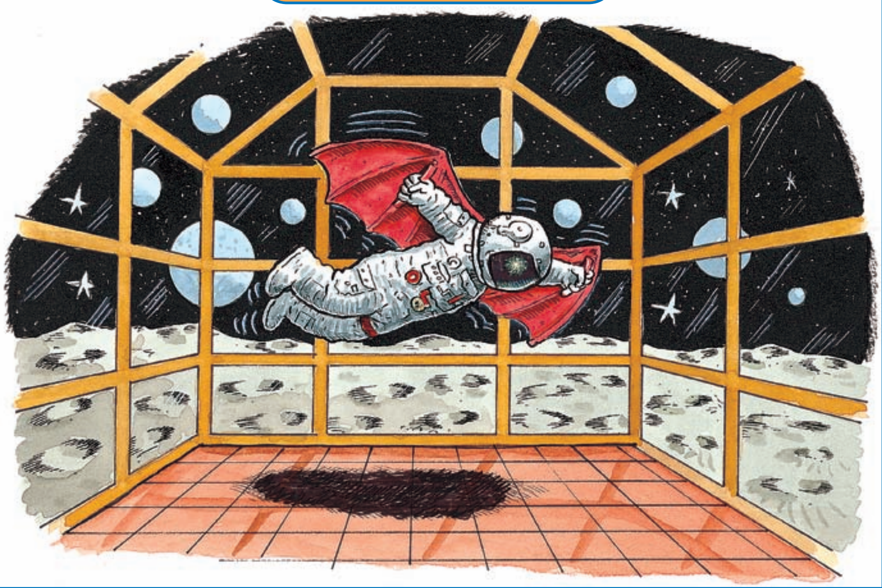
Section 9

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?**

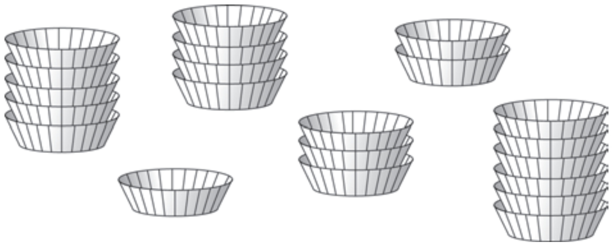
Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

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.



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 if 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.

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.

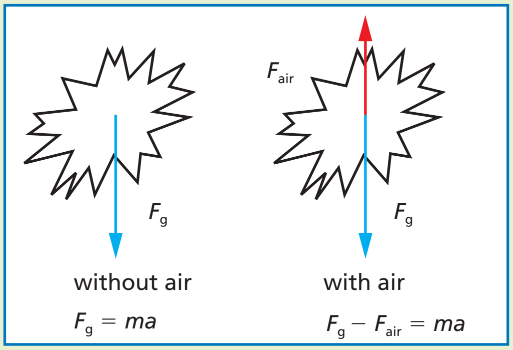
a) Compare the range of the whiffle-type ball with that of a golf ball. Estimate the range of a whiffle ball in comparison to a regular golf ball. By what factor does using the practice ball reduce the usual range of the golfer's drive? Why? Write your responses in your log.

b) Since the acceleration due to gravity is $\frac{1}{6}$ on the Moon of 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:

$$\text{If } F_{air} = F_g \text{ and}$$
$$F_g - F_{air} = ma \text{ then,}$$
$$0 = ma$$

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.

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 $55\ \text{m/s}$ (125 mi/h); with the parachute open, the terminal speed is reduced to a safe landing speed of about $11\ \text{m/s}$ (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.

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
	◆	◆	

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)?

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 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.