SECTION 3

Mass, Weight, and Gravity

Section Overview

Students explore the difference between mass and weight on Earth and the Moon in a prepared simulation. First, with a partner, they roll two bottles that represent equal masses on Earth and the Moon back and forth across a table. By pushing and stopping each bottle they "feel" the pushing force needed to accelerate and stop the bottles. They also realize that this force is the same for Earth and the Moon and is a measure of an object's resistance to a change in its state of rest or motion (the object's inertia). Then students lift a bottle labeled 1 kg, Earth and feel the downward force of Earth's gravitational pull while holding the bottle. They measure the weight of that bottle by attaching the bottle with a string to a spring scale. Using an identical procedure, students also find the weight of a bottle labeled 1 kg, Moon while pretending to have been transported to the Moon. This measurement represents the weight of the 1-kg bottle on the Moon. Students divide the weight of the bottle on the Moon by the weight of the bottle on Earth and find the ratio of the two weights, which is $1/6$. Eventually, they learn that the weight of an object is measured by the force of gravity on that object and its unit is the newton (N).

Background Information

Recall from the *Background Information* of *Physics in Action*, *Section 3*, that an object's gravitational mass (determined by using an equal arm balance to compare the object to a standard mass) is equal to an object's inertial mass (determined by comparing the object's acceleration in response to an equal force applied to a standard mass). In this section, the inertial masses of objects are compared as students estimate the amount of force required to produce equal accelerations on a 1-kg object on Earth and the Moon. The inertia, or inertial mass, of an object does not vary with location; an object should respond to an applied force in the same way on Earth as on the Moon.

A simplified version of Newton's universal law of gravitation is used for students to understand the reduced effect of gravity on the Moon and to predict, in general, what would be the local acceleration due to gravity on any planet (or another moon) in terms of the planet's mass and radius. For your information and for students, if you deem them capable of understanding it, the basis in Newton's universal law of gravitation for proportionality is presented below.

Assume that you have to calculate the gravitational force of attraction between a small object whose mass is m_{small} and a huge spherical object, such as a planet, whose mass is m_{huge}. Also assume that the distance between the centers of masses of the huge and small objects is r—this can be any distance, large or small, but the smallest possible value occurs when the surfaces of the objects are in contact. According to Newton's universal law of gravitation, each object experiences a force $F = (Gm_{small} \cdot m_{huge})/r^2$ toward the center of mass of the other object. This force is consistent with Newton's third law (an equal and opposite pair of forces on each object) and G is the universal gravitational constant equal to $6.67 \times 10^{-11}\ \text{m}^2/(\text{kg} \cdot \text{s}^2)$. According to Newton's second law, each object will accelerate toward the other object with an amount of acceleration $a = F/m$. The acceleration of the small mass should be equal to F/m_{small}, which can be found by rearranging the above equation as $a_{small} = F/m_{small} = (Gm_{huge})/r^2$. If the small object is located at or very near the surface of the huge spherical object, then, for practical purposes, the radius is the radius of the huge mass, $r = r_{huge}$, and the above equation becomes $a_{small} = F/m_{small} = (Gm_{huge})/(r_{huge}^2)$.

This equation gives the acceleration, which will be experienced by any small object located near the surface of a huge object, such as a planet or a Moon, in terms of properties of only the huge object. This acceleration is called the acceleration due to gravity, or g, of that planet or moon. Therefore, $g_{huge} = (Gm_{huge})/r^2_{huge}$.

You may wish to substitute values for G, the mass of Earth, and Earth's radius in the equation.

If you do, the answer obtained for a_{small} will be $g = 9.8\ m/s^2$. Doing the same for the Moon will result in 1.6 m/s². Only the proportionalities between g, m, and r in the above equation are used to reason toward comparison of the accelerations due to gravity at the surface of Earth and the Moon in the *Investigate*.

Crucial Physics

- The mass of an object is independent of its location, and is a measure of the object's inertia.
- The weight of an object depends upon the local value of the gravitational field, and can be found using the equation $W = mg$. Weight is a force that is expressed in newtons.
- The strength of a celestial body's gravitational field is proportional to the mass of the body and inversely proportional to the distance from the center of the body.
- The force of gravity can be expressed by the equation $F_g = Gmm_p/r_p^2$, where p is the notation for planet.

Learning Outcomes	Location in the Section	Evidence of Understanding
Compare the masses of objects using applied forces.	***Investigate*** Part A: Steps 2 and 3	Students roll a bottle labeled 1 kg, Earth and a bottle labeled 1 kg, Moon across the table by pushing and stopping the bottles and feeling the amount of force needed to push, stop, and accelerate the bottles.
Measure the weights of objects using a spring balance.	***Investigate*** Part B: Steps 2 and 3	Students attach a spring balance to bottles that are labeled 1 kg, Earth and 1 kg, Moon and measure their weight in newtons.
Understand and apply Newton's universal law of gravitation to compare the acceleration due to gravity on Earth and the Moon.	***Investigate*** Part B: Steps 2 and 3	Students lift the bottles labeled 1 kg, Earth and 1 kg, Moon, "feel" the downward pull, and record the weight of the bottles in newtons. They compare the two weights by dividing the weight of the bottle on Earth by the weight of the bottle on the Moon, and infer the reduced acceleration due to gravity of the Moon from the lower weight.

Section 3 Materials, Preparation, and Safety

Materials and Equipment

PLAN A and PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Bottle (labeled Earth)	2 per group	
Bottle (labeled Moon)	2 per group	
Spring scale, 0-10 N	1 per group	
Container, 32 oz (for sand)	1 per group	
String, ball		2 per class
Access to water*		1 per class

*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

- Prepare the 1-kg Earth and 1-kg Moon bottles, for the Mass and Weight stations in *Parts A* and *B* of the *Investigate*. If student groups can trade places without moving the bottles, this will reduce the number of bottles necessary to be prepared.
- If you do not have adequate bottles already available you will need to begin collecting 1-qt plastic bottles fitted with caps. Sports drink bottles in 1-qt size work very well. The bottles should be as cylindrical in nature as possible.
- If the bottles you are using are transparent, they should be spray painted or made opaque in some other manner. If painting, ensure the spray paint does not dissolve the plastic.
- Once painted and dry, three-fourths of the bottles (a total of 9 bottles for the example used) should be filled with water until the total mass of the bottle, cap, and water equals 1 kg, or some other value.
- You probably will find that the mass of the painted bottle and cap almost makes up for the amount by which the mass of one quart of water is less than 1 kg; the bottle probably will be almost full. Once the masses of the bottles have been "trimmed" by adding water to bring the mass of each to 1 kg (if you are a few grams off, it will do no harm), you may wish to permanently seal each bottle by using silicone cement to glue the tops to the bottles. Label 2/3 of the bottles "1 kg, Earth" and label 1/3 of the bottles "1 kg, Moon."
- Add sand to one-fourth of the bottles, bringing the total mass of each bottle, cap, and sand to 0.165 kg, or 165 g. (Sand is used to prevent "sloshing" of the filler within the partially filled bottle, making the simulation of lifting the bottle in a Moon environment more realistic.) Because the mass of a 1-qt plastic bottle typically is 50 g, only a small amount of sand (approximately 115 g) will be needed.
- Each of these bottles should be sealed and labeled "1 kg, Moon"—this label, of course, will not indicate the true mass of each of these bottles, but is "faked" for the simulation of weighing 1 kg in a Moon environment.
- Tie a string approximately 40-cm long around the neck of each bottle to be used at the weigh stations.

Safety Requirements

- Caution students not to open any of the bottles.
- If the bottles have been sealed with silicone cement, give the cement ample time to dry before allowing students to interact with the bottles.
- Use only plastic bottles to prevent any breakage should the bottles be mishandled or dropped.

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Reading comprehension	***Physics Talk***	**Augmentation** • Students who struggle with decoding and/or reading comprehension are going to have difficulty extracting information from *Physics Talk*. Remind students to read the *Checking Up* questions first because these questions provide a purpose for reading. Then after students are done, monitor accuracy of answers to these questions to see if students understand what they have read. • Divide the *Physics Talk* into smaller segments, give students time to read the section individually (7–10 minutes), and then discuss the section as a large group or provide direct instruction to supplement the reading. • As students are reading, ask them to write at least five questions they need answered to understand the content of this section. If students are struggling to write good questions, model some examples of different kinds of questions they could ask. • Ask students to develop a chart comparing mass, weight, and gravity on Earth and the Moon. Other topics such as force and inertia could be added to the chart to differentiate the level of challenge. **Accommodation** • Provide a copy of this section of text for students to highlight and write on as they read. • Provide a reading guide that intentionally cues students to pay attention to the key points of the text. • Provide a blank chart for students to use to compare mass, weight, and gravity on Earth and the Moon. Some students who have more significant difficulty with reading may need a list of choices to match up to the appropriate column in the chart.
Comparing the effects of mass and weight related to forces, distance, speed, and acceleration	***Physics to Go*** Questions 1–6	**Augmentation** • Students may be able to state that mass is the same on Earth and the Moon and that weight changes because of the change in the acceleration of gravity. However, these students may not be able to apply this concept to explain changes in distance, force, speed, and acceleration. • Help students create a list of formulas that they can use to compare weight, distances, forces, speed, and acceleration on Earth and the Moon. • Remind students that weight affects a person's ability to lift something and mass has more of an effect on a person's ability to push something. Ask students to develop a list of sports actions affected more by mass and a list of actions affected more by weight. Refer students to the examples in *Physics Talk* if they are struggling. **Accommodation** • Provide a list of equations for students to use to compare conditions on Earth and the Moon.
Describing the differences between shuffleboard on Earth and the Moon	***Physics to Go*** Question 7	**Augmentation** • Students will have a difficult time describing the differences between shuffleboard on Earth and the Moon if they do not really understand the sport. Show students an online video of shuffleboard being played. Students could be challenged to act as commentators for the game on Earth and then do the same for a game of shuffleboard on the Moon. Then they could discuss the reasons for the differences in their commentaries.

Strategies for Students with Limited English-Language Proficiency

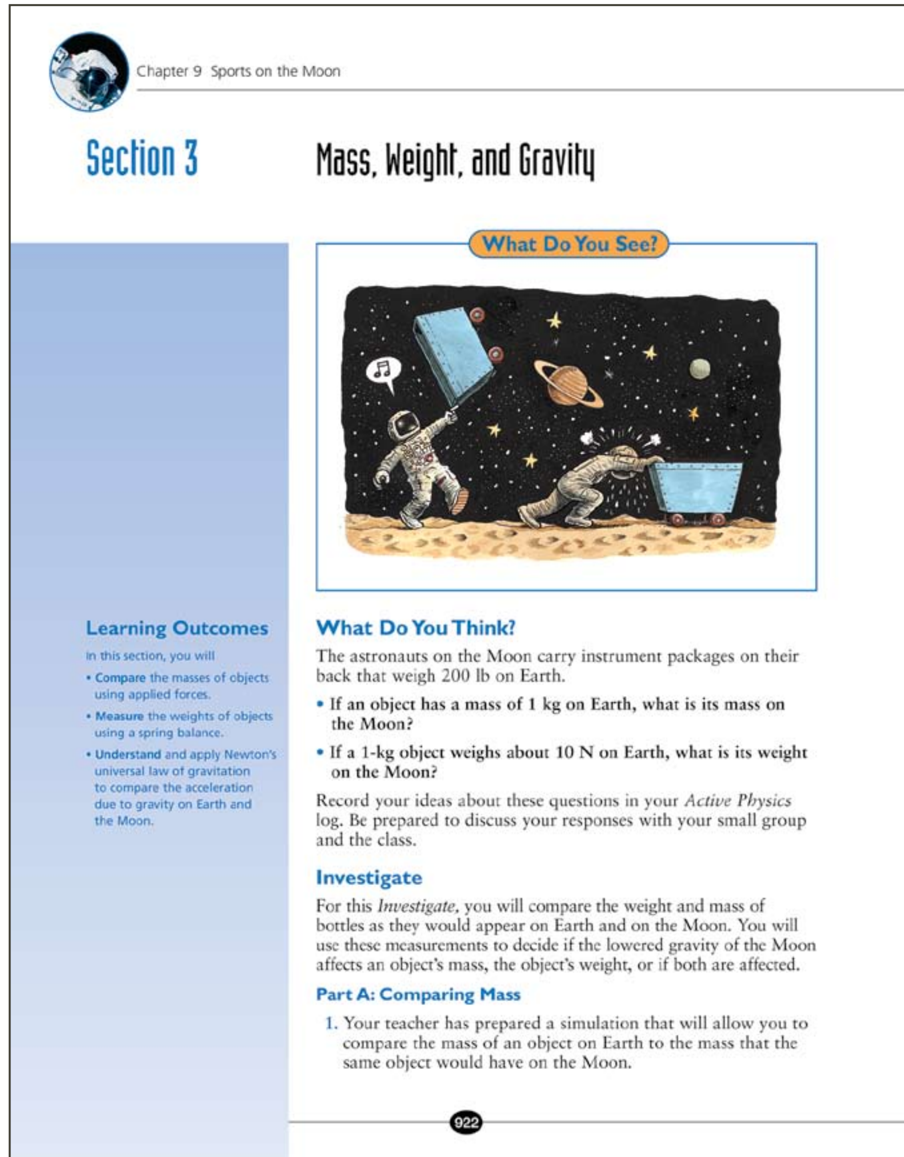
Learning Issue	Reference	Augmentation
Understanding concepts	***Investigate*** Part B: Step 3.e)	If students have difficulty telling how they could reproduce this simulation at home, ask these questions: Was the 1-kg simulated Moon mass the same as the 1-kg Earth mass? [Yes] Was the 1-kg simulated Moon weight the same as the 1-kg Earth weight? [No] Make sure students understand that you had to adjust the simulated Moon weight to give them the desired investigative experience, but in doing so, you also reduced the mass. Because the weight on the Moon is reduced without the mass being reduced, the experience on the Moon would be different. In a classroom on Earth, there is no way that a single simulation can represent actual Moon conditions for both weight and mass.
Comprehension	***Active Physics Plus***	Check students' comprehension of the terms "proportional," "inversely proportional," "proportionality constant," and "gravitational constant." A clear understanding of these terms is crucial to understanding the universal law of gravitation. The equations related to the universal law of gravitation can look intimidating, in part because of the subscripts and superscripts. Give students the opportunity to state the equations in words, both verbally and in writing, to help solidify their understanding. Also clarify for students that the ratio they find in *Step 4* compares the force of gravity at the surface of Earth to the force of gravity at the surface of the Moon.
Vocabulary comprehension	***What Do You Think Now?***	ELL students and others may struggle to make sense of the first two sentences in this section because of the terms "attribute," "derived," and "intrinsic." Pair ELL students with native speakers. Have them work together to come up with alternate ways to state the same concepts. Hold a brief class discussion so students can share their interpretations and you can monitor potential misconceptions.
Understanding concepts	***Physics to Go*** Question 4.c)	This question provides an opportunity for developing language skills through class discussion. Students should recall that, because there is no air on the Moon, sound vibrations would not travel through the empty space between the fan and the umpire. However, because sound can travel through solids, neighboring fans should be able to hear someone shouting into their space suits. The words shouted would perhaps be unintelligible, much like those of someone speaking underwater. Encourage students to discuss these points: How would players, coaches, umpires, and referees communicate with one another during an outdoor game on the Moon? How might players be affected by being unable to hear their fans cheering? If a baseball umpire is looking at a base to see when the runner's foot tags it, how will the umpire know when the infielder catches the ball if there is no noticeable "thwack" of the ball hitting the glove? If there is time for an extended discussion, allow students to identify additional, related issues, and provide the opportunity to also discuss some possible solutions.

SECTION 3

Teaching Suggestions and Sample Answers

What Do You See?

One astronaut can carry the steel cart on his finger easily but another struggles to push a steel cart! Students will most likely to respond to these images wondering why lifting something would be easier than accelerating it, and you can then steer a discussion toward the purpose of the illustration. Ask them to share their impressions among their classmates, and as they respond, take the opportunity to record a few initial impressions. Remind them that their initial perspectives will gradually shift to accommodate new knowledge and they should return to this illustration to gain a better appreciation of the artist's intent.



Chapter 9 Sports on the Moon

Section 3 Mass, Weight, and Gravity

What Do You See?

Learning Outcomes

In this section, you will

- **Compare** the masses of objects using applied forces.
- **Measure** the weights of objects using a spring balance.
- **Understand** and apply Newton's universal law of gravitation to compare the acceleration due to gravity on Earth and the Moon.

What Do You Think?

The astronauts on the Moon carry instrument packages on their back that weigh 200 lb on Earth.

- If an object has a mass of 1 kg on Earth, what is its mass on the Moon?
- If a 1-kg object weighs about 10 N on Earth, what is its weight on the Moon?

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

For this *Investigate*, you will compare the weight and mass of bottles as they would appear on Earth and on the Moon. You will use these measurements to decide if the lowered gravity of the Moon affects an object's mass, the object's weight, or if both are affected.

Part A: Comparing Mass

1. Your teacher has prepared a simulation that will allow you to compare the mass of an object on Earth to the mass that the same object would have on the Moon.

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Students' Prior Conceptions

Students have encountered the concepts of mass, weight, and gravity in previous chapters. Now, you have an opportunity to delve more deeply into student misconceptions of mass, weight, and the force due to the gravity of a planet or a Moon upon the weight of an object.

1. **Students do not associate falling objects with a causation force.** Referring to the masses of objects and their weights as recorded on a spring balance will reinforce the concept that an invisible force pulls down upon the object. This then pulls down upon the spring, stretching it in a linear manner to record or to measure the force upon the object. This force is the force due to gravity on the object, the weight of the object, and is a causative force even though it is invisible and acts at a distance from the center of Earth. You also have the opportunity to review the concepts of action and reaction and Newton's second and third laws in this section. Also mention that an object falls because an unbalanced force pulls it down toward the center of Earth or the Moon.
2. **Students do not associate mass with gravity and weight.** Talking about how a spring balance measures weight on Earth and on the Moon may enable students to differentiate between the mass of an object, its inertia as described by Newton, the weight of the object, and the force of Earth or the Moon on the object. Encourage students to discuss mass—the constant measure of matter throughout the universe—with weight, the variable force upon that matter at specific locations in the universe. Nudge students to predict and to discuss what happens to the stretch of a

What Do You Think?

As students think of how the mass of a 1-kg object would be affected when on the Moon, ask them to consider the difference between mass and weight. It is evident from the questions that both quantities have different units. You might want to point out this difference and have students record their answers in their *Active Physics* logs. You will also be able to note the misconceptions students have and their answers will provide the opportunity to address their immediate responses. *What Do You Think?* becomes the precursor to scientific inquiry if students are prompted with questions that encourage them to think about physics concepts. You should facilitate the continuous participation of shared responses and remind students that they will have another opportunity to revise their answers after they have carried out the *Investigate*.

What Do You Think?

A Physicist's Response

The mass on the Moon would remain the same, which is 1 kg. The weight on the Moon would be about $1/6 \times 10\ N = 1.6\ N$.

Investigate

Part A: Comparing Mass

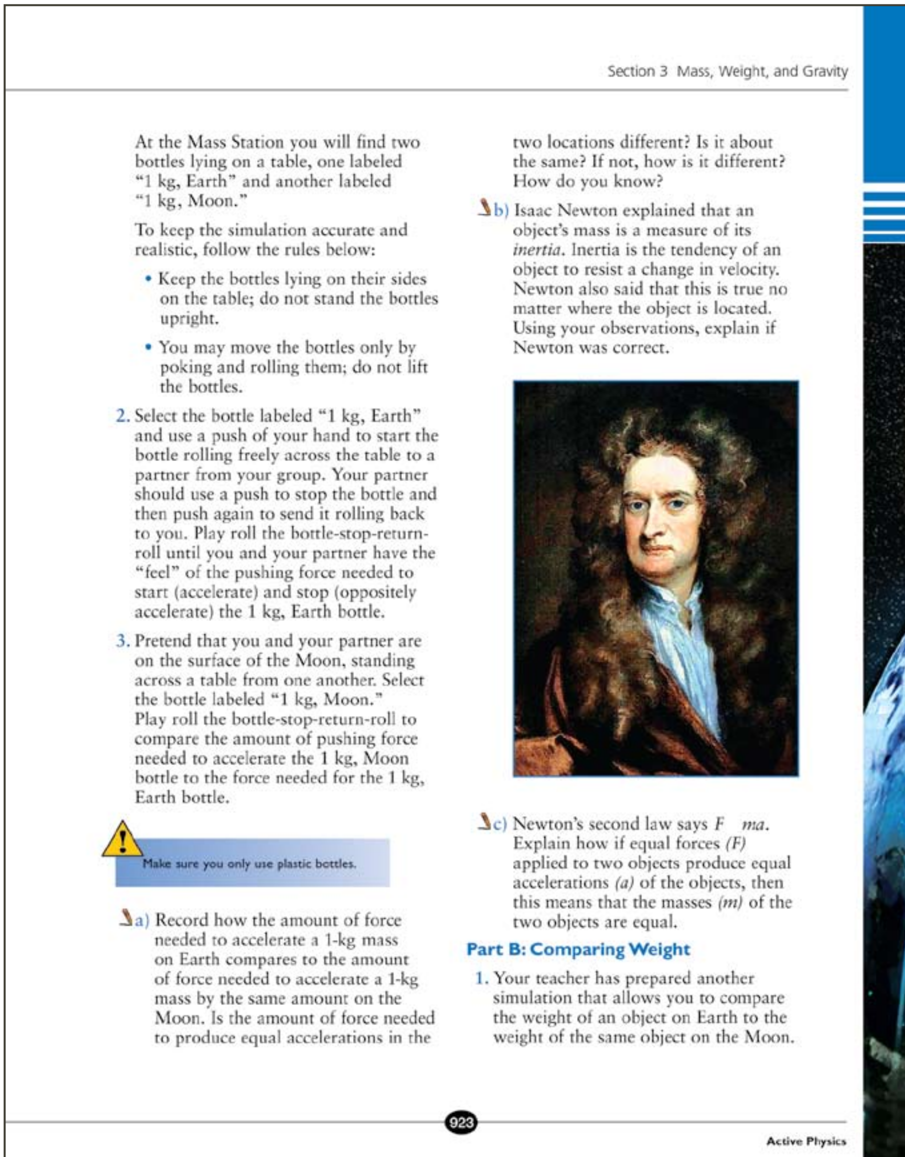
1.

Students observe the bottles labeled "1 kg, Earth" and "1 kg, Moon."

spring if the weight of the object on the Moon is less than the weight of the same identical object on Earth. Describe the mathematical comparison of the responses of objects to applied forces as it relates to the masses of objects.

3. **Students do not associate forces with non-moving things so they neglect to think of gravity as a force always acting on something.** You can combat this conception by emphasizing the mathematical application of Newton's universal law of gravitation. Apply concept mapping and use ratios and proportions to show how to derive the gravitational constant for Earth or the Moon. Compare the acceleration due to gravity on Earth to the Moon and emphasize their relation to the mass and to the radius of each attracting body.

NOTES



At the Mass Station you will find two bottles lying on a table, one labeled "1 kg, Earth" and another labeled "1 kg, Moon."

To keep the simulation accurate and realistic, follow the rules below:

- Keep the bottles lying on their sides on the table; do not stand the bottles upright.
- You may move the bottles only by poking and rolling them; do not lift the bottles.

2. Select the bottle labeled "1 kg, Earth" and use a push of your hand to start the bottle rolling freely across the table to a partner from your group. Your partner should use a push to stop the bottle and then push again to send it rolling back to you. Play roll the bottle-stop-return-roll until you and your partner have the "feel" of the pushing force needed to start (accelerate) and stop (oppositely accelerate) the 1 kg, Earth bottle.
3. Pretend that you and your partner are on the surface of the Moon, standing across a table from one another. Select the bottle labeled "1 kg, Moon." Play roll the bottle-stop-return-roll to compare the amount of pushing force needed to accelerate the 1 kg, Moon bottle to the force needed for the 1 kg, Earth bottle.

Make sure you only use plastic bottles.

a) Record how the amount of force needed to accelerate a 1-kg mass on Earth compares to the amount of force needed to accelerate a 1-kg mass by the same amount on the Moon. Is the amount of force needed to produce equal accelerations in the two locations different? Is it about the same? If not, how is it different? How do you know?

b) Isaac Newton explained that an object's mass is a measure of its *inertia*. Inertia is the tendency of an object to resist a change in velocity. Newton also said that this is true no matter where the object is located. Using your observations, explain if Newton was correct.

c) Newton's second law says *F* *ma*. Explain how if equal forces *(F)* applied to two objects produce equal accelerations *(a)* of the objects, then this means that the masses *(m)* of the two objects are equal.

Part B: Comparing Weight

1. Your teacher has prepared another simulation that allows you to compare the weight of an object on Earth to the weight of the same object on the Moon.

2.

Students roll the 1 kg, Earth bottle back and forth on the table.

Teaching Tip

When the bottles are rolling across the table, the water may tend to "slosh" back and forth when started and stopped. To minimize this effect, about 15–20 cm of fiberglass screen material may be rolled up and inserted into the bottle, which will then expand and slow down any back and forth motion of the water. Do not use too much screening, since this would tend to overly restrict the flow of water.

3.a)

Students should not be able to detect any differences in the two forces. The force needed to accelerate both bottles as they roll across the table should be the same.

3.b)

Students should indicate that since the same force was required to accelerate the "Earth" kilogram and the "Moon" kilogram, then the two masses should have the same inertia. This is proof that the inertia of an object does not depend upon location; that is, whether it is on Earth or the Moon.

3.c)

If equal forces are applied, and equal acceleration takes place, then according to Newton's second law, the masses must also be the same. As students compare the forces, have them explain what they are comparing (forces necessary to produce accelerations) and what the significance of their findings is in comparing the result of forces on Earth and the Moon.

Part B: Comparing Weight

1.

Students observe the bottles labeled "1 kg, Earth" and "1 kg, Moon" at the Weight Station.

CHAPTER 9

2.a)

Depending on the accuracy of the spring scale, students should find the weight of the "1 kg, Earth" to be approximately 10 N.

Teaching Tip

If time and your expertise permit, a dial-type bathroom scale may have a covering placed over the dial that takes all the reading and divides them by six. Students can then stand on the scale and record their weight on the Moon. If a second scale is available, it could either be left unchanged to show weight on Earth, or altered to show weight on another planet, such as Jupiter. For weight on Jupiter, multiply the weight on Earth by 2.7.

3.a)

Students should find the weight of the "1 kg, Moon" to be approximately 1.6 N.

3.b)

$F_{w(Earth)} / F_{w(Moon)} = 10\text{ N}/1.6\text{ N} = 6.25$

The rounded off ratio should be 6.

3.c)

2-kg masses on Earth would weigh 20 N and 2-kg masses on the Moon would weigh 3.2 N. The rounded-off ratio would again be 6.

3.d)

The weights of the same masses are different because the gravitational forces of Earth and the Moon on these objects are different. Because the force of gravity on the Moon is one-sixth the force of gravity on Earth, the weight of a 1-kg bottle on the Moon (1.6 N) is one-sixth of its weight on Earth (10 N). The weight in both cases is proportional to the mass, but the proportionality constant depends on the mass and radius of the planet or the Moon.

3.e)

Student's answers should be similar to what follows. To reproduce the simulation, you have to realize that objects on the Moon weigh one-sixth of what they do on Earth. To make a simulation at home, the two water bottles plus their contents have to have weights in the ratio of 6 to 1 for Earth and the Moon. This means, however, that the two bottles would not have the same inertia.

Chapter 9 Sports on the Moon

At the Weight Station, you will find two bottles resting upright on a surface, one labeled "1 kg, Earth" and another labeled "1 kg, Moon." To keep the simulation accurate and realistic, follow the steps described below.

2. Grasp the string attached to the bottle labeled 1 kg, Earth and lift the bottle vertically. Get the "feel" of Earth's downward gravitational pull on the bottle and then carefully lower it back to the surface to rest in an upright position. Attach a spring scale calibrated in newtons (N) to the string and measure the bottle's *weight*.

a) Record the weight in newtons of the 1 kg, Earth bottle in your log.

3. Pretend you have been transported to the Moon. Remember, this is only a simulation of what it would feel like to lift a kilogram mass on the Moon. Lift and weigh the bottle labeled 1kg, Moon.

a) Record the weight in newtons of the 1 kg, Moon bottle in your log.

b) Divide the weight of 1 kg on Earth by the weight of 1 kg on the Moon and round off the answer to the nearest integer. Show your work and record your answer in your log.

c) If 2-kg masses instead of 1-kg masses had been used, what do you think would have been the individual weights of the bottles on Earth and the Moon? What would the ratio of the weights be? Write your answers in your log.

d) Why do you think the weights of equal masses, one on Earth and the other on the Moon, are different? Be as specific as you can. Use the values in your log to support your answer.

e) Your teacher knew the difference in weight of an object on Earth and the Moon to produce this simulation. How could you reproduce this simulation with two water bottles at home?

Physics Talk

GRAVITY ON THE PLANETS AND THE MOONS

In *Section 2*, you saw that the acceleration due to gravity on the Moon is ⅙ of the acceleration due to gravity on Earth. Therefore, you probably were not surprised when the simulation in this *Investigate* showed that the weight of an object on the Moon is ⅙ of the weight of the same object on Earth. Since, according to $F = ma$, the amount of acceleration of an object depends directly on the amount of applied force, the reduced rate of free-fall acceleration on the Moon must be caused by a gravitational pull that is smaller on the Moon than on Earth. On the Moon, both the free-fall acceleration and the force causing the acceleration are ⅙ of the amounts on Earth, regardless of what object is compared at both locations. But why ⅙ and not some other ratio? Isaac Newton answered that question.

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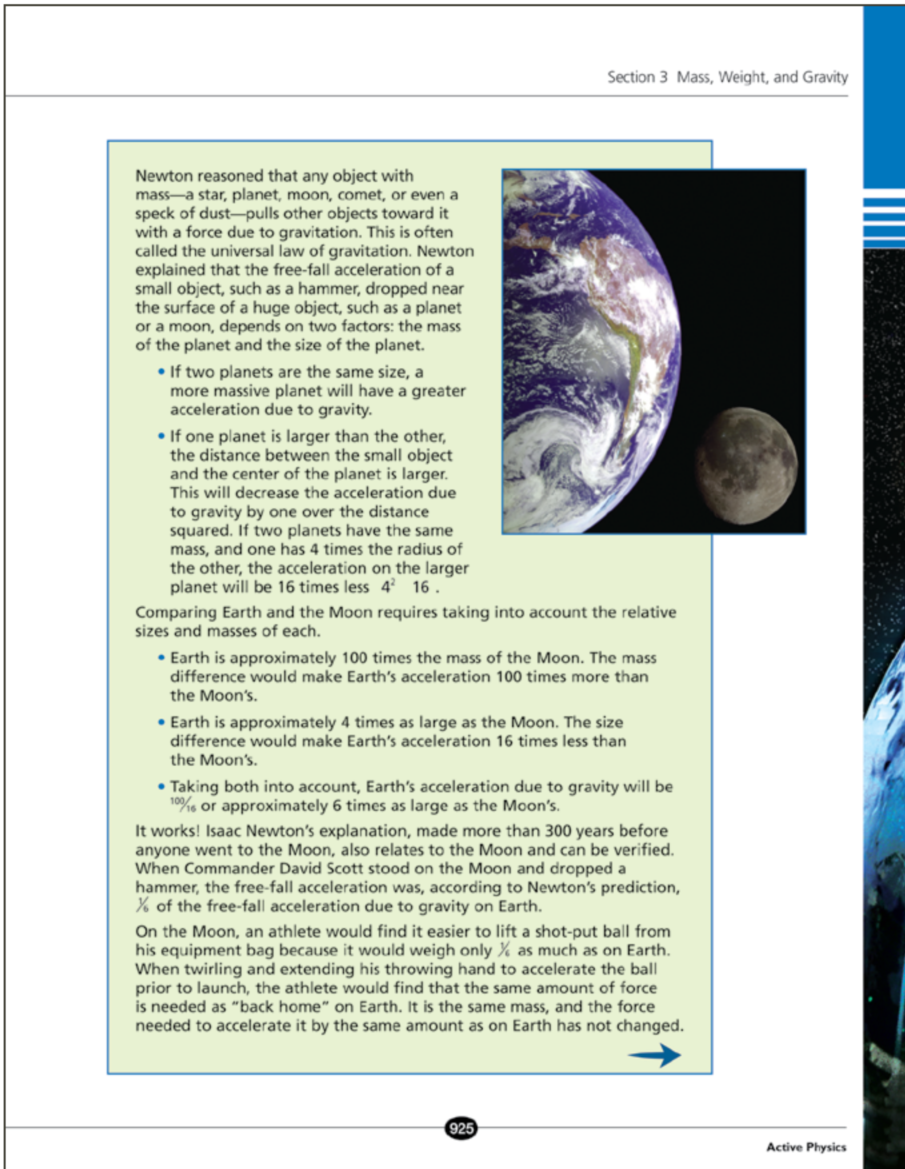

Newton reasoned that any object with mass—a star, planet, moon, comet, or even a speck of dust—pulls other objects toward it with a force due to gravitation. This is often called the universal law of gravitation. Newton explained that the free-fall acceleration of a small object, such as a hammer, dropped near the surface of a huge object, such as a planet or a moon, depends on two factors: the mass of the planet and the size of the planet.

- If two planets are the same size, a more massive planet will have a greater acceleration due to gravity.
- If one planet is larger than the other, the distance between the small object and the center of the planet is larger. This will decrease the acceleration due to gravity by one over the distance squared. If two planets have the same mass, and one has 4 times the radius of the other, the acceleration on the larger planet will be 16 times less 4^2 16 .

Comparing Earth and the Moon requires taking into account the relative sizes and masses of each.

- Earth is approximately 100 times the mass of the Moon. The mass difference would make Earth's acceleration 100 times more than the Moon's.
- Earth is approximately 4 times as large as the Moon. The size difference would make Earth's acceleration 16 times less than the Moon's.
- Taking both into account, Earth's acceleration due to gravity will be $^{100}/_{16}$ or approximately 6 times as large as the Moon's.

It works! Isaac Newton's explanation, made more than 300 years before anyone went to the Moon, also relates to the Moon and can be verified. When Commander David Scott stood on the Moon and dropped a hammer, the free-fall acceleration was, according to Newton's prediction, $^{1}/_{6}$ of the free-fall acceleration due to gravity on Earth.

On the Moon, an athlete would find it easier to lift a shot-put ball from his equipment bag because it would weigh only $^{1}/_{6}$ as much as on Earth. When twirling and extending his throwing hand to accelerate the ball prior to launch, the athlete would find that the same amount of force is needed as "back home" on Earth. It is the same mass, and the force needed to accelerate it by the same amount as on Earth has not changed.

Physics Talk

This section explains Newton's universal law of gravitation and why the gravitational pull on objects on the Moon is 1/6 the force of gravity experienced by objects on Earth. Students read that the force of gravity due to a celestial body is dependent on the body's mass and size. They discover that all objects exert a gravitational pull on all other objects, big or small, regardless of their size. The same theory is extended to planetary bodies.

It would be useful for students if they described Newton's law of universal gravitation between planets in their own words. To facilitate this process, ask students to provide an explanation, using Earth and the Moon as examples, to elaborate how acceleration due to gravity is affected by the mass and size of a planet. Consider asking students why Earth's size would make its acceleration due to gravity 16 times less than the Moon's acceleration if the masses were equal. Students should be able to describe why an object's acceleration on the Moon would be 1/6 times less than that on Earth.

To reinforce the difference between mass and weight, ask students to define the two quantities in terms of what they observed in the *Investigate*. It is important for students to realize that the rate of fall or acceleration due to gravity is the same for all objects on a given planet, but the force of the gravity on an object varies with mass. Point out to students that it is the ratio of the force of gravity on an object to an object's mass that determines the acceleration due to gravity. Students should note that this ratio is the same for objects on the planet's surface. Emphasize that the feather and a hammer fall at the same rate on the Moon due to the absence of air resistance, unlike Earth where air resistance alters the net force acting on an object and thus, the rate of fall.

Chapter 9 Sports on the Moon

Physics Words

inertia: the natural tendency of objects to resist a change in velocity (acceleration).

weight: the vertical, downward force exerted on a mass as a result of gravity, measured in newtons in the SI system.

However, the athlete would be thrilled at the result. For an amount of muscular work done by the athlete equal to a shot-put effort on Earth, the shot put would fly six times further.

Mass is a measure of the **inertia** or resistance to acceleration of an object. Mass is measured in units of kilograms (1000 g). **Weight** is the force of gravity on an object near the surface of a planet, moon, asteroid, and so on. It depends on the object's mass and the amount of gravitational pull on the specific planet. The unit of force is the newton (N).

A surprising result occurs when you look at weight and mass for different objects on Earth.

- A heavy object has a large weight on Earth. This means that the force of gravity is large. It also has large mass and therefore, it has a large inertia and it is hard to get it moving. Large force of gravity and a large inertia gives the heavy object an acceleration of $9.8\ m/s^2$ on Earth.
- A light object has a small weight on Earth. This means that the force of gravity is small. It also has a small mass and therefore, has a small inertia and it is easy to get it moving. Small force of gravity and a small inertia gives the light object an acceleration of $9.8\ m/s^2$ on Earth.
- All objects have the same acceleration of $9.8\ m/s^2$ on Earth. This is contrary to many people's "common sense." That is one reason many people did not believe Galileo when he tried to explain that all objects fall at the same rate.

The same thing happens on the Moon, where the acceleration of all objects is $1.6\ m/s^2$. That is why the feather and hammer dropped on the Moon fell at the same rate. (Feathers and hammers do not fall at the same rate on Earth because the air alters the fall on Earth. Without air resistance, everything on the Moon falls identically.)

Mass is the same on Earth, the Moon, and any other place in the universe. Weight on Earth is six times as large as weight on the Moon. A 90-kg high school football player weighs approximately 900 N on Earth (approximately 210 lb). That same 90-kg player weighs only 150 N (approximately 33 lb) on the Moon.

At the end of the last Apollo 15 Moon walk in 1971, Commander David Scott performed a live demonstration for the television cameras. He held out a geologic hammer and a feather and dropped them at the same time. If you look carefully at the photo, you can see a hammer in his right hand and a feather in his left hand.

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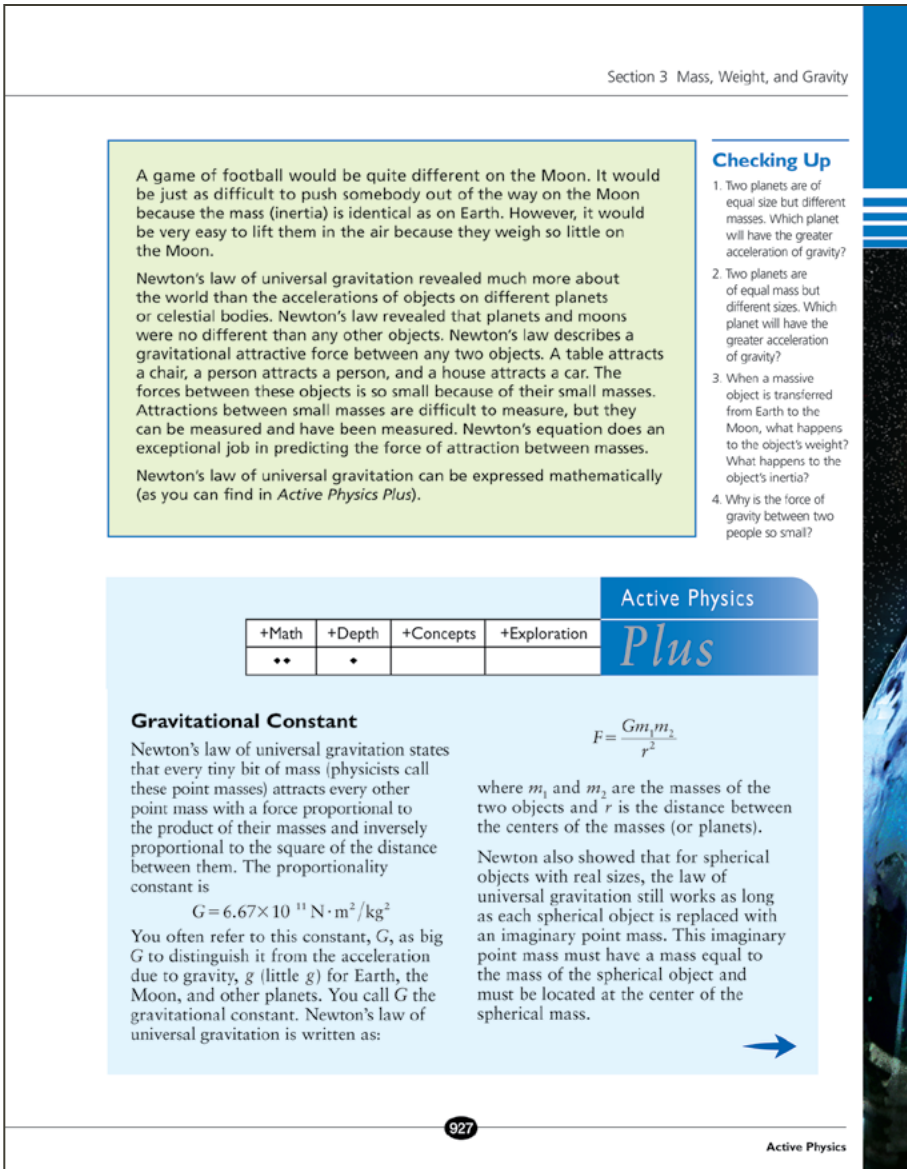


A game of football would be quite different on the Moon. It would be just as difficult to push somebody out of the way on the Moon because the mass (inertia) is identical as on Earth. However, it would be very easy to lift them in the air because they weigh so little on the Moon.

Newton's law of universal gravitation revealed much more about the world than the accelerations of objects on different planets or celestial bodies. Newton's law revealed that planets and moons were no different than any other objects. Newton's law describes a gravitational attractive force between any two objects. A table attracts a chair, a person attracts a person, and a house attracts a car. The forces between these objects is so small because of their small masses. Attractions between small masses are difficult to measure, but they can be measured and have been measured. Newton's equation does an exceptional job in predicting the force of attraction between masses.

Newton's law of universal gravitation can be expressed mathematically (as you can find in *Active Physics Plus*).

Checking Up

1. Two planets are of equal size but different masses. Which planet will have the greater acceleration of gravity?
2. Two planets are of equal mass but different sizes. Which planet will have the greater acceleration of gravity?
3. When a massive object is transferred from Earth to the Moon, what happens to the object's weight? What happens to the object's inertia?
4. Why is the force of gravity between two people so small?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
••	•		

Gravitational Constant

Newton's law of universal gravitation states that every tiny bit of mass (physicists call these point masses) attracts every other point mass with a force proportional to the product of their masses and inversely proportional to the square of the distance between them. The proportionality constant is

$$G = 6.67 \times 10^{11}\ \mathrm{N \cdot m^2/kg^2}$$

You often refer to this constant, G, as big G to distinguish it from the acceleration due to gravity, g (little g) for Earth, the Moon, and other planets. You call G the gravitational constant. Newton's law of universal gravitation is written as:

$$F = \frac{Gm_1m_2}{r^2}$$

where m_1 and m_2 are the masses of the two objects and r is the distance between the centers of the masses (or planets).

Newton also showed that for spherical objects with real sizes, the law of universal gravitation still works as long as each spherical object is replaced with an imaginary point mass. This imaginary point mass must have a mass equal to the mass of the spherical object and must be located at the center of the spherical mass.

two reasons: First, the force of gravity is a very weak force, which depends upon the masses attracting one another. Second, the mass of a person (even a very large person) is quite small compared to the mass of a planet. Masses such as planets exert gravitational forces which make the force between two small masses, such as people, look small in comparison.

Active Physics Plus

Students explore Newton's equation of universal gravitation. By equating the force of gravity on an object with that object's weight, they see that the acceleration due to gravity on a planet is directly proportional to a planet's mass and inversely proportional to the square of the planets' radii. Students then solve problems to calculate the acceleration due to gravity for Earth and the Moon, and compare these values using the relative mass and radii of the two bodies.

Checking Up

1.

For two planets with equal sizes (radii) but different masses, the planet with the larger mass will have the larger acceleration due to gravity.

2.

For two planets of equal mass but different sizes, the smaller planet will have the larger acceleration due to gravity.

3.

When a mass is transferred from Earth to the Moon, the object's weight decreases because the Moon's acceleration due to gravity is lower. The inertia of the mass will remain the same, since inertia depends upon the mass, not the weight.

4.

The force of gravity between two people is very small for

1.

$g_p = Gm_p/r_p^2$ for Earth,
$m_p = 5.98 \times 10^{24}$ kg,
$r_p = 6.38 \times 10^6$ m and
$G = 6.67 \times 10^{-11}\,\text{N}\cdot\text{m}^2/\text{kg}^2$
substituting in the formula yields

$$g_E = \frac{\left[\left(6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2\right) \times \left(5.98 \times 10^{24}\ \text{kg}\right)\right]}{\left(6.38 \times 10^6\ \text{m}\right)^2} =$$

9.8 N/kg.

2.

$g_p = Gm_p/r_p^2$ for the Moon
$m_p = 7.36 \times 10^{22}$ kg,
$r_p = 1.74 \times 10^6$ m and
$G = 6.67 \times 10^{-11}$ N $\cdot$ m^2/kg^2
substituting in the formula yields

$$g_M = \frac{\left[\left(6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2\right) \times \left(7.36 \times 10^{22}\ \text{kg}\right)\right]}{\left(1.74 \times 10^6\ \text{m}\right)^2}$$

$= 1.62$ N/kg.

3.

$g_E/g_M =$
$(9.8\ \text{N/kg})/(1.62\ \text{N/kg}) = 6.04.$

4.

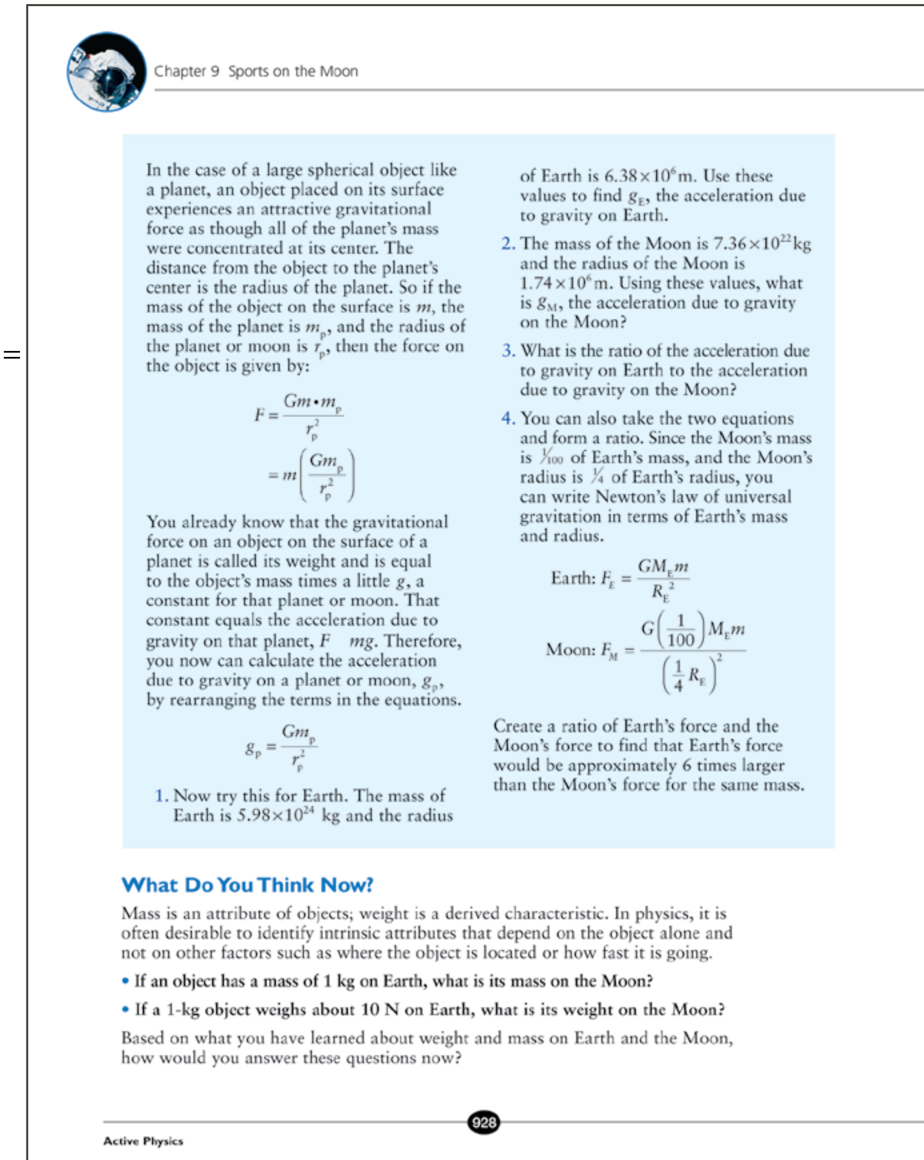
$$F_E = GM_E m/r_E^2$$

$$F_M = \frac{G(1/100)M_E m}{(1/4 r_E)^2}$$

Dividing F_E/F_M, G. M_E *and* r_E all cancel, leaving

$$\frac{1}{(1/100)/(1/4)^2} = \frac{100}{16} = 6.25,$$

which is close to the value for *Question 3*.



Chapter 9 Sports on the Moon

In the case of a large spherical object like a planet, an object placed on its surface experiences an attractive gravitational force as though all of the planet's mass were concentrated at its center. The distance from the object to the planet's center is the radius of the planet. So if the mass of the object on the surface is m, the mass of the planet is m_p, and the radius of the planet or moon is r_p, then the force on the object is given by:

$$F = \frac{Gm \bullet m_p}{r_p^2} = m\left(\frac{Gm_p}{r_p^2}\right)$$

You already know that the gravitational force on an object on the surface of a planet is called its weight and is equal to the object's mass times a little g, a constant for that planet or moon. That constant equals the acceleration due to gravity on that planet, F mg. Therefore, you now can calculate the acceleration due to gravity on a planet or moon, g_p, by rearranging the terms in the equations.

$$g_p = \frac{Gm_p}{r_p^2}$$

1. Now try this for Earth. The mass of Earth is 5.98×10^{24} kg and the radius of Earth is 6.38×10^6 m. Use these values to find g_E, the acceleration due to gravity on Earth.
2. The mass of the Moon is 7.36×10^{22} kg and the radius of the Moon is 1.74×10^6 m. Using these values, what is g_M, the acceleration due to gravity on the Moon?
3. What is the ratio of the acceleration due to gravity on Earth to the acceleration due to gravity on the Moon?
4. You can also take the two equations and form a ratio. Since the Moon's mass is $1/100$ of Earth's mass, and the Moon's radius is $1/4$ of Earth's radius, you can write Newton's law of universal gravitation in terms of Earth's mass and radius.

$$\text{Earth: } F_E = \frac{GM_E m}{R_E^2}$$

$$\text{Moon: } F_M = \frac{G\left(\frac{1}{100}\right)M_E m}{\left(\frac{1}{4}R_E\right)^2}$$

Create a ratio of Earth's force and the Moon's force to find that Earth's force would be approximately 6 times larger than the Moon's force for the same mass.

What Do You Think Now?

Mass is an attribute of objects; weight is a derived characteristic. In physics, it is often desirable to identify intrinsic attributes that depend on the object alone and not on other factors such as where the object is located or how fast it is going.

- **If an object has a mass of 1 kg on Earth, what is its mass on the Moon?**
- **If a 1-kg object weighs about 10 N on Earth, what is its weight on the Moon?**

Based on what you have learned about weight and mass on Earth and the Moon, how would you answer these questions now?

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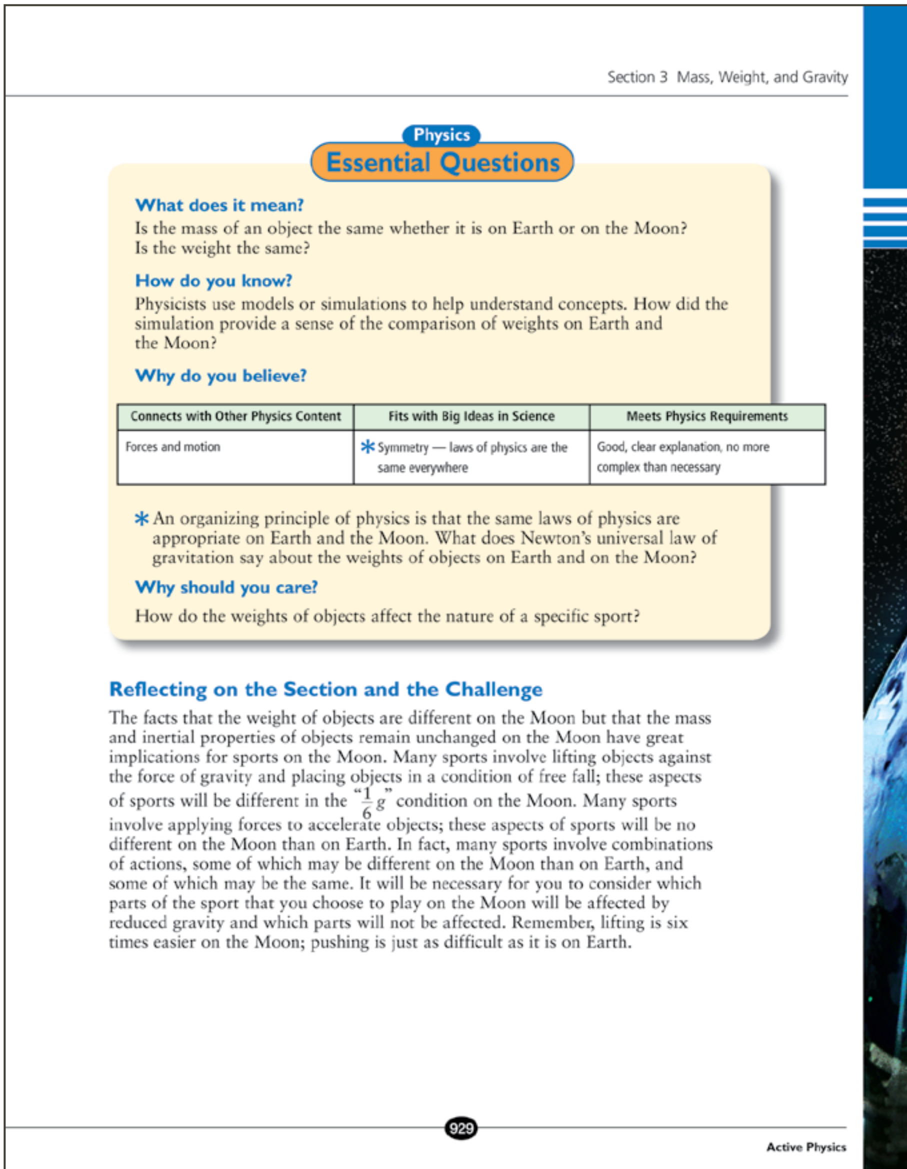
What Do You Think Now?

Encourage students to edit and update their answers. They should be able to distinguish between mass and weight using examples from the *Investigate* and *Physics Talk*. Ask them to explain why mass is an attribute of objects while weight is a derived characteristic. Determine what students understand when mass is described as an intrinsic property of objects. Share *A Physicist's Response* to highlight the concepts of mass and weight. Make sure that students have ample opportunity to discuss their preconceptions. Have them share their answers and revisit the *What Do You See?* section to see how their initial perceptions have changed with a better understanding of physics concepts.



Physics Essential Questions

What does it mean?

Is the mass of an object the same whether it is on Earth or on the Moon? Is the weight the same?

How do you know?

Physicists use models or simulations to help understand concepts. How did the simulation provide a sense of the comparison of weights on Earth and the Moon?

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

* An organizing principle of physics is that the same laws of physics are appropriate on Earth and the Moon. What does Newton's universal law of gravitation say about the weights of objects on Earth and on the Moon?

Why should you care?

How do the weights of objects affect the nature of a specific sport?

Reflecting on the Section and the Challenge

The facts that the weight of objects are different on the Moon but that the mass and inertial properties of objects remain unchanged on the Moon have great implications for sports on the Moon. Many sports involve lifting objects against the force of gravity and placing objects in a condition of free fall; these aspects of sports will be different in the "$\frac{1}{6}g$" condition on the Moon. Many sports involve applying forces to accelerate objects; these aspects of sports will be no different on the Moon than on Earth. In fact, many sports involve combinations of actions, some of which may be different on the Moon than on Earth, and some of which may be the same. It will be necessary for you to consider which parts of the sport that you choose to play on the Moon will be affected by reduced gravity and which parts will not be affected. Remember, lifting is six times easier on the Moon; pushing is just as difficult as it is on Earth.

Reflecting on the Section and the Challenge

Now that students know that lifting a mass is six times easier on the Moon than on Earth, ask them to reflect on how this will affect their sport on the Moon. Point out that all parts of a sport may not be affected when the location is changed from Earth to the Moon. Emphasize that accelerating an object requires just as much force on Earth as on the Moon. Ask students to reflect on all aspects of a sport from their *Chapter Challenge*. What students have learned in this section should give them more confidence in inventing a sport that meets the required criteria. Ask students to read the text of *Reflecting on the Section and the Challenge* carefully to gain ideas on what aspects of their presentations they could further strengthen.

Physics Essential Questions

What does it mean?

The mass is identical on Earth and the Moon. Mass is a measure of the amount of matter. The weights are not identical. Weight is a force that is dependent of the gravitational field strength on the planet or the Moon's surface.

How do you know?

The simulation provided a physical sense that the weights would be different on Earth and the Moon, even when the mass is identical.

Why do you believe?

Newton's law of gravitation states that $F = GMm/d^2$, where M is the mass of Earth or the Moon and d is equal to the radius of Earth or the Moon. By taking into consideration the ratio of the masses of Earth and the Moon and their relative sizes, it can be shown that the force of attraction (weight) is six times greater on Earth.

Why should you care?

In weightlifting, a person could lift 6 times as much mass. If someone can bench press 50 kg (110 pounds) on Earth, he can bench press 300 kg (660 pounds) on the Moon.

Physics to Go

Physics to Go

1. How would the sport of weight lifting be different on the Moon? If a person can lift 220 lb on Earth, what weight could that person lift on the Moon?
2. How would a baseball player's ability to swing (accelerate) a bat be affected on the Moon? Assume that a spacesuit does not inhibit the batter's movement.
3. For equal swings of the bat and equal speeds of the ball, how would the speed of a baseball when it leaves the bat compare on Earth and the Moon?
4. Imagine an outdoor game of baseball at Lunar Stadium.
   a) The center field wall is about 400 ft from home plate at a baseball park on Earth. Explain what the appropriate distance for the center field wall would be at Lunar Stadium. Use equations and numbers to explain your answers.
   b) Other aspects of baseball might be different on the Moon.
      - Should the pitcher's mound and the bases at Lunar Stadium be located at the same or different distances from home plate as on Earth? Explain your answer.
      - How fast would a major-league pitcher capable of a 100 mi/h "Earth pitch" be able to throw the ball on the Moon? Explain your answer.
      - How fast would players be able to run the bases on the Moon? Why?
   c) Describe the problems fans in the center field bleachers might have:
      - seeing a player slide into second base or home plate
      - watching a high fly ball
      - eating a hot dog
      - shouting at the umpire
5. Water would be very expensive on the Moon because it is unavailable.
   a) If you purchased a precious 1-L bottle of "Genuine Earth Water" at the Lunar Mall, what would be its mass, in kilograms? (Hint: On Earth, 1 L of water has a mass of 1 kg and a weight of 9.8 N.)
   b) What would be its weight, in newtons?
6. If you bought 10 kg of potatoes on the Moon, would they make as many servings as 10 kg of potatoes make on Earth?

1.

Because the strength of the Moon's gravitational field is 1/6 that of Earth, the weight of an object $F_w = mg$ would be 1/6th that on Earth. Thus, if a person can lift 220 lb on Earth, he or she could lift $220 \times 6 = 1320$ lb on the Moon.

2.

A bat's inertia or resistance to being accelerated would be unchanged on the Moon; therefore, a batter's ability to swing a bat would be unchanged on the Moon.

3.

A baseball's inertia would be equal on the Moon and Earth; therefore, a ball's response to being hit by a bat would be the same on the Moon as on Earth. An equally good explanation is that the law of conservation of momentum applies equally on the Moon and Earth.

4.a)

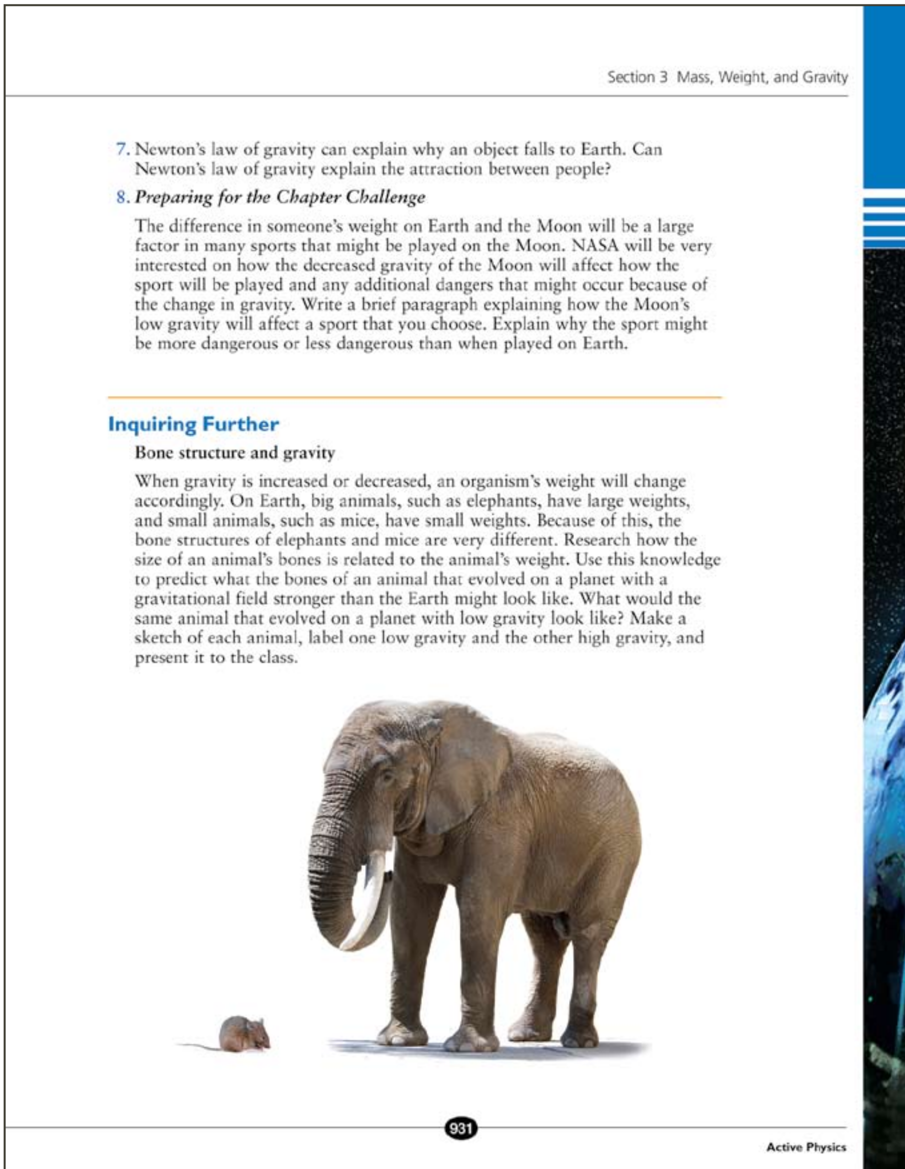
The correct distance for the center field wall on the Moon should be much farther away. (400 ft $\times$ 6 = 2400 ft) A baseball would spend 6 times as long in the air on the Moon as on Earth.

4.b)

- If a batted fly ball spends six times longer in the air on the Moon compared to on Earth, a change in base path distance or the rules of the game may be necessary. A significant change in the distance from the pitcher's mound to home plate would not be called for. (See the next bullet for an explanation.)
- A baseball pitcher would be able to throw a ball at the same speed on the Moon and on Earth because the "launch speed" depends on the inertia of the ball, which is the same in both locations. However, the pitcher is not able to accelerate his body forward as quickly on the Moon, due to a lower friction force.
- Players would not be able to run as usual on the Moon (as will be explained in detail in *Section 8* later in this chapter); therefore, research is needed to find out how fast players would be able to move from base to base in order to establish how to adjust the distance between bases.

4.c)

- Fans in the center field bleachers would be nearly $\frac{1}{2}$ mile from the infield—one mile is 5280 feet. Seeing a player slide into a base would be impossible.
- A fly ball would rise 6 times higher on the Moon than on Earth; a high fly ball would rise nearly out of sight.



7. Newton's law of gravity can explain why an object falls to Earth. Can Newton's law of gravity explain the attraction between people?

8. *Preparing for the Chapter Challenge*

The difference in someone's weight on Earth and the Moon will be a large factor in many sports that might be played on the Moon. NASA will be very interested on how the decreased gravity of the Moon will affect how the sport will be played and any additional dangers that might occur because of the change in gravity. Write a brief paragraph explaining how the Moon's low gravity will affect a sport that you choose. Explain why the sport might be more dangerous or less dangerous than when played on Earth.

Inquiring Further

Bone structure and gravity

When gravity is increased or decreased, an organism's weight will change accordingly. On Earth, big animals, such as elephants, have large weights, and small animals, such as mice, have small weights. Because of this, the bone structures of elephants and mice are very different. Research how the size of an animal's bones is related to the animal's weight. Use this knowledge to predict what the bones of an animal that evolved on a planet with a gravitational field stronger than the Earth might look like. What would the same animal that evolved on a planet with low gravity look like? Make a sketch of each animal, label one low gravity and the other high gravity, and present it to the class.

- Outdoor baseball would require space helmets for spectators; eating a hot dog would be difficult.
- Because there is no air on the Moon, sound is not transmitted. Therefore, shouting at an umpire would not be possible.

5.a)

On the Moon, 1 liter of water would have the same mass as on Earth, a mass of 1 kg.

5.b)

The weight of 1 kg of water on the Moon would be given by $F_w = mg = (1 \text{ kg})(1.6 \text{ m/s}^2)$ or a weight of 1.6 N.

6.

They would make the same number of servings.

7.

The answer is no, but students might enjoy realizing how words like "attraction" and "falling" are used in both scientific and non-scientific ways.

8.

Preparing for the Chapter Challenge

Student answers will vary depending upon the sport played. With decreased weight, a sport such as wrestling may lead to people being thrown long distances, and possibly landing in a bad place. Other sports like bowling would not be affected at all. Students should justify their reasons for why the sport would be safe or not safe due to the decreased weight.

Inquiring Further

Because the weight of an object is related to its volume, the weight increases as the cube of the size. This can be seen from the volume of a simple sphere given by $V = 4/3\pi r^3$. The ability of a bone to support a weight depends upon the bone's area, which increases as the square of the size (area of a circle $= \pi r^2$). Since the volume and weight increase faster than the bone's size, larger animals need progressively larger bones to support their increased weight. Mice have thin, delicate bones, while elephants have large, thick bones.

The bones of an animal evolved on a planet with high gravity would be thicker, and the animal might appear to be smaller, squat, and thick-boned. An animal evolved on a planet with low gravity might appear, tall, thin and have more delicate bones, since less force is required to support the lower weight.

SECTION 3 QUIZ

9-3a Blackline Master

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

1. A helium-filled balloon with a mass of 4 kg is moved from Earth to the Moon. The mass of the balloon on the Moon would be

   a) 4 kg.
   b) $4/6$ kg.
   c) 1 kg.
   d) 24 kg.

2. A 5-kg mass weighs 49 N on Earth. When the mass is transferred to the Moon, the weight of the mass would be

   a) 5 kg.
   b) 49 N.
   c) $5/6$ kg.
   d) $49/6$ N.

3. Two planets have identical masses, but planet A is one-half the radius of planet B. Compared to the acceleration due to gravity on planet A, the acceleration due to gravity on planet B is

   a) four times greater.
   b) twice as great.
   c) half.
   d) one quarter.

4. Two planets have identical radii, but planet A is one-half the mass of planet B. Compared to the acceleration due to gravity on planet A, the acceleration due to gravity on planet B is

   a) four times greater.
   b) twice as great.
   c) half.
   d) one quarter.

5. The reason a hammer and a feather accelerate at the same rate on the Moon when dropped, but not on Earth, is that

   a) the Moon pulls equally on all objects but Earth does not.
   b) the Moon is smaller than Earth.
   c) Earth has an atmosphere but the Moon does not.
   d) Earth has a larger mass than the Moon.

SECTION 3 QUIZ ANSWERS

1. a) The mass of an object does not change when transferred from Earth to the Moon, so it would still be 4 kg.

2. d) The weight of an object on the Moon is one-sixth the weight of an object on Earth because the Moon's gravitational field is one-sixth that of Earth.

3. d) If the masses are equal, the acceleration due to gravity decreases with the inverse square of the radius. Since planet B has twice the radius, the acceleration due to gravity on the planet will be $\left(\frac{1}{2}\right)^2$ or one-fourth as strong.

4. b) If the radii of the planets are equal, the acceleration due to gravity increases with planet's mass. A planet with double the mass will have double the acceleration due to gravity.

5. c) Without an atmosphere, all objects on the Moon fall at the same rate. Gravity pulls harder on objects of large mass than those with small mass. Although it is true that the Moon is smaller than Earth, *Choice b)* and that Earth has a larger mass than the Moon, *Choice d)*, these are not the reasons that all objects accelerate at the same rate.