SECTION 5

Gravity, Work, and Energy: Jumping on the Moon

Section Overview

Students investigate jumping on Earth using the principles of conservation of energy and with their results, predict how high a person could jump on the Moon. They identify the source of their energy when they crouch and jump as high as they can, then determine why their body is not able to leave the floor when they crouch and rise without jumping. Students further calculate their jump height and their total change in height by marking their position on a wall at different stages of their jump. The crouch position is their "ready height," the tiptoe position is their "launch height," and the highest they can jump is recorded as their "peak height." Later, students analyze data and find that the ratio of the jump height on Earth to the ratio of the jump height on the Moon is more than six times higher. Students eventually consider ways to apply their analysis to their *Chapter Challenge*.

Background Information

In this section, the analysis of a vertical jump from *Physics in Action*, *Section 9* is applied to a vertical jump on the Moon with the surprising result that humans can jump more than six times higher on the Moon than on Earth. You may find it surprising that the predicted height of a vertical jump by a person standing on the Moon would not simply be six times greater than a jump executed in the same way by the same person on Earth due to the $1/6$-g Moon environment. It is true that a ball thrown straight up with equal launch speeds on Earth and the Moon would fly six times higher on the Moon than on Earth, so why would a human body also not fly six times higher on the Moon than on Earth? The answer to this dilemma is that a human body would fly six times higher on the Moon than on Earth if the launch speeds were equal at both locations, but that would not be the case if equal jumping efforts were made on Earth and on the Moon.

As will be shown below, the law of conservation of energy shows that if a person were to replicate the same pre-launch technique used for a vertical jump on Earth to a jump from the surface of the Moon— that is, at both locations the person applies the same average muscular force to push their feet against the ground while rising the same distance from crouched to launch positions—the person's speed at the instant of launch would be significantly higher on the Moon than on Earth. The person's mass also is assumed to be equal at both locations. For direct comparison of gravitational effects on jumping height, the person jumping on the Moon is inside an air-filled facility, which does not require wearing a 100-kg space suit/life-support system. This complicates the comparison by introducing additional mass and limitations on movement as variables. The enhanced launch speed of a jumper on the Moon would cause the person's body to fly upward significantly higher than the "six times Earth" height for equal launch speeds on the Moon and Earth. Conservation of energy can be used to determine launch speeds for vertical jumps on Earth and the Moon:

(KE at launch) =
(Work done during push phase) –
(Gain in PE of center of mass during push phase) =
$mv^2/2 = Fh - mgh = h(F - mg)$,

where h is the increase in center of mass height during the push phase. Rearranging the above equation yields the predicted launch speed on Earth, $v_{\text{Earth}} = \sqrt{(2h/m)(F - mg)}$. The launch speed on the Moon is predicted by replacing the jumper's weight in the above equation, mg, by $(mg/6)$: $v_{\text{Moon}} = \sqrt{(2h/m)[F - (mg/6)]}$. Comparing the above two equations, v_{Moon} for a particular jumper is greater than v_{Earth} because the term $[F - (mg/6)]$ in the equation for v_{Moon} is greater than the term $(F - mg)$ in the equation for v_{Earth}.

Conservation of energy is used below to arrive at a general equation to predict a person's vertical jump height (the vertical distance that the person's center of mass rises from the instant of launch to the peak of flight), H, in terms of the average force, F, exerted during the push phase, the vertical distance, h, that the person's center of mass is lifted during the push phase, the person's mass, m, and the acceleration due to gravity, g. The person's weight is, of course, represented as mg. KE to represent kinetic energy, and PE to represent gravitational potential energy.

(Work done during push phase) =
(Gain in PE of center of mass during push phase) +
(Gain in PE of center of mass during flight phase);

$Fh = mgh + mgH = mg(h + H)$; $Fh/mg = H + h$;
$H = (Fh/mg) - h = h[(F/mg) - 1]$,

where H is the jump height above the ground. As presented in the student text for this section, the equation predicts a jump height 9.3 times higher when data for the same person is used in the analysis in the $(1/6)g$-Moon environment:

$$H = h[(F/mg) - 1] =$$

$$(0.35\text{ m})\left[\frac{1200\text{ N}}{(44\text{ kg})(1.6\text{ m/s}^2)} - 1\right] = 5.6\text{ m}.$$

5.6 m/(0.60 m) = 9.33 times higher on the Moon. Is this a "universal" answer? Would everyone jump 9.3 times higher on the Moon than on Earth? No, the height to which a person would be able to jump on the Moon compared to Earth depends not only on the different effects of gravity, but, in addition, three factors which may vary among individuals. As may be seen in the equation, $H = h[(F/mg) - 1]$, the jump height, H, depends not only on the "local" value of g ("g" on Earth, "$g/6$" on the Moon), but also on the vertical distance that the person's center of mass is lifted during the push phase, h, the average force exerted during the push phase, F, and the person's weight, mg. Obviously, the more force a jumper can generate for a given weight, the higher the person will be able to jump.

NOTES

CHAPTER 9

Crucial Physics

- When jumping, energy stored in the leg muscles is converted to gravitational potential energy to raise the body off the ground.
- At the point of launch, the body has kinetic energy $\left(KE = \frac{1}{2}mv^2\right)$ that is converted into gravitational potential energy $(GPE = mg\Delta h)$. The kinetic energy at launch equals the gravitational potential energy at the peak of the jump.
- The total energy supplied by the leg muscles goes to raising the body's position above the ground and increasing the *GPE*.

Learning Outcomes	Location in the Section	Evidence of Understanding
Measure changes in height during a vertical jump.	***Investigate*** Steps 2 and 3	Students measure the distances from the floor to the nearest 0.01 m as a student jumps upward from a "ready" position and label the positions as "ready," "launch," and "peak height."
Calculate changes in gravitational potential energy during a vertical jump.	***Physics Talk***	Students calculate changes in gravitational potential energy (*GPE*) on Earth and the Moon during a vertical jump by calculating the *GPE* at various positions. The changes in *GPE* are found by subtracting the ready *GPE* at the ready height from the *GPE* at the peak height.
Apply conservation of energy to analysis of a vertical jump, including weight, force, height, and time of flight.	***Physics Talk***	Students analyze how work is transformed into energy and the energy is transformed at three different positions of a jump. How the *GPE* is affected by the weight, jump height, and acceleration due to gravity is explored, as well as time of flight.
Make predictions about jumping on the Moon using information gained from analyzing jumping on Earth.	***Physics Talk***	Students predict their jump height on the Moon using data from their jump height on Earth.

Section 5 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Meter stick	2 per group	
Sticky notes, pad, 3 in. x 3 in.		5 per class
Marker, black		6 per class
Access to clear area with a wall*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow two class periods or 90 minutes for students to complete the *Investigate* portion of the section.

Teacher Preparation

- Obtain a VCR or DVD player and TV that has single frame advance capability to show stop-frame video to students of an athlete jumping.
- **OPTIONAL:** Set up a motion detector, computer and interface if available. Attach the motion detector to the classroom ceiling so students can jump underneath it to measure their jump height as a more accurate method of obtaining the difference between the launch and peak positions of the jump.

Safety Requirements

- Students who do not wish to jump should not be forced to do so. Check with the school nurse to see if any students might have physical limitations that would preclude their jumping in class.
- Make certain the jump area is clear of all obstructions.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Meter stick		1 per class
Sticky notes, pad, 3 in. x 3 in.		5 per class
Marker, black		6 per class
Access to clear area with a wall*		1 per class

*Additional items needed not supplied

Time Requirement

- Allow one class period or 45 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

- Obtain a VCR or DVD player and TV that has single frame advance capability to show stop-frame video to the students of an athlete jumping.
- **OPTIONAL:** Set up a motion detector, computer and interface if available. Attach the motion detector to the classroom ceiling so the student jumping can jump underneath it to measure their jump height as a more accurate method of obtaining the difference between the launch and peak positions of the jump.
- Prepare a transparency of the Ready, Launch, and Peak Height Position diagram in the *Teacher Resources* CD to clearly show the relative "ready, launch and peak" positions of the students, and to record the data.

Safety Requirements

- Choose a student volunteer to do the jump for the class.
- Make certain the jump area is clear of all obstructions.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Generating a scaled drawing	***Investigate*** Steps 5 and 7	**Augmentation** • Students who struggle with number concepts and have had a difficult time with the scaled drawings in the previous sections may need help deciding on an appropriate scale to use in their drawings. If they do not use a scale, their drawings will not fit on their papers, and without a set scale, it will be difficult for them to compare their Earth and Moon drawings. **Accommodation** • If students are really struggling to understand the scaled drawing, use the class average for each of the positions (ready, launch, and peak) to develop a real-life model for Earth and the Moon on the wall or floor using roll paper.
Interpreting information from a table Using academic vocabulary	***Physics Talk*** Energy Table	**Augmentation** • Understanding the type(s) of energy involved in each stage of the jump may be difficult for students who have not mastered the academic vocabulary needed to talk about energy conversions. Ask students to add energy labels to their scaled jump drawings. Then ask students to write a sentence explaining why that type of energy is included at the corresponding phase of the jump. • Students must understand the law of conservation of energy to solve problems in this section. Mastering the vocabulary will make it easier to apply the mathematical concepts.
Writing a general expression to represent a mathematical relationship	***Active Physics Plus*** Questions 1–5	**Augmentation** • Refer students back to the sample problems on the previous page in Active Physics Plus to help them write expressions with variables using the sample shown with given values. • Students may struggle to write expressions with variables. Ask them to write the expressions using words first and then substitute in variables. • Provide the expressions and ask students to write an explanation to support each expression. **Accommodation** • Provide a list of mathematical expressions and ask students to match the corresponding expression with *Questions 1–5* in Active Physics Plus.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Understanding concepts	***Investigate*** Step 6 ***Physics Talk***	The factor of 6 that relates Earth's gravity to the Moon's gravity does not show up in a comparison between Peak Height on the Moon and Peak Height on Earth. Rather, it shows up in a comparison of the difference between Peak Height and Ready Height on the Moon to the difference between Peak Height and Ready Height on Earth. As students read through the text and work through the calculations, they should achieve mastery of this concept. If they are struggling, show the relationships on the board. Give them an opportunity to state their ideas as to why the relationship works this way.
Higher-order thinking	***Active Physics Plus*** ***Reflecting on the Section and the Challenge***	Have students read the paragraphs just above and below the photo of the high jumper. Then ask: "What physiological changes is the text referring to?" Allow students to suggest ideas and describe their thinking. Then hold a brief discussion about how the lesser force of gravity on the Moon may cause an athlete's body to react differently to the same muscle movements used on Earth. Have students think about how an athlete performing his or her chosen sport on the Moon might be affected.

Explaining concepts accurately in science requires precise wording. As a result, explanations can often seem verbose, and therefore, may leave an ELL student feeling confused or overwhelmed. This section has several vocabulary terms composed of multiple words (for example, Ready Height, gravitational potential energy), and this may make the section seem more complicated than it really is. Organizing information in graphic form can reduce the number of words needed to show relationships and relate concepts. A table or chart is one tool students can use to condense the information into a more accessible form.

The chart below is an expanded version of the sketch at the end of the *Physics Talk* in the student text, merged with the two tables from the *Physics Talk*. Have students copy it into their *Active Physics* logs (or make copies from the *Teachers Resource* CD) and fill in the missing information. Students should feel free to add additional information they may find helpful, such as equations or additional information they would need for performing calculations. They can use the chart as a reference as they work through the rest of this section.

9-5a Blackline Master

Earth		Moon	
Gravitational Potential Energy (*mgh*) ____?____ J	Peak Height ____?____ m	Peak Height ____?____ m	Gravitational Potential Energy (*mgh*) ____?____ J
Kinetic Energy ____?____ J	Launch Height ____?____ m	Launch Height ____?____ m	Kinetic Energy ____?____ J
Leg Muscle Potential Energy ____?____ J	Ready Height ____?____ m	Ready Height ____?____ m	Leg Muscle Potential Energy ____?____ J
Total Energy (J) = change in ____?____ energy = body weight × (____?____ – Ready Height)			**Total Energy** (J) = Change in ____?____ energy = body weight × (____?____ – Ready Height)

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SECTION 5

Teaching Suggestions and Sample Answers

What Do You See?

Basketball on the Moon! The illustration evokes a sense of curiosity and awe at the scientific implications of such a venture. Students will most likely comment on the astronaut looking surprised at how high he's actually jumped. Encourage them to write down their responses in their *Active Physics* logs. Prompt them to make connections between the illustration and the title of this section.

You might want to ask how gravity, work, and energy are related to jumping on the Moon. Point out that their initial perceptions of what the artist has tried to capture will gradually shift as they learn more about the physics concepts explored in this section. To demonstrate how this happens, write down students' responses on the board and discuss the significance of their ideas when highlighting a physics principle.

What Do You Think?

The *What Do You Think?* questions stimulate students to think of gravity on the Moon and how that affects the hang time during a jump.

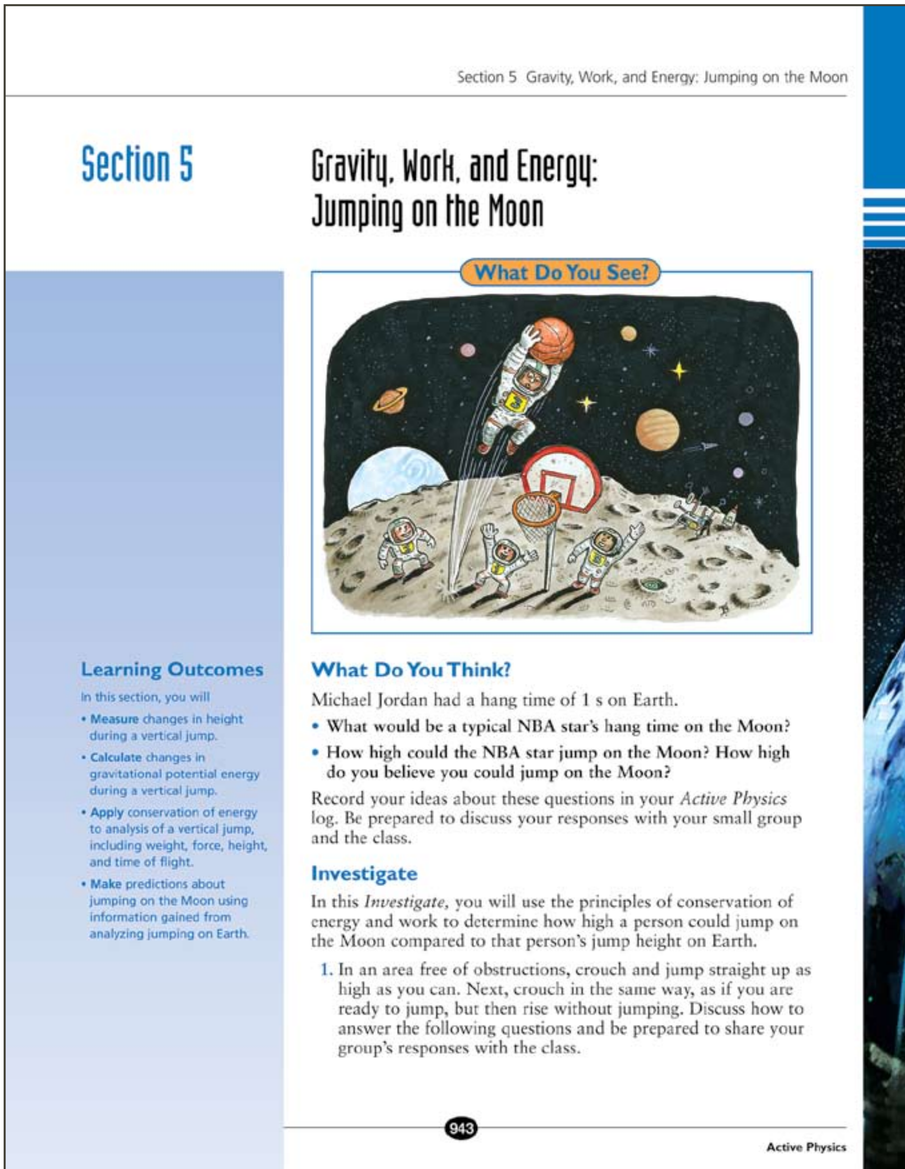
Ask students to recall what they have learned about gravity on Earth and the Moon from previous investigations and actively apply that knowledge to answering these questions. Remind them at this point they will not be evaluated for the correctness of there responses. It is important that they discuss their thoughts in class, making connections that will later help them in finding relevant answers. To initiate a lively discussion that feeds students' interest, you might want to ask students why the author has mentioned Michael Jordan and how familiar they are with his game.

Students' Prior Conceptions

This section reviews the relationships between Newton's laws as applied to the vertical jump and to the conservation of mechanical energy. In an ideal situation where there is no friction involved in the jump, the change in the mechanical energy equals the change in the potential energy. Explore the following student misconceptions to strengthen students' understanding of projectile motion.

1. **Constant forces produce constant motion; as soon as a force is removed from a projectile, it slows down or stops.** One of the most difficult concepts for students to accept is the fact that the initial force of the jumper from the floor no longer exists as soon as contact with the floor ceases; however, a constant force of gravity acts upon the jumper while the jumper is on the floor and in the air. The existence of this force, the force due to gravity, produces accelerated motion and the acceleration is always acting downward, slowing down the jumper on the way up and speeding up the jumper on the way down. The motion only stops when the jumper connects with the floor again and uses muscles to counterbalance the force of gravity and stop the motion. This is also a good time for you to emphasize that gravity is a force and hence the speed and/or the velocity of a projectile moving away from or toward Earth is constantly changing. This is true on the Moon as well.

2. **Students do not appreciate the idea of energy conservation as a tool to explain phenomena.** Again, by using mathematical modeling and proportional reasoning, you can enhance the understanding of the connection between the transformation of kinetic energy, $\frac{1}{2} mv^2$, into gravitational potential energy, *GPE,* and vice versa. The trajectory of the jumper and the change in velocity at each interval may easily be calculated by using the maximum height or the measured height at various equal time intervals.



Section 5 Gravity, Work, and Energy: Jumping on the Moon

Section 5

Gravity, Work, and Energy: Jumping on the Moon

What Do You See?

Learning Outcomes

In this section, you will

- **Measure** changes in height during a vertical jump.
- **Calculate** changes in gravitational potential energy during a vertical jump.
- **Apply** conservation of energy to analysis of a vertical jump, including weight, force, height, and time of flight.
- **Make** predictions about jumping on the Moon using information gained from analyzing jumping on Earth.

What Do You Think?

Michael Jordan had a hang time of 1 s on Earth.

- What would be a typical NBA star's hang time on the Moon?
- How high could the NBA star jump on the Moon? How high do you believe you could jump 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

In this *Investigate,* you will use the principles of conservation of energy and work to determine how high a person could jump on the Moon compared to that person's jump height on Earth.

1. In an area free of obstructions, crouch and jump straight up as high as you can. Next, crouch in the same way, as if you are ready to jump, but then rise without jumping. Discuss how to answer the following questions and be prepared to share your group's responses with the class.

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Active Physics

What Do You Think?

A Physicist's Response

After viewing a video of astronauts bounding on the Moon, one can easily see that someone on the Moon is able to jump higher and "hang" in the air longer on the Moon than on Earth. What is surprising is that there is not a simple "six times higher and longer" ratio that exists for a projectile launched on the Moon. If a jumper on the Moon is able to apply the same average force on the ground during the jump on the Moon as on Earth, less energy is lost to the effects of gravity before leaving the ground. This leaves more energy available for kinetic energy and consequently a higher leap greater than a factor of six. The "hang time" of an athlete depends upon the jumper's kinetic energy when leaving the surface. The higher kinetic energy means that the hang time also will be greater by more than a factor of six.

Investigate

1.a)

The source of energy used to push your body upward is the energy stored in the body cells, which is transformed by the leg muscles into gravitational potential and kinetic energy at first and then all into gravitational potential energy when the jumper is at the peak of the jump.

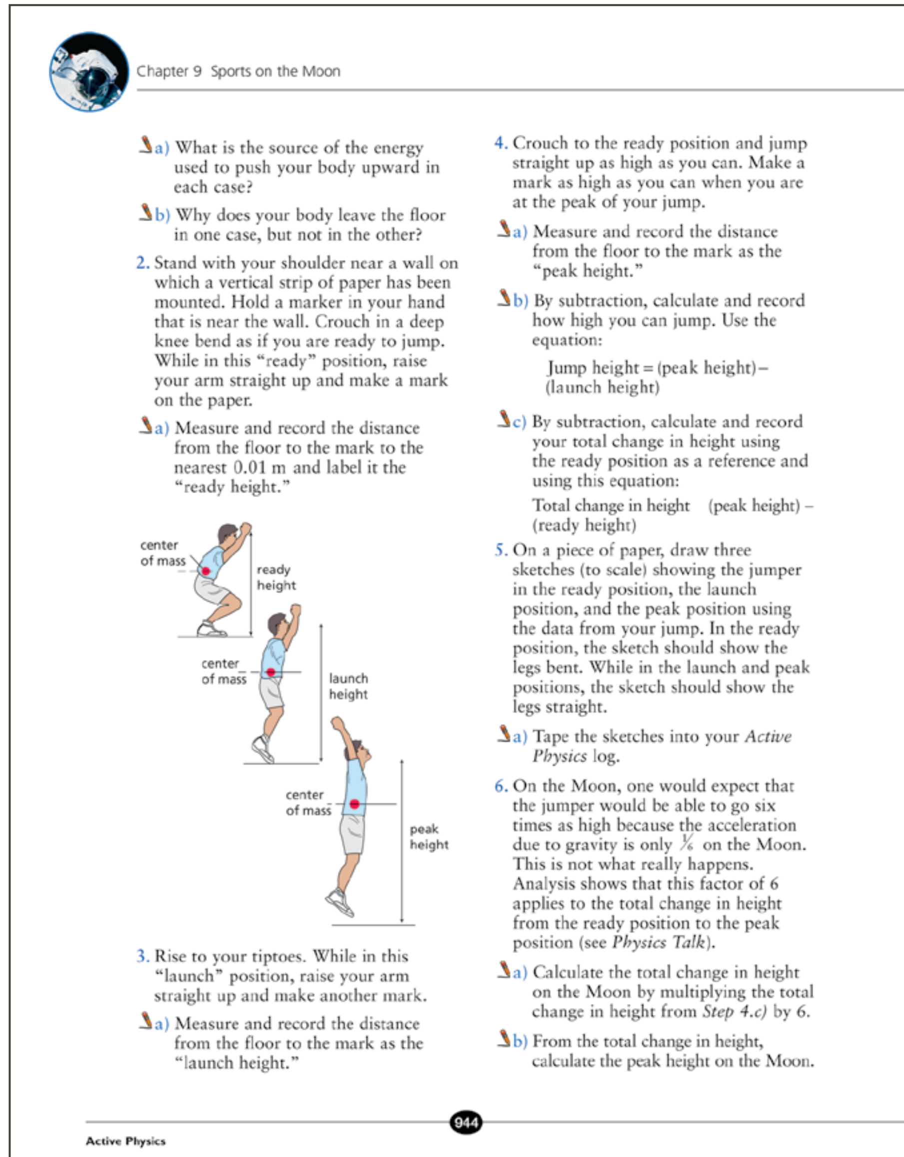
1.b)

In the first case, all the energy of the leg muscles is released quickly and goes toward exerting a force on the ground. The reaction force of the ground pushes the body upward with a force sufficient to accelerate the body upward and a velocity large enough to leave the ground. In the second case, the energy of the muscles is released slowly and the reaction force of the ground to the force of the muscles is smaller and not sufficient to allow the body to leave the ground.

2.a)

The height of the mark the student makes above the floor will depend upon the student's physical characteristics.

9-5b Blackline Master



a) What is the source of the energy used to push your body upward in each case?

b) Why does your body leave the floor in one case, but not in the other?

2. Stand with your shoulder near a wall on which a vertical strip of paper has been mounted. Hold a marker in your hand that is near the wall. Crouch in a deep knee bend as if you are ready to jump. While in this "ready" position, raise your arm straight up and make a mark on the paper.

a) Measure and record the distance from the floor to the mark to the nearest 0.01 m and label it the "ready height."

3. Rise to your tiptoes. While in this "launch" position, raise your arm straight up and make another mark.

a) Measure and record the distance from the floor to the mark as the "launch height."

4. Crouch to the ready position and jump straight up as high as you can. Make a mark as high as you can when you are at the peak of your jump.

a) Measure and record the distance from the floor to the mark as the "peak height."

b) By subtraction, calculate and record how high you can jump. Use the equation:

Jump height = (peak height) – (launch height)

c) By subtraction, calculate and record your total change in height using the ready position as a reference and using this equation:

Total change in height (peak height) – (ready height)

5. On a piece of paper, draw three sketches (to scale) showing the jumper in the ready position, the launch position, and the peak position using the data from your jump. In the ready position, the sketch should show the legs bent. While in the launch and peak positions, the sketch should show the legs straight.

a) Tape the sketches into your *Active Physics* log.

6. On the Moon, one would expect that the jumper would be able to go six times as high because the acceleration due to gravity is only $1/6$ on the Moon. This is not what really happens. Analysis shows that this factor of 6 applies to the total change in height from the ready position to the peak position (see *Physics Talk*).

a) Calculate the total change in height on the Moon by multiplying the total change in height from *Step 4.c)* by 6.

b) From the total change in height, calculate the peak height on the Moon.

3.a)

The height of the mark the student makes above the floor will depend upon the student's physical characteristics.

4.a)

Students' jump heights will vary, as will the location of the marks they make.

4.b)

Typical jump heights for students will range from 20–50 cm.

4.c)

Students record the change in height of their center of mass between the ready and launch positions using the equation provided.

5.a)

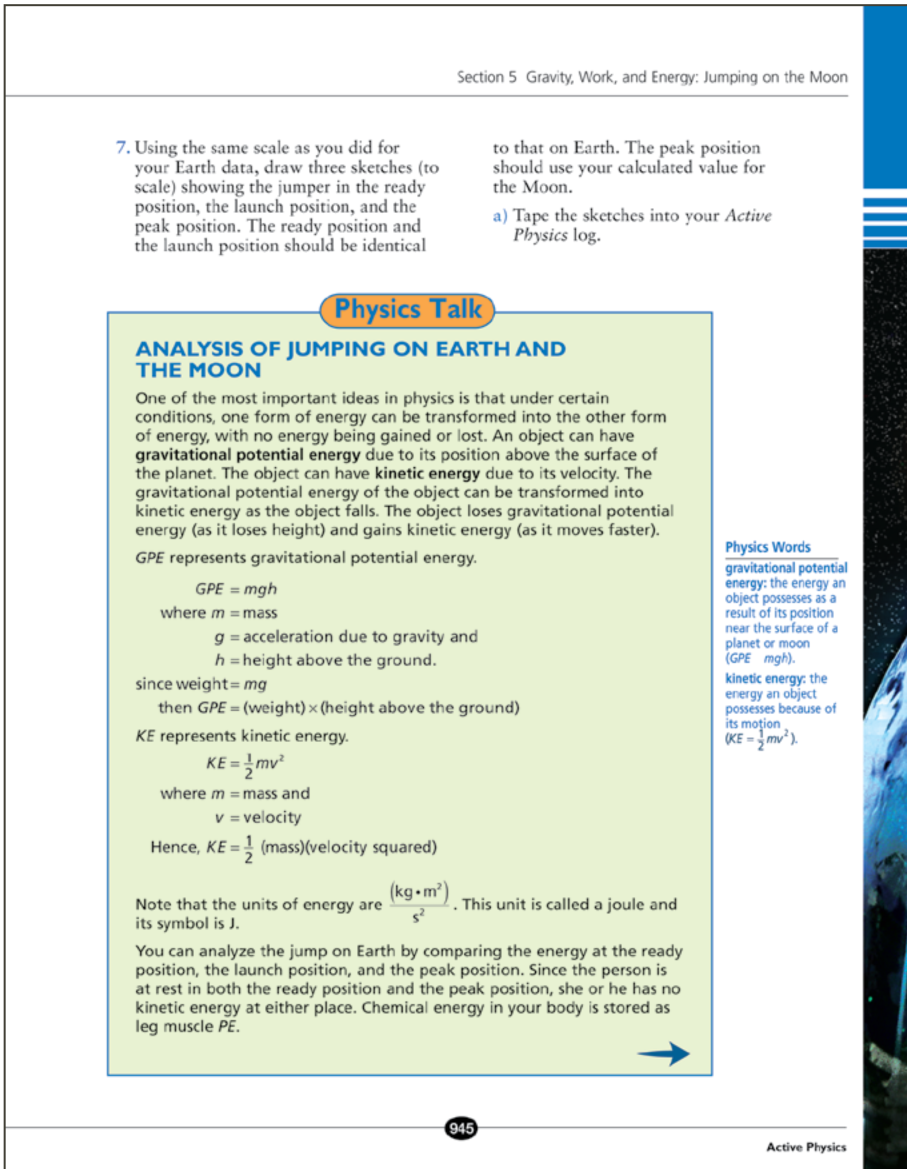
Students make scale drawings of their ready, launch, and jump heights on Earth.

6.a)

Assume a total change in height of 1.2 m for a student. The total change in height on the Moon would then be 6 times 1.2, or 7.2 m.

6.b)

Using the example in *Step 6.a)*, student's total jump height would be the total change in height plus the student's height at the ready position (say 1.3 m) giving a total height of 8.5 m at the peak.



7. Using the same scale as you did for your Earth data, draw three sketches (to scale) showing the jumper in the ready position, the launch position, and the peak position. The ready position and the launch position should be identical to that on Earth. The peak position should use your calculated value for the Moon.

a) Tape the sketches into your *Active Physics* log.

Physics Talk

ANALYSIS OF JUMPING ON EARTH AND THE MOON

One of the most important ideas in physics is that under certain conditions, one form of energy can be transformed into the other form of energy, with no energy being gained or lost. An object can have **gravitational potential energy** due to its position above the surface of the planet. The object can have **kinetic energy** due to its velocity. The gravitational potential energy of the object can be transformed into kinetic energy as the object falls. The object loses gravitational potential energy (as it loses height) and gains kinetic energy (as it moves faster).

GPE represents gravitational potential energy.

$GPE = mgh$

where m = mass

g = acceleration due to gravity and

h = height above the ground.

since weight = mg

then GPE = (weight) × (height above the ground)

KE represents kinetic energy.

$KE = \frac{1}{2}mv^2$

where m = mass and

v = velocity

Hence, $KE = \frac{1}{2}$ (mass)(velocity squared)

Note that the units of energy are $\frac{(kg \cdot m^2)}{s^2}$. This unit is called a joule and its symbol is J.

You can analyze the jump on Earth by comparing the energy at the ready position, the launch position, and the peak position. Since the person is at rest in both the ready position and the peak position, she or he has no kinetic energy at either place. Chemical energy in your body is stored as leg muscle *PE*.

Physics Words

gravitational potential energy: the energy an object possesses as a result of its position near the surface of a planet or moon (GPE mgh).

kinetic energy: the energy an object possesses because of its motion ($KE = \frac{1}{2}mv^2$).

7.a)

Students make scale drawings of their ready, launch, and jump heights on the Moon.

Physics Talk

Students read about the transformation and conservation of energy while analyzing the difference between the peak height of a person's jump on Earth and the Moon. The *Physics Talk* gives the definitions of gravitational potential energy and kinetic energy, and uses sample data to calculate the peak height of a jump on the Moon. The work-energy theorem is invoked to describe how the work done by the leg muscles of the jumper goes into raising the jumper's center of mass and giving the jumper kinetic energy at launch. This kinetic energy is then transformed into potential energy as the jumper rises to the peak of the jump. The information is provided in tables to make it readily available for students to calculate the relative jump heights on Earth and the Moon when the energy principles are applied. The surprising result that a jumper is able to jump more than six times higher on the Moon than on Earth is explained in terms of the decrease in energy required to lift the jumper's center of mass, leaving more of the work done by the jumper's muscles for kinetic energy.

Consider projecting the tables on an overhead to focus students' attention to an equation or illustrate a key point. Highlight the difference between gravitational and kinetic energy in a class discussion. Ask students how energy is transformed at various positions of a jump. It is important for them to get a firm grasp of how data is used for analysis and calculation. Encourage students to read and summarize the essential information in the *Physics Talk*. Point out that they must make a note of all the units used in the calculations. You might want to have a student volunteer come up to the board and explain how total energy and peak height for Earth and the Moon are calculated using the data provided.

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The ready position has only leg-muscle potential energy. The peak position has only gravitational potential energy. The launch position has both kinetic energy and gravitational potential energy.

	Ready position	Launch position	Peak position
Kinetic energy *KE*	0	✔	0
Gravitational potential energy *GPE*	0	✔	✔
Leg-muscle potential energy *LPE*	✔	0	0

This analysis uses sample data for the vertical jump of a person on Earth who has a mass of 44 kg:

- Body mass = 44 kg
- Body weight on Earth = mg = 44 kg x 9.8 m/s^2 = 430 N
- Ready height (from floor to ready mark) = 1.70 m
- Launch height (from floor to launch mark) = 2.05 m
- Peak height (from floor to peak mark) = 2.65 m

You may apply this analysis to your vertical jump by substituting your personal data for the sample data, or you can assign a mass to an "unknown" person if you wish.

The following table shows all of the results of the analysis. Exactly how each result is obtained is explained in the paragraphs after the table.

	Earth	Moon
Mass (kg)	44	44
Weight (N)	430	70
Ready height (m)	1.70	1.70
Launch height (m)	2.05	2.05
Peak height (m)	2.65	7.60
Jump height (m)	0.60	5.55
Total energy (J)	410	410

The total energy of the jump is equal to the overall gain in the jumper's gravitational potential energy from the ready position to the peak position:

Total energy change in gravitational potential energy
mg peak height ready height
430 N 2.65 m 1.70 m
430 N 0.95 m
410 J

This 410 J of energy was produced by the legs of the jumper during the push phase, while the feet were in contact with the ground.

Assuming the leg muscles work the same on the Moon, you would expect an increase of gravitational potential energy of 410 J on the Moon as well. However, the acceleration due to gravity, g_M, on the Moon is only $\frac{1}{6}$ the acceleration due to gravity on Earth ($1.6\ \text{m/s}^2$ compared to $9.8\ \text{m/s}^2$).

The Moon data would be:

- Body mass 44 kg (identical to mass on Earth)
- Body weight mg 44 kg $1.6\ \text{m/s}^2$ 70 N ($\frac{1}{6}$ the value on Earth)
- Ready height (from floor to ready mark) = 1.70 m (identical to the value on Earth)
- Launch height (from floor to launch mark) = 2.05 m (identical to the value on Earth)

With these data, you can compute the peak height on the Moon.

$$\begin{aligned} \text{Total energy} &= \text{change in gravitational potential energy} \\ &= mg[(\text{peak height}) - (\text{ready height})] \\ 410\ \text{J} &= 70\ \text{N} \times [(\text{peak height}) - 1.70\ \text{m}] \\ 5.9\ \text{m} &= [(\text{peak height}) - 1.70\ \text{m}] \\ \text{Peak height} &= 7.6\ \text{m} \end{aligned}$$

The jump height on Earth and Moon is found by subtracting the launch height from the peak height:

on Earth 2.65 m – 2.05 m 0.60 m
on Moon 7.6 m – 2.05 m 5.55 m

$$\frac{5.55\ \text{m}}{0.60\ \text{m}} = 9.25$$

The ratio of these heights on the Moon and Earth is clearly more than six. A person can jump more than six times as high on the Moon as on Earth. The difference between the peak height and ready height is 0.95 m on Earth and 5.9 m on the Moon. As you can see, this is close to a factor of 6.

CHAPTER 9

9-5c Blackline Master

Checking Up

1.

Before jumping, the energy stored in the legs is in the form of leg-muscle potential energy, which is derived from the chemical energy stored within the body.

2.

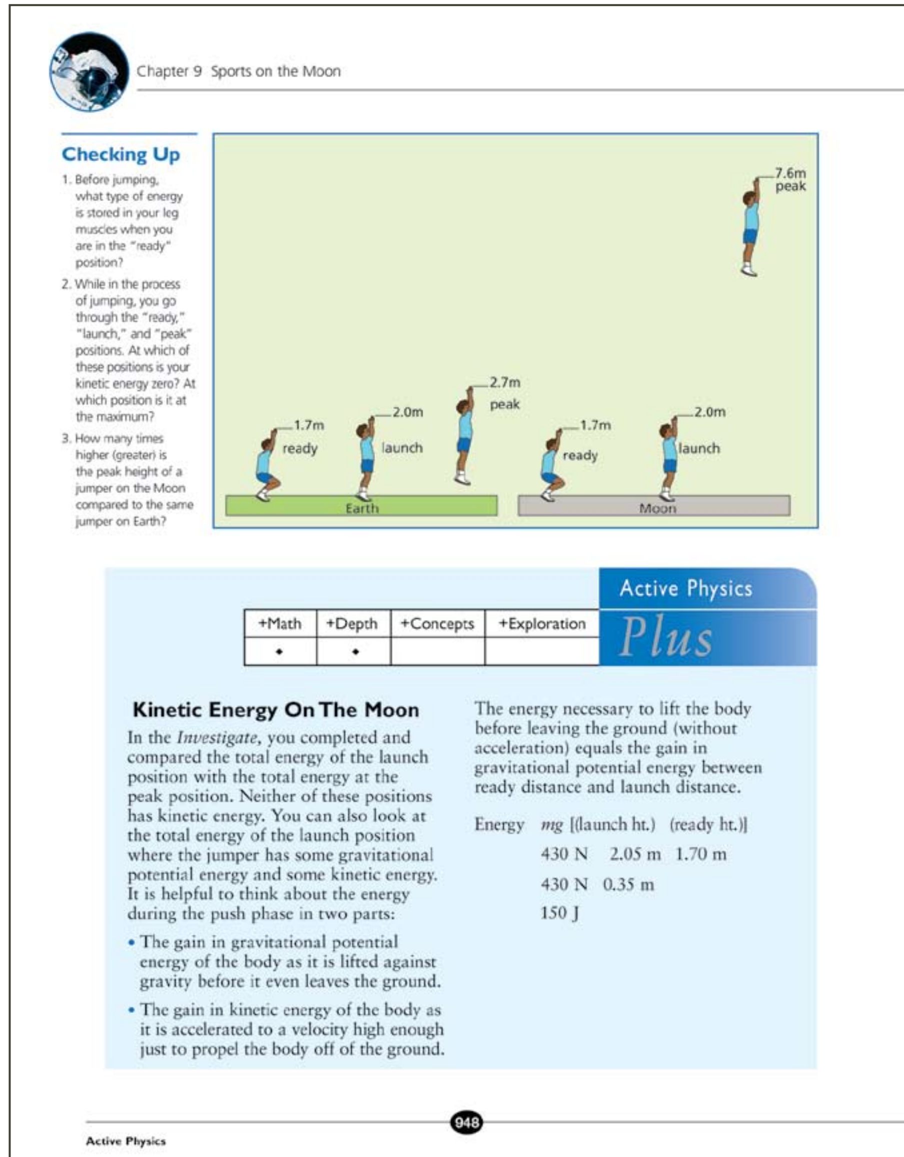
The kinetic energy of a jumper is zero when the jumper is in the "ready" position and also in the "peak" position. In both cases, the jumper's velocity is zero, so the *KE* must also be zero. The kinetic energy of the jumper is the maximum just as the jumper leaves the ground.

3.

From the "ready" position to the "peak" position, the jumper on the Moon is able to jump six times higher on the Moon than on Earth. If the height of the jumper's feet above the ground on the Moon is compared to the height above the ground on Earth, the distance is more than six times higher.

Active Physics Plus

Using the principle of conservation of energy and the equations for work, kinetic energy, and gravitational potential energy, this *Active Physics Plus* shows students how to calculate jump height on the Moon relative to a jump on Earth. Students then use this principle and the equations to derive a general expression for a person's jump height and "hang time" when jumping straight upward on the Moon.



Chapter 9 Sports on the Moon

Checking Up

1. Before jumping, what type of energy is stored in your leg muscles when you are in the "ready" position?
2. While in the process of jumping, you go through the "ready," "launch," and "peak" positions. At which of these positions is your kinetic energy zero? At which position is it at the maximum?
3. How many times higher (greater) is the peak height of a jumper on the Moon compared to the same jumper on Earth?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
•	•		

Kinetic Energy On The Moon

In the *Investigate*, you completed and compared the total energy of the launch position with the total energy at the peak position. Neither of these positions has kinetic energy. You can also look at the total energy of the launch position where the jumper has some gravitational potential energy and some kinetic energy. It is helpful to think about the energy during the push phase in two parts:

- The gain in gravitational potential energy of the body as it is lifted against gravity before it even leaves the ground.
- The gain in kinetic energy of the body as it is accelerated to a velocity high enough just to propel the body off of the ground.

The energy necessary to lift the body before leaving the ground (without acceleration) equals the gain in gravitational potential energy between ready distance and launch distance.

Energy *mg* [(launch ht.) (ready ht.)]

430 N 2.05 m 1.70 m

430 N 0.35 m

150 J

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Active Physics

Section 5 Gravity, Work, and Energy: Jumping on the Moon

The kinetic energy needed to propel the body off the ground must be equal to any amount of the total energy that "remains" after subtracting the amount of energy needed to lift the body against gravity.

$$\begin{aligned} KE \text{ at launch} &= (\text{total energy}) - (\text{energy to lift}) \\ &= 410\text{ J} - 150\text{ J} \\ &= 260\text{ J} \end{aligned}$$

Of the 410 J of total energy that the muscles in the leg provide, 150 J are used to raise the body to the launch position and the remaining 260 J represents the kinetic energy for the jump.

What would happen if the person were to repeat the same jump on the Moon? What would be the person's jump height?

The person's mass, 44 kg, would remain the same on the Moon, but the person's weight would be less on the Moon:

$$\begin{aligned} \text{Weight on the Moon} &= 44\text{ kg} \times 1.6\text{ m/s}^2 \\ &= 70\text{ N} \end{aligned}$$

The energy needed just to lift the body against gravity during the push phase on the Moon is equal to gain in gravitational potential energy between the ready height and the launch height.

$$\begin{aligned} \text{Energy} &= mg\ [(\text{launch ht.}) - (\text{ready ht.})] \\ &= 70\text{ N} \times (2.05\text{ m} - 170\text{ m}) \\ &= 70\text{ N} \times 0.35\text{ m} \end{aligned}$$

The kinetic energy needed to propel the body off of the ground on the Moon is equal to the total energy minus the energy needed just to lift the body against gravity:

$$\begin{aligned} KE \text{ at launch} &= (\text{total energy}) - (\text{energy to lift}) \\ &= 410\text{ J} - 25\text{ J} \\ &= 385\text{ J} \end{aligned}$$

Much more of the energy from the person's legs can go into propelling the body off of the ground. Although the leg muscles provided the same 410 J of energy as on Earth, only 25 J are required to lift the body on the Moon. More of the energy goes into kinetic energy allowing for a much higher jump.

The jump height can be predicted by assuming that the kinetic energy at launch is transformed into the gain in gravitational potential energy from launch to the peak of the jump. That is, at the launch position the person has some kinetic energy (385 J). But at the very top of the person's jump, the person's velocity is zero, so the person has no kinetic energy. The law of conservation of energy tells you that the 385 J of kinetic energy must be converted into 385 J of gravitational potential energy.

$$\begin{aligned} KE \text{ at launch} &= PE \text{ gained from launch to peak} \\ 385\text{ J} &= mg\ (\text{jump height}) \end{aligned}$$

Therefore:

$$\text{Jump height} = 5.47\text{ m}$$

This height is almost identical to the height you found in the *Physics Talk* section. Rounding errors in the calculations produced the difference.

Notice that the jump height on the Moon (as measured from the launch position to the peak position) is 5.47 m as compared to 0.60 m on Earth. This is a factor of nine times higher on the Moon than on Earth.

CHAPTER 9

1.

Total Energy $= mg(h_2)$

2.

Energy required to raise from ready to launch $= mg_M(h_1)$.

3.

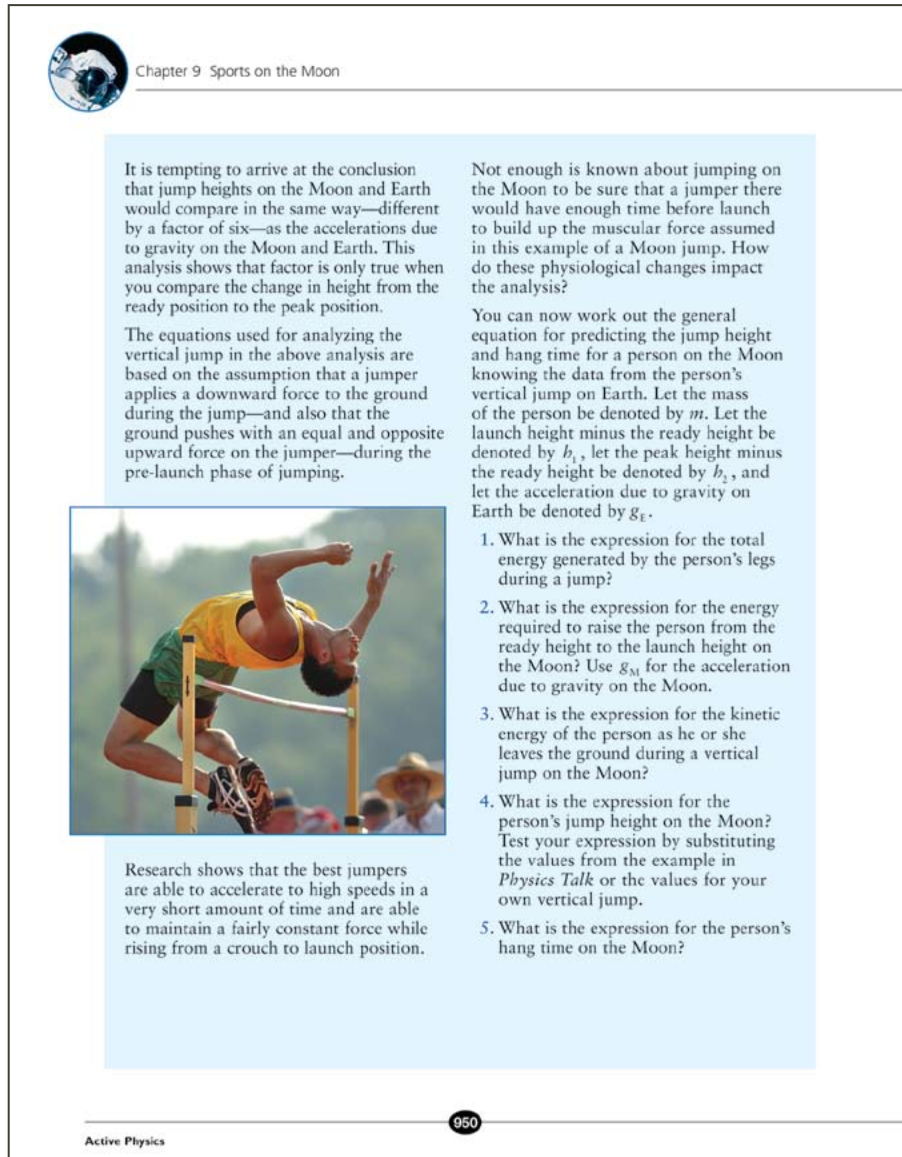
The KE of a person just as he or she leaves the ground is the difference between the Total Energy in the legs minus the energy needed to raise to the launch position, or $mg_M(h_2) - mg_M(h_1) = mg_M(h_2 - h_1)$.

4.

The expression for the jump height is $(h_2 - h_1)$, and since g_M is one sixth g_E the jump height on the Moon is six times the jump height on Earth.

5.

From *Section 4*, $t_{max} = v/g$, $t_{total} = 2t_{max} = 2v/g$.
The KE at launch $=$ $mg_M(h_2 - h_1) = \frac{1}{2}mv^2$.
Solving for v gives $\sqrt{2g_M(h_2 - h_1)}$. Substituting this into the equation for t_{total} gives $t_{total} = 2\sqrt{2g_M(h_2 - h_1)}/g_M$.



Chapter 9 Sports on the Moon

It is tempting to arrive at the conclusion that jump heights on the Moon and Earth would compare in the same way—different by a factor of six—as the accelerations due to gravity on the Moon and Earth. This analysis shows that factor is only true when you compare the change in height from the ready position to the peak position.

The equations used for analyzing the vertical jump in the above analysis are based on the assumption that a jumper applies a downward force to the ground during the jump—and also that the ground pushes with an equal and opposite upward force on the jumper—during the pre-launch phase of jumping.

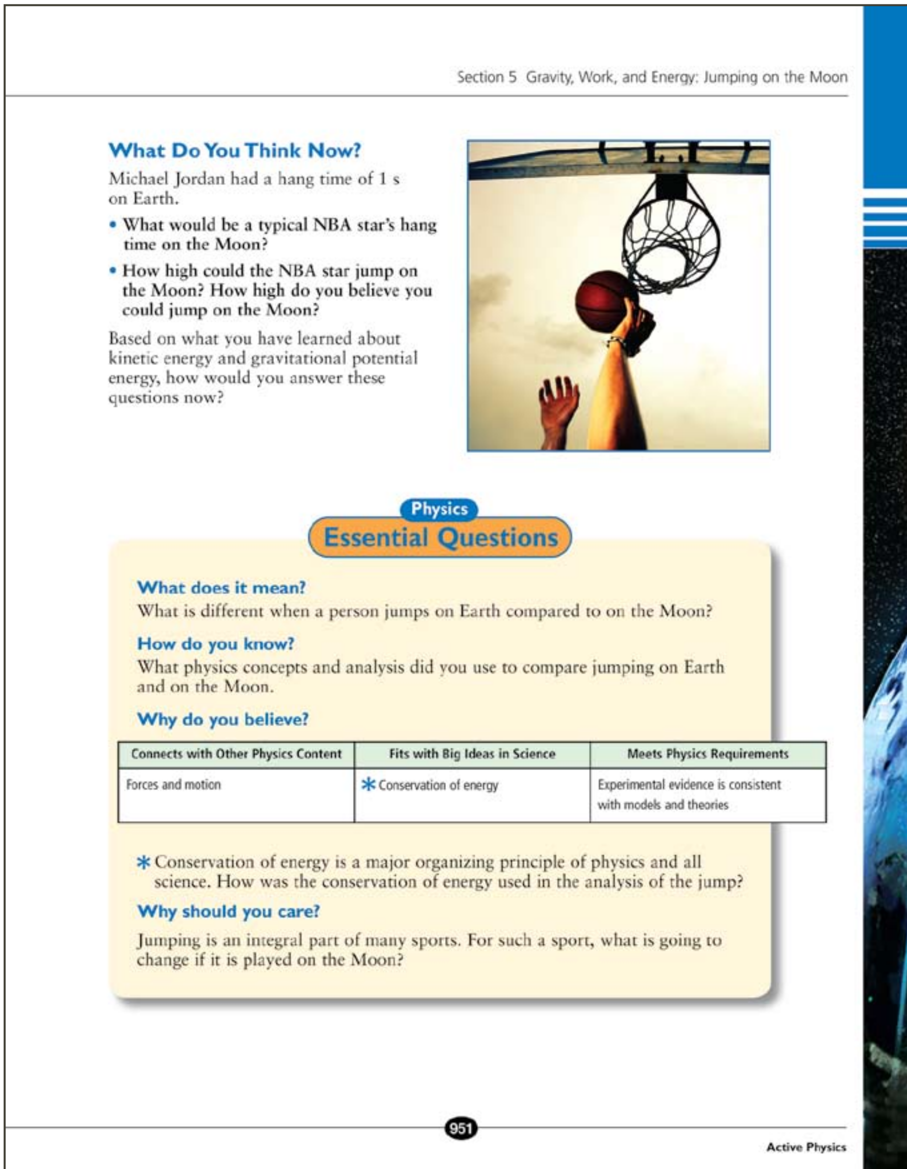
Research shows that the best jumpers are able to accelerate to high speeds in a very short amount of time and are able to maintain a fairly constant force while rising from a crouch to launch position.

Not enough is known about jumping on the Moon to be sure that a jumper there would have enough time before launch to build up the muscular force assumed in this example of a Moon jump. How do these physiological changes impact the analysis?

You can now work out the general equation for predicting the jump height and hang time for a person on the Moon knowing the data from the person's vertical jump on Earth. Let the mass of the person be denoted by m. Let the launch height minus the ready height be denoted by h_1, let the peak height minus the ready height be denoted by h_2, and let the acceleration due to gravity on Earth be denoted by g_E.

1. What is the expression for the total energy generated by the person's legs during a jump?
2. What is the expression for the energy required to raise the person from the ready height to the launch height on the Moon? Use g_M for the acceleration due to gravity on the Moon.
3. What is the expression for the kinetic energy of the person as he or she leaves the ground during a vertical jump on the Moon?
4. What is the expression for the person's jump height on the Moon? Test your expression by substituting the values from the example in *Physics Talk* or the values for your own vertical jump.
5. What is the expression for the person's hang time on the Moon?

Active Physics 950



Section 5 Gravity, Work, and Energy: Jumping on the Moon

What Do You Think Now?

Michael Jordan had a hang time of 1 s on Earth.

- What would be a typical NBA star's hang time on the Moon?
- How high could the NBA star jump on the Moon? How high do you believe you could jump on the Moon?

Based on what you have learned about kinetic energy and gravitational potential energy, how would you answer these questions now?

Physics
Essential Questions

What does it mean?
What is different when a person jumps on Earth compared to on the Moon?

How do you know?
What physics concepts and analysis did you use to compare jumping on Earth and on the Moon.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	* Conservation of energy	Experimental evidence is consistent with models and theories

* Conservation of energy is a major organizing principle of physics and all science. How was the conservation of energy used in the analysis of the jump?

Why should you care?
Jumping is an integral part of many sports. For such a sport, what is going to change if it is played on the Moon?

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Active Physics

What Do You Think Now?

Students will present a range of responses and it is important for them to recognize that hang time on the Moon will not be constant but will vary with the kinetic energy of the jumper as he or she leaves the ground. Consider sharing *A Physicist's Response* and encourage students to ask questions. You could also revisit the *What Do You See?* section and ask students how they would interpret the illustration now. Determine if students still present misconceptions during the class discussion. Point out that their responses should incorporate an understanding of kinetic energy and gravitational potential energy. Students should be told that what they think now does matter more and you will be evaluating their answers at this stage; therefore, it is necessary for them to update and revise their answers carefully.

Physics Essential Questions

What does it mean?

A person does not jump nearly as high on Earth as on the Moon.

How do you know?

Conservation of energy was used to compute the maximum jump on Earth and the Moon. The work provided by the leg muscles on Earth and the Moon is identical, while having equal gravitational potential energies requires the object to travel much higher on the Moon.

Why do you believe?

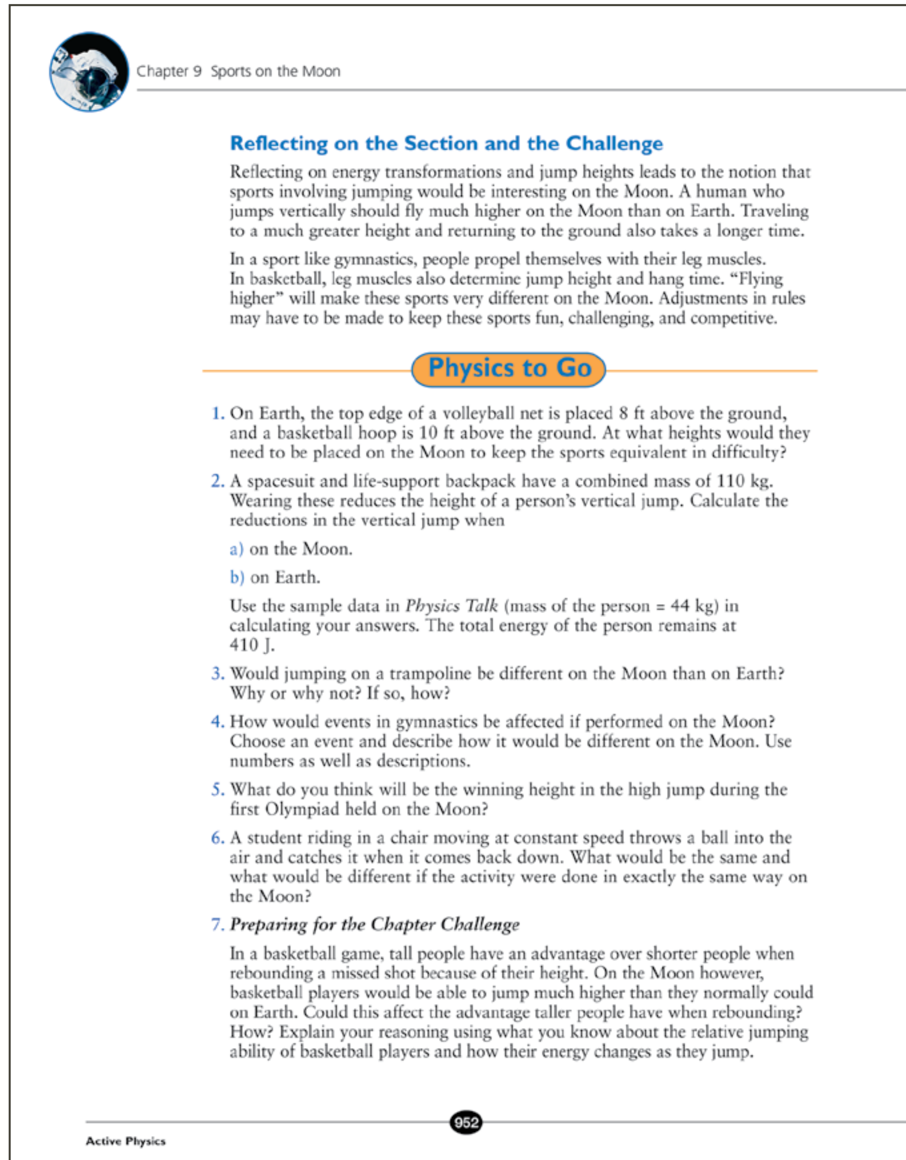
Energy is conserved when the chemical energy in the muscles is transformed to kinetic energy of the body, which in turn is transformed to gravitational potential energy. The gravitational potential energy is a measure of how high the person jumps.

Why should you care?

The spring potential energy will be identical on the Moon and Earth. The gravitational potential energy will also be identical on the Moon and Earth. Since $GPE = mgh$, the person will jump much higher on the Moon since the "g" on the Moon is much less than the "g" on Earth.

Reflecting on the Section and the Challenge

While considering energy transformations, students should reflect on how these transformations would affect jump heights. They are faced with the challenge of keeping a sport interesting but at the same time they have to keep in mind the reduced gravity of the Moon, which will change how the sport is played. Allow students time to ponder how the physics concepts they learned will help them design a competitive game for the *Chapter Challenge*. Consider highlighting steps of the *Investigate* and the important elements of the *Physics Talk* in a discussion in which students have the opportunity to clear lingering doubts and consolidate their knowledge of physics concepts.



Chapter 9 Sports on the Moon

Reflecting on the Section and the Challenge

Reflecting on energy transformations and jump heights leads to the notion that sports involving jumping would be interesting on the Moon. A human who jumps vertically should fly much higher on the Moon than on Earth. Traveling to a much greater height and returning to the ground also takes a longer time.

In a sport like gymnastics, people propel themselves with their leg muscles. In basketball, leg muscles also determine jump height and hang time. "Flying higher" will make these sports very different on the Moon. Adjustments in rules may have to be made to keep these sports fun, challenging, and competitive.

Physics to Go

1. On Earth, the top edge of a volleyball net is placed 8 ft above the ground, and a basketball hoop is 10 ft above the ground. At what heights would they need to be placed on the Moon to keep the sports equivalent in difficulty?
2. A spacesuit and life-support backpack have a combined mass of 110 kg. Wearing these reduces the height of a person's vertical jump. Calculate the reductions in the vertical jump when
   a) on the Moon.
   b) on Earth.
   Use the sample data in *Physics Talk* (mass of the person = 44 kg) in calculating your answers. The total energy of the person remains at 410 J.
3. Would jumping on a trampoline be different on the Moon than on Earth? Why or why not? If so, how?
4. How would events in gymnastics be affected if performed on the Moon? Choose an event and describe how it would be different on the Moon. Use numbers as well as descriptions.
5. What do you think will be the winning height in the high jump during the first Olympiad held on the Moon?
6. A student riding in a chair moving at constant speed throws a ball into the air and catches it when it comes back down. What would be the same and what would be different if the activity were done in exactly the same way on the Moon?
7. *Preparing for the Chapter Challenge*
   In a basketball game, tall people have an advantage over shorter people when rebounding a missed shot because of their height. On the Moon however, basketball players would be able to jump much higher than they normally could on Earth. Could this affect the advantage taller people have when rebounding? How? Explain your reasoning using what you know about the relative jumping ability of basketball players and how their energy changes as they jump.

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Active Physics

Physics to Go

1.

If you assume a volleyball player can just touch the top of the net on Earth and needs to jump at least 30 cm to correctly spike a ball, then on the Moon they would be able to jump over six times as high (and perhaps closer to nine times). The net would have to be at least 1.8 m or about 6 ft higher and perhaps as much as 2.7 m or 8 ft higher, making it between 14 and 16 ft high on the Moon. Applying the same analysis to a basketball hoop, a player who is 2 m tall might be able to dunk a basketball by jumping to a height of 50 cm. Since the same player should be able to jump between six and nine times higher on the Moon, the basket should be raised between 3 m and 4.5 m (or an additional 10–14 ft) to keep this aspect of the game equivalent.

2.

Using the 44 kg mass assigned in the *Physics Talk*, students mass now becomes 154 kg.

2.a)

Assuming a person is able to generate the same 410 J of total leg energy on the moon, the analysis becomes work done moving from the ready to the launch position equals the weight multiplied by difference in height between ready and launch positions or

$W = (154\ \text{kg})(1.6\ \text{m/s}^2) \times (2.05\ \text{m} - 1.70\ \text{m}) = 86\ \text{J}$

leaving an additional $410\ \text{J} - 86\ \text{J} = 324\ \text{J}$ to increase the jumper's *GPE*.

Thus, $GPE = mgh$ or $324 = (154\ \text{kg})(1.6\ \text{m/s}^2)(h)$ or $h = 1.3\ \text{m}$ for the jumper's feet above the surface, rather than the 5.6 m above the surface for a jump without the space suit. The reduction of the space suit would be expressed as the difference between the two heights, or 4.3 m.

2.b)

Applying the same analysis for Earth gives work done moving from the ready to the launch position equals the weight multiplied by difference in height between ready and launch positions or $W = (154\ \text{kg})(9.8\ \text{m/s}^2) \times (2.05\ \text{m} - 1.70\ \text{m}) = 528\ \text{J}$. This is more than the 410 J of work supplied by the legs. In other words, it is very doubtful that the person wearing the spacesuit and life-support backpack on Earth could even straighten up, let alone jump!

3.

A trampoline works in the same way on the Moon as on Earth, involving a repeating chain of energy transformations for each jump cycle. Initially, the jumper does work to jump; part of the work done during jumping is transformed into kinetic energy at take-off; the kinetic energy at take-off is transformed into gravitational potential energy at the peak of the jump; the gravitational potential energy at the peak of the jump is transformed into kinetic energy at landing; the kinetic energy at landing is transformed into work done to stretch the trampoline; the elastic potential energy stored in the stretched trampoline is transformed into work done to push the jumper's body upward; the work done by the trampoline is transformed into kinetic energy at take-off. If during the second and succeeding take-offs the jumper does "legwork," the legwork energy is added to the take-off kinetic energy provided by the trampoline, and the jumper "builds up" height with each jump. Due to reduced g on the Moon, the additional height gained due to work done by the jumper's muscles during each cycle of legwork will be greater on the Moon than on the Earth, and, therefore, much greater height should be able to be attained on the Moon.

4.

As one example, the floor exercises could be sensational on the Moon because the athletes are among the world's best jumpers. They would have more time to perform spins during flights on the Moon than on Earth. Other strength exercises such as the rings would be much easier however, allowing other spectacular moves and possible air-borne maneuvers.

5.

A men's world record for the high jump set in 1993 was 2.45 m. It seems sure that a similar effort on the Moon would result in a jump more than six times higher ($6 \times 2.45\ \text{m} = 14.7\ \text{m}$), but, for certainty, it would be necessary to measure— perhaps from a slow-motion video of a high jump—the position of a high jumper's center of mass during push and flight phases and then apply the methods of analysis and prediction similar to the methods used for vertical jumps on Earth and the Moon in this *Investigate*.

6.

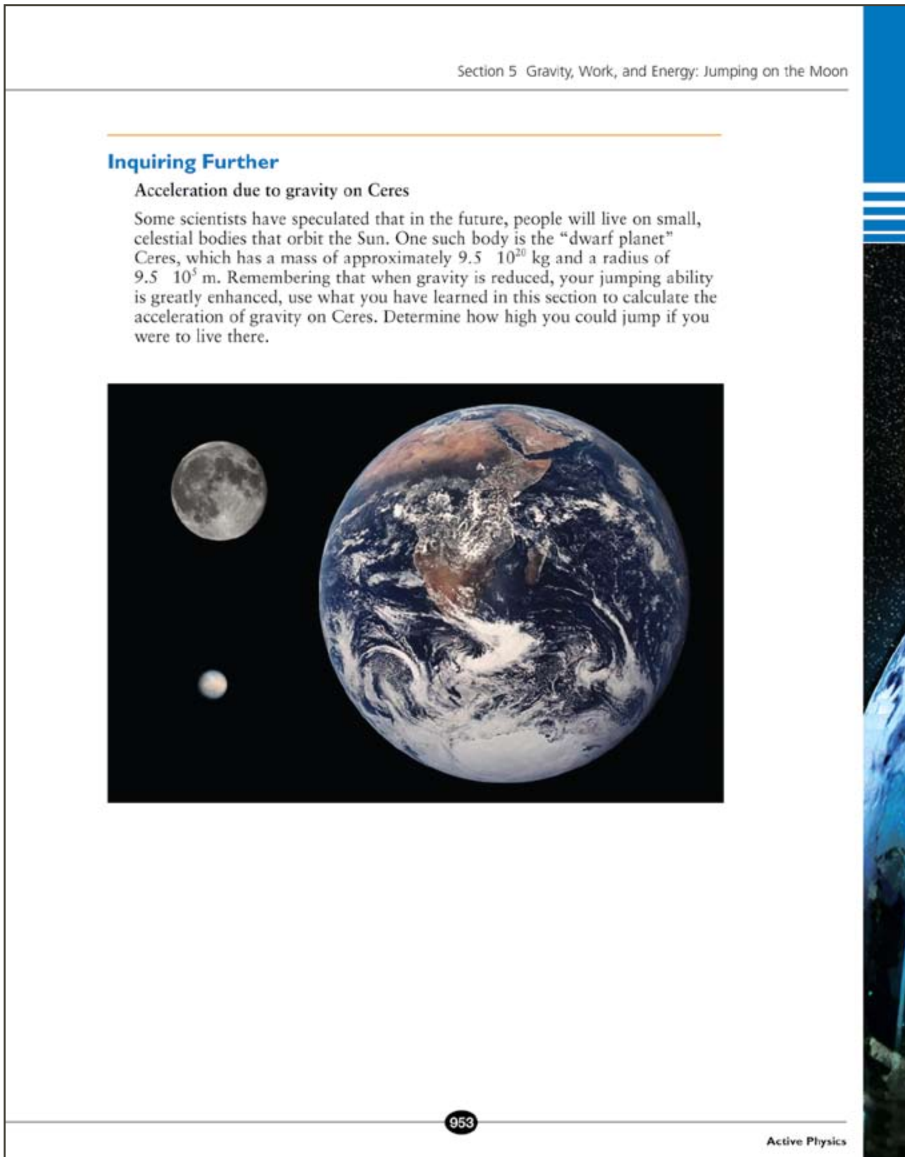
The ball would fly six times higher and would be in flight six times longer, but still would land in the student's hand.

7.

Preparing for the Chapter Challenge

Much of a taller player's rebounding advantage is due to their initial extra height and extra arm length, rather than their ability to jump higher than smaller players. Since basketball players on the Moon would be able to jump between six and nine times higher, smaller players who might have slightly better jumping ability would have their jumping advantage multiplied by this factor. This might easily be sufficient to equalize the advantage the taller players have in height and arm length.

NOTES



Section 5 Gravity, Work, and Energy: Jumping on the Moon

Inquiring Further

Acceleration due to gravity on Ceres

Some scientists have speculated that in the future, people will live on small, celestial bodies that orbit the Sun. One such body is the "dwarf planet" Ceres, which has a mass of approximately $9.5\ \ 10^{20}$ kg and a radius of $9.5\ \ 10^{5}$ m. Remembering that when gravity is reduced, your jumping ability is greatly enhanced, use what you have learned in this section to calculate the acceleration of gravity on Ceres. Determine how high you could jump if you were to live there.

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Active Physics

Inquiring Further

Using $g = GM_p/r_p^2$ and solving for the acceleration due to gravity on Ceres yields $g_{Ceres} = 0.0702\ m/s^2$. Using the relationship developed earlier in the section, the difference in height between the launch and the peak height is equal to the ratios of the accelerations due to gravity gives

$$\frac{g_{Earth}}{g_{Ceres}} = \frac{9.8\ m/s^2}{0.0702\ m/s^2} = 140!$$

On Ceres you could jump 140 times higher than on Earth and due to the very weak gravity, it would take a long time to come back down.

CHAPTER 9

SECTION 5 QUIZ

9-5d **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. An astronaut on the Moon has a mass of 60 kg and jumps to a height of 8 meters. What is his gravitational potential energy at this height?

   a) 4700 J b) 770 J

   c) 470 J d) 77 J

2. For *Question 1*, the amount of work the astronaut's muscles did to get him to jump to a height 8 meters must have been

   a) 6300 J. b) 4700 J.

   c) 3100 J. d) 770 J.

3. An astronaut on the Moon has a mass of 45 kg and jumps upward with a speed of 3 m/s. Her kinetic energy at this speed is closest to

   a) 1350 J. b) 405 J.

   c) 200 J. d) 88 J.

4. A dog on Earth with a mass of 30 kg jumps straight up to a height of 1.5 m while trying to catch a flying disc. At the peak of the jump the dog's kinetic energy is

   a) 450 J. b) 75 J.

   c) 34 J. d) 0 J.

5. An astronaut travels from the Moon to Mars. Which of the following would have no effect on how high the astronaut could jump on Mars?

   a) The acceleration due to gravity on Mars

   b) The astronaut's mass

   c) The weight of the space suit being worn

   d) The acceleration due to gravity on the Moon

SECTION 5 QUIZ ANSWERS

1. b) Gravitational potential energy (*GPE*) is given by $GPE = mgh$ or $GPE = (60\ \text{kg})(1.6\ \text{m/s}^2)(8\ \text{m}) \approx 770\ \text{J}$.

2. d) The work done by the muscles goes to increasing the body's *GPE* at the peak of the jump, so it must be equal to the *GPE* of 770 J.

3. c) Kinetic energy (*KE*) is given by $KE = \frac{1}{2}mv^2$ or $\frac{1}{2}(45\ \text{kg})(3\ \text{m/s})^2 \approx 200\ \text{J}$. The fact that this is done on the Moon makes no difference to the kinetic energy.

4. d) The velocity at the peak of a jump is zero, so the kinetic energy there must also be zero.

5. d) The acceleration due to gravity on the Moon will have no effect on the jump height on Mars.

CHAPTER 9