Khan Academy

High School Physics

Unit 3: Gravitation

Overview

In this unit students will explore the gravitational force and the behaviors of falling and orbiting objects.

Lesson 1: Students will apply Newton's law of gravitation to determine the gravitational force between objects and the gravitational acceleration near Earth's surface **using mathematical and computational thinking.**

Lesson 2: Students will **analyze and interpret** the behavior of objects in free fall and explain why all objects near Earth's surface experience the same gravitational acceleration, **using evidence** to support their explanations.

Lesson 3: Students will learn about centripetal force and explore the orbital motion of celestial objects.

Lesson 4: Hands-on science activity (see below).

Hands-on science activity

Why is a Neptune year so long?

Students will **analyze and interpret data** for an object moving along a curved path, **use mathematics and computational thinking** to determine the gravitational force each planet experiences from the Sun, and use **patterns** to explain why planets have different orbital periods.

Click here for links to the activity.

Standards

Performance expectations: **HS-PS2-1 | HS-PS2-4 | HS-ESS1-4**

Disciplinary core ideas: **HS-PS2.A.1 | HS-PS2.B.1 | HS-ESS1.B.1**

Science and engineering practices:

- Using mathematics and computational thinking
- Analyzing and interpreting data
- Engaging in argument from evidence
- Constructing explanations and designing solutions

Crosscutting concepts:

- Cause and effect
- Patterns
- Stability and change

Click here to read the full standards.

Essential questions

- How does gravitational force between two objects depend on the masses of the objects and the distance between them?
- Why do all objects near Earth's surface accelerate at the same rate in a vacuum?
- Why do orbiting objects follow curved paths rather than falling into each other?

Lesson notes

Lesson 1: Newton's law of gravitation

PEs: HS-PS2-4
DCIs: HS-PS2.B.1

Resources

Video	Exercise
1	2

Objectives

- Explain the **direct relationship** between mass and gravitational force, and the **inverse square relationship** between distance and gravitational force, as described by **Newton's law of gravitation**.
- Apply Newton's law of gravitation to calculate the magnitude of gravitational force between two objects.
- Demonstrate that the force of gravity acting on objects near Earth's surface can be expressed as $\vec{F}_g = mg$.

Teaching tips

- Use the PhET simulation "*Gravity Force Lab: Basics*" for a mathematical exploration of Newton's law of gravitation. Guide students to create a graph of $\vec{F}_g$ vs distance using data from the simulation to reinforce the relationships between variables in an inverse square law.
- Refer to Newton's third law when calculating gravitational force using Newton's law of gravitation. Students should understand that an equal magnitude force acts on each object in the interaction, but in opposite directions. Include free body diagrams to model the equal but opposite gravitational forces.
- Emphasize that "*r*" in the equation is the distance between the centers of mass of the two objects. When an object is on a planet's surface, "*r*" is measured from the center of the planet to the object.

Lesson 2: Falling objects

PEs: HS-PS2-1, HS-PS2-4
DCIs: HS-PS2.A.1, HS-PS2.B.1

Resources

Video	Exercise
1	1

Objectives

- Describe the magnitude and direction of velocity, acceleration, and net force acting on objects in **free fall**, including **projectiles** following a parabolic path.
- Explain why objects that fall through an atmosphere are not considered to be in free fall, and provide real world examples as evidence.
- Apply the relationships between **weight**, gravitational force, and normal force to explain why the **apparent weight** of an object can vary in different situations.

Teaching tips

- Define free fall as a state in which gravity is the only force acting on an object. Use free body diagrams to reinforce that free fall is not determined by the direction of motion.
- Emphasize that for an object *near Earth's surface*, its velocity changes continuously during free fall, but its acceleration remains constant.
- Guide students to create free body diagrams to explain why projectiles experience acceleration in the vertical dimension, but not in the horizontal.
- Use the lesson video "*Falling objects*" to enhance student understanding of free-fall acceleration. The video provides a detailed explanation of why the magnitude of acceleration of an object in free fall near Earth's surface is always 9.81 m/s^2, regardless of its mass.
- Discuss the effect of air resistance on falling objects, and provide simple demonstrations that show the effect. For example, wad up a sheet of paper tightly. Compare the mass of the paper with the mass of a tennis ball. Drop the wad of paper and tennis ball simultaneously from the same height. Despite the significant difference in mass, the two objects will reach the floor at about the same time. Unwad the paper and repeat the drop. The tennis ball will reach the ground first.
- Demonstrate how a scale measures weight by placing an object on a digital scale. Raise and lower the scale, noting how the reading

	increases when the scale begins moving up and decreases as it begins moving down, similar to feeling heavier or lighter on an elevator. Explain that the scale reading reflects the normal force, and ask students what the scale would show if dropped with the object on it.

Lesson 3: Orbital motion

PEs: HS-ESS1-4, HS-PS2-4
DCIs:HS-ESS1.B.1, HS-PS2.B.1

Resources

Video 2 | Exercise 3

Objectives	Teaching tips

• Explain why an object traveling along a curved path is accelerating, and identify the force that acts as the **centripetal force** on an object.
• Use Newton's law of gravitation and **Kepler's laws** to explain the behavior of orbiting bodies.
• Relate each of Kepler's laws to the orbital motion of planets in the solar system.
	• Use a brief review activity or exercise to reinforce that acceleration occurs when an object's speed and/or *direction* changes.
	• Examine various scenarios of objects moving along curved paths to show that centripetal force is a role that can be played by different forces.
	  ○ The force of friction acts as the centripetal force to keep plates from sliding off a tray when a server changes directions.
	  ○ During the olympic hammer throwing event, the force of tension acts as the centripetal force to keep the metal ball on a circular path until the athlete releases it.
	  ○ The force of gravity acts as the centripetal force to keep an object in orbit.
	• Use the video for this lesson, "*Orbital motion*," to support students' understanding of Kepler's laws. It provides detailed, concise explanations of each law, along with helpful illustrations. After viewing the video, ask students to summarize each law in simple conceptual statements. The PhET simulation "*Kepler's Laws*" allows for a virtual exploration of the laws.
	• Implement the hands-on activity "*Why is a Neptune year so long?*" after this lesson to allow students to explore the relationships between centripetal force, Kepler's laws, and planetary orbits. (See Lesson 4.)

Lesson 4: Hands-on science activity
Why is a Neptune year so long?

PEs: HS-PS2-4, HS-ESS1-4
DCIs: HS-PS2.B, HS-ESS1.B

Resources

Activity 1

Description	Links
Students will **analyze and interpret data** for an object moving along a curved path, **use mathematics and computational thinking** to determine the gravitational force each planet experiences from the Sun, and identify **patterns** to explain why planets have different orbital periods.	• Full activity overview (**Khan Academy article**) • Student activity guide (**Doc** | **PDF**) • Teacher guide (**Doc** | **PDF**)

Related phenomena

Example phenomenon

Why do the velocity and acceleration of a skydiver change during their fall?

A skydiver falls before opening their parachute.

Background information

Skydiving is a popular activity for thrill-seekers. A skydiver can reach exceptional speeds before opening their parachute and landing safely on the ground. The velocity and acceleration of a skydiver varies greatly throughout their descent depending on the magnitudes of two forces: gravity and air resistance (drag force).

When a skydiver first exits the airplane, they are in true free fall, with gravity being the only force acting on them. However, as they begin moving through the air, they experience drag force as their body interacts with air molecules. The amount of drag force depends on several factors like the skydiver's shape and surface area. Generally, there is a quadratic relationship between the velocity of a falling object and the amount of drag force it experiences. As the skydiver gains speed while falling, the magnitude of the drag force increases significantly.

When the magnitude of the drag force equals the magnitude of gravitational force acting on the skydiver, the net force acting on the skydiver becomes zero, and they stop accelerating. This state of motion is called terminal velocity. On average, skydivers falling belly-first will reach speeds of about 120 mph, but this can be changed by moving the body into different positions. Once the skydiver opens the parachute, the amount of drag force acting on them increases dramatically. It becomes greater in magnitude than the force of gravity, resulting in a net force and acceleration that are directed upward. Because the acceleration and velocity vectors point in different directions, the skydiver's speed decreases. The skydiver continues slowing down until they reach a new terminal velocity that will allow them to land safely.

When a skydiver leaves the airplane, they have a horizontal velocity equal to the plane's velocity. As the skydiver falls, they also experience drag force in the horizontal dimension that acts opposite to their horizontal velocity vector. By the time they reach the ground, they have very little horizontal velocity.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ The direction and magnitude of forces acting on an object determine its acceleration.
- ☐ When gravity is the only force present, all objects near Earth's surface will accelerate uniformly regardless of their mass.
- ☐ Objects falling through the air will reach terminal velocity and no longer accelerate when the force of gravity and drag force are equal in magnitude.

Tips for implementing phenomenon-based learning

- Introduce the phenomenon in Lesson 2 with an exciting video of extreme skydiving, such as the jumps completed by Alan Eustace and Felix Baumgartner.
- Incorporate brief activities that allow students to see the effect of drag force on different objects. For example, compare the fall times of objects with the same shape but different masses by using two stacks of coffee filters with different numbers of filters (two filters vs six filters, for instance). Then, compare the fall times of objects with the same mass but different shapes by using two single coffee filters, one left unchanged and the other tightly wadded into a ball.

- Explain that a skydiver does not continuously gain speed until the moment the parachute is deployed. Because of the drag force, a skydiver will reach a terminal velocity after about five to ten seconds of falling. Guide students to create free body diagrams for several stages of a skydiver's trip, starting from the instant the skydiver leaves the plane (before they begin falling), and including important moments like when the skydiver reaches terminal velocity, and immediately after the parachute is deployed. Here is a sample activity sheet and teacher guide that includes five portions of the fall.
- Prompts to engage student thinking:
    - At which points during the skydiver's fall is the acceleration vector upward, downward, or zero?
    - Why does changing their positioning (for example, from belly-down to head-down and vice-versa) change a skydiver's acceleration and, consequently, their speed?
    - How does the motion of a skydiver compare to that of an object dropped in a vacuum?
    - Why doesn't a skydiver follow a continuous parabolic path all the way to the ground?

Example phenomenon

Why do astronauts aboard the International Space Station (ISS) experience weightlessness even though the ISS remains in orbit due to Earth's gravity?

Image credit: Three NASA astronauts on the ISS pose for a portrait on Veterans Day 2024 by NASA, Public domain.

Background information

The sensation of weightlessness can be tricky for students to understand physically. They may incorrectly assume that since astronauts (and other objects in the ISS) appear weightless, that there is zero gravitational force acting on them. This is NOT true!

Elicit students' initial ideas by inviting them to predict how much gravitational force the ISS astronauts experience in orbit compared to what they would experience on Earth's surface. After exploring Newton's law of gravitation, revisit the question. Students will discover that the ISS and the astronauts aboard experience about 89% of the gravitational force that would be experienced on Earth's surface.

Although they experience gravitational force on the ISS, astronauts are considered to be weightless while in orbit. Stepping on a weight scale would register zero on the ISS! Their weightlessness results from a *continuous state of free fall*. This concept is explored thoroughly in Lesson 2. Weight is generally felt when the normal force applied by a surface opposes the force of gravity. Because the space station is accelerating toward Earth at the same rate as the astronauts, there is no normal force present. Amusement park attractions that drop riders briefly give the same effect. While free falling, the rider no longer feels the normal force applied by the seat, and feels weightless.

Bring the exploration of this phenomenon full circle by tying together the concepts of gravitational force, free fall, and centripetal force to explain orbital motion. Objects undergoing orbital motion experience a centripetal force caused by the force of gravity, and must have a high enough forward speed to avoid crashing into the object they're orbiting. The orbiting object remains in free fall. So, while the astronauts in the ISS experience gravitational force, they do not experience a normal force because they and the station are orbiting the planet in constant free fall.

Exploring this phenomenon helps students develop and master the following understandings:

- ☐ Newton's law of gravitation explains the relationships between gravitational force, mass, and distance.
- ☐ Weight is a measure of the gravitational force acting on an object, which can *appear* to change depending on the relative motion between the object and the surface supporting it via normal force.
- ☐ Free fall is a state in which the only force acting on an object is the force of gravity. Objects in free fall experience weightlessness because there is no normal force pushing up against them.
- ☐ The force of gravity acts as the centripetal force to keep orbiting objects following a curved path.

Tips for implementing phenomenon-based learning

- Introduce this phenomenon in Lesson 1. Identify students' preconceptions about weightlessness, gravity, and orbiting objects. Encourage them to share their thoughts and compare ideas.
- Use the videos of astronauts experiencing weightlessness to engage learners. NASA provides an extensive multimedia library that details life aboard the ISS.
- Have students predict how much gravitational force astronauts experience on the ISS compared to Earth. Return to their predictions, and calculate the gravitational force after introducing Newton's law of gravitation.
- Investigate how astronauts aboard the ISS measure mass without using the same type of scales used on Earth's surface.
- For a deeper exploration of orbiting objects, check out the PhET simulation "*My Solar System*."
- Prompts to engage learners:
    - How much gravitational force do astronauts experience in orbit compared to on Earth's surface?
    - If astronauts still experience gravity in orbit, why doesn't a regular weight scale register their weight on the ISS?
    - How is the motion of the ISS similar to the motion of a dropped object on Earth? How is it different?

Possible misconception: *The acceleration of an object due to gravity depends on its velocity.*

Students may believe that the downward free fall acceleration of magnitude 9.81 m/s^2 only applies to objects moving directly downward toward Earth. This misconception often arises when analyzing objects thrown upward or traveling along a parabolic trajectory, where the direction of motion is not directly toward Earth. Students may believe that because an object is traveling upward it must have an upward acceleration. They may also assume that the acceleration becomes zero when the object reaches the top of its path.

Critical concepts

- The gravitational acceleration of an object near a planet's surface is not affected by the object's velocity.
- When air resistance is negligible, projectiles have no acceleration in the horizontal dimension. The acceleration in the vertical dimension is equal to the gravitational acceleration.
- An object can have an instantaneous velocity of zero while accelerating (i.e., at the peak for an object thrown straight up).

How to address this misconception

Utilize free body diagrams to reinforce that the force of gravity acting on an object near Earth is approximately constant and always directed downward. When air resistance is negligible, the force of gravity is the net force and will always cause a downward acceleration of magnitude 9.81 m/s^2.

If slow-motion video is available, have students conduct a simple activity in which a tennis ball is thrown straight upward in front of a measuring tape and allowed to fall back to its initial position. Define and agree upon a coordinate system—the descriptions below assume a coordinate system in which up is the +y direction.

- Collect time data by placing a stopwatch in the video frame. Record the vertical position of the tennis ball at equal time intervals in a data table.
- First plot the vertical position of the tennis ball vs time from the instant it leaves the thrower's hand until it comes to rest at the top of its path. The graph will be a smooth, positively sloped parabola that becomes less steep, indicating that the ball is slowing down. Recall from Unit 1 that a curved graph on a position vs time plot indicates constant acceleration. Because the ball is slowing down, the acceleration vector must point opposite the velocity vector while the ball is traveling upward.
- Next, continue plotting the vertical position of the ball from the top of its path to its initial position. The graph will be a smooth, negative sloped parabola that becomes more steep, indicating that the ball is speeding up. The acceleration and velocity vectors must point in the same direction while the ball is traveling downward. At the top of the path, the vertical velocity was zero but the downward acceleration remained constant.
- Repeat the activity with an additional measuring tape placed horizontally. Toss the tennis ball in a parabolic path, and capture its flight using slow-motion video.
- Plotting the vertical motion of the ball yields the same parabolic graphs as before. Plotting the horizontal position produces a diagonal line, indicating zero acceleration in the horizontal dimension.
- Videos of this activity that include data for students to record are available on the internet. The PhET simulation "*Projectile Motion*" allows for virtual exploration and data collection.

Possible misconception: *An object doesn't need an unbalanced force to keep it moving along a curved path.*

The force (or forces) acting as the centripetal force on an object following a curved path aren't always immediately apparent. Consider a marble swirling around a bowl, or a vehicle navigating a curve in the road. Students may incorrectly assume that if an object starts moving along a curved or circular path, it will continue along the curve "on its own." The fact that objects can move along a curved path at a constant speed also contributes to the misconception. Students who do not differentiate between constant speed and constant velocity may conclude that a constant speed along a curved path means that the net force acting on the object is zero.

Critical concepts

- Objects move at a constant velocity unless acted upon by a net external force.
- A force directed toward the center of the curve is necessary to keep an object moving along a curved path. This force could be provided by tension, gravity, friction, or a combination of forces.
- A centripetal force causes an object to accelerate by changing the object's velocity (specifically, the *direction* of its velocity). The velocity of an object moving along a circular path at constant speed is always tangent to the circle and perpendicular to the acceleration and net force vectors.

How to address this misconception

Revisiting Newton's first law of motion is helpful to address this misconception. The law states that objects maintain a constant velocity unless acted on by an external unbalanced force. Rather than ask why an object is able to continue along a curved path, consider asking why the object does not continue along a straight path, as would be expected due to its inertia. Apply this to the two examples given. In the case of a marble in a bowl, or any object moving around a banked surface, the normal force provides the centripetal force to keep the marble moving along the curved path. For a vehicle navigating a flat, curved road, the force of friction between the tires and the road supplies the necessary centripetal force. Orbiting objects maintain their curved paths because of the force of gravity.

Some scenarios make it easier to observe the effects of centripetal force. For instance, an object tethered to a string and swung in a circular motion offers a simple and effective demonstration of centripetal force. The tension in the string pulls the object toward the center, keeping it in circular motion.

To check for understanding, ask students to describe and explain what happens when the centripetal force is removed. For example, how would a car traveling around a curve behave if it hits a patch of ice with negligible friction? Or, how would an object tethered to a string behave if the string suddenly broke?

Unit resources

Student resources

- PhET Gravity Force Lab Basics: Use this simulation for a virtual exploration of Newton's law of gravitation.
- PhET Kepler's Laws: Use this simulation to have students observe the effects of Kepler's laws on orbital motion.
- PhET Projectile Motion: Use this virtual activity to investigate the behavior or projectiles.
- PhET My Solar System: Use this simulation to observe the behavior of orbiting objects.
- The International Space Station (NASA): Use NASA's ISS information page for images and videos to supplement your phenomenon-based investigations of the apparent weightlessness of astronauts.
- Falling skydiver student version (**Doc** | **PDF**) | Falling skydiver teacher guide (**Doc** | **PDF**): Use this printable exercise to engage student thinking about the forces affecting a skydiver.
- Article and video note taking template (**Doc** | **PDF**): Use this printable template for structured note taking on the articles and videos in this unit.
- Graph paper template (**Doc** | **PDF**): Use this printable template for manual graphing exercises.
- Venn diagram template (**Doc** | **PDF**): Use this printable template for comparing and contrasting concepts.

Classroom implementation resources

- Weekly Khan Academy quick planning guide (**Doc** | **PDF**): Use this template to easily plan your week.
- Using Khan Academy in the classroom (**Doc** | **PDF**): Learn about teaching strategies and structures to support your students in their learning with Khan Academy.
- Differentiation strategies for the classroom (**Doc** | **PDF**): Read about strategies to support the learning of all students.
- Using phenomena with the NGSS: Learn more about how to incorporate phenomena into NGSS-aligned lessons.
- Hands-on science activities from Khan Academy: Choose from Khan Academy's collection of high-quality, ready-to-use, and free hands-on science activities. Each one is engaging, three-dimensional, phenomenon-based, and simple to implement.

NGSS PE and DCI reference guide

Performance expectations

- **HS-PS2-1:** Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.
- **HS-PS2-4:** Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects.
- **HS-ESS1-4**: Use mathematical or computational representations to predict the motion of orbiting objects

in the solar system.

Disciplinary core ideas

- **HS-PS2.A.1:** Newton's second law accurately predicts changes in the motion of macroscopic objects.
- **HS-PS2.B.1:** Newton's law of universal gravitation and Coulomb's law provide the mathematical models to describe and predict the effects of gravitational and electrostatic forces between distant objects.
- **HS-ESS1.B.1**: Kepler's laws describe common features of the motions of orbiting objects, including their elliptical paths around the sun. Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system.

Science and engineering practices (SEPs)

- **Analyzing and interpreting data:** Students progress to introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data.
- **Using mathematics and computational thinking:** Students progress to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.
- **Constructing explanations and designing solutions:** Students progress to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.
- **Engaging in argument from evidence:** Students progress to using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about the natural and designed world(s). Arguments may also come from current scientific or historical episodes in science.

Crosscutting concepts (CCCs) and their implementation

Crosscutting concept	Unit implementation
Patterns: Observed patterns of forms and events guide organization and classification, and they prompt questions about relationships and the factors that influence them.	Students use Kepler's laws to explain the patterns observed in planetary orbits.
Cause and effect (Mechanism and explanation): Events have causes, sometimes simple, sometimes multifaceted. A major activity of science is investigating and explaining causal relationships and the mechanisms by which they are mediated. Such mechanisms can then be tested across given contexts and used to predict and explain events in new contexts.	Students examine the cause and effect relationship between gravitational force, mass, and distance.
Stability and change: For natural and built systems alike, conditions of stability and determinants of rates of change or evolution of a system	Students examine how a body can remain in a stable orbit while constantly changing its velocity.

are critical elements of study.	