

SECTION 7

Frictional Forces: The Mu of the Shoe

Section Overview

In this section, students investigate the effect of different surfaces and different weights on the force of friction. By pulling a shoe across a surface, the students examine the factors that affect the force of friction between the shoe and the surface. They measure and record the amount of force needed to keep the shoe sliding on the surface at a slow, constant speed when the mass of the shoe is varied. The force required to slide an object on a surface at constant speed determines the force of friction. They also measure the weight of the shoe and determine that the perpendicular (normal) force exerted by the surface on the object is equal in magnitude to the weight but opposite in direction. The students then discover that the ratio of the force of friction to the normal force is a constant known as the *coefficient of friction*. The coefficient of friction is found to be independent of the force holding the surfaces together, and depends only upon the nature of the surfaces in contact. Finally, the students investigate various surfaces to determine their coefficients of friction.

Background Information

To accelerate an object (change its speed, its direction, or both), a net force must act on the object. If a person is standing still on a sidewalk and wants to get moving, he or she must somehow cause a force to be exerted on the body's mass, which is accomplished by the application of a force in the backward direction, parallel to the surface of the sidewalk. How much the person can push his or her feet depends on how much frictional force can be sustained by the interaction of the sole of the shoe and the sidewalk's surface. If the shoe does not slip on the surface, the sidewalk surface's equal and opposite reaction to the rearward force of friction

causes the body to accelerate forward; if there is ice on the sidewalk, the available force will be reduced, and shoes may just slide on the surface with the result that one goes nowhere.

The maximum frictional force, F_{\max} , that can be generated between the surfaces of two materials in contact but not sliding relative to each other is expressed by the equation $F_{\max} = \mu_s F_N$. F_N is the “normal force” (perpendicularly pushing the two surfaces together) and μ_s is the “coefficient of static or starting friction” (for the pair of materials from which the surfaces are made). The word “normal” in this context means “perpendicular.” Expect students to need some time to get comfortable with the use of this word. In the above example, the normal force, F_N , would be equal to your weight.

The value of μ_s depends on the quality of the two materials in contact. If the two surfaces are sliding relative to each other, the frictional force, F , is given by the equation $F = \mu F_N$, where μ is the “coefficient of sliding friction” (sometimes called the coefficient of “kinetic”—meaning “moving”—friction). The coefficient of static friction is larger than the coefficient of sliding friction. The coefficient of sliding friction applies when the surfaces are moving with respect to each other in a sliding mode and the formula $F = \mu F_N$ gives the value of the frictional force. It is this frictional force that is measured in this section because it is a bit easier conceptually.

When objects are not sliding relative to each other, the frictional force can be anything between zero and $\mu_s F_N$. When objects are sliding relative to each other, the frictional force is simply μF_N . The frictional force generated between the shoe and the sidewalk due to pushing the foot rearward, as gravity and the upward restoring force of the sidewalk squeeze the sole of the shoe and the surface of the sidewalk together, is answered by a

corresponding equal forward push by the sidewalk on the foot. The latter force, the forward push by the sidewalk, is the push you “feel” and which causes you to accelerate forward. It is not always the case that the normal force, F_N , is equal to the weight of the object. In the case of an object on a sloped surface, the normal force is less than the weight, equaling the component or effectiveness, of the object’s weight in the direction perpendicular to the sloped surface. Other examples of cases where F_N is not equal to the weight of an object bearing on a surface would include the frictional force between belts riding on pulleys in machines;

in such cases, tensioned springs usually are used to force the surfaces together to provide sufficient F_N to prevent sliding, or, intentionally as when stopping a machine, to reduce tension to cause F_N to be reduced to an amount where a belt will slide on a pulley. Another example of an increased normal force would be when an athlete’s sudden thrust downward creates a much larger force than the weight of the athlete. This is a temporary condition because the athlete’s body will soon be accelerated upward, lifting that foot away from the surface. Similar conditions may occur when the athlete descends from this leap for the next stride.

Crucial Physics

- For any two surfaces sliding past each other, the ratio of the force necessary to keep the surfaces sliding and the force between the surfaces perpendicular to the surfaces is called coefficient of sliding friction.
- The coefficient of sliding friction depends on the nature of the two surfaces, not on the force between the surfaces perpendicular to the surfaces.

Learning Outcomes	Location in the Section	Evidence of Understanding
Apply the definition of the coefficient of sliding friction, μ .	<i>Investigate</i> Steps 2.a) and 3	Students measure and record the weight of a shoe and the amount of force in newtons needed to keep the shoe moving at a slow constant speed. They then use an equation to find the coefficient of friction.
Measure the coefficient of sliding friction between soles of athletic shoes and a variety of surfaces.	<i>Investigate</i> Steps 3-5	Students measure and record the amount of force needed to pull different shoes on a variety of surfaces and then by recording the weight, as well, calculate the coefficient of friction.
Calculate the effects of frictional forces on the motion of objects.	<i>Investigate</i> Steps 4 and 5	Students use different surfaces and weights to measure the force required to slide an object on each surface.

Section 7 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	Group (4 students)	Class
Calculator, basic	1 per group	
Weight, slotted, 100 g	10 per group	
Scale, spring, 0-20 N	2 per group	
Surface, felt, rough, 6 in. x 36 in.	1 per group	
Box, friction, 5 3/4 in. (length) x 3 3/4 in. (width) x 3 in. (depth) (with hook)	1 per group	
Access to a flat surface (such as a table, floor or other open space)*	1 per group	
Shoe, athletic*	1 per group	

*Additional items needed not supplied

PLAN B		
Materials and Equipment	Group (4 students)	Class
Calculator, basic	1 per group	
Weight, slotted, 100 g	10 per class	
Scale, spring, 0-20 N	2 per group	
Surface, felt, rough, 6 in. x 36 in.	1 per group	
Box, friction, 5 3/4 in. (length) x 3 3/4 in. (width) x 3 in. (depth) (with hook)	1 per group	
Access to a flat surface (such as a table, floor or other open space)*	1 per group	
Shoe, athletic*	1 per group	

*Additional items needed not supplied

Note: Time, Preparation, and Safety requirements are based on Plan A, if using Plan B, please adjust accordingly.

Time Requirements

This *Investigate* should take one class period or 40 minutes.

Teacher Preparation

- Prior to the day of the *Investigate*, tell your students they will be measuring the friction of their athletic shoes. Ask the students to wear a pair of athletic shoes or bring one to class on that day. If you choose not to use athletic shoes, the same activity may be done by pulling material such as a wooden block across the surface, however students are much more engaged when they are using their shoes.
- In addition, you will need several samples of different surfaces to measure the frictional force. Sandpaper and/or a rough cloth taped to a lab table work quite well as a surface different from the lab table. Have masses available to place inside the shoes to increase the shoe's weight.

Safety Requirements

No particular safety precautions are required for this investigation.

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Designing an experiment	<i>Investigate</i> Step 2	<p>Augmentation</p> <ul style="list-style-type: none"> • Check to make sure groups choose variables that can be safely tested using the classroom equipment. • Prior to beginning the experiment, check for data tables that will allow students to record useful data. • Carefully plan groups by mixing students of different learning styles and strengths. A student who does poorly on tests may be great at designing an experiment. <p>Accommodation</p> <ul style="list-style-type: none"> • Provide a graphic organizer to guide student planning. The organizer could have sections for a purpose, hypothesis, diagram of the lab setup, procedure, data table, analysis, and conclusions. • Use the experiment that has already been designed in <i>Steps 3</i> and <i>4</i>.
Following directions Using a spring scale Reading comprehension	<i>Investigate</i> Steps 2.b), 3, and 4	<p>Augmentation</p> <ul style="list-style-type: none"> • Model how to properly use the spring scale. Students may also need to learn how to “read” the spring scale, especially those with visual motor and executive function issues. • Students have learned about the forces that act on objects earlier in this chapter. For the <i>Investigate</i>, Step 2.b), ask students what forces they think might be acting on the shoe before they read this step. The students may be able to identify all four forces without having to read this task. Activating prior knowledge may empower students who struggle with reading comprehension. • Assist students with setting up a data table that will allow them to record all of the required data including the type of surface, the shoe description, the weight of the shoe, the force required to slide the shoe, and μ. <p>Accommodation</p> <ul style="list-style-type: none"> • Pair students intentionally to include someone with strong reading skills and someone who struggles with reading. • Provide a step-by-step task checklist and time limits for students who really struggle to maintain focus/attention.
Understanding the concept of a ratio	<i>Physics Talk</i>	<p>Augmentation</p> <ul style="list-style-type: none"> • Provide direct instruction to teach the concept of a ratio because many students may not remember the math vocabulary word, <i>coefficient of sliding friction</i> (μ).
Solving word problems	<i>Physics to Go</i> Step 5	<p>Augmentation</p> <ul style="list-style-type: none"> • Students are asked to rearrange the coefficient of friction formula to solve for a “horizontal force.” • Remind students that the helpful circle can assist them in rearranging the formula if they struggle with algebra. • Students may have no idea that they are being asked to find the force of friction in this question.

Learning Issue	Reference	Augmentation and Accommodations
Choosing a formula and solving word problems	<i>Investigate</i> Step 6	<p>Augmentation</p> <ul style="list-style-type: none"> • Students with executive-function, reading, and math-learning issues struggle to extract information from a word problem and use the numbers to find a solution. • Review key phrases such as “what is,” “find the value of,” and “calculate the.” These phrases give students clues about what the problem is asking them to find. • Require that students show their work, especially for multi-step problems that expect students to use answers they have calculated as given values. • Remind students to use their formula sheet. Also, tell students that they may need to use formulas from other sections or chapters. <p>Accommodation</p> <ul style="list-style-type: none"> • Provide students with a page of blank problem-solving boxes. • Limit choice for the formulas. Show students the four formulas they need to solve these problems, and then ask them to choose the appropriate formula for each step.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension	<i>Investigate</i>	The concept of variables is crucial to scientific investigation. Explain to students that the root of the word “variable” is “vary,” meaning “to change.” A variable is a quantity that can change. When scientists conduct an experiment, they change only one variable at a time, which ensures that any change in the results must be caused by the change in the variable.
Demonstrating understanding	<i>Investigate</i> Step 3.b)	To give students a chance to demonstrate their understanding of the forces acting on the shoe, have them draw a free-body diagram that shows the direction of the four forces, and label the forces as well. Then have students indicate the two forces necessary for figuring out the value of μ . Encourage students to swap diagrams and check one another’s work.
Vocabulary comprehension	<i>Physics Talk</i> , Coefficient of Sliding Friction, μ	To help ELL students understand “material,” “surface texture,” “moisture,” and “lubrication” of surfaces and their effect on friction, bring in some samples of different materials, such as smooth plastic, wood, brick, and sandpaper, for students to touch. Allow students to push a coin, pencil eraser, or other small object over the different surfaces. Then dampen part of each material with water and part with mineral oil and allow students to do the same things again. Hold a class discussion about the friction associated with each dry material and what change wetting it makes. Encourage students to use the terms in context during the discussion.
Vocabulary comprehension Understanding concepts	<i>Active Physics Plus</i>	Thus far, students have been working only with sliding friction. Here, they encounter static friction. They likely will be able to infer the meaning of “static”—not moving—from context. Reinforce their inference by telling them that static in science refers to bodies at rest and to balanced forces. Once students have grasped the meaning of “static,” allow them time to write in their <i>Active Physics</i> log the description of how static friction works. Encourage them to write in their own words. Collect the logs and check descriptions for accuracy. Correct any misunderstandings of science and improper English before proceeding.
Vocabulary comprehension	<i>Physics to Go</i> Step 9	ELL students are likely familiar with the word “copy” as a synonym for “duplicate” (a photocopy, for example). But they may need help understanding the term to mean “the words that make up an advertisement.”

SECTION 7

Teaching Suggestions and Sample Answers

What Do You See?

The person slipping on ice captures this section's theme. This is an opportunity to steer students toward the concept of the coefficient of friction. You may want to ask them to pay close attention to each object in the picture and query whether one particular object stands out in relation to the title of the section. As this is a time to stimulate interest, remind students that they should primarily focus on giving answers and revisit this visual at a later stage.



Section 7

Frictional Forces: The Mu of the Shoe

What Do You See?



Learning Outcomes

In this section, you will

- Apply the definition of the coefficient of sliding friction, μ .
- Measure the coefficient of sliding friction between the soles of athletic shoes and a variety of surfaces.
- Calculate the effects of frictional forces on the motion of objects.

What Do You Think?

A shoe store may sell as many as 100 different kinds of sport shoes.

- Why do some sports require special shoes?
- Why would different features of a shoe be useful for different sports?

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 examine how difficult it is to pull a shoe across a surface.

1. Take an athletic shoe. Use a spring scale to measure the weight of the shoe, in newtons.
 - a) Record a description of the shoe (such as its brand) and the shoe's weight, in your log.
 - b) List some things (which scientists call "variables") that may affect the force required to pull the shoe.

Students' Prior Conceptions

This section introduces the idea that friction occurs between the surfaces of objects and that the nature of the attraction of the surface particles to one another gives rise to static friction and subsequently to kinetic or sliding friction when one object slides or moves over another.

1. **Students may confuse friction with inertia and inertial mass.** This preconception may persist even after inertia was introduced in *Sections 1* and *2*.
2. **Students believe that the force needed to accelerate an object at rest works against friction; inertia and inertial mass are not relevant.** Reviewing concepts studied in

earlier activities is a good instructional technique to apply here.

3. **Frictional forces only are due to irregularities in surfaces moving past each other.** Significant changes in the nature of either contact surface (molecular attraction of surface molecules, type of material, surface texture, moisture, or lubrication) affects the value of μ , the coefficient of friction.

What Do You Think?

As students answer these questions, ask them to think of the shoes they wear daily and how they are different from the sports shoes they wear on the field. You might want to remind them that this is the time for them to write their responses without any hesitation. It is important that at this stage students discuss answers among themselves. Facilitate their discussion and make sure that your students are engaged in the process of preparing for the concepts they are about to learn.

What Do You Think?

A Physicist's Response

A shoe for a specific surface should have the best traction possible without causing too much stickiness, which might delay the athlete. A second consideration is the safety of athletes in contact sports where having a shoe that sticks too strongly to the ground when the player collides with another player might result in a broken leg. A shoe for many surfaces would have to reflect some compromise as to what works best on average.

Certain shoes require additional features to improve the athlete's performance. Golf shoes, and baseball and football cleats use spikes that allow the athletes to get extra traction on grass surfaces. Basketball shoes have higher tops to protect players' ankles from injury. The boots used by skiers have additional support to withstand the strains of the long skis.

Teaching Tip

Although using a shoe may not appear to be the most sanitary method of performing this activity, the students' enthusiasm for it more than makes up for this aspect. Keeping a spray can of deodorant/disinfectant handy is usually a good idea. If the students do not list the weight of the shoe as a variable, ask them if a heavy crate is easier or harder to push across a floor.

1.b)

Some variables the students may come up with include shoe size, tread style, shoe brand, weight of shoe, whether the shoe is high or low cut, etc.

The students should quickly realize that if they are to use just one shoe, factors such as size, brand, etc., would not be variables for that shoe. They may also think that the "weight" (mass) is not a variable, but point out that objects can easily be slipped inside the shoe to increase its weight. The students' design should show how a variable might affect the shoe's frictional force. Check it for safety and feasibility using available equipment.

Investigate

1.a)

Answers will vary depending on the brand of shoe used and the size of the shoe. If you wish, you may use blocks of wood; some instructors prefer the increased precision. Students really like using shoes though.

2. Design an experiment that would allow you to determine how one of the variables you listed affects the force required to pull the shoe. Include in your design:

- What you will be able to conclude as a result of your experiment.
- What data you will record.
- What tools you will use to measure your data.
- How you will analyze your data.

a) Record your procedure in your log.

Your teacher may ask you to continue with your experimental design or, because of equipment or safety concerns, ask you to proceed with the experiment as described below.

3. Your teacher may ask you to use blocks of wood instead of shoes for greater precision in your results. However, wooden shoes are not recommended for sports. Place the shoe on a horizontal surface (either rough or smooth) designated by your teacher. Attach the spring scale to the shoe as shown below (low down at the toe or heel or hooked onto the front lace loop) so that the spring scale can be used to slide the shoe across the surface while, at the same time, the scale can be read. Be sure to keep the spring scale parallel to the surface.



a) Record a description of the surface in your log.

b) Measure and record the amount of force, in newtons, needed to keep the shoe sliding on the surface at a slow, constant speed. Be careful to pull horizontally so that you do not tend to lift the shoe or pull downward on the shoe. Do not measure the force needed to start the shoe moving. Measure the force needed to keep it sliding at a slow, constant speed. How will you determine if the shoe is moving with a constant speed?

When the shoe is being pulled across the surface, there are four forces acting on it. The first is the horizontal force you apply and is measured by the spring scale. But since the shoe moves at a slow, constant speed, it is not accelerating horizontally. There must be a second force on the shoe of equal strength and in the opposite direction to the force you apply. This second horizontal force is the force due to *friction* between the shoe and the surface. The third force is the downward force of gravity on the shoe, which is equal to the weight of the shoe. But since the shoe is not accelerating downward, there must be a fourth force on the shoe. This is the force of the table on the shoe; this force is equal in strength and in the opposite direction to the shoe's weight. Since this force is directed perpendicularly to the surface, it is often called the *normal force*, since the word "normal" sometimes means "perpendicular to."

The *coefficient of sliding friction*, symbolized by the Greek letter μ (mu), is calculated using the following equation:

$$\mu = \frac{\text{force of friction}}{\text{perpendicular force exerted by the surface on the object}}$$

2.a)

Students should record a data table in their logs that includes mass, force of spring scale, surface type, etc. Students should also realize that graphing the data will be a good analysis tool.

3.a)

Students should record the surface type. Surfaces may be varied by taping sandpaper or rubber mats to the lab tables, or the students may use the floor. Using a carpeted area may prove problematic, since the loops of the carpet will provide a very uneven frictional force as they bend under the applied force.

3.b)

Encourage students to strive for consistent results. Hooking the scale to a low point on the shoe helps make it slide rather than tilt. Ask them if they notice whether the force necessary to start the shoe moving is more or less than the force necessary to keep it moving at a slow, constant speed. Students should look for a consistent average reading on the spring scale.

3.c)

μ results will vary. Generally, the coefficient of friction should be less than 1, and in the region of 0.3-0.8.

4.a)

Any masses that will approximately double the weight of the shoe or block will be fine. Adding the other shoe is an easy way to double the weight. If wooden blocks are used, be certain the students use the same side of the block for this part of the activity as for *Step 3*.

4.b)

Students should find that μ remains approximately the same as mass is added to the shoe.

Teaching Tip

To demonstrate that the frictional force between two surfaces is roughly independent of the contact area, you may want to do the following demonstration. Pull a shoe with a spring scale and measure the force required to overcome friction. Now double the mass of the shoe by adding masses equal to the mass of the shoe. The frictional force, and the force required to pull it with the spring scale, should double. Now remove the masses from the first shoe, and tie a second identical shoe side-by-side with the first so they can both be pulled at the same time. The mass and normal force is doubled as before, now with twice the contact area. The force required to pull the two-shoe combination will be essentially the same as the one shoe with masses added to double it.

4.c)

Taking into account possible errors in measurement, students should find that the value of μ is not affected by the weight

**Example:**

Brand X athletic shoe has a weight of 5.0 N. If 1.5 N of applied horizontal force is required to cause the shoe to slide with constant speed on a smooth concrete floor, what is the coefficient of sliding friction?

The force of friction is equal to the applied horizontal force because there was no acceleration. The perpendicular force exerted by the surface on the shoe must be equal to the force exerted by the shoe on the surface (which is the weight of the shoe). In this case, that would be the same as the weight of the shoe.

$$\mu \text{ on concrete} = \frac{1.5 \text{ N}}{5.0 \text{ N}} = 0.30$$

- 3.c)** Use the data you have gathered to calculate μ , the coefficient of sliding friction for this particular kind of shoe on the particular kind of surface used. Show your calculations in your log.
- 4.** Add something to the shoe to approximately double its weight. Pull the shoe with a spring scale.
- 4.a)** Record the force to pull the heavier shoe.

- 4.b)** Calculate μ for the heavier shoe, showing your work in your log.
- 4.c)** Taking into account possible errors of measurement, does the weight of the shoe seem to affect μ ? Use data to answer the question in your log.
- 4.d)** How do you think the weight of an athlete wearing the shoe would affect μ ? Why?
- 5.** Place the shoe on the second surface designated by your teacher. Repeat the procedure.
- 5.a)** Make a sketch (free-body diagram) to show the forces acting on the shoe.
- 5.b)** Calculate μ for this new surface and the shoe.
- 5.c)** How does the value of μ for this surface compare to the value of μ for the first surface used? Suggest reasons for any difference in μ .
- 5.d)** Would it make any difference if you used the empty shoe or the weighted shoe to calculate μ in this step? Explain your answer.

Physics Talk**FRICION****Analyzing the Forces Acting on the Shoe**

In this *Investigate*, you pulled the shoe at a constant velocity. Newton's second law informs you that motion with a constant velocity happens only when there is no net force on the shoe. So all the forces on the shoe must add up to zero.

You applied a horizontal pulling force and measured the value of the force with the spring scale. The shoe moved at a slow, constant speed. It was not accelerating horizontally. Therefore, there must be a second force on the shoe of equal strength and in the opposite direction to the force you applied. This second force was the force due to **friction** between the shoe and the surface. The pulling force you applied was equal to the frictional force, and since the two forces were in opposite directions, the net or

Physics Words

friction: a force that resists relative motion between two bodies in contact.

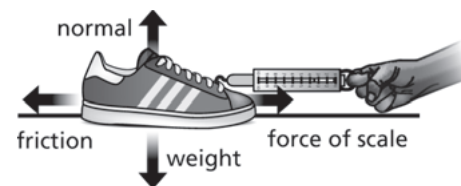
of the shoe. Ask students how the horizontal force and weight changed from trial to trial, hinting that μ stays the same because it is the ratio of these two forces.

4.d)

Students should understand that the mass of the athlete would not matter, since μ was independent of mass.

5.a)

Student sketch (see example below).

**5.b)**

Students calculate the new value of μ from their data.

5.c)

Students should recognize that the value of μ will be different for different surfaces. The “rougher” the surface, the greater the coefficient of friction. For example, the coefficient of friction for rubber on dry concrete is 140 times greater than that for rubber on ice.

5.d)

The previous step in this *Investigate* indicates that the weight of the shoe should not make a difference in the coefficient of friction. If time permits, urge the students to change the weight and recalculate μ , just to show that the first result was general. Whether the students explore this more or not, make sure you emphasize that the value of μ does not depend on the weight of the object.

Physics Talk

The *Physics Talk* will help the students in understanding that the different forces may act on an object moving with constant velocity. Find out if students understand why the shoe moved at a slow constant speed and did not accelerate horizontally. Be sure to ask them why the shoe did not accelerate even though there was a constant force exerted by the spring scale. Students should also be able to apply the same concept to explaining why the shoe did not move in the vertical direction. Ask them to illustrate the normal force and how its value is determined. Students should draw free-body diagrams to show all the forces acting on the shoe as it slides across a level surface that has friction. The students should be able to identify the direction of the frictional force as always being opposed to the direction of motion.

Students should also realize that when the shoe is at rest, there is no frictional force acting, since a horizontal force of friction would be unbalanced and cause the shoe to accelerate in the direction of friction. The dependence of the frictional force and the coefficient of friction on different surfaces should be emphasized, as well as how forces cancel each other when an object is at rest. Have students explain why the coefficient of friction does not have units, although the force of friction is expressed in newtons. Have the students write down the definition of the coefficient of friction in their *Active Physics* log. Emphasize that the value of μ is different for different surfaces. Finally, point out that although the coefficient of friction between two surfaces will not change, the frictional force between these surfaces will be different if the surface is tilted due to the normal force being different.

NOTES

2-7a Blackline Master

Section 7 Frictional Forces: The Mu of the Shoe

total force due to them was zero. Note that you actually measured the pulling force but used its value as the value for the frictional force. This is perfectly fine, since the two forces are equal in strength.

In the *Investigate*, the shoe did not move in the vertical direction. Newton's second law informs you that the vertical forces on the shoe must add up to zero. The downward force of gravity on the shoe (weight) must be equal to the upward force applied to the shoe by the surface. Since this force is directed perpendicularly to the surface, it is often called the **normal force**, since the word "normal" sometimes means "perpendicular to." This force is equal in strength and in the opposite direction to the shoe's weight. Note that you measured the weight of the shoe, but used its value as the value for the normal force. Again, this is perfectly fine, since the two forces are equal in strength.

A free-body diagram can help you see the relationships among the four forces when the shoe moves with a constant speed.



Coefficient of Sliding Friction, μ

The **coefficient of sliding friction**, symbolized by μ , is defined as the ratio of two forces:

$$\mu = \frac{\text{force of friction}}{\text{perpendicular force exerted by the surface on the object (normal force)}} = \frac{F_f}{F_N}$$

The force of friction is equal to the force required to slide the object on the surface with a constant speed.

Physics Words

normal force: the force acting perpendicularly or at right angles to a surface.

coefficient of sliding friction: a dimensionless quantity symbolized by the Greek letter μ ; its value depends on the properties of the two surfaces in contact and is used to calculate the force of friction.

Checking Up

1.

According to Newton's first law, an object in motion will continue with constant velocity unless there is an unbalanced force. Because the shoe travels with constant speed, the forces of the spring scale must be exactly balanced by the force of friction.

2.

The coefficient of friction is defined as the force of friction divided by the normal force. Because this is a force divided by a force, the units cancel.

3.

The coefficient of friction only depends upon the two surfaces in contact.



Chapter 2 Physics in Action

Note the following about the coefficient of sliding friction:

- μ does not have any units because it is a force divided by a force; it has no unit of measurement.
- μ usually is expressed in decimal form, such as 0.85 for rubber on dry concrete (0.60 on wet concrete).
- μ is valid only for the pair of surfaces in contact when the value is measured; any significant change in either of the surfaces (such as the kind of material, surface texture, moisture, or lubrication on a surface, etc.) may cause the value of μ to change.
- The situation in this section was chosen deliberately so that the "perpendicular force exerted by the surface on the object" was exactly equal to the weight. If the surface were tilted, or if the pulling force were angled upward or downward, then the force exerted by the surface on the object would be more difficult to determine.

The Greek Alphabet

There are not enough letters in the English alphabet to provide the number of symbols needed in physics, so letters from another alphabet, the Greek alphabet, are also used as symbols. The Greek alphabet has been used for centuries to write the Greek language. It is one of the oldest alphabets in use today.

The letters of the Greek alphabet are often used in physics and mathematics. The letter μ (pronounced like "mew" and rhymes with "you") traditionally is used in physics as the symbol for the "coefficient of sliding friction." There are other Greek letters you may use in *Active Physics* or other physics courses that are shown below. For example, you have already used the Greek letter " Δ " to represent "a change in."

Checking Up

1. Why can you say that the force of friction is equal to the force reading on the spring scale when pulling an athletic shoe across a surface with a constant speed?
2. Why does the coefficient of friction have no units?
3. What determines the coefficient of friction?



214

Active Physics

Active Physics

+Math	+Depth	+Concepts	+Exploration
••		•	

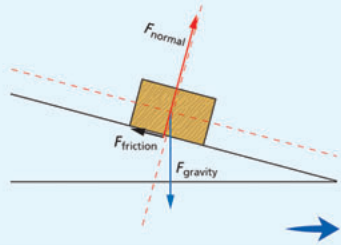
Plus

Static Friction

As you worked on this *Investigate*, you might have noticed that it takes a larger force to get an object sliding across a surface than to keep it sliding once it has started to move. In that section, only sliding friction is discussed. When the object is not sliding, friction still acts between the surface and the object, but the force of friction now assumes the appropriate value between zero and a maximum so that the object remains at rest.

Imagine the athletic shoe at rest and you are not pulling on it. Now start to pull very gently. You are clearly applying a force to the shoe, but since the shoe is still at rest, the force of static friction must be equal and opposite to the force you are applying. Now pull on it a bit harder. If the shoe does not move, then the frictional force has also increased, so it is still equal and opposite to the force you are applying. Notice that the static frictional force can take on various values. This is unlike the sliding frictional force that always has a definite value for a given situation. If you keep increasing your pull on the shoe, the static frictional force also keeps increasing, until it reaches its maximum value given by $F_s = \mu_s F_N$. As soon as the force you are applying is greater than the maximum static frictional force possible, the shoe breaks loose and accelerates. Because this force is greater than the sliding frictional force ($\mu_s > \mu$), you have to decrease the force you exert on the shoe in order for it to slide with a constant velocity. This is something that you may have noticed.

1. A block sitting on an incline makes an angle of 30° with the horizontal. The block has a mass of 1.5 kg.
 - a) Sketch the block. Draw three arrows representing the forces on the block (weight pointing downward, perpendicular force [also known as the normal force] of the incline on the block, and the force of static friction pointing parallel to the incline opposite to the direction the block may slide).
 - b) Draw a set of axes with one axis parallel to the incline and one axis perpendicular to the incline. Notice that two of the forces fall along these axes.
 - c) Draw the two components of the weight along these axes. Use a scale diagram or trigonometry (sines and cosines) to find the values of these components.
 - d) Because the block is at rest (not accelerating), all the forces must add up to zero. Use this fact to find the normal force and the force of static friction.



215

Active Physics

Active Physics Plus

This section highlights the difference between static and kinetic friction. Static friction is a reaction force that only appears in response to a force that is trying to accelerate an object. The result of static friction is a force just large enough to cancel the applied force and leave the object at rest. Once the force being applied

exceeds the value that static friction can apply, the object starts to move, and kinetic friction takes over. The coefficient of kinetic friction is always less than the coefficient of static friction. Point out to students that this section explains static friction. Ask them to write down the equation for maximum frictional value. You might want to mix students in groups and have them explore

this concept in more detail. Ask students to explain to each other how a shoe is made to slide with constant velocity.

The formula for static friction on an inclined plane can be determined as follows. For an object at rest on an inclined plane, the components of the weight perpendicular and parallel to the plane are

$F_{\perp} = mg \cos \theta$, which is also equal to the normal force (F_N)

$F_{\parallel} = mg \sin \theta$, which is equal to the component of the weight acting down the plane

Using the equation for static friction when the shoe is at rest on the plane tells us that the force of friction up the plane must balance the component of weight acting down the plane, or

$$mg \sin \theta = F_f = \mu_s F_N = \mu_s (mg \cos \theta)$$

Solving this equation for the coefficient of static friction (μ_s) gives

$$\mu_s = \sin \theta / \cos \theta = \tan \theta$$

This provides an alternative method for finding the coefficient of friction. Simply raise an inclined plane slowly until the object starts to slide, and the tangent of the angle where the slide begins is the coefficient of static friction. While some students might be able to solve the problems given in this section, some may not. Ask students who are able to get answers to share their solutions with other students in their group.

2.

The coefficient of static friction is

$$\mu = \frac{mg \sin \theta}{mg \cos \theta} = \tan \theta.$$

2.a)

The coefficient of friction found by pulling the object horizontally across a table is

$$F_f = \mu mg$$

$$\mu = \frac{F_f}{mg}.$$

2.b)

The coefficient of friction from tilting is $\mu = \frac{mg \sin \theta}{mg \cos \theta} = \tan \theta.$

2.c)

The two values for the coefficient of friction should agree to within 10%.

What Do You Think Now?

Encourage your students to revise their earlier responses in their logs and come up with more definite responses that indicate how much they have understood the new concepts, and to what extent they can now apply them to their answers in the *What Do You Think Now?* section.



2. Imagine that you can vary the angle of the incline in the previous problem. As you increase the angle, at first, the block just stays where it is. However, at some angle θ , the block begins to slide down the incline. Let the mass of the block be m so you can work only with symbols. The coefficient of friction is equal to the tangent of this angle.

$$\mu = \tan \theta$$

(Tangent is a trigonometry function that you can find on many calculators.)

- Find the frictional force by pulling a block at a constant speed across a horizontal table. Calculate μ .
- Find the μ by tilting the table so that once started, the block can move with a constant speed. Measure the angle of the tilt, and calculate $\tan \theta$.
- Compare the values in *a)* and *b)*.

What Do You Think Now?

At the beginning of this section, you were asked the following:

- Why do some sports require special shoes?
- Why would different features of a shoe be useful for different sports?

Record your ideas about these questions now. Use the concept of sliding friction to answer the questions this time.



Physics

Essential Questions

What does it mean?

An athlete may complain that the field is slippery. How can you describe the same situation using the terms friction, coefficient of sliding friction, forces, and the symbol μ ?

How do you know?

A running shoe is pulled along the ground at a constant speed. How do you know that a frictional force was equal to the pulling force?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Force and motion	Change and constancy	* Experimental evidence is consistent with models and theories

* Physicists often believe in invisible forces. Friction is invisible; it happens without you seeing it. A sliding object slows down and stops. If you did not believe in friction, could Newton's first and second laws explain this motion?

Why should you care?

Friction, or the lack of enough friction, is critical to sports. Describe two parts of your sport where friction is critical and what you are going to say about it in your voice-over.

Reflecting on the Section and the Challenge

Many athletes seem more concerned about their shoes than other items of equipment, and for good reason. Small differences in the shoes (or skates or skis) can affect performance. Athletic shoes have become a major industry because people in all "walks" of life have discovered that athletic shoes are great just about anywhere. Now that you have studied friction, you know about a major aspect of what makes shoes function well. You are prepared to do physics commentary on athletic footwear and other effects of friction in sports when the need exists to be "sure-footed." Your sports commentary may discuss the μ of the shoe, the change in friction when a playing surface gets wet, and the need for friction when running. You may also wish to discuss the use of cleats on certain surfaces or the friction of tires on the road in stock car races. No matter which sport you choose, friction will play an important role.

Reflecting on the Section and the Challenge

Have students summarize the *Reflecting on the Section and the Challenge* from their textbooks. Discuss how they could apply what they know about friction to the sports commentary in their *Chapter Challenge*. Ask them to reflect on athletic footwear, and why it is so crucial to the outcome of a sport. It is important for students to realize the role of different surfaces in determining the effects of friction. Encourage students to explain the connections between the *Investigate* and *Physics Talk*, including the *Checking Up* questions. This strategy will help them see how their understanding has developed and how they can benefit from it in *Preparing for the Chapter Challenge*.

Physics Essential Questions**What does it mean?**

There is a low coefficient of friction, μ , causing a small frictional force.

How do you know?

Because the shoe moved at a constant speed, the net force on it must be zero. Therefore, the frictional force must be equal to the pulling force.

Why do you believe?

If you did not believe in friction, then this behavior would violate Newton's first and second laws.

Why should you care?

When you run, you need friction between your shoes and the ground. In auto racing, the friction of the wheels on the ground provides the force for acceleration and for turning.

Physics to Go

1.

In football, for example, players change the length of shoe cleats or sometimes wear shoes without cleats to improve footing in bad weather.

2.

Downhill skiers use wax to reduce friction; ice skaters “sharpen” their skates, which makes sure they are as smooth as possible (and have the sharp edges needed for ice skating).

3.


A common misconception is that the coefficient of friction—and, therefore, the force of friction—depends only on the shoe. In fact, it depends as much on the nature of the surface beneath the shoe. The athlete cannot be assured that the same amount of frictional force will be present when the same shoe is used on a court having a different surface. The athlete would need to know what the surface is made of and what preparation is used on the surface before a game.

4.

The way a tennis player responds to a shot varies greatly with the court type. Clay courts allow the player to slide across the court easily, while “hard courts” bring the player to a sudden stop. A shoe with a smooth bottom on clay allows the player to glide into a shot, while on a “hard court” the player would want a shoe that grips firmly to allow a quicker change in direction.

5.

The minimum amount of horizontal force, F , that would


Chapter 2 Physics in Action

Physics to Go

1. Think of a sport and changing weather conditions that would cause an athlete to want to increase friction to have better footing. Name the sport, describe the change in conditions, and explain what the athlete might do to increase friction between the shoes and the surface of the ground.
2. Think of a sport in which athletes desire to have frictional forces as small as possible and describe what the athletes do to reduce friction.
3. If a basketball player's shoes provide an amount of friction that is “just right” when she plays on her home court, can she be sure the same shoes will provide the same amount of friction when playing on another court? What details about the other court would she need to know to answer this question?
4. Tennis is played on clay, grass and hard surfaces. Please explain why you think tennis players have or don't have different shoes for each surface.
5. A cross-country skier who weighs 600 N has chosen ski wax that provides $\mu = 0.03$. What is the minimum amount of horizontal force, perhaps from a tailwind, that would keep the skier coasting at constant speed across level snow?
 - a) What is the weight of the vehicle?
 - b) The frictional force produces the negative acceleration (often called deceleration) that reduces the velocity of the vehicle from its initial unknown speed to zero. Find the value of the frictional force.
 - c) Use the frictional force to calculate the acceleration (remember that it is a negative number).
 - d) Using the acceleration and the time over which acceleration occurred, calculate the change in speed that the acceleration would produce.
 - e) Use the change in speed to find the original speed of the vehicle when the brakes were applied. Write a statement of your findings, including your opinion of the driver's claim.
6. A vehicle having a mass of 1000 kg had an accident on a wet, but level, concrete road under foggy conditions. The tires were measured to have $\mu = 0.55$ on wet concrete. The driver locked the brakes, skidded for 6 seconds, and then hit the guardrail causing a very small dent because the vehicle stopped just as it touched the guardrail. The driver claimed to be driving 65 miles per hour (29 m/s). You have been hired as an investigator to determine if the driver is telling the truth.

Active Physics
218

keep the skier coasting at constant speed would be $F = (0.03)(600 \text{ N}) = 18 \text{ N}$.

6.a)

Weight of vehicle $= mg = (1,000 \text{ kg})(10 \text{ m/s}^2) = 10,000 \text{ N}$

6.b)

Frictional (stopping) force $= \mu F_N = (0.55)(10,000 \text{ N}) = 5,500 \text{ N}$

6.c)

Acceleration $= F/m = (-5,500 \text{ N})/(1,000 \text{ kg}) = -5.5 \text{ m/s}^2$

6.d)

Initial speed $= at = (-5.5 \text{ m/s})(6 \text{ s}) = -33 \text{ m/s} = -75 \text{ mi/h}$

6.e)

Since the final speed was zero, the initial speed was 33 m/s or

7. In some sports, the air or water have limiting effects on motion similar to sliding friction. Do you think that the forces of “air resistance” and “water resistance” remain constant or do they change when speeds change? Use examples from your own experience with these forms of resistance as a basis for your answer.
8. If there is a maximum frictional force between your shoe and the track, does that set a limit on how fast you can start (accelerate) in a sprint? Does that mean you cannot have more than a certain acceleration even if you have incredibly strong leg muscles? What is done to solve this problem?
9. How might an athletic shoe company use the results of your experiment to “sell” a shoe? Write copy for such an advertisement.
10. Explain why friction is important to running. Why are cleats used in football, soccer, and other sports?
11. **Preparing for the Chapter Challenge**
Choose a sport and describe an event in which friction with the ground or the air plays a significant role. Create a voice-over or script that uses physics to explain the action.

Inquiring Further

Frictional force and the weight of a player

You found that for a given coefficient of sliding friction, the frictional force increased with the weight of the shoe. Of course, if a person is wearing the shoe, it is the weight of the person that determines the frictional force (assuming the person has only one foot on the surface). This means that the heavier the athlete, the greater the frictional force. Does this imply that the heavier a person is, the greater his or her acceleration can be?

- Calculate the force of sliding friction for a 50-kg person using a shoe with a μ of 0.6.
- Calculate the acceleration of the 50-kg person due to the force of sliding friction.
- Calculate the force of sliding friction for a 90-kg person using a shoe with a μ of 0.6.
- Calculate the acceleration of the 90-kg person due to the force of sliding friction.
- Can the heavier person achieve a greater acceleration using the same shoes?

75 mi/h. The driver has a problem because the laws of physics will prevail in court.

7. Any sports that involve objects moving through air or water will involve fluid resistance. For objects moving through these media, the resistance depends upon the speed. Any student who has held a hand outside a car window while the car is in motion has felt the force of the air

increase with speed. Air resistance affects all sports that use objects traveling through the air, but for sports such as sky diving it is critical. Without the limiting effects of air resistance, sky diving would quickly die out as a sport.

8. Yes, the maximum frictional force between your shoe and the track does place a limit on acceleration. Sprinters use blocks when beginning a race, thereby

providing a surface that is not horizontal, and does not depend on the weight of the runner.

9.

See the **Assessment Rubric** following this chapter in the *Teacher's Edition*.

10.

Without friction it would be impossible to walk or run, since it is the force of friction between the shoe and the surface that provides the forward force to propel the athlete. Cleats increase the friction between the shoe and the ground by increasing the amount of surface in contact, and also by changing the situation from plain friction into a gear-like intermeshing with the top layer of soil.

11.

Preparing for the Chapter Challenge

The voice-over should include why friction is important to athletes, how the normal force affects the force of friction, and how athletes choice of athletic shoes is important.

Inquiring Further

a)

$$F = (0.6)(50 \text{ kg})(10 \text{ m/s}^2) = 300 \text{ N}$$

b)

$$a = (300 \text{ N})/(50 \text{ kg}) = 6 \text{ m/s}^2$$

c)

$$F = (0.6)(90 \text{ kg})(10 \text{ m/s}^2) = 540 \text{ N}$$

d)

$$a = (540 \text{ N})/(90 \text{ kg}) = 6 \text{ m/s}^2$$

e)

No

5. Jill is pulling a 200-N sled through the snow at constant speed with a constant horizontal force of 10 N. What is the coefficient of friction between the sled and the snow?

a) 0.02

b) 0.05

c) 0.20

d) 20

SECTION 7 QUIZ ANSWERS

- 1** a) The force of friction accelerates the runner. To accelerate at 5 m/s^2 the frictional force $\mu F_N = ma$, where the normal force equals the weight, mg . Thus $\mu mg = ma$ or, $\mu = a/g = (5 \text{ m/s}^2)/(10 \text{ m/s}^2) = 0.5$.
- 2** d) The force of friction will oppose the motion.
- 3** b) Rough surfaces generally have a higher coefficient of friction than smooth surfaces, so sand will increase the coefficient.
- 4** b) $\mu = F_f/F_N$ and here all the objects will have the same normal force, since they are all 1-kg blocks. Hence, the lowest friction force would correspond to the lowest μ .
- 5** b) $\mu = F_f/F_N = (10 \text{ N})/(200 \text{ N}) = 0.05$