SECTION 2

Acceleration Due to Gravity: Free Fall on the Moon

Section Overview

Students investigate how gravity and air resistance affect the way objects fall on Earth and compare their observations to how objects fall on the Moon. They drop objects of different masses from the same height and record whether these objects fall to the ground at the same time or one object takes longer than the other to fall. For a comparison of how gravity affects falling things on the Moon and Earth, students observe a video sequence of an astronaut dropping a hammer and a feather at the same time while standing on the surface of the Moon. They calculate the distance it takes a hammer to fall on the Moon and on Earth by using scale measurements. Students find the ratio of the hammer's acceleration on the Moon to its acceleration on Earth by determining the ratio of the distance the hammer falls on the Moon to the distance it falls on Earth. Once they find that the gravity on the Moon is 1/6 of the gravity on Earth, they use it to calculate the distance an object would fall in a given time, or the time it would take for an object to fall a given distance on the Moon, using the equation $d = \frac{1}{2}at^2$. Subsequently, students also learn that the force of gravity on a planet depends on the size and mass of a planet.

Background information

The difference in the acceleration due to gravity on Earth and the acceleration due to gravity on the Moon is based on a comparison of distances that an identical object falls from a position of rest during equal time intervals on Earth and the Moon.

The equation $d = \frac{1}{2}at^2$ derived in the student text is a special case that applies only to situations where the initial speed of an object is zero when it begins to undergo uniform acceleration. The general case which applies to situations where the initial speed of an object is not zero, resulting in the equation $d = v_i t + \frac{1}{2}at^2$ is derived below only for your information.

Acceleration is defined as $a = \frac{\Delta v}{\Delta t} = \frac{(v_f - v_i)}{t}$,

where a is the uniform acceleration, v_i is the object's (nonzero) initial speed, v_f is the object's final speed, and t is the amount of time elapsed since the object began accelerating.

Solving for v_f,

$v_f = at + v_i$

The object's average speed during the period of uniform acceleration is

$$v_{average} = \frac{(v_f + v_i)}{2}.$$

The distance traveled during the period of acceleration is

$$d = v_{average}t = \frac{v_f + v_i}{2}t = \frac{(at + v_i) + v_i}{2}t = \frac{2v_i t + at^2}{2}$$

$$d = v_i t + \frac{1}{2}at^2$$

This equation applies to cases where an object is already moving when acceleration begins, such as an automobile already traveling down the highway accelerating to pass another automobile. The equation also serves to calculate how far an object thrown straight up with an initial speed will be from its starting point at any time, t. In such a case, it is necessary to assign a negative value to the acceleration due to gravity if distances upward from the starting point are assigned positive values. The special case of $v_i = 0$, or starting from rest applies to the student investigation in which the equation reduces to $d = \frac{1}{2}at^2$.

The acceleration due to gravity on the Moon is, for practical purposes with your students, 1/6 of the acceleration due to gravity on Earth. You have a choice here. If you have been using 10 m/s^2 as the "rounded-off" value of g on Earth, then $10/6\ m/s^2 = 1.7\ m/s^2$ would be the value of g on the Moon rounded to two significant figures. If you choose at this point to "shift" to using the more refined widely used value of g, 9.8 m/s^2 to two significant figures, the value on the Moon would be $9.8/6\ m/s^2 = 1.6\ m/s^2$.

Crucial Physics

- Objects in free fall accelerate at the local value for the acceleration due to gravity (g).
- The distance covered by an object in free fall that starts from rest is given by the equation $d = \frac{1}{2} gt^2$.
- The distance covered by an object in free fall is directly proportional to the acceleration due to gravity.
- On the Moon, due to the lack of an atmosphere and air resistance, all objects fall at the same rate.

Learning Outcomes	Location in the Section	Evidence of Understanding
Compare the accelerations due to gravity on Earth and the Moon through a video analysis.	***Investigate*** Step 2	Students watch a video of how a hammer and a feather fall on the surface of the Moon and compare the acceleration of the falling hammer on Earth and the Moon.
Apply proportions to compare situations.	***Investigate*** Step 4	Students find the ratio of the distance a hammer falls on the Moon to the distance it falls on Earth to find the ratio of the acceleration due to gravity on Earth to that of the Moon.
Apply scale models for measurement and comparison.	***Investigate*** Step 3	Students examine double exposure diagrams to measure the distance the hammer falls in 0.5 s on the Moon and Earth and apply the "scale factor" to determine the real-world distances that show how far the hammer falls. Students then compare the acceleration due to gravity on Earth and the Moon.

Section 2 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Multimedia DVD/CD Set		1 per class
Hammer, small		4 per class
Ruler, metric, in./cm	1 per group	
Feather, large		4 per class
Book*	4 per group	
Piece of paper*	4 per group	
Pencil*	8 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and a half class periods or 80 minutes for students to complete the *Investigate* portion of the section.

Teacher Preparation

- Make a transparency of the side-by-side drawings of the astronaut dropping a hammer on the Moon and on Earth from the color overhead provided on the *Teacher Resources* CD.
- Obtain feathers and hammers (or similar high-density substitutes for a hammer) to compare as they are dropped; the feather/hammer pair could be done as a demonstration for the class if a supply of feathers for each group is not available. However, feathers are readily available at craft and hobby stores.
- Have a foam-rubber pad or other soft material for the hammer to land on to prevent floor damage.
- Reserve a VCR and TV monitor for showing the sequence of the astronaut dropping a hammer and feather on the Moon from the *Active Physics* video, or search the Internet for a Web site that shows a clip of the hammer and feather drop on the Moon.

Safety Requirements

- Students should wear safety goggles.
- Caution the students when dropping heavy objects to keep their feet clear of the landing area and to ensure no one else is near the landing area or in a radius where a bounce may occur.
- Students should pick up the hammer and landing pad immediately after completing the hammer drop portion of the *Investigate*.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Multimedia DVD/CD Set		1 per class
Hammer, small		4 per class
Ruler, metric, in./cm		1 per class
Feather, large		4 per class
Book*	4 per group	
Piece of paper*	4 per group	
Pencil*	8 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and a half class periods or 80 minutes to complete the *Investigate* portion of the section as a whole-class demonstration, discuss the *Physics Talk*, plus all associated material in the *Pacing Guide*.

Teacher Preparation

- Make a transparency of the side-by-side drawings of the astronaut dropping a hammer on the Moon and on Earth from the color overhead provided on the *Teacher Resources* CD.
- Obtain feathers and hammers (or similar high-density substitutes for a hammer) to compare as they are dropped. Feathers are readily available at craft and hobby stores.
- Have a foam-rubber pad or other soft material for the hammer to land on to prevent floor damage.
- Reserve a VCR and TV monitor for showing the sequence of the astronaut dropping a hammer and feather on the Moon from the *Active Physics* video, or search the Internet for a Web site that shows a clip of the hammer and feather drop on the Moon.

Safety Requirements

- Wear safety goggles.
- When dropping heavy objects, keep all feet clear of the landing area and ensure no one else is near the landing area or in a radius where a bounce may occur.
- Pick up the hammer and landing pad immediately after completing the hammer drop demonstration.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Using a "scale factor"	***Investigate*** Steps 3.a) and 3.c)	**Augmentation** • Understanding a "scale factor" is very difficult for students who struggle with mathematical concepts including measuring and estimating, as well as calculations that require the use of ratios. Provide direct instruction to explain the concept of "scale factors" to students. They may have seen a map scale in another class, and this previous experience could be used to support the instruction. • Another idea is to allow students to explain the concept of "scale factors" to each other until they reach an agreement about what the concept means. Then before moving on, they must explain their understanding to you or another pair of students. • Model how to use the "scale factor" to compare values in a diagram or map to real-life values, especially since many students struggle with calculations involving fractions or conversion factors. **Accommodation** • For students with more severe limitations with mathematical concepts, complete *Investigate*, *Step 3* as a larger group. Allow students to use their academic strengths to add to the group discussion. Some students can explain their thoughts using numbers, others prefer to use words, and some can best explain what is happening by using the diagram.
Measuring to the nearest millimeter	***Investigate*** Step 3.b)	**Augmentation** • Students have not done much measuring in the past few chapters and may need a refresher to use a ruler to measure to the nearest millimeter. If most of the class needs a review, model how to measure to the nearest millimeter with an overhead projector or a larger scale model on the board. • If only a few students need help, check in with those individual students to review how to measure accurately with a ruler. • Ask students if they remember how to convert from millimeters to centimeters to make sure the rest of the *Investigate* can be completed accurately.
Deriving an equation	***Investigate*** Step 5 ***Active Physics Plus*** ***Physics to Go*** Questions 4–7	**Augmentation** • Deriving equations is difficult for students because they are doing math with letters (variables) that often hold very little meaning for the students. Completing the derivations will be much easier for some students if you help them substitute in values for all variables except for the unknown. For example, $d = \frac{1}{2}at^2$, solved for a, could become $2 = \frac{1}{2}a(3)^2$. Then ask students to solve that equation for a in a two-column format in which the mathematical steps are shown in the left-hand column, and the corresponding explanation is written in the right column. (Note: Students may need to see a model of this format the first few times it is used.) The next step is to model for students how their written explanation can be applied to derive the formula with the variables substituted back in for the values. This activity will take some time but should help students have a better understanding of derivations, especially if they are still struggling with basic algebraic concepts. • Review the order of operations to help students perform calculations with their derived formulas. **Accommodation** • As a group, derive all variations of the formula that students can then pick from to solve problems for different unknown variables.

Strategies for Students with Limited English-Language Proficiency

<table>
<tr><th>Learning Issue</th><th>Reference</th><th>Augmentation</th></tr>
<tr><td>Higher-order thinking</td><td>Investigate
Step 2.b)</td><td>Look in students’ Active Physics logs to read their responses to this item. Make sure students recognize that the Moon does not have an atmosphere. If you find that students are not recognizing this critical point, hold a class discussion, allowing students to ask each other questions as they revisit the experiments and the video.</td></tr>
<tr><td>Comprehension</td><td>Investigate
Step 2.d)</td><td>Help students focus by asking if they could compare the accelerations of the hammer on the Moon and on Earth using only video footage. At this stage in the course, ELL students should be comfortable participating in a discussion of the variables that affect acceleration because the necessary vocabulary has been used in several chapters.</td></tr>
<tr><td>Comprehension</td><td>Reflecting on the Section and the Challenge

Physics to Go
Question 6</td><td>Collaborate with students’ math teachers to determine what level of comprehension students have obtained for working with square roots.</td></tr>
<tr><td>Understanding concepts</td><td>Physics Talk

What Do You Think Now?</td><td>Students may find a chart similar to the one below helpful for organizing their thoughts about the three sets of conditions discussed in this section (conditions on Earth, conditions outside on the Moon, and conditions on the Moon inside a stadium containing air).

<table>
<tr><th></th><th>Earth</th><th>Moon (outside)</th><th>Moon (inside stadium with air)</th></tr>
<tr><td>Gravity</td><td></td><td></td><td></td></tr>
<tr><td>Air resistance</td><td></td><td></td><td></td></tr>
<tr><td>Hammer vs. feather</td><td></td><td></td><td></td></tr>
<tr><td>Ball</td><td></td><td></td><td></td></tr>
</table>

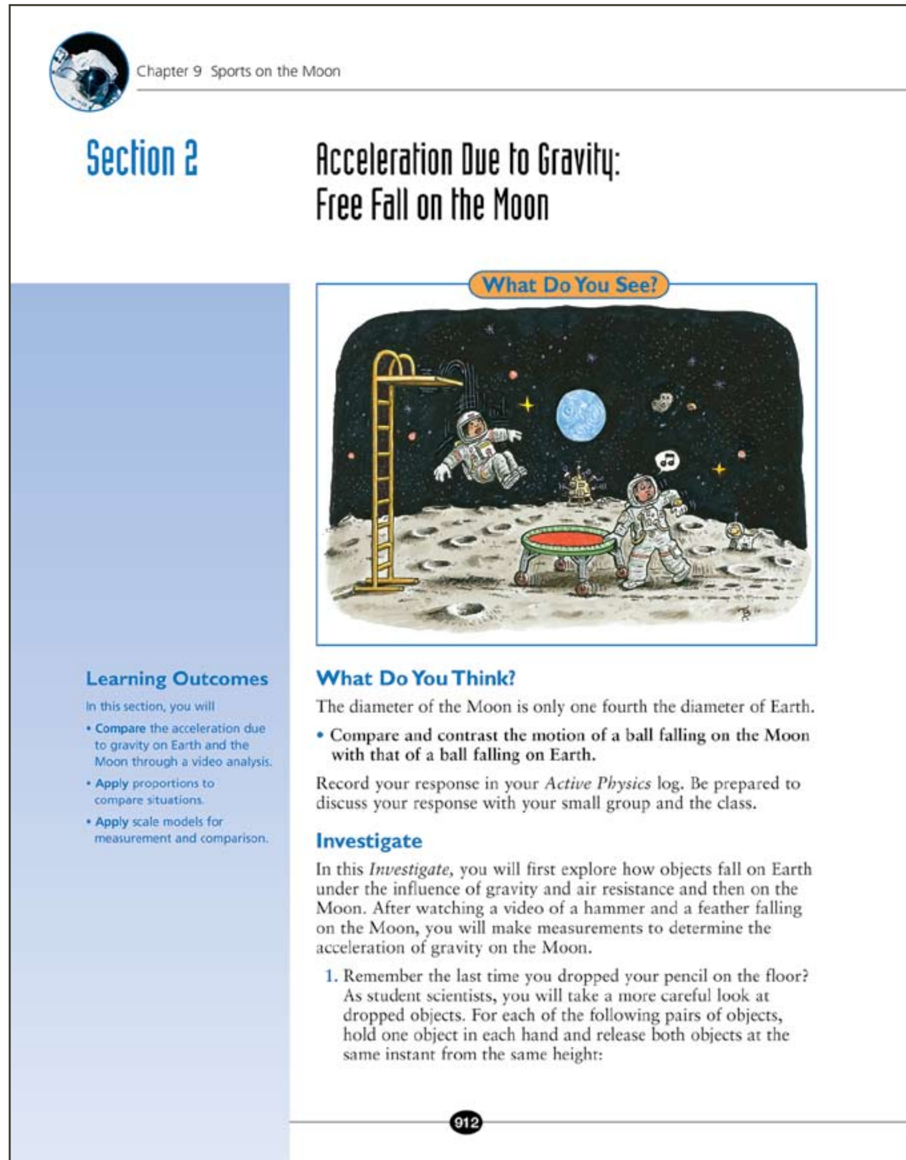
ELL students also benefit greatly from writing practice. Have them write a brief explanation of each set of conditions, with mention of gravity and air resistance. Make sure they compare and contrast how a hammer and a feather would fall under each set of conditions. Finally, ask pairs of students to exchange papers and comment on each other’s sentences and descriptions.</td></tr>
<tr><td>Vocabulary comprehension</td><td>Physics to Go
Question 9</td><td>Some students may not be familiar with the soapbox derby. A simple Internet search will reveal numerous images of cars and race scenes to clarify the event for them. You may need to briefly discuss the term “sponsor,” as well as “coast” used as a verb. Make sure students also understand “accelerometer,” “speedometer,” and “odometer.”</td></tr>
<tr><td>Understanding concepts</td><td>Physics to Go
Question 13</td><td>To facilitate communication skills, appoint an ELL student to the role of sports commentator on Earth and another to the role of sports commentator on the Moon. Have the students take turns giving their respective “broadcasts” of the home run to the class.</td></tr>
<tr><td>Understanding concepts</td><td>Inquiring Further</td><td>Before students take on this assignment, have them look up the meanings of “impact speed” and “escape velocity.”</td></tr>
</table>

SECTION 2

Teaching Suggestions and Sample Answers

What Do You See?

Students will try to figure out what is happening in the illustration and you could easily use this opportunity to ask questions that will initiate a logical mode of thinking. You might want to ask, what are the astronauts doing? Why is one astronaut slowly moving the trampoline under the falling astronaut? What is he whistling about? Does the title of this section give any clues? Encourage students to query and respond to give free rein to their thinking about *What Do You See*? Consider pointing out that students will have other opportunities to review their initial ideas and see how their perceptions of a visual will grow with fresh insights into the laws of physics.



Chapter 9 Sports on the Moon

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:

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Students' Prior Conceptions

The mathematics and modeling of data involved in learning a comparison of how free fall occurs on the Moon with respect to how it occurs on Earth may lead students to the following prior conceptions that deal with proportion and statistical reasoning.

1. **Problems using ratios are easier than problems using non-ratios.** It is vital for you to guide students to see the patterns that exist when they compare motion equations for finding the acceleration due to gravity on the Moon to those on Earth. Students might want to make the ratios more complex than they are.
2. **Statistical reasoning misconceptions relate to the probability of independent and dependent events and the how they determine an event.** Guide students to recognize that Newton's laws and the force of gravity work in the same manner on the Moon as on Earth; the primary difference emerges due to the mass and the diameter of the Moon as compared to the mass and the diameter of Earth.
3. **Students show a tendency to infer cause from correlation.** Listen critically to explanations on how students apply proportions and compare situations as they design their scale models for comparative measurements. Point out to the students that just because there is a correlation between two quantities, they are not necessarily due to cause and effect. For example, although taller people generally weigh more than smaller people, losing weight does not mean you become shorter.

What Do You Think?

The introductory sentence in this section indicates a link between the question that follows and the different sizes. You might want to highlight the sentence in a brief discussion. As students begin with a comparison of how a ball falls on Earth and how it would fall on the Moon, ask them to make a list of all answers that they might come up with. Consider providing prompts to students that link the question to probable answers.

Remind them that at this point their main concern should be arriving at answers that relate to the context of the question. Encourage them to make connections between the title and the images that are intended to send clear signals about the physics concepts that students will be investigating. Ask students to enter their responses in their *Active Physics* logs and share them with their group members.

What Do You Think?

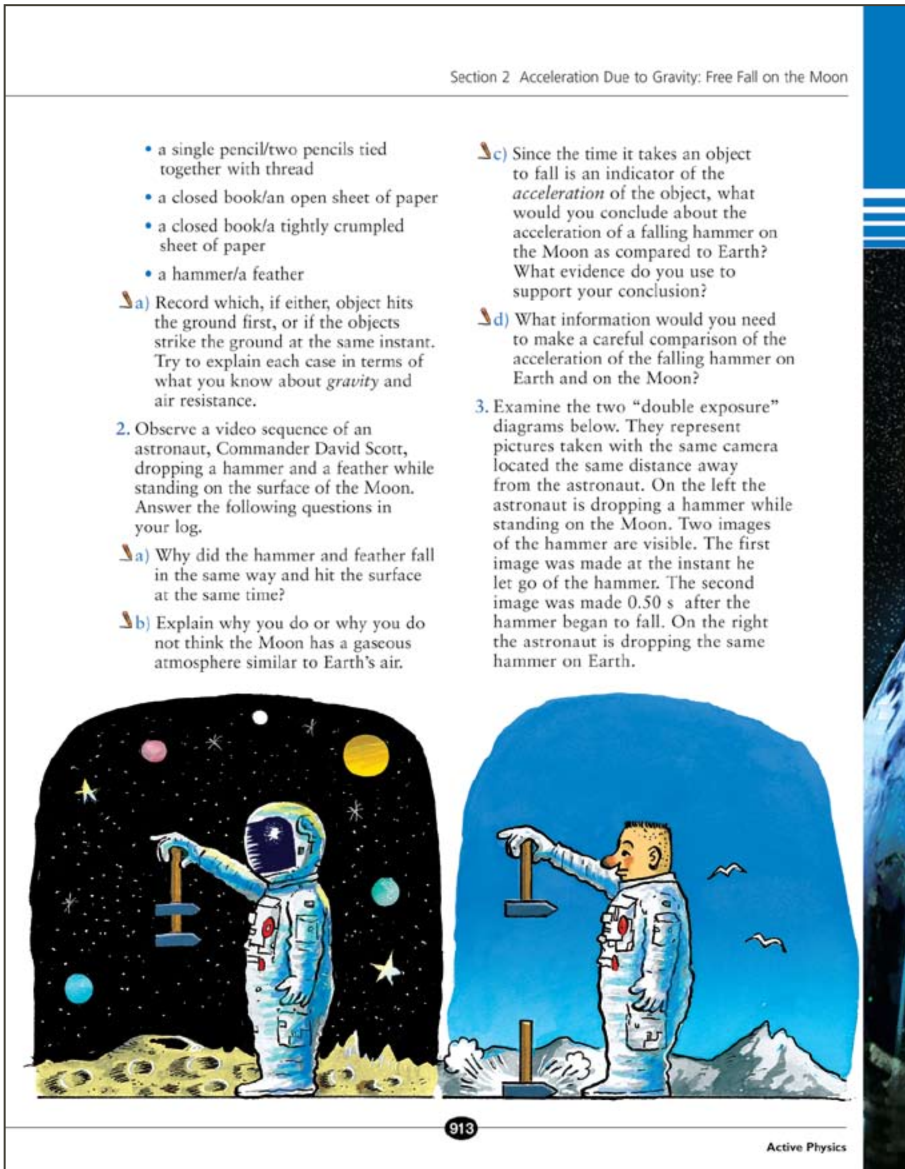
A Physicist's Response

A ball will take longer to fall on the Moon than it will on Earth by a factor of six, which means that the force of gravity on Earth is six times stronger than the force of gravity on the Moon. The force of gravity is also related to the diameter of a planet, and the planet's mass. Earth has a larger diameter and mass than the Moon and has a force of gravity greater than the Moon.

NOTES

CHAPTER 9

NOTES



Section 2 Acceleration Due to Gravity: Free Fall on the Moon

- 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.

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Active Physics

Investigate

1.a)

- A single pencil and two pencils tied together will hit at the same time.
- A closed book and an open sheet of paper demonstrate that the time of fall is independent of mass. The book hits the ground first because the force of air resistance is probably the same on both objects, but the book with the greater mass has the greater net force.
- The book and the paper will hit at approximately the same time. The crumpled paper has much reduced air resistance compared to the sheet of paper, and the ratio of net force to mass for the book and the paper are now much closer together.
- A hammer and feather hit the ground at different times because the feather encounters much more air resistance than the hammer.

2.a)

The hammer and feather land together on the Moon because there is no atmosphere and therefore, no air resistance to slow down the feather more than the hammer.

2.b)

Students' answers may simply state that there can be no air because the astronauts need space-suits. The real reason is that the Moon has no atmosphere because the velocity of an air molecule on the Moon would be greater than the velocity required to escape from the Moon's gravitational pull. On Earth, an air molecule with a similar velocity is not going fast enough to overcome the gravitational attraction of Earth.

2.c)

The acceleration of the hammer due to gravity on Earth is greater than on the Moon. Accurate measurements of distance and time will confirm this observation.

2.d)

Measurements of distance and time of fall would confirm that the acceleration of gravity is greater on Earth.

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3.a)

Students verify the scaling factor is correct from their measurements.
Height of the astronaut = 210 cm.
The height of the image of the astronaut is 6.3 cm.
$210 \text{ cm}/6.3 \text{ cm} = 33.3$.

3.b)

Students should measure a distance of 42 mm for the hammer on Earth, and for the Moon, students should measure a distance of 8 mm.

3.c)

For Earth, the distance is $42 \text{ mm} \times 33.3 = 1.4 \text{ m}$ and for the Moon $8 \text{ mm} \times 33.3 = 0.266 \text{ m}$.

3.d)

$$\frac{d_{\text{Moon}}}{d_{\text{Earth}}} = \frac{a_{\text{Moon}}}{a_{\text{Earth}}} = \frac{0.20 \text{ m}}{1.25 \text{ m}}.$$

3.e)

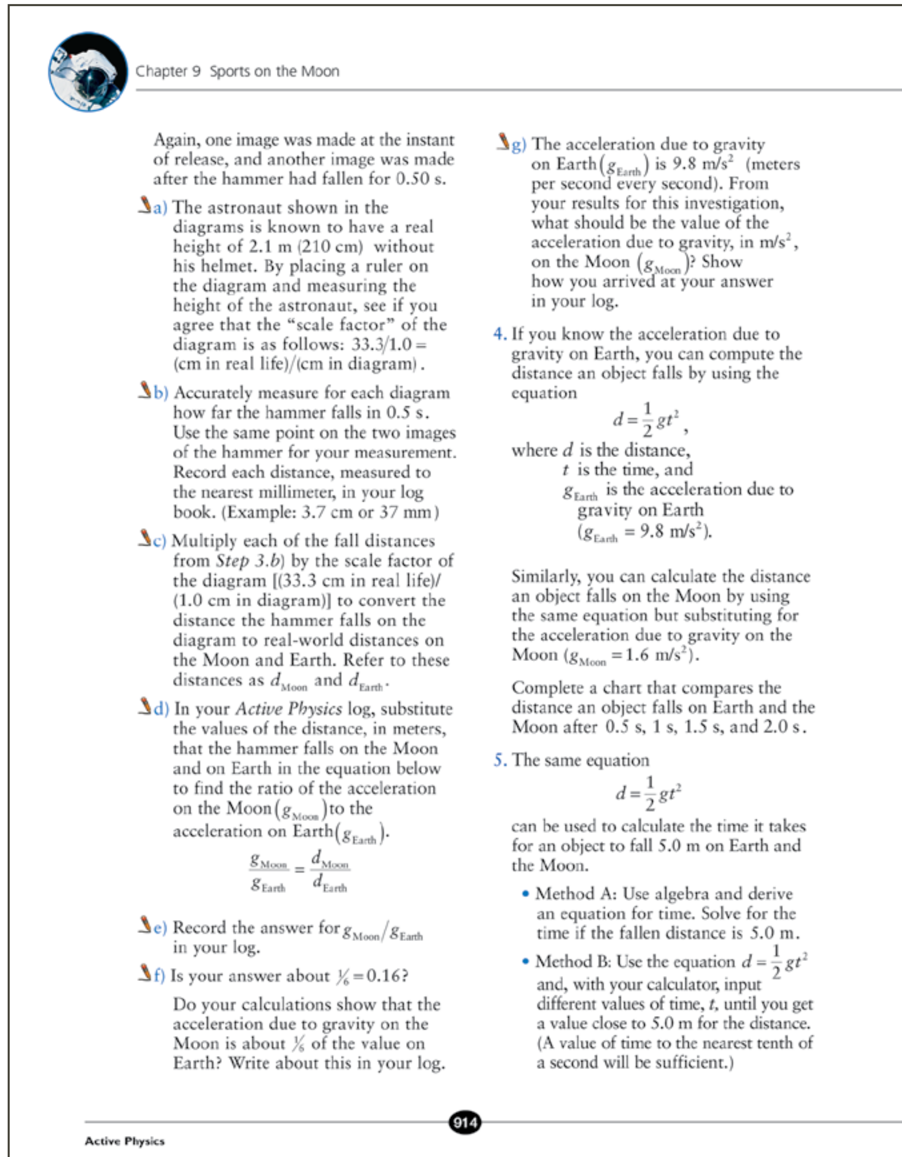
$a_{\text{Moon}}/a_{\text{Earth}} = 0.16$.

3.f)

Students' answer should be close to the value of 1/6.

3.g)

The fraction 1/6 in decimal form is, to two significant figures, 0.17; the experimental value of $a_{\text{Moon}}/a_{\text{Earth}}$, 0.16. Therefore, it is reasonable to use 1/6 of Earth's acceleration due to gravity as the acceleration due to gravity on the Moon. If $g_{\text{Earth}} = 10 \text{ m/s}^2$, then $g_{\text{Moon}} = (10 \text{ m/s}^2)/6 = 1.7 \text{ m/s}^2$.



Chapter 9 Sports on the Moon

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}).

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

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

f) Is your answer about $\frac{1}{6} = 0.16$?

Do your calculations show that the acceleration due to gravity on the Moon is about $\frac{1}{6}$ 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/s² (meters per second every second). From your results for this investigation, what should be the value of the acceleration due to gravity, in m/s², 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 ($g_{\text{Earth}} = 9.8 \text{ m/s}^2$).

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 ($g_{\text{Moon}} = 1.6 \text{ m/s}^2$).

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.)

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Time	Earth distance	Moon distance
0.5 s	1.23 m	0.2 m
1.0 s	4.9 m	0.8 m
1.5 s	11 m	1.8 m
2.0 s	19.6 m	3.2 m

5.

Method A: Using algebra, the time of fall for a given distance, $t = \sqrt{(2d/g)}$, yields a time of 1 s for Earth. On the Moon, the answer would be 2.5 s.

Method B: This method will still yield 1 s and 2.5 s, respectively.

Section 2 Acceleration Due to Gravity: Free Fall on the Moon

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.

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Active Physics

resistance on the Moon. It would be helpful for students to compare the two situations so that they can invent or adapt the sport they have in mind to conditions that affect motion of objects on the Moon. Emphasize that the laws of physics will apply to the Moon as well. Point out that gravity on a planet is directly related to the size and mass of the planet and the falling motion of any object would be described by the same equation for distance, $d = \frac{1}{2}gt^2$, for any planet.

Physics Talk

Students revisit the differences between how things behave on Earth and how they behave on the Moon. They recall the video of the astronaut dropping the hammer and the feather on the Moon and read why the hammer took longer to fall on the Moon than it did on Earth. Knowing the factors that affect how things fall on the Moon, students are led to consider how the aspects of a sport they are considering would change for their NASA proposal.

To reinforce the factors affecting the acceleration on the Moon, ask students why it takes longer for things to reach the ground on the Moon than it does on Earth when falling from the same height. Have them make a list of how a sport on Earth would be affected by air resistance and how the same sport would be affected in the absence of air

CHAPTER 9

Checking Up

1.

The acceleration due to gravity on the Moon is one-sixth the acceleration due to gravity on Earth.

2.

The planet's mass and radius determine the force of gravity of a planet.

3.

Astronauts would weigh different amounts on different planets because the mass and radius of the planets vary. In general, the larger the radius of the planet, the stronger the force of gravity is for that planet. A larger radius generally implies a much greater mass if all else is equal.

Active Physics Plus

The equation for distance traveled, acceleration, and time for an object starting from rest is derived to show how different relationships can be combined to produce a new and useful relationship. After deriving the equation, students read why the distance an object falls on the Moon under the influence of gravity is one-sixth the distance that an object on Earth would fall in the same time.

Encourage students to realize the usefulness of the equation by giving them several situations where the time and acceleration are known and the distance traveled is desired. Emphasize that this relationship is only valid when the object is at rest at the beginning of the time interval.

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:

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

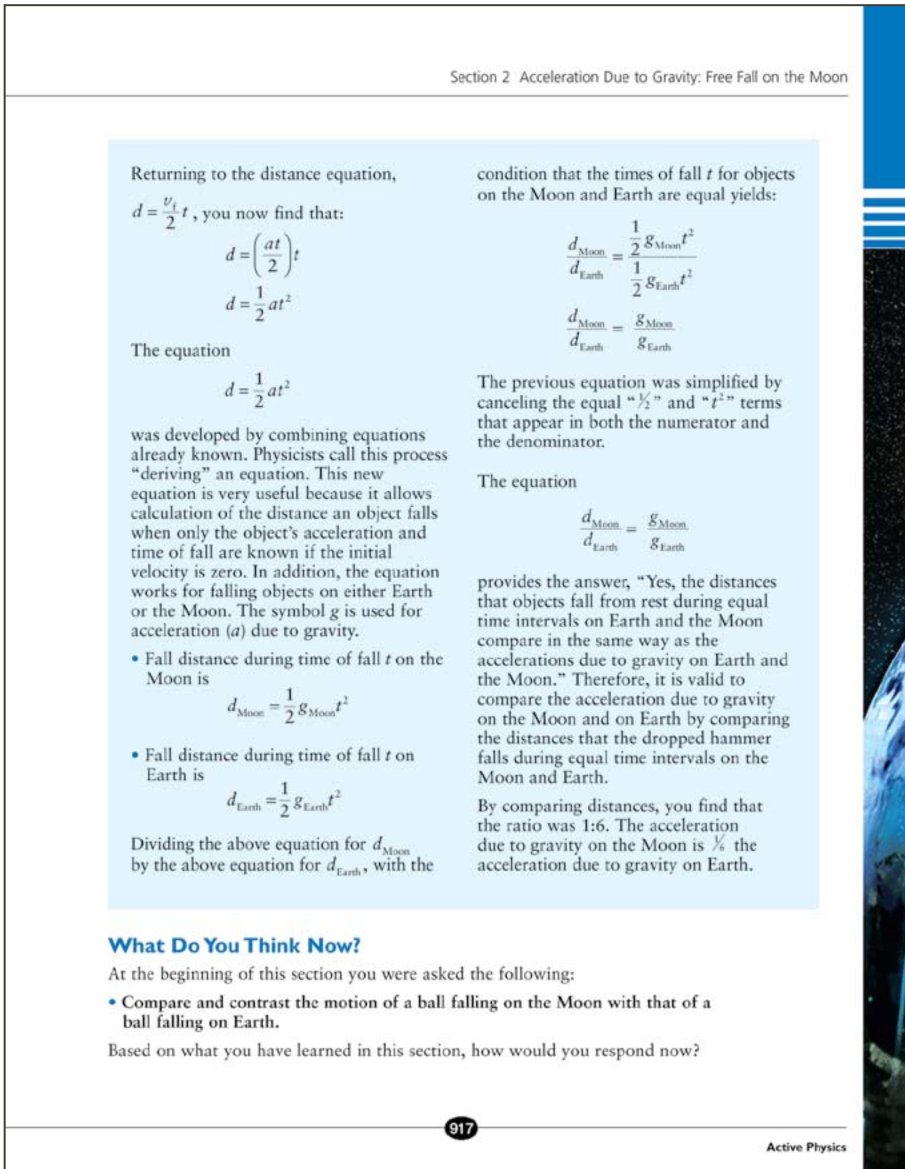
Acceleration, by definition, is equal to the change in velocity/change in time.

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

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.**

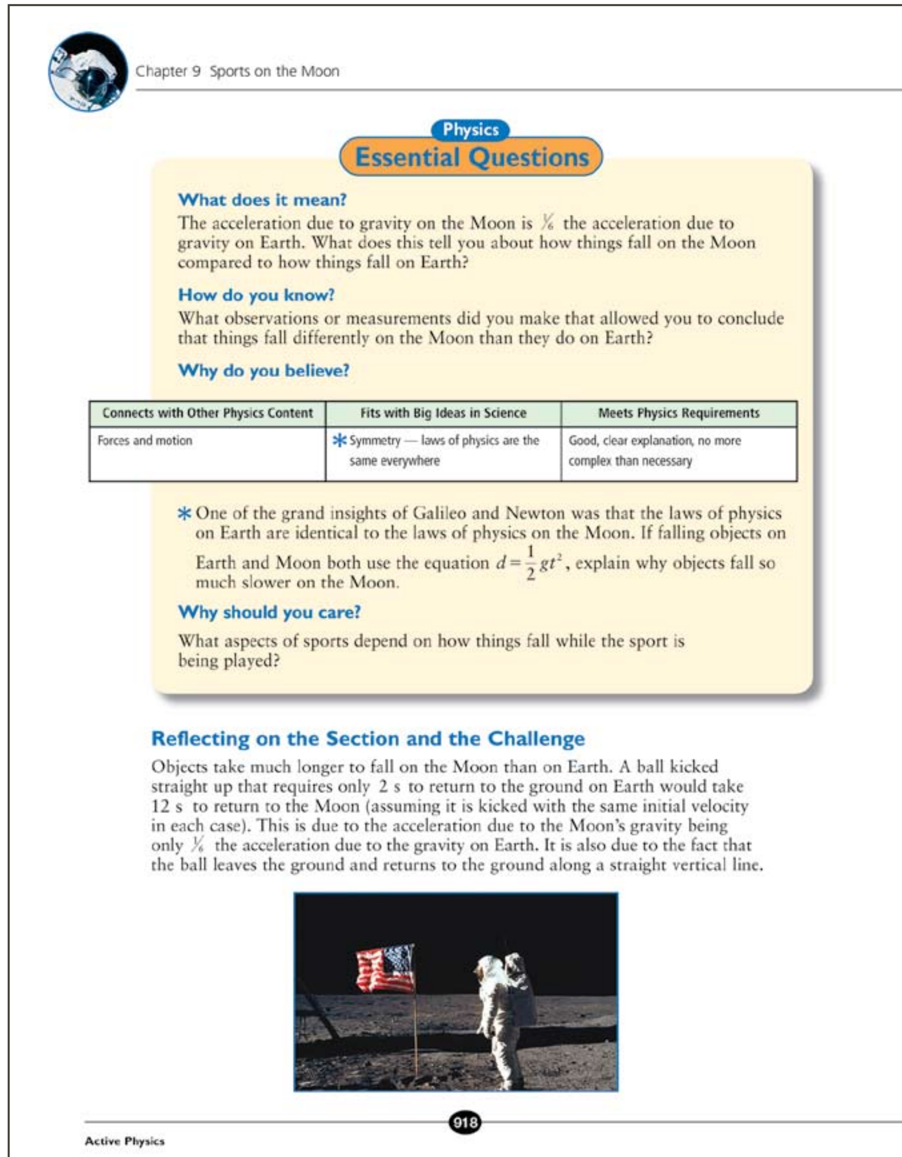
Based on what you have learned in this section, how would you respond now?

What Do You Think Now?

Ask students to review their previous answers to this question and make the necessary changes. Students should now be able to conclude that objects fall faster on Earth than on the Moon. Their answers must include that the acceleration due to gravity on the Moon is 1/6 the acceleration due to gravity on Earth. You might want to share *A Physicist's Response* with your students. Encourage them to ask questions and discuss their doubts. Remind them to revisit the *What Do You See?* illustration and see how their perception might have altered with an increased understanding of how gravity affects motion of objects on the Moon.

Reflecting on the Section and the Challenge

Students now have time to reflect on how gravity affects falling objects on Earth. If air resistance on Earth is included, it would take longer for objects to fall. By extension, students also have time to reflect on how gravity affects falling objects on the Moon. After they have read this section, ask them to write a brief paragraph on what they understand about objects taking longer to fall on the Moon than on Earth. Emphasize that time and distance of fall can be calculated using $d = \frac{1}{2}gt^2$. Point out that it takes more time for objects to fall on the Moon than on Earth. When air resistance is not a factor, the fall time on the Moon for an object dropped from rest is six times longer than for the same distance of fall on Earth. Ask students to ponder how their sport will have to be developed for the Moon, knowing that objects take longer to reach the ground.



Chapter 9 Sports on the Moon

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.

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Physics Essential Questions

What does it mean?

With 1/6 the gravity, objects will take 6 times more time to fall to the ground from the same height.

How do you know?

The video of the astronaut dropping the wrench and feather showed that objects fall slower on the Moon. Measuring the distances from the photo simulation showed that the time was 6 times as long.

Why do you believe?

Although the equation describing the time for an object to fall on Earth and the Moon are identical, the value of the acceleration due to gravity is different on Earth and the Moon $\left(g_{\text{Earth}} = 9.8 \text{ m/s}^2;\ g_{\text{Moon}} = 1.6 \text{ m/s}^2\right)$.

Why should you care?

Any object in a sport that travels in the air will be affected by the decrease in the acceleration due to gravity.

Section 2 Acceleration Due to Gravity: Free Fall on the Moon

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

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Physics to Go

1.

Using $d = \frac{1}{2}gt^2$ and substituting in the acceleration due to gravity on the Moon of 1.6 m/s² and the time of 1 second gives $d = \frac{1}{2}(1.6\ \text{m/s}^2)(1\ \text{s})^2 = 0.8\ \text{m}$ for the Moon. Repeating the procedure for Earth and using Earth's acceleration due to gravity of 9.8 m/s² gives $d = \frac{1}{2}(9.8\ \text{m/s}^2)(1\ \text{s})^2 = 4.9\ \text{m}$.

2.

Using $d = \frac{1}{2}gt^2$ and substituting in the acceleration due to gravity on the Moon of 1.6 m/s² and the time of 3 seconds gives $d = \frac{1}{2}(1.6\ \text{m/s}^2)(3\ \text{s})^2 = 7.2\ \text{m}$ for the Moon. Repeating the procedure for Earth and using Earth's acceleration due to gravity of 9.8 m/s² gives $d = \frac{1}{2}(9.8\ \text{m/s}^2)(3\ \text{s})^2 = 44.1\ \text{m}$.

3.

Using $d = \frac{1}{2}gt^2$ and substituting in the acceleration due to gravity on the Moon of 1.6 m/s² and a height of 10 m gives a fall time of $10\ \text{m} = \frac{1}{2}(1.6\ \text{m/s}^2)t^2$ or $t = 3.5$ seconds for the diver to fall to the water. Repeating the calculation for Earth gives $10\ \text{m} = \frac{1}{2}(9.8\ \text{m/s}^2)t^2$ or $t = 1.4$ seconds of fall time. Since the Moon diver has more than twice the time in the air, the diving turns, flips and spins on the Moon would be expected to be much more complicated. In addition, the diver would hit the water at a much lower speed.

4.

Starting with $d = \frac{1}{2}gt^2$. Multiply both sides of the equation by 2 and divide both sides of the equation by t^2. Then $g = 2d/t^2$.

5.

Using the equation derived in *Question 4*, $g = 2d/t^2$ and substituting in the values for distance and time, gives $g = 2(2.0\ \text{m})/(0.50)^2 = 1.6\ \text{m/s}^2$.

6.

Start with $d = \frac{1}{2}gt^2$. Multiply both sides of the equation by 2, divide both sides of the equation by g, and then take the square root of both sides of the equation. Then, $t = \sqrt{2d/g}$.

7.

Using the equation derived in *Question 6* gives $t = \sqrt{2d/g}$, and substituting in the distance and the acceleration due to gravity on the Moon gives $t = \sqrt{2(2.0\ \text{m})/(1.6\ \text{m/s}^2)}$ or $t = 1.6\ \text{s}$.

CHAPTER 9

8.a)

As the ball rises, it loses 1.6 m/s of its speed every second. It will take the ball $(30 \text{ m/s})/(1.6 \text{ m/s}^2) = 18.75 \text{ s}$ to reach the peak of its upward flight.

8.b)

It will also take 18.75 s to fall back down; therefore, the fielder has 37.5 s.

8.c)

Using equation $y = -\frac{1}{2}gt^2 + v_0 t$, we can find maximum the height when $t = 18.75$ s.
$-\frac{1}{2}(1.6 \text{ m/s}^2)(18.75 \text{ s})^2 + (30 \text{ m/s})(18.75 \text{ s}) = 281.25 \text{ m}$.
281.25 m is more than three times the length of a 91-m football field.

Chapter 9 Sports on the Moon

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			

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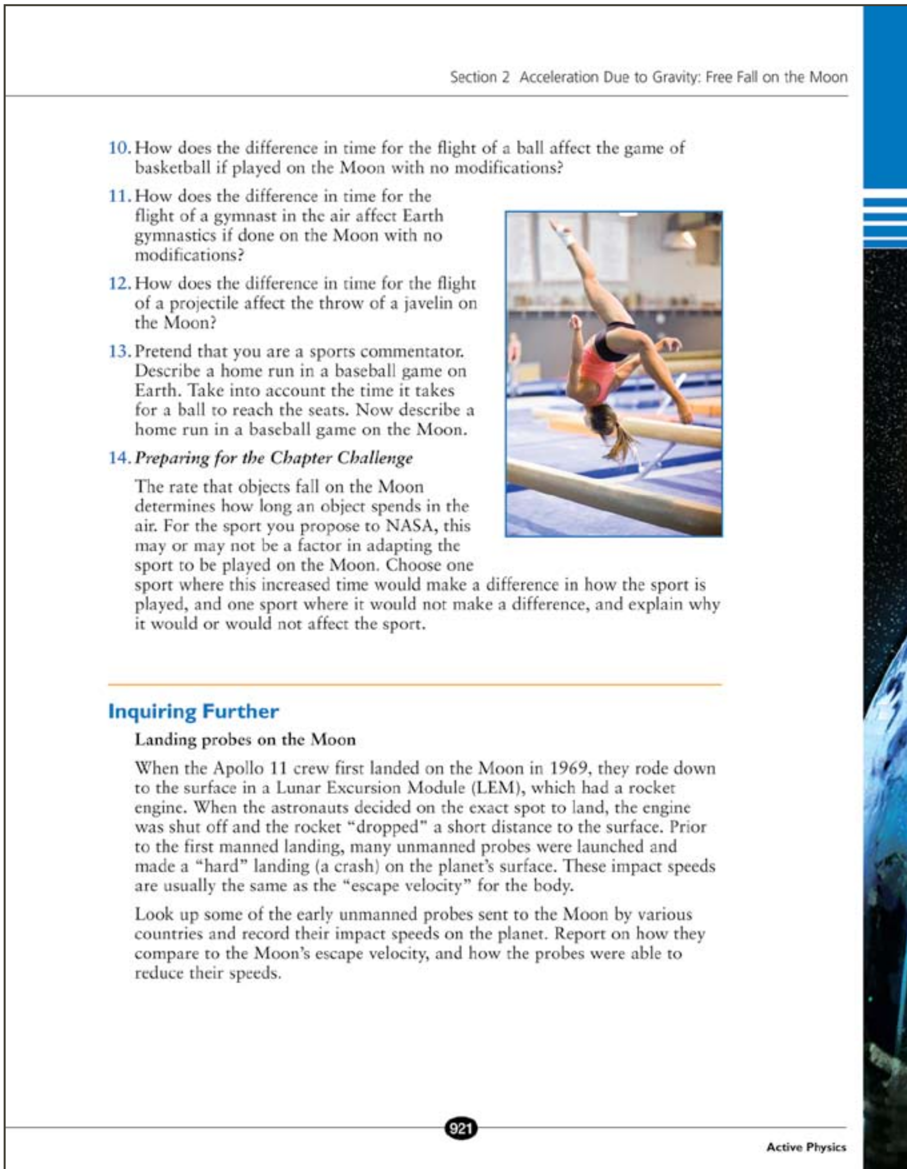
9.

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	1.6
4.0	0.8	3.2	6.4
6.0	0.8	4.8	14.4
8.0	0.8	6.4	25.6
10	0.8	8.0	40
12	0.8	9.6	57.6
14	0.8	11.2	78.4
16	0.8	12.8	102.4
18	0.8	14.4	129.6
20	0.8	16	160



Section 2 Acceleration Due to Gravity: Free Fall on the Moon

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.

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10.

Because a ball on the Moon will take much longer to reach its peak and to fall back down, the person shooting will be able to shoot from much farther away. However, the crowd will have to wait 6 times as long to find out if the shot was good!

11.

The increased time in the air will allow the gymnast to perform many more acrobatic maneuvers.

12.

Since a projectile like a javelin spends 6 times as long in the air, a javelin will travel 6 times as far and go 6 times as high during its flight. Spectators may have to sit quite far from the sport for safety reasons.

13.

A sports commentator will have to build the suspense about whether or not the ball will be a home run to fill the time until the ball comes down. Because the time will be 6 times longer than on Earth, a description of what the fielder is doing and how any runners are responding to the ball could be added, and maybe even some statistics on the batter!

14.

Preparing for the Chapter Challenge

Students' answers will vary depending upon the sport chosen. Sports that are affected by the flight time will include any sport using a projectile, and will be affected by both the time in the air and the distance the projectile travels. A sport that would not be affected might be bowling or running.

Inquiring Further

Students will have to complete an Internet search on the Moon probes. The escape velocity for the Moon is approximately 1.7 km/s, so a space probe falling into the Moon would have at least this speed when striking the surface, unless it has some mechanism to slow its fall. An impact speed this high (about 3800 mi/h), would destroy the craft. Many early Moon probes accepted this fact, and only tried to send back data until the point of impact. Later probes used retro-rockets to slow the landing speed, as did the astronauts who landed on the Moon.

CHAPTER 9

SECTION 2 QUIZ

9-2a **Blackline Master**

The acceleration due to gravity on the Moon is 1.6 m/s^2 and on Earth 10 m/s^2.

1. A rock is dropped on the Moon and takes 2 s to strike the ground. From what height was the rock dropped?

   a) 1.6 meters.
   b) 3.2 meters.
   c) 4.8 meters.
   d) 6.4 meters.

2. A 1.0-kg stone and a 3.0-kg stone on the Moon are both released from a height of 9.0 meters above level ground at the same time. Compared to the time required for the 1.0-kg stone to fall to the ground, the time for the 3.0-kg stone to fall would be

   a) one-ninth as great.
   b) one-third as great.
   c) the same.
   d) three times as great.

3. Two objects, one on Earth and one on the Moon, of equal mass are dropped in a vacuum. After one second of fall, the distance the object on Earth falls compared to the distance the object on the Moon falls is

   a) one-sixth as great.
   b) one-third as great.
   c) the same.
   d) 6 times as great.

4. A rock on Earth is dropped from a height of 45 meters above the ground. Approximately how long does it take the rock to hit the ground?

   a) 7.5 s
   b) 4.5 s
   c) 3 s
   d) 9.8 s

5. Which of the following statements about the acceleration due to gravity on the Moon is incorrect?

   a) The mass of the object being dropped has an effect on the acceleration.
   b) The mass of the Moon determines the acceleration.
   c) The size of the Moon determines the acceleration.
   d) The acceleration due to gravity is different on other planets.

SECTION 2 QUIZ ANSWERS

1. b) A falling object on the Moon accelerates. Using the formula $d = \frac{1}{2}gt^2$ and solving for d gives $d = \frac{1}{2}\left(1.6\ \text{m/s}^2\right)\left(2\ \text{s}\right)^2 = 3.2\ \text{m}$.

2. c) Since all objects fall at the same rate like the hammer and the feather, the two rocks will take exactly the same time to fall.

3. d) The distance an object falls in free fall is directly proportional to the acceleration due to gravity of the planet. (See *Step 3.d)* of the *Investigate*.) Since $g_{\text{Earth}}/g_{\text{Moon}}$ is $\left(10\,\text{m/s}^2\right)/\left(1.6\ \text{m/s}^2\right) \approx 6$, An object on Earth will fall 6 times farther in one second than on the Moon.

4. c) Using the formula $d = \frac{1}{2}gt^2$ for an accelerating object on Earth, and solving for t gives $45\ \text{m} = \frac{1}{2}\left(10\ \text{m/s}^2\right)\left(t^2\right)$ or $t = 3$ s.

5. a) The acceleration due to gravity depends upon the mass and size of the planet or moon. The acceleration due to gravity is different on other planets or moons.