SECTION 9

Air Resistance and Terminal Velocity: "Airy" Indoor Sports on the Moon

Section Overview

Students investigate how air resistance affects falling objects on Earth and how the same objects would fall on the Moon in the absence of air resistance. They also determine how an object would fall on the Moon in an enclosed space with air. Students begin their investigation by first dropping a pencil and a feather to describe their motion. Then they drop coffee filters and observe how the time of fall of a single coffee filter and groups of nested coffee filters are affected by mass and air resistance. Students also note how some of the filters start to fall at constant speed after a while. They describe how the filters fall on Earth and how the filters would fall if they were dropped on the Moon. Next, they analyze a game of badminton and describe how the range of a shuttlecock is affected by air resistance. They discover that hitting a shuttlecock twice as hard does not result in a doubling of the range. They describe how a game of badminton could be played on the Moon indoors with air and outdoors without air. Students also explore how a game of golf would be played on the Moon if golf balls were replaced by "whiffle" golf balls to reduce the range of the balls on the Moon, and whether playing golf indoors on the Moon with air would impact the range of the golf balls. Students eventually discover how falling objects reach terminal velocity in air.

Background Information

The main phenomenon introduced in this section is air resistance and its effect on moving objects. The dependence of the force of air resistance on a projected area and the speed in the student text is a simplified version of the governing equation for the resistive force acting on an object moving through a fluid, which is presented below:

$$F = 0.5 \times (\text{drag coefficient}) \times (\text{projected area}) \times (\text{fluid density}) \times (\text{speed squared})$$

- The drag coefficient depends on the object's shape and the so-called "Reynolds number." The Reynolds number, in turn, depends on the object's speed, diameter, and the viscosity of the fluid through which the object is moving. A typical value of the drag coefficient for a sphere falling through air on Earth is 0.42.
- The projected area is the area of the object as viewed from ahead or behind as the object travels.
- The fluid density applies to the fluid through which the object is moving.
- The speed is the speed of the object relative to the air. Obviously, air resistance is complicated to predict with high precision except for very simple shapes.

That is why engineers who work with air resistance often use wind tunnels to measure air resistance directly. For the purposes of the investigations performed by students here, the primary dependence of air resistance on projected area and speed as described in *Physics Talk* is sufficient.

Crucial Physics

- The force of air resistance opposes the force of gravity for a falling object.
- The force of air resistance is proportional to the object's speed.
- A falling object may reach a terminal velocity where the force of air resistance is equal to the object's weight. At terminal velocity the object is no longer accelerating and is traveling at constant velocity.
- The amount of air resistance on an object depends upon the object's speed, size and shape.

Learning Outcomes	Location in the Section	Evidence of Understanding
Observe how air resistance changes when the speed of objects moving in air increases.	***Investigate*** Step 4	Students hit badminton shuttlecocks with different speeds and note how the distance traveled varies with the initial speed of the shuttlecock.
Observe the terminal speed of falling objects.	***Investigate*** Steps 2–4	Students drop objects of different masses and record how air resistance affects the movement of these objects. They observe how light objects reach a terminal speed after which they stop accelerating and continue to fall at a constant pace.
Apply effects of air resistance to adapting sports to the Moon.	***Investigate*** Steps 4 and 5	Students use their understanding of air resistance and reduced weight on the Moon to adapt sports like badminton and golf to the Moon.
Consider requirements for self-propelled human flight in an air-filled shelter on the Moon.	***Physics Talk***	Students discuss how using a pedal-powered helicopter on the Moon could be used for an indoor activity and how equipping people with long, webbed fingers to substitute for wings could be used for "swimming" through indoor air.

Section 9 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Stopwatch	1 per group	
Coffee filters	25 per group	
Ball, golf, practice	1 per group	
Racquet, badminton		1 per class
Shuttlecock		1 per class
Pencil*	8 per group	
Easel pad (used for *Chapter Challenge*)*	1 per group	
Markers (used for *Chapter Challenge*)*	1 per group	

*Additional items needed not supplied

Time Requirements

- Allow two class periods or 90 minutes for the students to do the *Investigate* and other parts of the section.

Teacher Preparation

- It would be helpful if you were able to provide either real-time, or a video of a golfer driving a practice golf ball to maximum possible range (probably 30 to 40 yards). It would save class time to do this in advance via video; otherwise, a quick trip outdoors or to a gymnasium can be done. As a poor substitute, "canned" data can be reported to students.
- A badminton shuttlecock probably can be served to maximum range in your classroom or in a hallway of the school. Have a large enough area in mind and available.
- Stacks of coffee filters may be purchased from office supply stores or other locations for use by the students.
- **OPTIONAL:** If available, set up a motion detector and computer to determine the velocity of the falling coffee filters to determine their fall time and at which point they achieve terminal velocity.

Safety Requirements

- Students should wear safety goggles for this *Investigate*.
- When hitting the shuttlecock, caution the students to ensure the area where they are hitting it is clear of all obstructions, and other students. Students should pay particular attention to any "back swing" areas as well as areas in front of them.
- Students should immediately pick up anything that falls on the floor (coffee filters, practice golf balls, shuttlecocks, etc.) that might cause other students to slip if stepped upon.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Stopwatch		1 per class
Coffee filters		25 per class
Ball, golf, practice		1 per class
Racquet, badminton		1 per class
Shuttlecock		1 per class
Pencil*	8 per group	
Easel pad (used for *Chapter Challenge*)*	1 per group	
Markers (used for *Chapter Challenge*)*	1 per group	

*Additional items needed not supplied

Time Requirements

- Allow one class period or 45 minutes for the students to do the *Investigate* portion of the section as a teacher demonstration, the *Physics Talk* and any associated material from the *Pacing Guide*.

Teacher Preparation

- It would be helpful if you were able to provide either real-time, or a video of a golfer driving a practice golf ball to maximum possible range (probably 30 to 40 yards). It would save class time to do this in advance via video; otherwise, a quick trip outdoors or to a gymnasium can be done. As a poor substitute, "canned" data can be reported to students.
- A badminton shuttlecock probably can be served to maximum range in your classroom or in a hallway of the school. Have a large enough area in mind and available.
- Stacks of coffee filters may be purchased from office supply stores or other locations for use by the students.
- **OPTIONAL:** If available, set up a motion detector and computer to determine the velocity of the falling coffee filters to determine their fall time and at which point they achieve terminal velocity.

Safety Requirements

- Students should wear safety goggles for this *Investigate*.
- When hitting the shuttlecock, ensure the area where you are hitting it is clear of all obstructions, and any students. Pay particular attention to any "back swing" areas as well as areas in front and to the side. Immediately pick up anything that falls on the floor (coffee filters, practice golf balls, shuttlecocks, etc) that might cause someone to slip if stepped upon.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Organizing information	***Investigate*** Step 3	**Augmentation** • In order for the information collected in *Step 3* to be useful, it must be organized to allow students to compare the results. Students should create a table or other organizational system to record the order the filters hit the floor, the time it takes, a description of the motion, the mass of the filters, and if the filters are at a constant speed or accelerating as they fall. It is important for students to create the data table before they begin experimenting because students who struggle with their executive function skills have a difficult time organizing information, as well as performing many tasks at one time. **Accommodation** • For students who will need to spend a lot of time creating a data table, provide a blank data table for students to add column and row headers and begin making observations and collecting data.
Applying Newton's laws to understand air resistance	***Physics Talk***	**Augmentation** • This *Physics Talk* provides a great opportunity for students to become "experts" on a topic and then use the jigsaw method to teach the concept to their classmates. Using this method, students are divided into base groups of four. Then students are assigned a letter within their base group. Next, students move to join their letter group (A, B, C, and D) while making sure to remember their base group. Group A students become experts about Newton's first law related to air resistance, Group B about Newton's second law related to air resistance, Group C about Newton's third law related to air resistance, and Group D about terminal velocity. Students can create posters, drawings, a script, etc., to teach the concept to their base group. After letter groups are ready to explain their assigned concepts, students rejoin their base groups and each person teaches their assigned concept. • Group D could be intentionally comprised of students who could stretch their minds to use the *Active Physics Plus* as part of their explanation. • The jigsaw method makes students responsible and accountable for their own learning and their classmates' learning, while at the same time providing scaffolding and group cooperation for students who struggle with reading comprehension or long-term memory issues.
Organizing a long-term project	***Physics to Go*** Question 8 ***Chapter Challenge***	**Augmentation** • At this point, students have spent a lot of time working on small parts of the *Chapter Challenge* as they completed the *Preparing for the Chapter Challenge* questions in each section. It would be beneficial for students who have a difficult time organizing big projects to review the work they have done in this chapter to help them plan for the completion of the challenge. Ask students to use sticky notes or tabs of tape to mark the pages in their *Active Physics* logs that contain information about the sport they have chosen for the challenge. It may take some time for students to complete this task, but it will be time well spent. If students have already spent a lot of time thinking about the physics behind their sports on the Moon, they will have a much easier time compiling the information to convince NASA to approve their proposal.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Writing skills	***Investigate***	There are many opportunities in this *Investigate* for students to write in their *Active Physics* logs. They are asked to record observations, draw conclusions, and make predictions. Make sure ELL students write in full sentences, use correct grammar and punctuation, and choose appropriate science terminology in their responses. Feedback from you on these issues, as well as on science content, is important for helping students expand their usage of English in and out of the classroom.
Higher-order thinking	***Inquiring Further***	You may wish to perform this augmentation as a class discussion or have students write out their thoughts. Have students read through the first paragraph of *Inquiring Further* as a class. Ask: "Is it possible for both mathematical models for calculating air resistance to be correct? Is it possible for both models to be wrong?" Have students use what they know of the laws of physics to explain their responses. Then use the example as a way of helping students understand in greater depth what scientists go through to develop and refine scientific models.

Consider finishing this section with a cloze activity. Cloze activities are useful tools for summarizing material and for giving English-language learners an opportunity to practice using their science vocabulary words in context. Write the following paragraphs on the board, or type and photocopy them, replacing the underlined words with a write-on line. Encourage volunteers to fill in the blanks, or have all students do the activity on paper.

9-9a Blackline Master

The upward <u>force</u> exerted on an object as it falls through air is called <u>air resistance</u>. The amount of this force depends on the object's <u>speed</u>, volume, <u>mass</u>, and shape, and on properties of the air (such as <u>density</u>). According to Newton's <u>second</u> law of motion, air resistance causes falling objects to experience negative <u>acceleration</u>.

Air resistance opposes the downward <u>gravitational</u> force. When the air resistance on a falling object equals the force of <u>gravity</u> ($F_{air} = F_g$), then the acceleration of the object is <u>zero</u>. The speed reached under these conditions is called <u>terminal velocity</u>. Remember that an object's mass does not depend on the force of gravity, but an object's <u>weight</u> does. Terminal velocity occurs when the force of air resistance is equal and <u>opposite</u> to the object's weight.

CHAPTER 9

SECTION 9

Teaching Suggestions and Sample Answers

What Do You See?

This section provides an interesting clue to title of the illustration. An astronaut flying like a bat! Encourage students to analyze what they see and discuss their initial impressions. Once students are actively engaged in determining what the images are trying to convey, record their ideas on the board that you would like to review later during the course of this section. You might want to ask students why the astronaut is flying in an enclosed area and if a space suit would be necessary. Remind students that they will have other opportunities to visit this illustration and they must remember that what they observe now may undergo a change in what they perceive later.

What Do You Think?

Students will most likely come up with a range of responses based on what they have learned in previous sections. Indoor sports in air taking place on the Moon are bound to stir their curiosity; however, they may confuse the reduced gravity on the Moon with the lack of atmosphere. Consider asking how the absence of air on the Moon would impact these sports, and if this will affect the strength of gravity on the Moon. What would happen if the astronaut tried to fly outdoors? As students get engaged in responding to the *What Do You Think?* question, encourage them to record their answers and discuss their ideas with their group members. This is a good opportunity for you to assess what students know about gravity and what prior conceptions they have about playing a sport on the Moon.

What Do You Think?

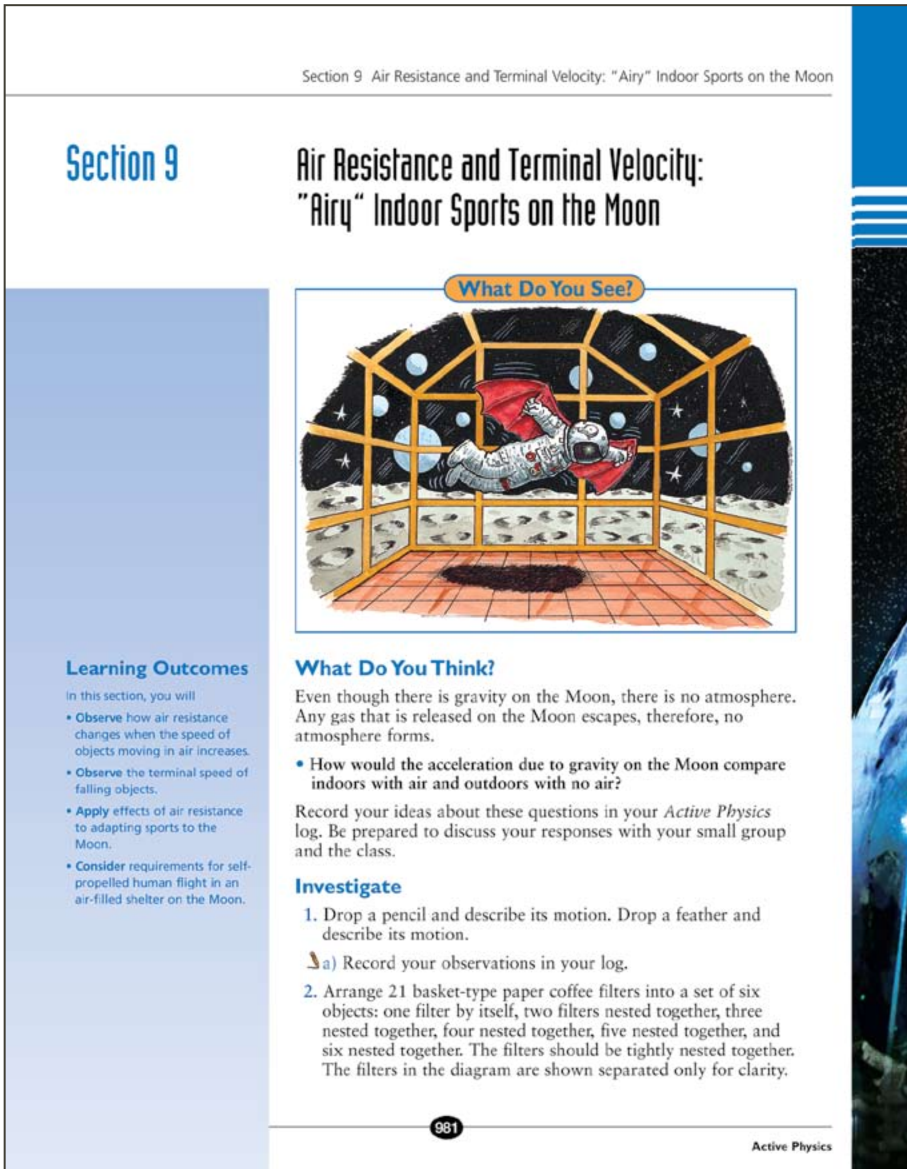
A Physicist's Response

The acceleration due to gravity on the Moon would be equal indoors and outdoors. Air resistance would behave the same way inside an air-filled facility on the Moon as on Earth. For a sport such as baseball played indoors, the horizontal component of a projectile's motion would be retarded (decelerated) in the same way as on Earth. Terminal velocity for falling objects would be reached at lower speeds than on Earth in an air- filled facility on the Moon due to the reduced weight of objects on the Moon.

Students' Prior Conceptions

Students may consider the effects of air resistance and terminal velocity important to sports on the Moon, since terminal velocity is reached when the force of air resistance equals the force of gravity. The gravitational force being less for a given mass on the Moon than on Earth can be an intriguing concept in the design of a sport for the Moon.

1. **Students envision air resistance as a constant thing, a steady resistive force.** When students are investigating terminal velocity with the coffee filters, help them analyze their data so that they recognize patterns that indicate that the upward force resisting the downward force of gravity is not a constant force, but increases with an increase in velocity. Student data should not model a linear relationship. There are fine computer simulations of terminal velocity and it is instructive for teachers to provide appropriate Web sites for students to view and to study.
2. **Students may think of terminal speed as the final speed of a moving body and not recognize the equilibrium state of the forces involved.** Ask students about some of the stages of a skydiver. First, the diver wants the thrill of free fall, trying to decrease air resistance as much as possible. Then, the diver uses the folds of the diving suit to slow down the descent by creating a larger area for resistance. This is followed by opening a parachute to slow the descent more or even if an updraft exists once slowed so that the diver can rise in the air. Throughout each of these stages, the teacher might ask, "What is the constant downward force on the sky diver?" Aha…the constant force of gravity or the weight of the diver and the equipment. For terminal velocity to be reached during any of these stages, the upward force of air resistance must balance the constant force of gravity so that the net acceleration is zero. Hence, terminal velocity is an equilibrium state and not necessarily the final state during a sky dive. The diver might reach terminal velocity once with the parachute, change the equilibrium state by allowing air to slip from the parachute to reach a terminal speed that differed from the previous one, and then adjust the parachute to reach a really slow terminal velocity for a safe and accurate landing.



Section 9

Air Resistance and Terminal Velocity: "Airy" Indoor Sports on the Moon

What Do You See?

Learning Outcomes

In this section, you will

- Observe how air resistance changes when the speed of objects moving in air increases.
- Observe the terminal speed of falling objects.
- Apply effects of air resistance to adapting sports to the Moon.
- Consider requirements for self-propelled human flight in an air-filled shelter on the Moon.

What Do You Think?

Even though there is gravity on the Moon, there is no atmosphere. Any gas that is released on the Moon escapes, therefore, no atmosphere forms.

- How would the acceleration due to gravity on the Moon compare indoors with air and outdoors with no air?

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

1. Drop a pencil and describe its motion. Drop a feather and describe its motion.

a) Record your observations in your log.

2. Arrange 21 basket-type paper coffee filters into a set of six objects: one filter by itself, two filters nested together, three nested together, four nested together, five nested together, and six nested together. The filters should be tightly nested together. The filters in the diagram are shown separated only for clarity.

Investigate

1.a)

Students observe that the pencil falls quickly to the ground, accelerating under the influence of Earth's gravity. The feather falls slowly, greatly affected by air drag.

2.

Students arrange 21 basket-type paper coffee filters into six sets.

Teaching Tip

If a motion detector is to be used to measure the velocity of the mass falling, an index card taped to the inside of the top coffee filter should help the motion detector to follow the falling filters.

3.a)

The more air filters there are in a group, the more they act like the falling pencil.

3.b)

Students set up a table like the one below to record the time of fall for the different groups of coffee filters.

Number of filters	Fall Time (s)
1	
2	
3	
4	
5	
6	

The filters will have fall times ranging in nonlinear order (not equally separated in time) from the heaviest set of six nested filters (least time, almost equal to free fall) to the single filter (which reaches a low terminal speed almost immediately after it begins to fall).

3.c)

The greater the object's mass, the less time it takes to fall. More precisely, the greater the net downward force acting on the object—the object's weight minus the force due to air resistance (which changes with the object's speed)—the greater the object's acceleration at any time during its fall.

3. Have three members of your group stand side by side along a line, each person holding two of the objects, one in each hand, with the flat side facing down. Drop all six objects at the same instant from equal heights. Observe the order they hit the floor. Also measure the time it takes each object to fall to the floor. Finally, observe the kind of motion each object has as it falls. Repeat dropping the objects until you are able to make all of the observations.

a) Compare and contrast the motion of the coffee filters with that of the pencil.

b) Record your observations in your log. Record the mass of each object as "1," "2," "3," "4", "5" and "6," depending on how many filters make up the object. You can assume each filter has the same mass.

c) How are the times to fall to the floor related to the masses of the objects? Write your answer in your log.

d) Do any of the objects seem to fall at a constant speed instead of accelerating as they fall? If so, which ones, and why? Write your answers in your log.

e) Describe in your log what you think would happen if the coffee filters were dropped in the same way as above, but indoors, in air, on the Moon.

f) Describe how they would fall outdoors on the Moon, without air.

4. To find out what the game of badminton would be like on the Moon, observe as a member of your class or your teacher hits or tosses a badminton shuttlecock.

a) What is the range when the shuttlecock is hit very hard in a direction approximately parallel to the ground using a tennis-like overhand serve? Record the range in your log.

b) How is the range of the shuttlecock affected as the person "eases up" by hitting with less and less strength? Describe in your log how the range is affected.

c) The shuttlecock's speed changes a lot during the first one half of its flight. What is the difference in the way the speed changes when the hit is hard or soft? Write your response in your log.

d) Hitting a shuttlecock harder and harder does not result in proportionately greater and greater ranges. For example, hitting it five times harder probably did not make it go five times farther. Why not?

e) Imagine playing badminton on the Moon indoors with air. Including effects of $\frac{1}{6}g$, which aspects of the game would be the same as on Earth and which would be different? Would badminton be playable indoors on the Moon? Write your answers in your log.

3.d)

Certainly, the single filter seems to reach terminal speed, and so may some of the others. A motion detector, if used as an option, would reveal which filters reach terminal speed; if at all possible, use a motion detector to seek details of the motions of the filters.

3.e)

Indoors, in air, on the Moon terminal speed would be reached at a lower speed due to the reduced weight of the filters on the Moon.

3.f)

Outdoors on the Moon, in the absence of air resistance, the filters would fall in the same way as the Moon's rocks.

4.a)

The maximum range of a badminton shuttlecock is in the neighborhood of 10 m. It is important that students recognize how important air resistance is to the motion of a shuttlecock. This motion is so different from the "projectile motion" with which they are familiar, that it takes considerable thought for them to appreciate the differences. Recognizing that the shuttlecock's motion is dominated by its terminal speed is a crucial consideration.

4.b)

The range does not decrease dramatically as the hits are made softer, due to the fact that most of the speed is lost soon after launch when the air resistance is many times greater than later in the flight.

4.c)

The speed during the first half of the flight appears greater for hard serves and soft serves, but the speeds are about equal during the last part of the flight. Because the last parts of both flights are about equal, the total ranges are not extremely different for hard and soft hits.

4.d)

The air resistance acting on the shuttlecock increases as its speed increases; it's a limiting proposition to try to make a shuttlecock go farther by hitting it harder.

4.e)

The way the shuttlecock flies and is affected by air resistance would not change greatly when played on the Moon. The shuttlecock would fall more slowly, however, allowing the players more time to reach it before it strikes the ground. Badminton would be playable indoors on the Moon, but a larger court might be needed because players would have more time to reach the shuttlecock.

NOTES

NOTES

4.f)

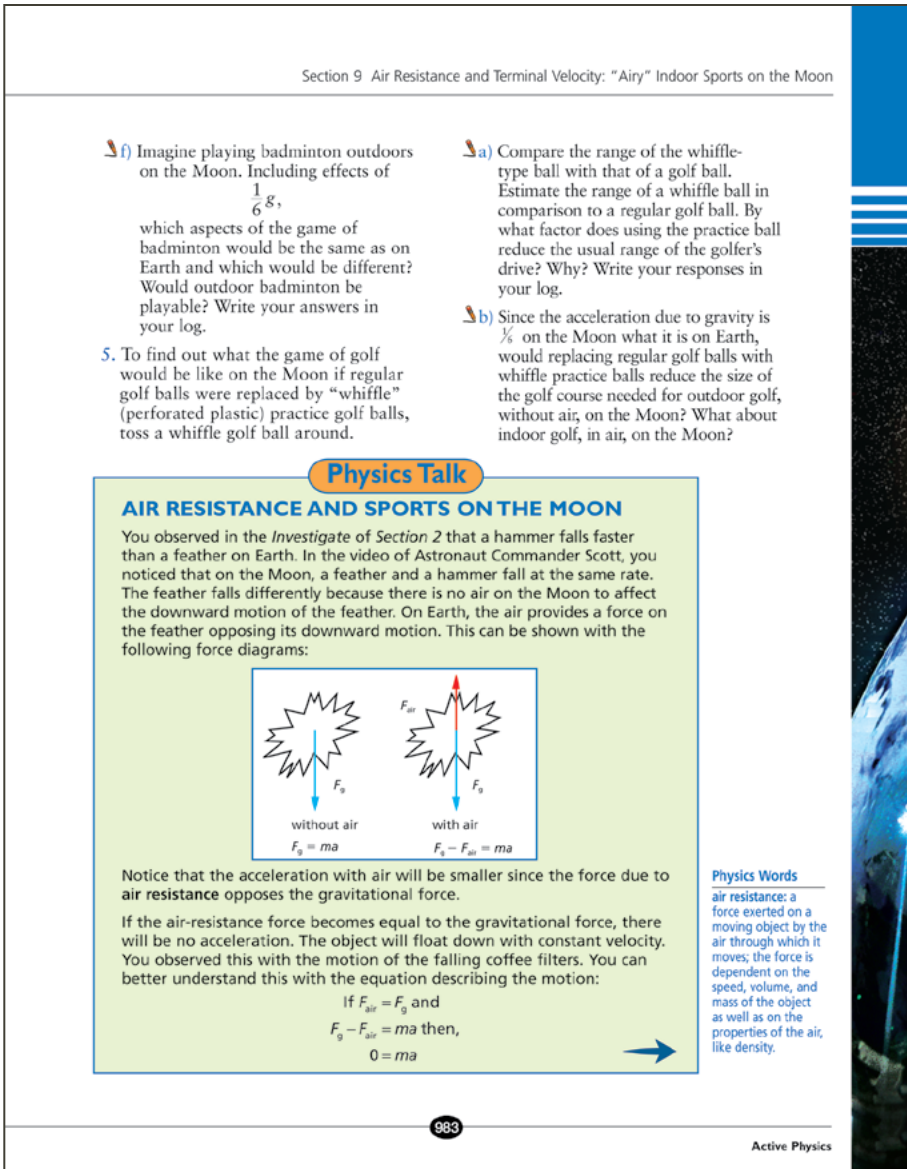
Playing badminton outdoors on the Moon would be more like playing tennis, since the shuttlecock would not be slowed at all by air resistance. It would still fall slowly, but the speed of the shuttlecock would be much faster, since it would not slow down after leaving the racket.

5.a)

The range of a "whiffle" golf ball used for practice would be about 10 percent of the range of a regular golf ball due to the greatly increased air resistance. As a result, the distance a whiffle golf ball would be driven by a golf club would also be less than 10 percent of the regular golf ball's range.

5.b)

Using whiffle golf balls would not reduce the size of an outdoor golf course a great deal. A whiffle practice ball would not go as far as a regular golf ball. However, when hit outdoors on the Moon, due to the lower rebound speed of the golf club, the whiffle ball would still go quite far. If played



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f) Imagine playing badminton outdoors on the Moon. Including effects of $\frac{1}{6}g$, which aspects of the game of badminton would be the same as on Earth and which would be different? Would outdoor badminton be playable? Write your answers in your log.

5. To find out what the game of golf would be like on the Moon if regular golf balls were replaced by "whiffle" (perforated plastic) practice golf balls, toss a whiffle golf ball around.

a) Compare the range of the whiffle-type ball with that of a golf ball. Estimate the range of a whiffle ball in comparison to a regular golf ball. By what factor does using the practice ball reduce the usual range of the golfer's drive? Why? Write your responses in your log.

b) Since the acceleration due to gravity is ⅙ on the Moon what it is on Earth, would replacing regular golf balls with whiffle practice balls reduce the size of the golf course needed for outdoor golf, without air, on the Moon? What about indoor golf, in air, on the Moon?

Physics Talk

AIR RESISTANCE AND SPORTS ON THE MOON

You observed in the *Investigate* of *Section 2* that a hammer falls faster than a feather on Earth. In the video of Astronaut Commander Scott, you noticed that on the Moon, a feather and a hammer fall at the same rate. The feather falls differently because there is no air on the Moon to affect the downward motion of the feather. On Earth, the air provides a force on the feather opposing its downward motion. This can be shown with the following force diagrams:

Notice that the acceleration with air will be smaller since the force due to **air resistance** opposes the gravitational force.

If the air-resistance force becomes equal to the gravitational force, there will be no acceleration. The object will float down with constant velocity. You observed this with the motion of the falling coffee filters. You can better understand this with the equation describing the motion:

If $F_{air} = F_g$ and

$F_g - F_{air} = ma$ then,

$0 = ma$

Physics Words

air resistance: a force exerted on a moving object by the air through which it moves; the force is dependent on the speed, volume, and mass of the object as well as on the properties of the air, like density.

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indoors, the whiffle ball would greatly reduce the size of the needed golf course due to the air resistance it encounters. The air resistance would slow the whiffle ball to such a degree, that the extra time it spends in the air due to the lower gravity on the Moon would not be a very large contributor to the distance it flies.

9-9b **Blackline Master**

Physics Talk

Students analyze how lack of an atmosphere on the Moon affects acceleration of different falling objects. They are asked to recall their observation of the *Investigate* of *Section 2* in which a hammer and a feather each fall at the same rate. In contrast, they compare how a feather falls differently on Earth due to the presence of air resistance. To reinforce their understanding of how air resistance affects the downward acceleration of falling objects, draw their attention to the visual in the *Physics Talk*. Ask students to explain why objects float down with constant velocity by considering the forces acting. Have them describe the term terminal velocity in their *Active Physics* logs. Consider asking students to illustrate through a diagram how air resistance acts on objects using its description in the student text.

Discuss how objects reach terminal velocity while falling. Write the equation for total force on a falling object when it no longer experiences acceleration. Ask students how parachutes help a skydiver to land safely. Discuss why terminal velocity on the Moon would be less in an indoor stadium. Invite students to give their opinion on whether using a pedal powered helicopter would be possible for an indoor activity on the Moon. Ask them why equipping people with gloves similar to a bat's wings might be used to "swim" through indoor air on the Moon in reference to the concept of terminal velocity.

CHAPTER 9

Physics Words

terminal velocity: the speed reached by an object falling through air when the force of air resistance equals the force of gravity on the object.

Newton's second law of motion: if a body is acted upon by an external force, it will accelerate in the direction of the unbalanced force; the acceleration is proportional to the force and inversely proportional to the mass.

Newton's third law of motion: forces exist in pairs; the force of object A on object B is equal and opposite to the force of object B on object A.

A zero acceleration means that there is no change in velocity and the coffee filter moves at a constant velocity. This is called the **"terminal velocity."**

Air resistance could have important implications for adapting sports, or even for inventing new sports, that could be played in an air-filled indoor facility on the Moon.

Air resistance exists because, as an object moves through air, it collides with air molecules in its path. Each collision with an air molecule is governed by **Newton's third law** and the law of conservation of momentum. The air molecule is pushed in the direction of the object's motion, and, in reaction, the object experiences a tiny push by the air molecule in the direction opposite the object's motion. The result of steady collisions with many, many air molecules is that the object experiences a force due to the air and, therefore, an acceleration in the direction opposite to its motion. The amount of force due to air resistance depends on the object's speed, size, and shape.

According to **Newton's second law of motion**, $F = ma$, the effect of air resistance is to cause objects moving through air to slow down (negative acceleration).

Fly Like a Bird on the Moon?

Air resistance on a falling object causes the object's net downward acceleration to decrease. If the object reaches a great enough speed during its fall, it stops accelerating and continues its fall at a constant speed known as its "terminal speed" or "terminal velocity." This happens if and when the amount of the force of air resistance builds up enough to be equal and opposite to the object's weight.

Terminal speed is reached when

$$\text{Total force on object} = (\text{weight}) - (\text{force of air resistance}) = 0$$

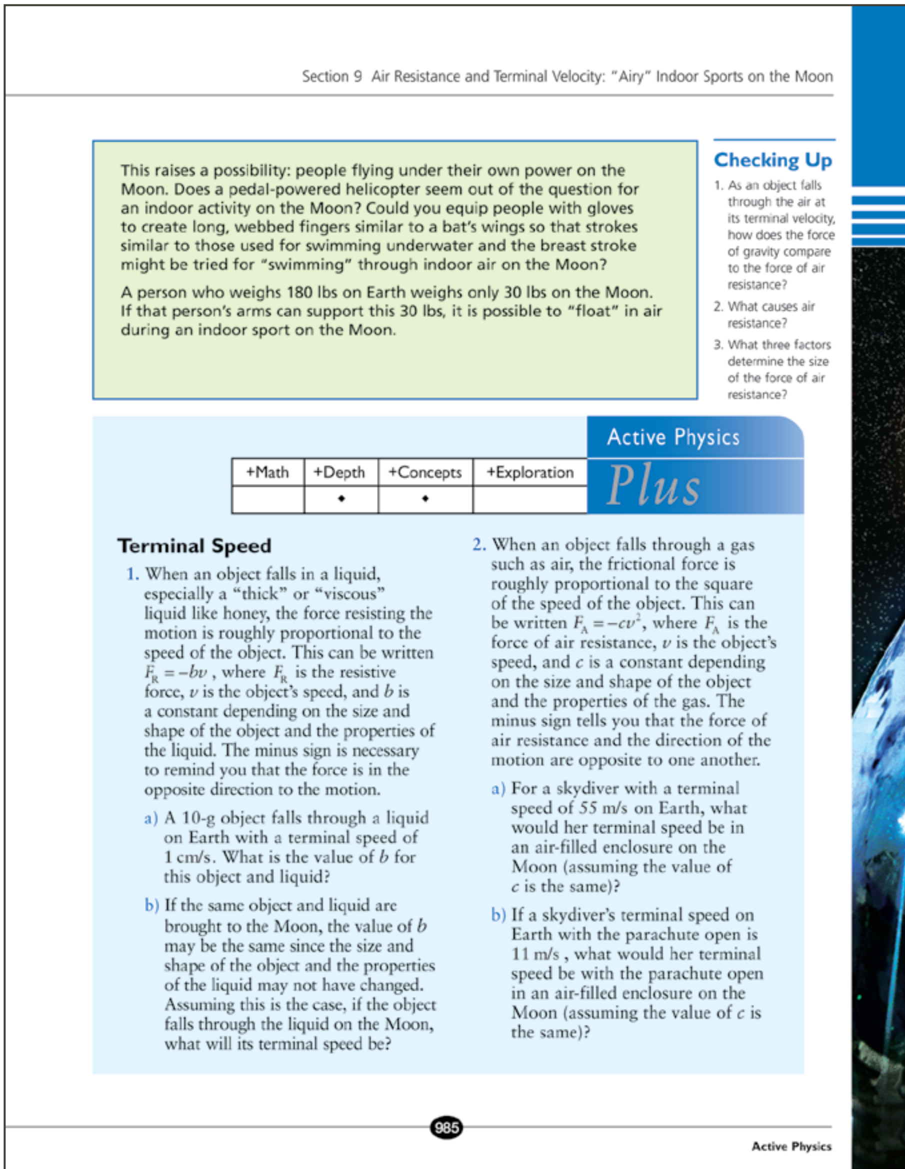
When the total force acting on the object is zero, there no longer is any acceleration.

On Earth, a skydiver of average weight falling with an unopened parachute has a typical terminal speed of about 55 m/s (125 mi/h); with the parachute open, the terminal speed is reduced to a safe landing speed of about 11 m/s (25 mi/h). On the Moon, the skydiver's weight would be $\frac{1}{6}$ as much as on Earth, and so the force of air resistance needed to balance the skydiver's weight would also be $\frac{1}{6}$ of the amount on Earth. If an indoor stadium on the Moon had an atmosphere like Earth's, and since the force of air resistance depends on the speed, the skydiver's terminal speed falling without a parachute through a Moon atmosphere would be less.

Checking Up

1.

An object falling through air at its terminal velocity is in equilibrium. Thus, the force of gravity pulling the object downward is exactly balanced by the force of air resistance acting against its downward motion.



This raises a possibility: people flying under their own power on the Moon. Does a pedal-powered helicopter seem out of the question for an indoor activity on the Moon? Could you equip people with gloves to create long, webbed fingers similar to a bat's wings so that strokes similar to those used for swimming underwater and the breast stroke might be tried for "swimming" through indoor air on the Moon?

A person who weighs 180 lbs on Earth weighs only 30 lbs on the Moon. If that person's arms can support this 30 lbs, it is possible to "float" in air during an indoor sport on the Moon.

Checking Up

1. As an object falls through the air at its terminal velocity, how does the force of gravity compare to the force of air resistance?
2. What causes air resistance?
3. What three factors determine the size of the force of air resistance?

Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
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Terminal Speed

1. When an object falls in a liquid, especially a "thick" or "viscous" liquid like honey, the force resisting the motion is roughly proportional to the speed of the object. This can be written $F_R = -bv$, where F_R is the resistive force, v is the object's speed, and b is a constant depending on the size and shape of the object and the properties of the liquid. The minus sign is necessary to remind you that the force is in the opposite direction to the motion.
   a) A 10-g object falls through a liquid on Earth with a terminal speed of 1 cm/s. What is the value of b for this object and liquid?
   b) If the same object and liquid are brought to the Moon, the value of b may be the same since the size and shape of the object and the properties of the liquid may not have changed. Assuming this is the case, if the object falls through the liquid on the Moon, what will its terminal speed be?
2. When an object falls through a gas such as air, the frictional force is roughly proportional to the square of the speed of the object. This can be written $F_A = -cv^2$, where F_A is the force of air resistance, v is the object's speed, and c is a constant depending on the size and shape of the object and the properties of the gas. The minus sign tells you that the force of air resistance and the direction of the motion are opposite to one another.
   a) For a skydiver with a terminal speed of 55 m/s on Earth, what would her terminal speed be in an air-filled enclosure on the Moon (assuming the value of c is the same)?
   b) If a skydiver's terminal speed on Earth with the parachute open is 11 m/s, what would her terminal speed be with the parachute open in an air-filled enclosure on the Moon (assuming the value of c is the same)?

Active Physics Plus

This *Active Physics Plus* looks at the concept of drag acting on an object moving through a fluid, such as air or water. The equations for the force of resistance for the two media are discussed, then students solve the equations for the terminal velocity of an object traveling through the medium on Earth and the Moon.

1.a)

A 10-g object weighs 0.98 N on Earth. Therefore, the value of b must be
(0.098 N)/(0.01 m/s) = 9.8 Ns/m.

1.b)

On the Moon, the weight is one-sixth of 0.098 N or 0.016 N. The terminal speed on the Moon is then

$$(0.016\ \text{N})/(9.8\ \text{Ns/m}) = 0.0016\ \text{m/s} = 0.16\ \text{cm/s}.$$

2.a)

Notice in the previous question that because b is the same on Earth and the Moon, reduction of the weight by 1/6 reduces the terminal speed by a factor of 1/6. For air resistance, similar reasoning shows that it is not the terminal speed that is reduced by 1/6, but the square of the terminal speed that is reduced by a factor of 1/6. To reduce the terminal speed squared by 1/6, the terminal speed must be reduced by a factor of 0.4 ($0.4 \times 0.4 = 0.16$). Therefore, the skydiver's terminal speed on the Moon is 55 m/s × 0.4 = 22 m/s.

2.b)

The skydiver's terminal speed with a parachute on the Moon is 11 m/s × 0.4 = 4.4 m/s.

2.

Air resistance is caused by the collisions with the air molecules in the object's path. When the object collides with the molecules, it pushes them out of the way, and according to Newton's third law, the molecules push back on the object to slow it down.

3.

The object's speed, size, and shape determine the force of air resistance on a moving object. The faster the object travels or the larger the object is, the more molecules/second will be pushed out of the way. The shape of the object determines how much the air molecules have to be pushed opposite to the direction of motion, or if they may be pushed off to the side, requiring less force to deflect them.

CHAPTER 9

What Do You Think Now?

Students should now be able to understand that the gravity of the Moon is the same in both the presence and absence of air. They should also realize that the effect of air resistance is to oppose the force of gravity for a falling object. You might want to ask students to recall what they have learned about the effects of air resistance on falling objects and how terminal velocity is reached. Emphasize that their answers should be carefully edited and should reflect a good grasp of concepts they have investigated in this section. Share *A Physicist's Response* and invite students to discuss their doubts. Encourage them to visit the *What Do You See?* illustration and point out how significant the images are to understanding concepts introduced in this section. The illustration should also be more meaningful to them now in understanding how concepts are connected.

What Do You Think Now?

Even though there is gravity on the Moon, there is no atmosphere. Any gas that is released on the Moon escapes, therefore no atmosphere forms.

- **How would the acceleration due to gravity on the Moon compare indoors with air and outdoors with no air?**

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

Physics Essential Questions

What does it mean?

Why are the effects of air resistance different for various objects? Why do calculations that ignore air resistance often predict the trajectory of an object quite well?

How do you know?

What did you observe that helps to explain what determines the effects of air resistance on an object?

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	* Optimal prediction and explanation

* Physics often predicts what will happen in circumstances where the experiment cannot be done. Why do you think you can believe a prediction of how air resistance will be different on the Moon compared to on Earth without doing the experiment on the Moon?

Why should you care?

Many sports involve objects moving through the air. Will the sport in your proposal be affected by air resistance?

Reflecting on the Section and the Challenge

This section has demonstrated that air resistance has profound effects on some sports on Earth and, if desired, could have profound effects on indoor sports in an air-filled sports facility on the Moon. Further, it seems possible that the eternal human quest of self-propelled flight could be realized in an Earth-like atmosphere combined with the Moon's reduced gravity.

Physics Essential Questions

What does it mean?

Air resistance depends on both the shape of the object and its mass. For small, massive objects, the air resistance force is much smaller than the force of gravity and can be ignored.

How do you know?

Nested coffee filters were dropped and it was determined that the lighter sets reached a terminal velocity. Traveling at a constant velocity implies that the force of air resistance is equal to the weight.

Why do you believe?

The physics of free fall and the behavior of air on an object should probably be identical on Earth and the Moon because the laws of physics should be identical at all locations.

Why should you care?

Air resistance will probably be more of an issue on the Moon because all objects weigh one-sixth of what they would on Earth. That makes it more probable that the air resistance will be comparable to the weight.

Reflecting on the Section and the Challenge

Allow students time to reflect on concepts they have investigated in this section. Ask them to describe in their *Active Physics* logs how air resistance and mass affect falling objects on Earth. Students should consider how the Moon's reduced gravity can affect indoor sports. Emphasize that students now have another opportunity to relate what they have learned so far to their *Chapter Challenge*. When inventing or adapting a sport to the Moon, students will be able to show how different aspects of a sport will be impacted on the both indoors in air and outdoors without air.

NOTES

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NOTES

Physics to Go

1.

Since weight on the Moon is one-sixth weight on Earth, one-sixth the force would be required to allow "lift-off" under self-propelled flight. This still might be too much force for a person to apply with a set of wings attached to their body. If the flying took place over an area with rising air currents like a giant air hockey game, the added force exerted by the upward rushing wind might be enough when combined with the force of the flyer to create a legitimate flying effect.

2.

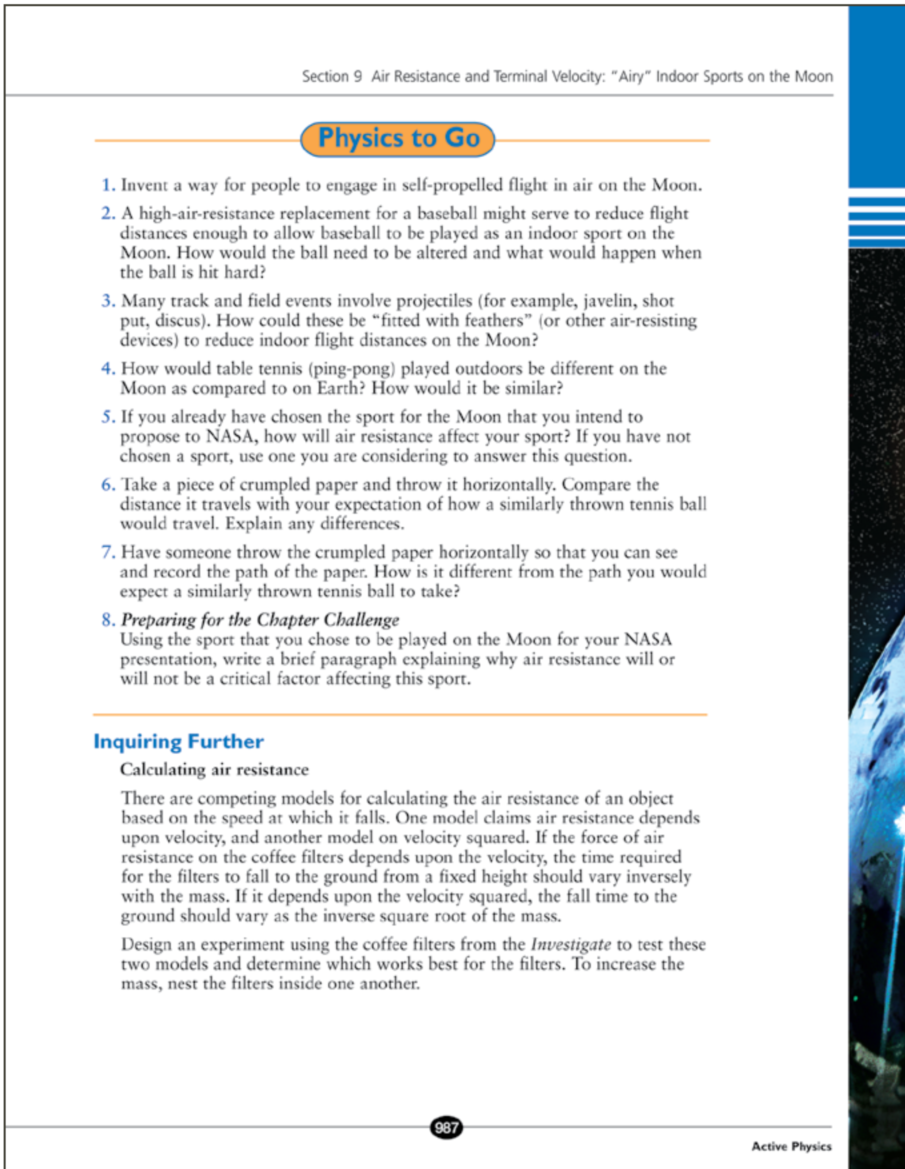
A baseball the size and composition of a practice golf ball could work since it would have a much greater air resistance. Since the ball would be made of hollow plastic with many small holes, the ball would likely deform severely when hit hard. The ball might have to be replaced every few innings due to the stress caused by the hits.

3.

Low-inertia devices might be slowed down enough to be used indoors on the Moon, but heavy devices such as the javelin, discus, and shot-put ball would have too much inertia (too much force is required to change their speed) to be slowed down even by adding "feathers." A much stiffer analog of feathers would be required, and would be particularly successful on a rotating device like the discus or javelin.

4.

Outdoor table tennis on the Moon would have the ball travel faster due to lack of air resistance and fall slower due to reduced gravity. Spin applied to the ball would not affect its motion during flight. Indoor table tennis would work about the same way as badminton in an



Section 9 Air Resistance and Terminal Velocity: "Airy" Indoor Sports on the Moon

Physics to Go

1. Invent a way for people to engage in self-propelled flight in air on the Moon.
2. A high-air-resistance replacement for a baseball might serve to reduce flight distances enough to allow baseball to be played as an indoor sport on the Moon. How would the ball need to be altered and what would happen when the ball is hit hard?
3. Many track and field events involve projectiles (for example, javelin, shot put, discus). How could these be "fitted with feathers" (or other air-resisting devices) to reduce indoor flight distances on the Moon?
4. How would table tennis (ping-pong) played outdoors be different on the Moon as compared to on Earth? How would it be similar?
5. If you already have chosen the sport for the Moon that you intend to propose to NASA, how will air resistance affect your sport? If you have not chosen a sport, use one you are considering to answer this question.
6. Take a piece of crumpled paper and throw it horizontally. Compare the distance it travels with your expectation of how a similarly thrown tennis ball would travel. Explain any differences.
7. Have someone throw the crumpled paper horizontally so that you can see and record the path of the paper. How is it different from the path you would expect a similarly thrown tennis ball to take?
8. *Preparing for the Chapter Challenge*
   Using the sport that you chose to be played on the Moon for your NASA presentation, write a brief paragraph explaining why air resistance will or will not be a critical factor affecting this sport.

Inquiring Further

Calculating air resistance

There are competing models for calculating the air resistance of an object based on the speed at which it falls. One model claims air resistance depends upon velocity, and another model on velocity squared. If the force of air resistance on the coffee filters depends upon the velocity, the time required for the filters to fall to the ground from a fixed height should vary inversely with the mass. If it depends upon the velocity squared, the fall time to the ground should vary as the inverse square root of the mass.

Design an experiment using the coffee filters from the *Investigate* to test these two models and determine which works best for the filters. To increase the mass, nest the filters inside one another.

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air-filled Moon sports facility—the greatest difference would be in the downward motion of the ball.

5.

The response will depend on the student's choice of sport. All should explain how air resistance would slow the motion of any moving objects in the sport.

6.

The crumpled paper does not go nearly as far as the tennis ball thrown with the same velocity. The force of air resistance is probably similar for the two objects, but the tennis ball has a larger mass, so would have a smaller negative acceleration and thus take a larger distance to come to a stop.

7.

The path of the paper will not be a parabola. Because the horizontal component of its velocity decreases so quickly, it will appear to fall more "straight down" after it loses most of its velocity.

8.

Preparing for the Chapter Challenge

The student's answers will depend upon which sport is chosen. For a sport that is highly affected by air resistance, the students should explain why air resistance would be greater on the Moon.

Inquiring Further

Students should design an experiment to see if air resistance for falling coffee filters depends on the velocity or the velocity squared. If the air resistance depends upon the velocity, then at terminal velocity, the force of air resistance must equal the force of gravity or mg = air resistance. For the two models, this would be either $mg = bv$, or $mg = cv$. Assuming a coffee filter dropped from a height of more than 2 m quickly reaches terminal velocity, then for constant speed you can say that $v = d/t$. Substituting for the velocity into the two equations gives $mg = b(d/t)$ and $mg = c(d/t)^2$. Solving both equations for t yields $t = bd/mg$ if air resistance is proportional to velocity and $t = d\sqrt{c/mg}$ if air resistance is proportional to velocity squared. By dropping first one coffee filter, then two nested coffee filters, then three or more nested filters and graphing the fall time vs. the mass of the filters, students can determine if the relationship between the variables is proportional to t or t^2. This will allow them to determine which model is more appropriate.

CHAPTER 9

SECTION 9 QUIZ

9-9c **Blackline Master**

For the purpose of answering the following questions, the acceleration due to gravity on the Moon is 1.6 m/s^2 and on Earth 10 m/s^2.

1. Two identical badminton shuttlecocks are falling with terminal velocity indoors on both the Earth and the Moon. Which statement below best describes the motion of the shuttlecocks?

   a) The shuttlecock on Earth will fall faster due to Earth's larger gravity.

   b) The shuttlecock on the Moon will fall faster due to Moon's smaller gravity.

   c) Both shuttlecocks will fall at the same rate since the air resistance is the same.

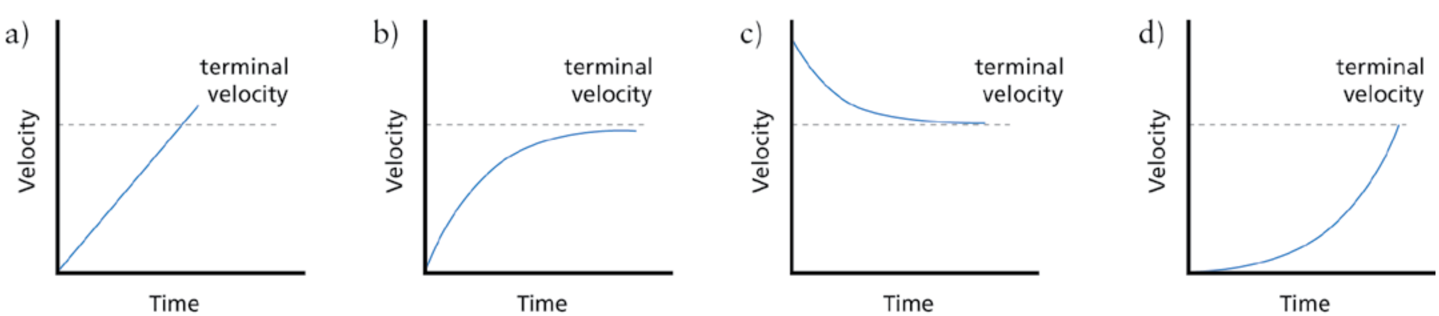
   d) The shuttlecock on Earth will fall faster due to Earth's lower air resistance.

2. Which of the following has no effect on the amount of air resistance of a falling object?

   a) the object's speed b) the object's mass

   c) the objects shape d) the objects size

3. A shuttlecock is struck with a racquet giving it an initial velocity downward greater than its terminal velocity in air. Which velocity vs. time graph below best describes the motion of the shuttlecock as it moves through the air?



4. When a falling object reaches terminal velocity

   a) the force of air resistance is greater than the object's weight.

   b) the force of air resistance exactly matches the object's weight.

   c) the force of air resistance is slightly less than the object's weight.

   d) air resistance will start to decrease.

5. A whiffle ball with a mass of 0.10-kg is falling on the Moon. If the force of air resistance on the whiffle ball at this speed is 0.1 N, the object will accelerate at

a) 1.6 m/s^2.
b) 1 m/s^2.
c) 0.6 m/s^2.
d) 0 m/s^2.

SECTION 9 QUIZ ANSWERS

1. a) For an object falling at terminal velocity, $F_{gravity} - F_{air} = 0$. Because the force of gravity on Earth is larger than the force of gravity on the Moon, a larger air resistance force is needed. Because the shuttlecocks are identical, the one on Earth must fall faster to have a greater air resistance force.

2. b) An object's mass does not affect its air resistance, but will affect its terminal velocity. Heavier objects have a higher terminal velocity since they weigh more, but unless the shape, size or speed of travel changes, the air resistance will remain the same.

3. c) The shuttlecock will have a force of air resistance greater than its weight since its speed is higher than the terminal velocity. Because $F_{gravity} - F_{air} = ma$, and F_{air} is greater than $F_{gravity}$, the shuttlecock will have a negative acceleration slowing it down until it reaches terminal velocity where $F_{gravity} - F_{air} = 0$, and it then travels with constant velocity.

4. b) At terminal velocity, the force of air resistance equals the weight exactly, giving no net force, and the object then continues with constant velocity by Newton's first law.

5. c) Using $F_{gravity} = mg$ gives $F_{gravity} = (0.10 \text{ kg})(1.6 \text{ m/s}^2) = 0.16 \text{ N}$. Then, substituting into $F_{gravity} - F_{air} = ma$, gives $0.16 \text{ N} - 0.10 \text{ N} = (0.10 \text{ kg})(a)$ or $a = 0.6 \text{ m/s}^2$.