Exploring Frictional Forces 2.4

In Section 2.1, we looked at the definition of frictional forces, which include static friction and kinetic friction. In this section, we apply Newton's first law of motion, in which $\Sigma\vec{F} = 0$, and his second law, in which $\Sigma\vec{F} = m\vec{a}$, to situations involving friction. We will also consider situations in which one object slides over another and situations that involve air resistance and other forces of fluid friction. We will discover that analyzing friction has numerous practical applications, such as designing a nonstick frying pan, spinning a ball to curve its path in sports activities, maximizing the speed of skis, and maximizing the acceleration of racing cars.

There are some instances where scientists and engineers search for ways to increase friction. For example, an airport runway must be designed so that when it is wet, the friction between the airplane tires and the runway is almost as great as in dry conditions. Rock climbers (like the one shown in the introduction to this chapter) use footwear and gloves that provide the largest possible friction.

In other instances, reducing friction is the main objective. If you were responsible for designing an artificial limb, such as the hand shown in **Figure 1**, you would want to minimize the friction between the moving parts. Car manufacturers face a similar challenge as they try to maximize the efficiency of engines by minimizing the friction in the moving parts.

Figure 1
Artificial hands are designed to operate with as little friction as possible. How much friction do you feel within your hand when you wrap your fingers around a pen?

Practice

Understanding Concepts

1. List examples (other than those given here) of situations in which it would be advantageous to have (a) increased friction and (b) decreased friction.

Coefficients of Friction

Consider what happens when you pull or push a box of bottled water across a countertop. Static friction acts on the stationary box and prevents it from starting to move. Once the box is in motion, kinetic friction acts to oppose the motion. For example, if you use a force meter or a spring scale to pull horizontally with an ever-increasing force on a stationary object, you will notice that the force increases steadily until, suddenly, the object starts moving. Then, if you keep the object moving at a constant velocity, you will notice that the applied force remains constant because there is no acceleration ($\Sigma\vec{F} = m\vec{a} = 0$). The magnitude of the force needed to start a stationary object moving is the *maximum static friction*, $F_{S,max}$. The magnitude of the force needed to keep the object moving at a constant velocity is the *kinetic friction*, F_K. The results of such an experiment are depicted in **Figure 2**.

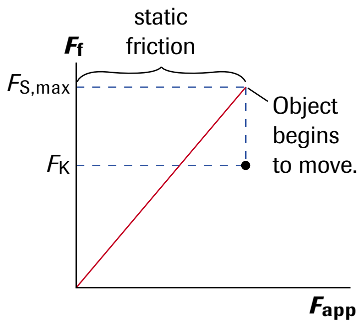


Figure 2
This graph depicts the magnitude of friction as a function of the magnitude of the applied force on an object up to the instant the object begins to move. The magnitude of kinetic friction is usually less than the maximum static friction.

The magnitudes of the forces of static and kinetic friction depend on the surfaces in contact with each other. For example, a fried egg in a nonstick frying pan experiences little friction, whereas a sleigh pulled across a concrete sidewalk experiences a lot of friction. The magnitude of the force of friction also depends on the normal force between the objects, which is logical when you consider the situations shown in **Figure 3**.

The coefficient of friction is a number that indicates the ratio of the magnitude of the force of friction between two surfaces to the normal force between those surfaces. The value for the coefficient of friction depends on the nature of the two surfaces in contact and the type of friction—static or kinetic. The **coefficient of static friction**, μ_S, is the ratio

coefficient of static friction (μ_S) the ratio of the magnitude of the maximum static friction to the magnitude of the normal force

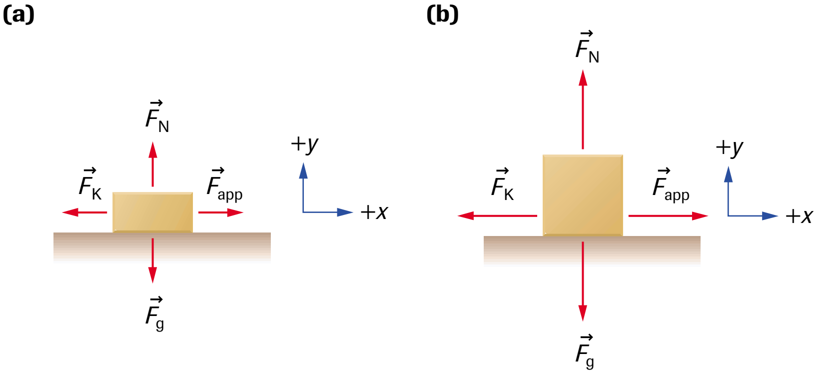


Figure 3
The greater the mass of an object, the greater is the normal force exerted on the object by the underlying surface, and the greater is the applied force needed to keep the object moving.
(a) If the mass is small, the normal force on it is small and so is the applied force needed to overcome kinetic friction.
(b) If the mass doubles, the normal force doubles and so does the applied force needed to overcome kinetic friction.

coefficient of kinetic friction (μ_K) the ratio of the magnitude of the kinetic friction to the magnitude of the normal force

of the magnitude of the maximum static friction to the magnitude of the normal force. The **coefficient of kinetic friction**, μ_K, is the ratio of the magnitude of the kinetic friction to the magnitude of the normal force. The corresponding equations are

$$\mu_S = \frac{F_{S,max}}{F_N} \quad \text{and} \quad \mu_K = \frac{F_K}{F_N}$$

Determining μ_S and μ_K for given substances is done empirically, or through experimentation. Results of such experiments may differ from one laboratory to another, even with careful measurements and sophisticated equipment. For example, if several scientists at different locations in Canada measure the coefficient of kinetic friction between wood and dry snow, the wood and snow samples would vary; therefore, the coefficient values would not be consistent. The approximate coefficients of friction for several common pairs of surfaces are listed in **Table 1**.

LEARNING TIP

Using Magnitudes of Forces
It is important to realize that the force of friction is perpendicular to the normal force. Thus, equations involving the coefficient of friction deal with magnitudes only; directions are decided by analyzing the given situation.

Table 1 Approximate Coefficients of Friction of Some Common Materials

Materials	μ_S	μ_K
rubber on concrete (dry)	1.1	1.0
rubber on asphalt (dry)	1.1	1.0
steel on steel (dry)	0.60	0.40
steel on steel (greasy)	0.12	0.05
leather on rock (dry)	1.0	0.8
ice on ice	0.1	0.03
steel on ice	0.1	0.01
rubber on ice	?	0.005
wood on dry snow	0.22	0.18
wood on wet snow	0.14	0.10
Teflon® on Teflon	0.04	0.04
near-frictionless carbon, NFC (in air)	?	0.02 to 0.06
synovial joints in humans	0.01	0.003

SAMPLE problem 1

A crate of fish of mass 18.0 kg rests on the floor of a parked delivery truck. The coefficients of friction between the crate and the floor are $\mu_S = 0.450$ and $\mu_K = 0.410$. The local value of gravitational acceleration is, to three significant figures, 9.80 m/s^2. What are the force of friction and the acceleration (a) if a horizontal force of 75.0 N [E] is applied to the crate, and (b) if a horizontal force of 95.0 N [E] is applied?

Solution

Figure 4 shows both the system diagram and the FBD for this situation.

(a) $m = 18.0$ kg $\quad \mu_S = 0.450$

$\vec{F}_{app} = 75.0$ N [E] $\quad |\vec{g}| = 9.80$ N/kg

To determine whether the crate will accelerate or remain stationary, we find the maximum static friction. We first determine the normal force, using the equation for the second law in the vertical direction:

$$\begin{aligned} \sum F_y &= ma_y = 0 \\ F_N + (-mg) &= 0 \\ F_N &= mg \\ &= (18.0 \text{ kg})(9.80 \text{ N/kg}) \\ F_N &= 176 \text{ N} \end{aligned}$$

We can now determine the magnitude of the maximum static friction:

$$\begin{aligned} F_{S,max} &= \mu_S F_N \\ &= (0.450)(176 \text{ N}) \\ F_{S,max} &= 79.4 \text{ N} \end{aligned}$$

Since the applied force is 75.0 N [E], the static friction (a reaction force to the applied force) must be 75.0 N [W], which is less than the magnitude of the maximum static friction. Consequently, the crate remains at rest.

(b) In this case, the magnitude of the applied force is greater than the magnitude of the maximum static friction. Since the crate is, therefore, in motion, we must consider the kinetic friction:

$\vec{F}_{app} = 95.0$ N [E]

$F_N = 176$ N

$\mu_K = 0.410$

$$\begin{aligned} F_K &= \mu_K F_N \\ &= (0.410)(176 \text{ N}) \\ F_K &= 72.3 \text{ N} \end{aligned}$$

To determine the acceleration of the crate, we apply the second-law equation in the horizontal direction:

$$\begin{aligned} \sum F_x &= ma_x \\ F_{app} + (-F_K) &= ma_x \\ a_x &= \frac{F_{app} + (-F_K)}{m} \\ &= \frac{95.0 \text{ N} - 72.3 \text{ N}}{18.0 \text{ kg}} \\ a_x &= 1.26 \text{ m/s}^2 \end{aligned}$$

Since the applied force is eastward, the acceleration of the crate is 1.26 m/s^2 [E].

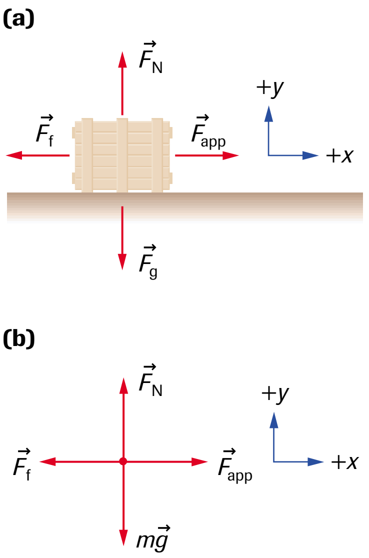


Figure 4
For Sample Problem 1
(a) System diagram for the crate
(b) FBD for the crate

SAMPLE problem 2

In a lab practical test, students are asked to determine the coefficient of static friction between the back of their calculator and the cover of their (closed) textbook. The only permitted measuring instrument is a ruler. The students realize that, having placed the calculator on the book, they can very slowly raise one end of the book until the instant the calculator begins to slide, and can then take the measurements for "rise" and "run," indicated in **Figure 5**. Show how to calculate the coefficient of static friction from a measurement of 12 cm for rise and 25 cm for run.

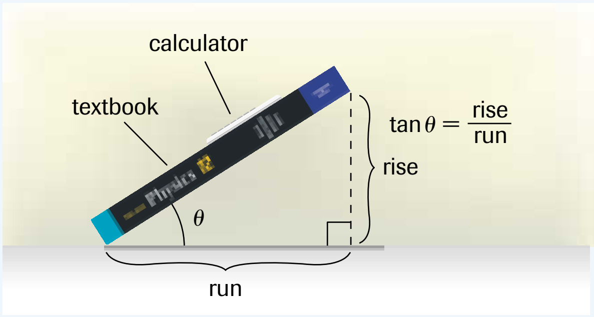


Figure 5
The system diagram for a calculator on a book

Solution

We begin by showing, as in **Figure 6(a)**, that the angle between the component of the force of gravity perpendicular to the book's surface equals the angle of the book above the horizontal.

Next, we derive an expression for the normal force:

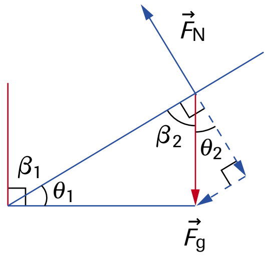
$$\sum F_y = ma_y = 0$$
$$F_N - mg\cos\theta = 0$$
$$F_N = mg\cos\theta$$

Finally, we analyze the forces along the x-axis and substitute the expression for the normal force. **Figure 6(b)** shows the FBD of the calculator.

$$\sum F_x = ma_x = 0$$
$$mg\sin\theta - F_{S,max} = 0$$
$$mg\sin\theta = F_{S,max} \text{ where } F_{S,max} = \mu_S F_N$$
$$mg\sin\theta = \mu_S F_N$$
$$\mu_S = \frac{mg\sin\theta}{F_N}$$
$$= \frac{mg\sin\theta}{mg\cos\theta}$$
$$= \frac{\sin\theta}{\cos\theta}$$
$$= \tan\theta$$
$$= \frac{12\text{ cm}}{25\text{ cm}}$$
$$\mu_S = 0.48$$

The coefficient of static friction is 0.48.

(a)



$$\theta_1 + \beta_1 = 90°$$
$$\theta_2 + \beta_2 = 90°$$
$\beta_1 = \beta_2$ (from the Z pattern)

Therefore, $\theta_1 = \theta_2$
($= \theta$, the angle in the problem)

(b)

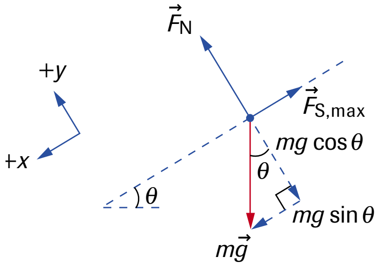


Figure 6
(a) Proof of angular equality
(b) The FBD of the calculator

It is relatively easy to determine the coefficient of static friction experimentally. Experiments can also be conducted to determine the coefficient of kinetic friction. Investigation 2.4.1, in the Lab Activities section at the end of this chapter, gives you the opportunity to measure both of these coefficients of friction.

TRY THIS activity — Observing Triboluminescence

Triboluminescence (from the Greek *tribein,* "to rub") is the production of light by friction. You can observe triboluminescence by crushing some crystals of hard candy, such as a WintOGreen Lifesaver®. Darken the room completely, allow your eyes to adapt, then crush the candy with pliers.

Wear goggles when crushing the candy.

Practice

Understanding Concepts

2. A car accelerates southward due to a frictional force between the road and the tires.
 (a) In what direction is the frictional force of the road on the tires? Why does that force exist?
 (b) Is the frictional force static or kinetic? Explain your answer.

3. The coefficients of friction between a 23-kg exercise mat and the gym floor are $\mu_S = 0.43$ and $\mu_K = 0.36$.
 (a) Determine the magnitude of the minimum horizontal force needed to start the mat moving.
 (b) Once the mat is moving, what magnitude of horizontal force will keep it moving at a constant velocity?

4. A musician applies a horizontal force of 17 N [W] to an instrument case of mass 5.1 kg. The case slides across a table with an acceleration of 0.39 m/s^2 [W]. What is the coefficient of kinetic friction between the case and the table?

5. A small box is resting on a larger box sitting on a horizontal surface. When a horizontal force is applied to the larger box, both boxes accelerate together. The small box does not slip on the larger box.
 (a) Draw an FBD of the small box during its acceleration.
 (b) What force causes the small box to accelerate horizontally?
 (c) If the acceleration of the pair of boxes has a magnitude of 2.5 m/s^2, determine the smallest coefficient of friction between the boxes that will prevent slippage.

6. Draw an FBD for the larger box in question 5 when it is accelerating.

7. An adult is pulling two small children in a sleigh over level snow. The sleigh and children have a total mass of 47 kg. The sleigh rope makes an angle of 23° with the horizontal. The coefficient of kinetic friction between the sleigh and the snow is 0.11. Calculate the magnitude of the tension in the rope needed to keep the sleigh moving at a constant velocity. (*Hint:* The normal force is not equal in magnitude to the force of gravity.)

Applying Inquiry Skills

8. (a) Describe how you would perform an experiment to determine the coefficient of kinetic friction between your shoes and a wooden board, using only a metre stick to take measurements.
 (b) Describe likely sources of random and systematic error in this experiment.

INVESTIGATION 2.4.1

Measuring Coefficients of Friction (p. 113)
What adjustments to the experiment described in Sample Problem 2 would you make to determine the coefficient of kinetic friction? Your answer will help you prepare for this investigation.

Answers

3. (a) 97 N
 (b) 81 N
4. 0.30
5. (c) 0.26
7. 53 N

DID YOU KNOW?

Low-Friction Materials
Scientists have found ways of producing materials with very low coefficients of friction. Teflon®, a compound of fluorine and carbon developed in 1938, experiences extremely weak electrical forces from molecules such as those in foods, so it makes an excellent coating for frying pans. (To make the coating stick to the pan, the Teflon is blasted into tiny holes in the metal.) Since Teflon does not interact with body fluids, it is also useful in surgical implants.

Making Connections

9. In the kitchen, friction sometimes helps and sometimes hinders.
   (a) Describe at least two ways in which you can increase friction when you are trying to open a tight lid on a jar.
   (b) What materials and methods can be used to decrease friction between food and a cooking surface?

Fluid Friction and Bernoulli's Principle

fluid substance that flows and takes the shape of its container

A **fluid** is a substance that flows and takes the shape of its container. Both liquids and gases are fluids, with water and air being common examples. Fluids in relative motion are an important and practical part of our lives. One type of fluid motion occurs when a fluid, such as water or natural gas, moves through a pipe or a channel (motion of a fluid relative to the object). The other type of fluid motion occurs when an object, such as a golf ball, moves through air, water, or some other fluid (motion of an object relative to the fluid).

Newton's laws of motion can be applied to analyze relative fluid motion. Such analysis allows us to explore the factors that affect air resistance, as well as to learn how to research and reduce turbulence, and to control the motion of objects moving through fluids or the motion of fluids moving through objects.

viscosity internal friction between molecules caused by cohesive forces

laminar flow stable flow of a viscous fluid where adjacent layers of a fluid slide smoothly over one another

As a fluid flows, the cohesive forces between molecules cause internal friction, or **viscosity**. A fluid with a high viscosity, such as liquid honey, has a high internal resistance and does not flow readily. A fluid with a low viscosity, such as water, has low internal resistance and flows easily. Viscosity depends not only on the nature of the fluid, but also on the fluid's temperature: as the temperature increases, the viscosity of a liquid generally decreases and the viscosity of a gas generally increases.

TRY THIS activity — Oil Viscosity

Observe the effect of temperature changes on the viscosity of various grades of motor oil (e.g., SAE 20, SAE 50, and SAE 10W-40) in stoppered test tubes provided by your teacher. Make sure that each tube has a small air space near the stopper. Record the time it takes for an air bubble to travel through the oil in a test tube that has been placed in a cold-water bath. Compare your results with the time it takes for a bubble to travel through the oil in a test tube that has been placed in a bath of water from the hot-water tap.

Wear gloves and goggles to handle the oil. Exercise care when using hot water from the tap.

(a)

(b)

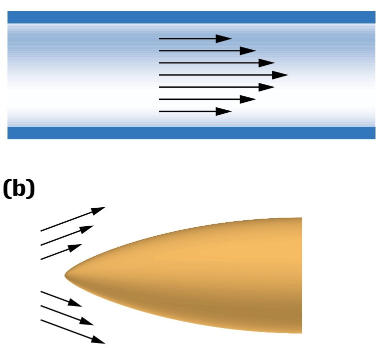


Figure 7
Laminar flow in fluids. The length of each vector represents the magnitude of the fluid velocity at that point.
(a) Water in a pipe
(b) Air around a cone

As a fluid flows, the fluid particles interact with their surroundings and experience external friction. For example, as water flows through a pipe, the water molecules closest to the walls of the pipe experience a frictional resistance that reduces their speed to nearly zero. Measurements show that the water speed varies from a minimum at the wall of the pipe to a maximum at the centre of the pipe. If the speed of a fluid is slow and the adjacent layers flow smoothly over one another, the flow is called a **laminar flow** (**Figure 7(a)**). Laminar flow can also occur when a fluid such as air passes around a smooth object (**Figure 7(b)**).

In most situations involving moving fluids, laminar flow is difficult to achieve. As the fluid flows through or past an object, the flow becomes irregular, resulting, for example, in whirls called *eddies* (**Figure 8**). Eddies are an example of **turbulence**, which resists the fluid's motion. A fluid undergoing turbulence loses kinetic energy as some of the energy is converted into thermal energy and sound energy. The likelihood of turbulence increases as the velocity of the fluid relative to its surroundings increases.

turbulence irregular fluid motion

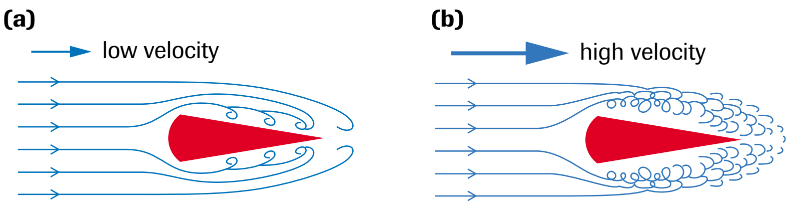


Figure 8
The turbulence caused by eddies increases as the fluid velocity increases.
(a) Low turbulence at a low velocity
(b) Higher turbulence at a high velocity

Turbulence in tubes or pipes can be reduced in various ways. For example, in London, UK, small amounts of liquid plastic are injected into the sewage system. The plastic particles mix with the sewage particles, reducing the liquid's viscosity and adhesion to the sewer pipe and walls, and thereby making it easier for the pumps to transfer the sewage. A similar method can be used to reduce the turbulence of water ejected from a fire-hose nozzle, allowing the water-jet to stream farther. This is advantageous, especially in fighting fires in tall buildings. In the human body, liquid plastic can be added to the bloodstream of a person with blood-flow restrictions. Doing this helps reduce turbulence in the blood and lessens the chances of a blood stoppage.

Turbulence around an object moving through a fluid is a problem observed both in nature and in the transportation industry. **Streamlining** is the process of reducing turbulence by altering the design of an object, such as a car body or an airplane. To aid their designs, designers have found it useful to study fish, birds, and other animals that move quickly in the water or air, and provide excellent examples of streamlining. The transportation industry in particular devotes much research trying to improve the streamlining of cars, trucks, motorcycles, trains, boats, submarines, airplanes, spacecraft, and other vehicles. Streamlining often enhances the appearance of a vehicle, but more importantly it improves safety and reduces fuel consumption.

Streamlining is an experimental science and the best way to research it is in large wind tunnels and water tanks. **Figure 9** shows a wind tunnel design used to investigate the

DID YOU KNOW?

Urban Wind Gusts

Wind turbulence can be a problem in a district with multiple high towers. Tall buildings direct fast-moving air from near the top, where the winds are greatest, toward the bottom. At street level, gusts of wind can have a devastating effect on an unsuspecting pedestrian. To help overcome this problem, engineers fine-tune their designs after running wind-tunnel tests on models of a proposed structure and its surroundings.

streamlining process of reducing turbulence by altering the design of an object

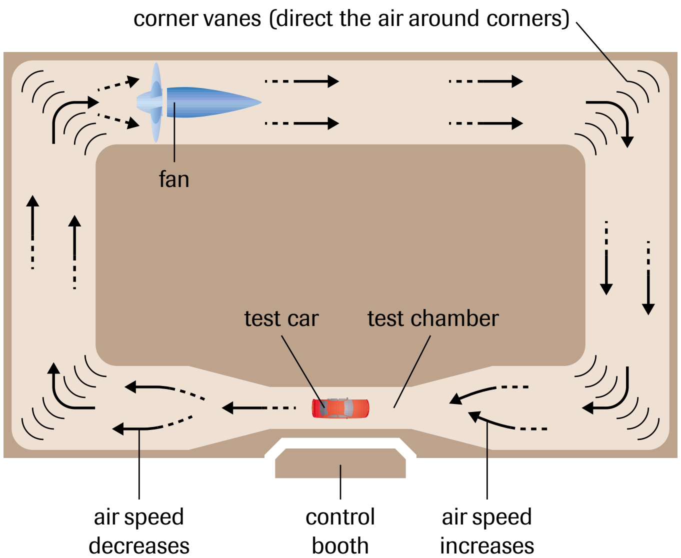
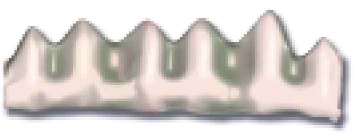


Figure 9
A typical wind tunnel for analyzing the streamlining of automobiles

streamlining of automobiles. A fan directs air along the tunnel, around two corners, and then through the smaller tunnel. As the air moves into the smaller tunnel it accelerates, reaching speeds up to 100 km/h, and flows past the automobile being tested. It then returns to the fan to be recirculated. Researchers view the action from behind an adjacent glass wall and analyze the turbulence around the automobile. Pressure-sensitive beams, electronic sensors, drops of coloured water, small flags, and plumes of smoke are among the means of detecting turbulence.

Researchers have found interesting ways of reducing the turbulence that limits the speed of submarines travelling underwater. For example, to reduce the adhesion of water particles to a submarine's hull, compressed air is forced out from a thin layer between the hull and its porous outer skin. Millions of air bubbles then pass along the submarine, preventing adhesion and thus reducing the turbulence. Turbulence around a submarine can also be reduced by taking some of the water the submarine is passing through and expelling it under pressure from the rear. (What law of motion is applied here?) A third method of turbulence reduction for submarines, which at first seems surprising, applies a principle evolved by sharks. It has long been assumed that the best means of reducing turbulence is to have perfectly smooth surfaces and hidden joints. However sharks, which are obviously well adapted to moving through water with reduced fluid friction, have tiny grooves in their skin that are parallel to the flow of water. Similarly, a thin plastic coating with fine grooves applied to the surface of a submarine can reduce turbulence and increase the maximum speed (see **Figure 10**). Some of the innovations in submarine design can also be adapted to ships and boats, as well as to airplanes.

(a)



(b)

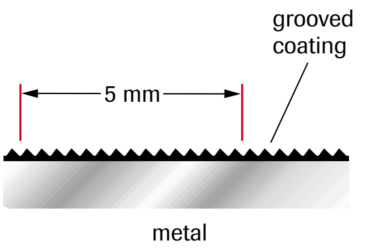


Figure 10
Using grooves to improve streamlining
(a) A patch of shark skin, shown here magnified to about 3000 times its actual size, contains grooves parallel to the water flow.
(b) A thin plastic coating with three grooves per millimetre reduces the drag of a metal surface in water.

The speed of a moving fluid has an effect on the pressure exerted by the fluid. Consider water flowing under pressure through a pipe having the shape illustrated in **Figure 11**. As the water flows from the wide section to the narrow section, its speed increases. This effect is seen in a river that flows slowly at its wider regions, but speeds up when it passes through a narrow gorge.

The water flow in **Figure 11** accelerates as the water molecules travel from region A into region B. Acceleration is caused by an unbalanced force, but what is its source in this case? The answer lies in the pressure difference between the two regions. The pressure (or force per unit area) must be greater in region A than in region B to accelerate the water molecules as they pass into region B.

These concepts were analyzed in detail by Swiss scientist Daniel Bernoulli (1700–1782). His conclusions became known as *Bernoulli's principle.*

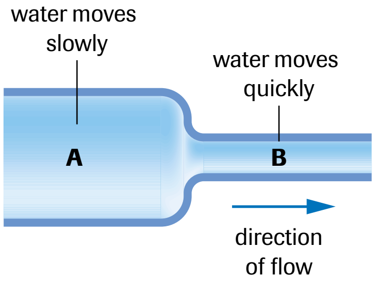


Figure 11
The flow speed depends on the diameter of the pipe.

Bernoulli's Principle

Where the speed of a fluid is low, the pressure is high. Where the speed of the same fluid is high, the pressure is low.

Throwing a curve in baseball is also an application of Bernoulli's principle. In **Figure 12(a)**, a ball is thrown forward, which means that, relative to the ball, the air is moving backward. When the ball is thrown with a clockwise spin, the air near the ball's surface is dragged along with the ball (**Figure 12(b)**). To the left of the moving ball, the speed of the air is slow, so the pressure is high. The ball is forced to curve to the right, following the path shown in **Figure 12(c)**.

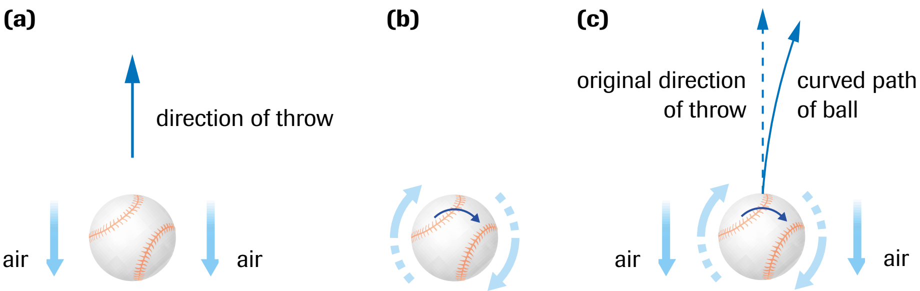


Figure 12
Bernoulli's principle explains curve balls as viewed from above.
(a) A ball thrown without spin is undeflected.
(b) Air is dragged around the surface of a spinning ball.
(c) Since the flow speed around a spinning ball is not equal on both sides, the pressure is not equal. The ball is deflected in the direction of lower pressure.

DID YOU KNOW?

Dimpled Golf Balls

The earliest golf balls were smooth. When it was discovered that a ball with scratches travelled farther than a smooth ball, the surface was redesigned with dimples. Experiments show that a person who can drive a dimpled ball over 200 m can drive a smooth ball of equal mass only about 50 m! As a smooth ball travels through the air, laminar flow produces a high pressure at the front of the ball and a low pressure at the rear, causing substantial frictional drag. As a dimpled ball travels through the air, however, turbulence minimizes the pressure difference between front and rear, thereby minimizing drag.

TRY THIS activity — How Will the Cans Move?

Predict what will happen when you blow air between the two empty beverage cans arranged as shown in **Figure 13**. Verify your prediction experimentally and explain your results.

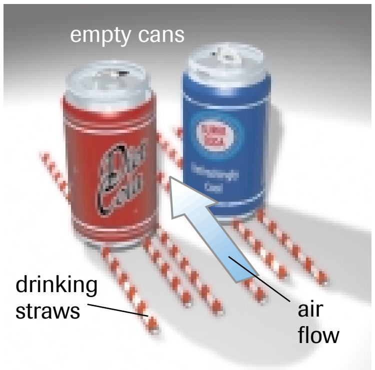


Figure 13
What happens when you blow air between the cans?

Practice

Understanding Concepts

10. List four liquids, other than those mentioned in the text, in order of increasing viscosity.

11. Describe what you think is meant by the following phrases:
(a) As slow as molasses in January. (Molasses is the syrup made from sugar cane.)
(b) Blood runs thicker than water.

12. Compare the speeds of the top and bottom of the bulge where the syrup leaves the jar (**Figure 14**). How does this pattern relate to laminar flow?

13. Identify design features commonly used to reduce drag in
(a) the cabs of heavy trucks
(b) launch rockets
(c) sport motorcycles
(d) locomotives

14. Explain the following observations in terms of Bernoulli's principle.
(a) As a convertible car with its top up cruises along a highway, the top bulges upward.
(b) A fire in a fireplace draws better when wind is blowing over the chimney than when the air is calm.

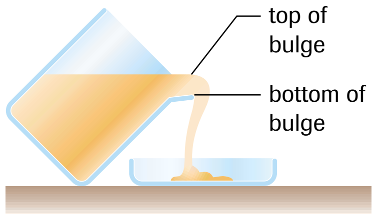


Figure 14
For question 12

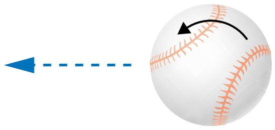


Figure 15
For question 15

15. A baseball (viewed from above) is thrown in the direction indicated by the dashes in **Figure 15**. If the ball is spinning counterclockwise, determine the approximate direction of the path of the ball. Use diagrams in your explanation.

Applying Inquiry Skills

16. Describe how you would perform an experiment to measure the linear speed of water leaving a horizontal hose of known nozzle diameter. (*Hint:* Show that if you collect a measured volume of water for a certain amount of time, then divide that value by the area of the nozzle, you obtain the speed. You can see that this reasoning is plausible by considering units: $(cm^3/s)/cm^2 = cm/s$.) If possible, try the experiment.

Making Connections

17. Burrowing animals, such as prairie dogs and gophers, require air circulation in their burrows. To set the air into motion, these creatures give their burrow a front entrance and a back entrance, piling dirt up to make one entrance higher than the other. Draw a cross-section sketch of this burrow design and explain how it promotes air circulation.

SUMMARY *Exploring Frictional Forces*

- As the force applied to an object increases, the static friction opposing the force increases until the maximum static friction is reached, at which instant the object begins to move. After that instant, kinetic friction opposes the motion.
- The coefficients of static friction and kinetic friction are the ratios, respectively, of the magnitude of the static friction force and the kinetic friction force to the normal force between an object and the surface with which it is in contact. These coefficients have no units.
- Internal friction in a fluid is called viscosity and depends on the nature and temperature of the fluid.
- Laminar flow of a fluid occurs when the layers of the fluid flow smoothly over one another.
- The irregular flow of a fluid is called turbulence; this problem can be reduced by streamlining.
- Bernoulli's principle states: Where the speed of a fluid is low, the pressure is high, and where the speed of the same fluid is high, the pressure is low. Among the illustrations of this principle is the throwing of curve balls in baseball.

Section 2.4 Questions

Understanding Concepts

1. When you rub your hands together vigorously, the temperature of the skin rises. Why?

2. A team of horses at a winter carnival is starting to pull a loaded sleigh with wooden runners along a horizontal trail covered in dry snow. The total mass of the sleigh, including its passengers, is 2.1×10^3 kg. The horses apply a force of 5.3×10^3 N [horizontally]. Determine the magnitude of (a) the frictional force and (b) the acceleration of the sled. (*Hint:* Look up the appropriate coefficient of friction in **Table 1**.)

3. Two skiers, A and B, each of mass *m*, are skiing down a snow-covered hill that makes an angle ϕ above the horizontal. A is moving with constant velocity. B is accelerating.
(a) Derive an equation for the coefficient of kinetic friction experienced by A, in terms of the angle ϕ.
(b) Derive an equation for the magnitude of the acceleration experienced by B, in terms of g, ϕ, and μ_K.
(c) What effect would a change in the mass of skier B have on the magnitude of the acceleration? Explain your answer.

4. A race car is accelerating on a level track. The coefficient of static friction between the tires and the track is 0.88. The tires are not slipping.
   (a) Draw an FBD of the car.
   (b) Determine the maximum possible magnitude of acceleration if the car is to travel without slipping.
5. A steel ball reaches a terminal speed when falling in glycerine. Will the terminal speed be greater if the glycerine is at 20°C or at 60°C? Explain.
6. Why are pumping stations required at regular intervals along the cross-Canada natural gas pipeline?
7. **Figure 16** shows a *venturi flowmeter*, used to measure the speed of gas flowing through a tube. How does its design illustrate Bernoulli's principle?

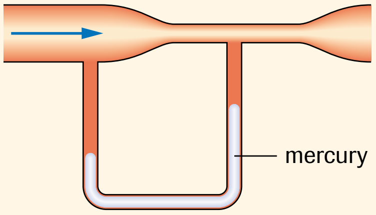


Figure 16
A venturi flowmeter

Applying Inquiry Skills

8. (a) With your hand facing palm downward, slide your fingers across the cover of your textbook. Estimate the coefficient of kinetic friction between your fingers and the cover.
   (b) Turn your hand over and repeat the procedure with your fingernails.
   (c) Devise and carry out an experiment (using a ruler for measurements) to determine values for the coefficients in (a) and (b). Compare your estimated and calculated values.
   (d) Describe what you could do to improve your skill in estimating coefficients of friction.
9. Predict, with an explanation, what will happen when a person blows through the horizontal straw in **Figure 17**. Verify your prediction experimentally with teacher approval. Relate your explanation to the design principle of a paint sprayer.

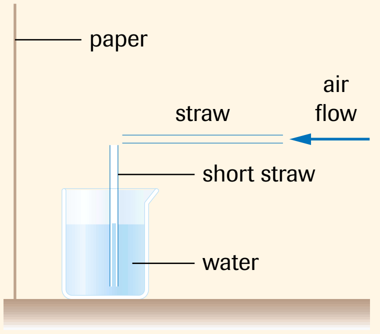


Figure 17

Making Connections

10. In 1896, Carl E. Johansson of Sweden produced the first *gauge blocks* (also called "Jo blocks" in his honour) for quality control in manufacturing. Since the blocks have extremely smooth sides, the coefficient of static friction is high. The blocks thus stick together upon contact. (You have likely noticed a similar strong bonding when microscope slides stick together.) Research the topic of gauge blocks, describing their properties and uses.

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11. What are the meanings of the terms "slice" and "hook" in golf? What causes slices and hooks? What can you do to prevent them?

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12. Running-shoe designs have changed with advances in technology. Research how the soles of running shoes have evolved, writing a few sentences on your findings.

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13. The near-frictionless carbon (NFC) listed in **Table 1** is a new, ultra-hard carbon film with a coefficient of kinetic friction of only about 0.001 in an environment of nitrogen or argon. Although the coefficient is greater in an ordinary environment of air, the friction remains low enough to give this amazing material many applications. Research the advantages and uses of NFC, and write a report on what you discover.

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