Section 2

Acceleration Due to Gravity: Free Fall on the Moon

What Do You See?

Learning Outcomes

In this section, you will

- **Compare** the acceleration due to gravity on Earth and the Moon through a video analysis.
- **Apply** proportions to compare situations.
- **Apply** scale models for measurement and comparison.

What Do You Think?

The diameter of the Moon is only one fourth the diameter of Earth.

- **Compare and contrast the motion of a ball falling on the Moon with that of a ball falling on Earth.**

Record your response in your *Active Physics* log. Be prepared to discuss your response with your small group and the class.

Investigate

In this *Investigate*, you will first explore how objects fall on Earth under the influence of gravity and air resistance and then on the Moon. After watching a video of a hammer and a feather falling on the Moon, you will make measurements to determine the acceleration of gravity on the Moon.

1. Remember the last time you dropped your pencil on the floor? As student scientists, you will take a more careful look at dropped objects. For each of the following pairs of objects, hold one object in each hand and release both objects at the same instant from the same height:

- a single pencil/two pencils tied together with thread
- a closed book/an open sheet of paper
- a closed book/a tightly crumpled sheet of paper
- a hammer/a feather

a) Record which, if either, object hits the ground first, or if the objects strike the ground at the same instant. Try to explain each case in terms of what you know about *gravity* and air resistance.

2. Observe a video sequence of an astronaut, Commander David Scott, dropping a hammer and a feather while standing on the surface of the Moon. Answer the following questions in your log.

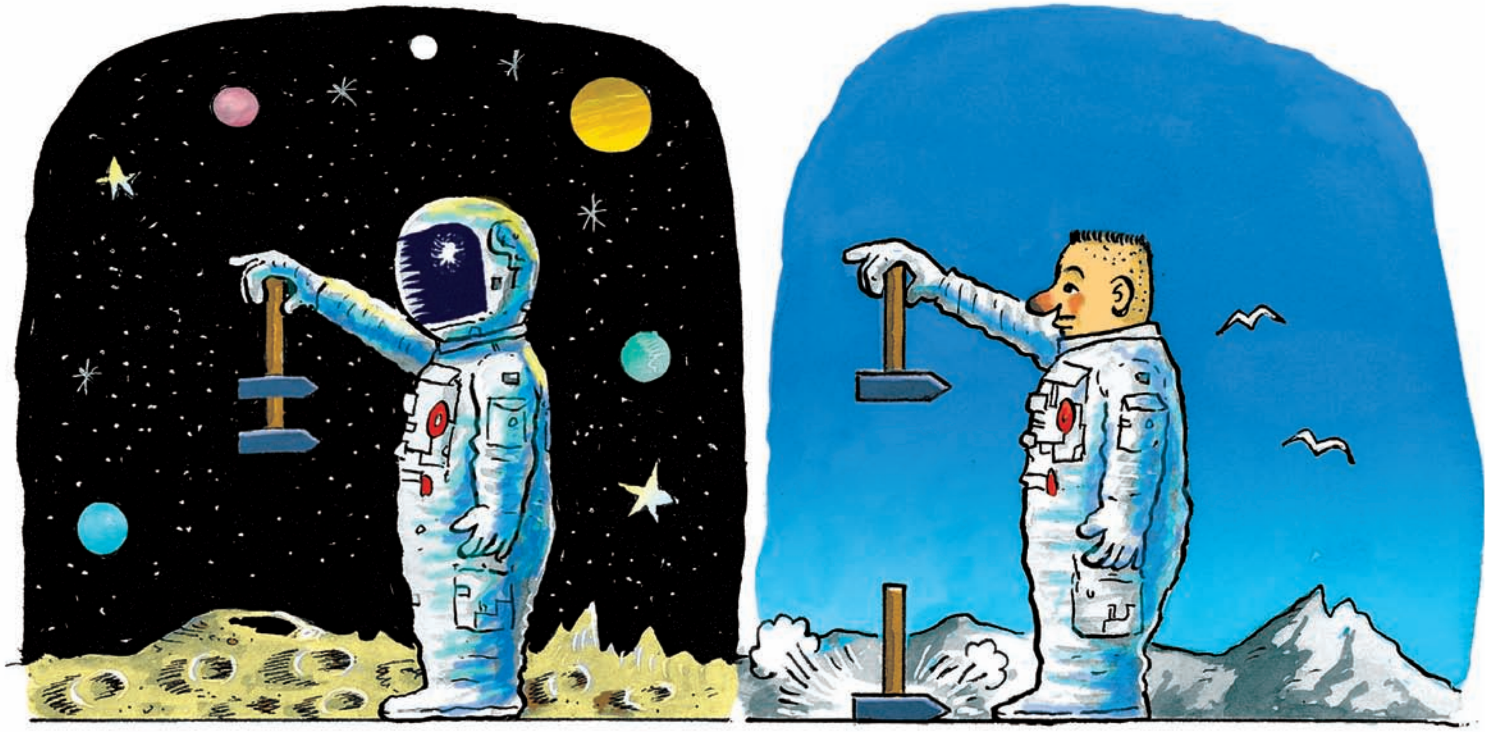
a) Why did the hammer and feather fall in the same way and hit the surface at the same time?

b) Explain why you do or why you do not think the Moon has a gaseous atmosphere similar to Earth's air.

c) Since the time it takes an object to fall is an indicator of the *acceleration* of the object, what would you conclude about the acceleration of a falling hammer on the Moon as compared to Earth? What evidence do you use to support your conclusion?

d) What information would you need to make a careful comparison of the acceleration of the falling hammer on Earth and on the Moon?

3. Examine the two "double exposure" diagrams below. They represent pictures taken with the same camera located the same distance away from the astronaut. On the left the astronaut is dropping a hammer while standing on the Moon. Two images of the hammer are visible. The first image was made at the instant he let go of the hammer. The second image was made 0.50 s after the hammer began to fall. On the right the astronaut is dropping the same hammer on Earth.



Again, one image was made at the instant of release, and another image was made after the hammer had fallen for 0.50 s.

a) The astronaut shown in the diagrams is known to have a real height of 2.1 m (210 cm) without his helmet. By placing a ruler on the diagram and measuring the height of the astronaut, see if you agree that the "scale factor" of the diagram is as follows: 33.3/1.0 = (cm in real life)/(cm in diagram).

b) Accurately measure for each diagram how far the hammer falls in 0.5 s. Use the same point on the two images of the hammer for your measurement. Record each distance, measured to the nearest millimeter, in your log book. (Example: 3.7 cm or 37 mm)

c) Multiply each of the fall distances from *Step 3.b*) by the scale factor of the diagram [(33.3 cm in real life)/(1.0 cm in diagram)] to convert the distance the hammer falls on the diagram to real-world distances on the Moon and Earth. Refer to these distances as d_{Moon} and d_{Earth}.

d) In your *Active Physics* log, substitute the values of the distance, in meters, that the hammer falls on the Moon and on Earth in the equation below to find the ratio of the acceleration on the Moon (g_{Moon}) to the acceleration on Earth (g_{Earth}).

$$\frac{g_{Moon}}{g_{Earth}} = \frac{d_{Moon}}{d_{Earth}}$$

e) Record the answer for g_{Moon}/g_{Earth} in your log.

f) Is your answer about $1/6 = 0.16$?

Do your calculations show that the acceleration due to gravity on the Moon is about 1/6 of the value on Earth? Write about this in your log.

g) The acceleration due to gravity on Earth (g_{Earth}) is 9.8 m/s^2 (meters per second every second). From your results for this investigation, what should be the value of the acceleration due to gravity, in m/s^2, on the Moon (g_{Moon})? Show how you arrived at your answer in your log.

4. If you know the acceleration due to gravity on Earth, you can compute the distance an object falls by using the equation

$$d = \frac{1}{2}gt^2,$$

where d is the distance,
t is the time, and
g_{Earth} is the acceleration due to gravity on Earth ($g_{Earth} = 9.8$ m/s^2).

Similarly, you can calculate the distance an object falls on the Moon by using the same equation but substituting for the acceleration due to gravity on the Moon ($g_{Moon} = 1.6$ m/s^2).

Complete a chart that compares the distance an object falls on Earth and the Moon after 0.5 s, 1 s, 1.5 s, and 2.0 s.

5. The same equation

$$d = \frac{1}{2}gt^2$$

can be used to calculate the time it takes for an object to fall 5.0 m on Earth and the Moon.

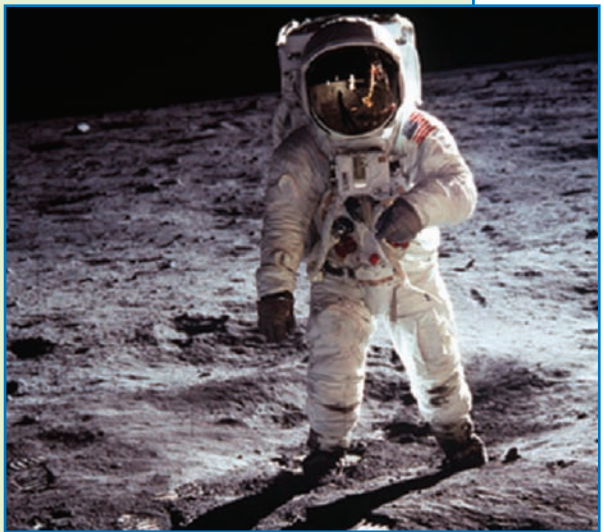
- Method A: Use algebra and derive an equation for time. Solve for the time if the fallen distance is 5.0 m.
- Method B: Use the equation $d = \frac{1}{2}gt^2$ and, with your calculator, input different values of time, *t*, until you get a value close to 5.0 m for the distance. (A value of time to the nearest tenth of a second will be sufficient.)

Physics Talk

GRAVITY AND FREE FALL

When you watched the video of the astronaut dropping the hammer and the feather on the Moon, you were immediately exposed to two of the major differences between Earth and the Moon. The Moon's weaker gravity caused the hammer to fall much more slowly than it would on Earth. In addition, the feather, which normally would lag far behind the hammer on Earth due to air resistance, falls at the same rate as the hammer. These two factors by themselves may cause you to rethink many aspects of a sport you may be considering proposing to NASA.

You found that the acceleration due to gravity on the Moon is $\frac{1}{6}$ the acceleration due to gravity on Earth. A diver will take much more time to get to the water than she would on Earth. In developing a sport for the Moon, you will have to always take into account how slowly objects accelerate on the Moon after being dropped.



All sports on Earth are affected by air resistance. It is air resistance that makes a curve ball curve. A wind can affect a runner's speed. On the Moon, you will have to make a decision about whether you want your sporting event to be outside or inside. Outside, there is no air and no air resistance. Athletes will have to wear spacesuits, which include air to breathe, if your sport is outside. Inside a stadium, you will have air and will have to be concerned with air resistance.

You may have been surprised that you were able to use the same equation for the distance covered by a falling object on the Moon,

$$d = \frac{1}{2}gt^2,$$

that is used to describe the motion on Earth. Falling objects on the Moon **accelerate** or increase speed the same way objects on Earth do, but at a different rate.

It was the work of Galileo and others, including Sir Isaac Newton, who showed that the rules of physics, which describe motion on Earth, apply to the Moon as well. It is a fundamental belief of scientists that the rules of physics are the same everywhere in the universe. Astronomers and other scientists are constantly testing the laws of physics to see if they need to be modified in any way to describe what they observe. If any changes are made to the laws of physics, they will also have to apply to how things behave on Earth and the Moon.

Physics Words

accelerate: to change the velocity per unit time.

Physics Words

gravity: the force of attraction between two bodies due to their masses.

Checking Up

1. How does the acceleration due to gravity compare on Earth and on the Moon?
2. What determines the force of gravity of a planet?
3. Why would the weight of an astronaut be different on different planets?

The rate at which all objects fall will vary from planet to planet, but their falling motion will always be described by the same equation. For example, on Mars, where **gravity** is approximately 40 percent as strong as that on Earth, the acceleration due to gravity is 4 m/s^2, so an object would fall 4 m for every 9.8 m an object falls on Earth. On Jupiter, where the acceleration due to gravity is approximately 26 m/s^2, in the time it takes an object to fall 26 m, an object on Earth would only fall 9.8 m. This ignores air resistance for both planets. The acceleration of gravity is directly related to the size and mass of the planet, which determines the gravitational force a planet is able to exert on a falling mass. This same force of gravity also determines the weight of the astronaut. Knowing a planet's mass and radius allows scientists to calculate the acceleration of gravity before an astronaut ever visits the planet. If NASA did not know what the acceleration of gravity for the planet was, landing on the planet could be dangerous to the spacecraft and astronauts.

Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
◆◆			

Deriving a Useful Equation

Using the definitions of acceleration and velocity, you can derive an equation that relates the fallen distance to the elapsed time.

The distance an object falls can be found from the definition of velocity.

$$\text{Average velocity} = \frac{\text{change in distance}}{\text{change in time}}$$

$$v_{av} = \frac{\Delta d}{\Delta t}$$

Therefore: $d = v_{av}\, t$

For a constant acceleration, the average velocity can be found by calculating the average of the initial and final velocity.

$$v_{av} = \frac{v_f + v_i}{2}$$

Combining these two equations yields:

$$d = \left(\frac{v_f + v_i}{2}\right)t$$

If the object starts from rest, $v_i = 0$ and the equation simplifies:

$$d = \frac{v_f}{2}t$$

Acceleration, by definition, is equal to the change in velocity/change in time.

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t}$$

If the object starts from rest, then

$$a = \frac{v_f}{\Delta t}$$

This can be rewritten as $v_f = at$.

Returning to the distance equation, $d = \frac{v_f}{2} t$, you now find that:

$$d = \left(\frac{at}{2}\right)t$$

$$d = \frac{1}{2}at^2$$

The equation

$$d = \frac{1}{2}at^2$$

was developed by combining equations already known. Physicists call this process "deriving" an equation. This new equation is very useful because it allows calculation of the distance an object falls when only the object's acceleration and time of fall are known if the initial velocity is zero. In addition, the equation works for falling objects on either Earth or the Moon. The symbol g is used for acceleration (a) due to gravity.

- Fall distance during time of fall t on the Moon is
$$d_{\text{Moon}} = \frac{1}{2}g_{\text{Moon}}t^2$$
- Fall distance during time of fall t on Earth is
$$d_{\text{Earth}} = \frac{1}{2}g_{\text{Earth}}t^2$$

Dividing the above equation for d_{Moon} by the above equation for d_{Earth}, with the condition that the times of fall t for objects on the Moon and Earth are equal yields:

$$\frac{d_{\text{Moon}}}{d_{\text{Earth}}} = \frac{\frac{1}{2}g_{\text{Moon}}t^2}{\frac{1}{2}g_{\text{Earth}}t^2}$$

$$\frac{d_{\text{Moon}}}{d_{\text{Earth}}} = \frac{g_{\text{Moon}}}{g_{\text{Earth}}}$$

The previous equation was simplified by canceling the equal "½" and "t^2" terms that appear in both the numerator and the denominator.

The equation

$$\frac{d_{\text{Moon}}}{d_{\text{Earth}}} = \frac{g_{\text{Moon}}}{g_{\text{Earth}}}$$

provides the answer, "Yes, the distances that objects fall from rest during equal time intervals on Earth and the Moon compare in the same way as the accelerations due to gravity on Earth and the Moon." Therefore, it is valid to compare the acceleration due to gravity on the Moon and on Earth by comparing the distances that the dropped hammer falls during equal time intervals on the Moon and Earth.

By comparing distances, you find that the ratio was 1:6. The acceleration due to gravity on the Moon is ⅙ the acceleration due to gravity on Earth.

What Do You Think Now?

At the beginning of this section you were asked the following:

- **Compare and contrast the motion of a ball falling on the Moon with that of a ball falling on Earth.**

Based on what you have learned in this section, how would you respond now?

Physics Essential Questions

What does it mean?

The acceleration due to gravity on the Moon is $\frac{1}{6}$ the acceleration due to gravity on Earth. What does this tell you about how things fall on the Moon compared to how things fall on Earth?

How do you know?

What observations or measurements did you make that allowed you to conclude that things fall differently on the Moon than they do on Earth?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	* Symmetry — laws of physics are the same everywhere	Good, clear explanation, no more complex than necessary

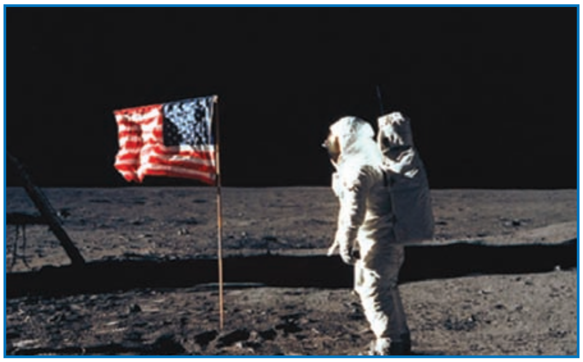
* One of the grand insights of Galileo and Newton was that the laws of physics on Earth are identical to the laws of physics on the Moon. If falling objects on Earth and Moon both use the equation $d = \frac{1}{2}gt^2$, explain why objects fall so much slower on the Moon.

Why should you care?

What aspects of sports depend on how things fall while the sport is being played?

Reflecting on the Section and the Challenge

Objects take much longer to fall on the Moon than on Earth. A ball kicked straight up that requires only 2 s to return to the ground on Earth would take 12 s to return to the Moon (assuming it is kicked with the same initial velocity in each case). This is due to the acceleration due to the Moon's gravity being only $\frac{1}{6}$ the acceleration due to the gravity on Earth. It is also due to the fact that the ball leaves the ground and returns to the ground along a straight vertical line.



Time and distance can be computed using $d = \frac{1}{2}gt^2$. It is important to understand that some properties of motion on Earth and the Moon do not have a ratio of 1:6. The rate of falling is an example. It takes an object on Earth 2 s to fall 20 m. On the Moon, an object takes 5 s to fall 20 m. The time is still longer on the Moon, but not six times longer. For falling objects, the Moon's time to fall is $\sqrt{6}$ or 2.45 times longer than that on Earth.

Now that you are equipped with a specific value for the acceleration due to gravity on the Moon, it is possible to make calculations to show exactly how anything in a sport that involves free fall would be affected if the sport were played on the Moon. This would include not only simple "up" and "down" cases of free fall—such as vertical jumps—but also all cases of projectile motion—such as the shot put or golf—in sports on the Moon. You will study these in a later section.

When developing a sport for the Moon, you will have to take time into account. How long an object is in the air is important since a sport can get boring if most of the time is spent waiting for a ball to drop or to return to the surface.

Physics to Go

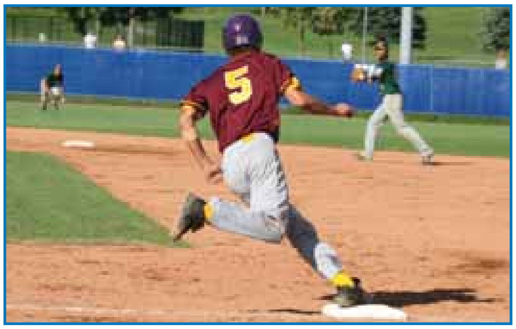
1. Calculate the distance that an object falls after one second on the Moon and on Earth.
2. Calculate the distance that an object falls after three seconds on the Moon and on Earth.
3. Compare the sport of platform diving on Earth and on the Moon if both places use a 10-m high concrete platform.
4. Show that the equation $d = \frac{1}{2}gt^2$ can be rewritten as

$$g = \frac{2d}{t^2}$$

5. When exploring a planet, it was found that a rock dropped from 2.0 m above the planet's surface took 0.50 s to fall to the surface. What is the acceleration due to gravity on that planet? (Hint: Find the acceleration from the equation $d = \frac{1}{2}gt^2$.)
6. Show that the equation $d = \frac{1}{2}gt^2$ can be rewritten as

$$t = \sqrt{\frac{2d}{g}}$$

7. If a rock drops from 2.0 m above the surface of the Moon, how much time does it take to fall to the surface? (Hint: Find the time from the equation $d = \frac{1}{2}gt^2$.)



8. A baseball player on the Moon hits a fly ball straight up at an initial speed of 30 m/s.

   a) How much time does it take the ball to reach the highest point in its flight?

   b) How much time does the fielder have to prepare to catch the ball when it comes back down?

   c) What is the maximum height of the ball in its flight? Compare your answer to the length of a football field: 100 yards between goal lines equals about 91 m.

9. A group of physics students plans to adapt the soapbox derby to the Moon. The contestants' cars will start from rest and coast down a 160-m mountainside on the Moon. The mountain has a straight slope. The slope is great enough that a derby car that has low friction will accelerate at about ½ of the acceleration due to gravity on the Moon. Before each car's run, the race sponsors will place a high-tech instrument package on the car that will allow the driver to read the elapsed time, acceleration, speed, and distance traveled throughout the run. Copy and complete the table below to show the highest possible readings that the accelerometer, speedometer, and odometer could show at the end of each 2 s during an ideal, friction-free run. Be sure to fill in each empty cell in the table. You may want to use a spreadsheet.

Clock (s)	Accelerometer reading (m/s^2)	Speedometer reading (m/s)	Odometer reading (m)
0	0.8	0	0
2.0	0.8	1.6	
4.0	0.8		
6.0			
8.0			
10			
12			
14			
16			
18			
20			

10. How does the difference in time for the flight of a ball affect the game of basketball if played on the Moon with no modifications?

11. How does the difference in time for the flight of a gymnast in the air affect Earth gymnastics if done on the Moon with no modifications?

12. How does the difference in time for the flight of a projectile affect the throw of a javelin on the Moon?

13. Pretend that you are a sports commentator. Describe a home run in a baseball game on Earth. Take into account the time it takes for a ball to reach the seats. Now describe a home run in a baseball game on the Moon.

14. ***Preparing for the Chapter Challenge***

    The rate that objects fall on the Moon determines how long an object spends in the air. For the sport you propose to NASA, this may or may not be a factor in adapting the sport to be played on the Moon. Choose one sport where this increased time would make a difference in how the sport is played, and one sport where it would not make a difference, and explain why it would or would not affect the sport.

Inquiring Further

Landing probes on the Moon

When the Apollo 11 crew first landed on the Moon in 1969, they rode down to the surface in a Lunar Excursion Module (LEM), which had a rocket engine. When the astronauts decided on the exact spot to land, the engine was shut off and the rocket "dropped" a short distance to the surface. Prior to the first manned landing, many unmanned probes were launched and made a "hard" landing (a crash) on the planet's surface. These impact speeds are usually the same as the "escape velocity" for the body.

Look up some of the early unmanned probes sent to the Moon by various countries and record their impact speeds on the planet. Report on how they compare to the Moon's escape velocity, and how the probes were able to reduce their speeds.