initial speed, so the horizontal distance that the ball travels increases. If the initial speed is great enough, the curvature of Earth will cause the cannonball to continue falling without ever landing.
Gravitational Force, continued

• The centripetal force that holds the planets in orbit is the same force that pulls an apple toward the ground—gravitational force.

• Gravitational force is the mutual force of attraction between particles of matter.

• Gravitational force depends on the masses and on the distance between them.

Newton’s Law of Universal Gravitation

• Newton developed the following equation to describe quantitatively the magnitude of the gravitational force if distance \( r \) separates masses \( m_1 \) and \( m_2 \):

\[
F = G \frac{m_1 m_2}{r^2}
\]

• The constant \( G \), called the constant of universal gravitation, equals \( 6.673 \times 10^{-11} \) Nm\(^2\)/kg.

Gravitational Force, continued

• The gravitational forces that two masses exert on each other are always equal in magnitude and opposite in direction.

• This is an example of Newton’s third law of motion.

• One example is the Earth-moon system, shown on the next slide.

• As a result of these forces, the moon and Earth each orbit the center of mass of the Earth-moon system. Because Earth has a much greater mass than the moon, this center of mass lies within Earth.
Applying the Law of Gravitation

- Cavendish applied Newton’s law of universal gravitation to find the value of \( G \) and Earth’s mass.

- When two masses, the distance between them, and the gravitational force are known, Newton’s law of universal gravitation can be used to find \( G \).

- Once the value of \( G \) is known, the law can be used again to find Earth’s mass.

Gravitational field vectors represent Earth’s gravitational field at each point.
Applying the Law of Gravitation, continued

- \textbf{weight} = \text{mass} \times \text{gravitational field strength}
- Because it depends on gravitational field strength, \textit{weight} changes with location:

- On the surface of any planet, the value of \( g \), as well as your weight, will depend on the planet’s mass and radius.

Multiple Choice, continued

4. Earth \(( m = 5.97 \times 10^{24} \text{ kg})\) orbits the sun \(( m = 1.99 \times 10^{30} \text{ kg})\) at a mean distance of \( 1.50 \times 10^{11} \text{ m} \). What is the gravitational force of the sun on Earth? \(( G = 6.673 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)\)

A. \( 5.29 \times 10^{32} \text{ N} \)
B. \( 3.52 \times 10^{23} \text{ N} \)
C. \( 5.90 \times 10^{-2} \text{ N} \)
D. \( 1.77 \times 10^{-8} \text{ N} \)

5. Which of the following is a correct interpretation of the expression \( a = g = G \frac{m_1 m_2}{r^2} \)?

A. Gravitational field strength changes with an object’s distance from Earth.
B. Free-fall acceleration changes with an object’s distance from Earth.
C. Free-fall acceleration is independent of the falling object’s mass.
D. All of the above are correct interpretations.