CHAPTER 6

Fluids and Motion

Fluids are fascinating when they move. Stationary water and air may be essential to life, but they're also fairly simple; only their pressures vary from place to place, and even these are determined primarily by gravity. Rushing rivers or gusts of wind, however, with their wonderful variety of simple and complicated behaviors, are much more interesting. The motions of fluids aren't just interesting; they're also important, since our world is filled with objects and machines that work in whole or part because of the behaviors of moving fluids. In this chapter, we'll look at a variety of situations in which fluid motion contributes to the way things work.

EXPERIMENT: A Vortex Cannon

Fluids are real; they exist independent of any solids that might move through them. That notion is easy to accept in reference to water, since we can see that water doesn't

Courtesy Lou Bloomfield

wait for a boat to pass before moving in interesting ways. Air is harder to visualize in this fashion because we seldom see it by itself, apart from its effects on buildings or airplanes or our skin.

To begin seeing air as something tangible and to demonstrate the rich possibilities of motion available to it, build a vortex cannon—a device that sends rings of air sailing across a room. Although a serious vortex cannon is best constructed from a large drum or crate, you can make a simple one from an empty cardboard cereal box.

Seal the rectangular box on all edges with tape, and cut a circular hole 5 centimeters (2 inches) in diameter in the center of one face. To use your cannon, just tap hard on the other face of the box. Rings of air will leap out of the hole and sail across the room at about 5 m/s (11 mph).

Although you can't see these rings, you can follow their motion by looking for their effects on objects they encounter. The rings can easily blow out candles or rustle light window drapes across a small room. If you have a friend blow some rings at you, you'll feel exactly where they hit on your face or shirt.

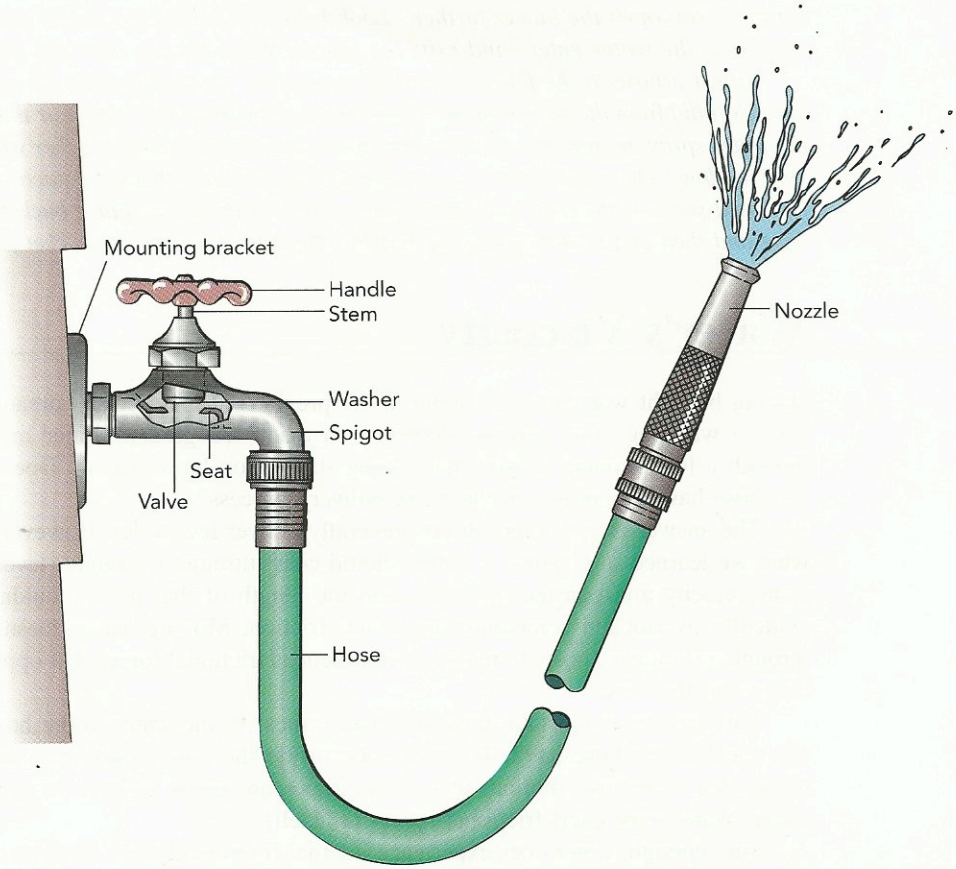
To see these rings directly, fill the cereal box with smoke, mist, or dust. What do you think the rings will look like when they emerge from the hole. Will the smoke in each ring be stationary, or will it be swirling about the ring in some manner? How will the ring's size and speed of travel depend on the size of the hole from which it emerges? Will it depend on how hard you tap the cereal box? Will the ring's size and speed change in flight?

Now tap the box and watch the smoke rings. What motions do you see? Change the hole size and see how this change affects the rings and their motion. As you can see, the air can execute some very complicated movements all by itself. In this chapter, we will examine how moving air, water and other fluids affect our everyday lives.

Chapter Itinerary

In particular, we'll explore (1) *garden watering*, (2) *balls and air*, and (3) *airplanes*. In *garden watering*, we'll look at how water's pressure and speed vary as it flows through a faucet, a hose, and a nozzle. In *balls and air*, we'll investigate the effects of air on the motions of balls. Last, in *airplanes*, we'll study the ways in which moving air supports and propels airplanes in flight. A more complete preview can be found in the Chapter Summary at the end of the chapter.

This chapter continues to develop the concept of energy conservation along a streamline that was introduced in Chapter 5. It also brings up several new types of forces that are present when fluids move past one another or past solid objects. These ideas are present in a vast array of commonplace activities, from washing windows with a hose to pumping water with a windmill.



SECTION 6.1 Garden Watering

Tending a flower garden often involves watering. While this once meant walking the garden's paths with a watering can, modern plumbing has made such effort unnecessary. With a hose and nozzle attached to a faucet, you can do your job without leaving your lawn chair. Although the tools involved—faucets, hoses, and nozzles—are simple and unsophisticated, the principles behind them are not. All three make elegant use of the laws of fluid flow, letting openings and channels control the delivery rate and speed of the water so that it arcs gracefully through the air to the farthest reaches of your garden.

Questions to Think About: *What determines the rate at which water flows through a hose? If honey ran through your hose instead of water, how would that affect the flow? Why does water make noise as you sprinkle your garden? Why does a nozzle make the water spray so fast and so far? Why do the pipes sometimes clank when you abruptly close the faucet?*

Experiments to Do: *Open a faucet gradually and watch the water begin to flow. What's pushing the water out of the faucet? What happens to the flow rate and speed of the*

water as you open the faucet further? Look below or behind the faucet and try to determine how the water enters and exits the faucet. When do you hear the water flowing?

Attach a hose to the faucet. Does the water flow as quickly from the open end of the hose as it did from the faucet alone? Cover most of the hose end with your thumb and watch the water spray out into the air. Why does the water travel so much farther when you almost stop its flow? Do you feel the water pressing against your thumb? Attach a nozzle to the hose and see how the flow rate affects the strength of the spray. Fill a bucket with the open hose and then again while using the nozzle. Which method fills the bucket fastest?

Water's Viscosity

Having brought water to your home in the previous chapter, we're already well on our way to watering your garden. However, to reach the garden, water must first travel through a long stretch of hose that's lying straight on level ground. Does the length of this hose have any effect on the water delivery process?

The answer is yes, longer hoses generally deliver less water. However, according to what we learned in Chapter 5, water should coast through a straight, level hose at constant velocity and constant pressure, and the length of that hose shouldn't matter. We evidently overlooked something important: friction. Moving water doesn't slide freely through a stationary hose. In reality, it experiences frictional forces that oppose its motion relative to the hose.

This friction is unusual, though, because most of the water in the hose never actually touches the hose itself. If water deep inside the hose is going to experience any forces due to relative motion, then those forces are going to have to occur *within* the water. Water must exert frictional forces on itself!

Sure enough, water does experience internal frictional forces. They're called **viscous forces**—forces that appear whenever one layer of a fluid tries to slide across another layer of that fluid. Viscous forces oppose relative motion, and you can observe their effects easily when you pour honey out of a jar. The honey at the jar's surface is stuck there by chemical forces and remains stationary. But even honey that's far from the walls can't move easily; it experiences viscous forces as it tries to move relative to nearby honey. Since honey is a "thick" or *viscous* fluid, viscous forces act quite effectively to keep all the honey moving with nearly the same velocity. Since the honey at the walls can't move, viscous forces tend to prevent any of the honey from moving.

Water isn't as thick as honey (Table 6.1.1), so it's less resistant to relative motion. The measure of this resistance to relative motion within a fluid is called **viscosity**, and

Table 6.1.1 Approximate Viscosities of a Variety of Fluids

FLUID	VISCOSITY*
Helium (2 K)	0 Pa · s
Air (20 °C)	0.0000183 Pa · s
Water (20 °C)	0.00100 Pa · s
Olive oil (20 °C)	0.084 Pa · s
Shampoo (20 °C)	100 Pa · s
Honey (20 °C)	1000 Pa · s
Glass (540 °C)	10^{12} Pa · s

*The pascal-second (abbreviated Pa · s and synonymous with kg/m · s) is the SI unit of viscosity. Only the superfluid portion of ultracold liquid helium exhibits zero viscosity.

water's viscosity is less than that of honey. In fact, if you heat the water up it will become even less viscous and thus flow more easily. Typical of most liquids, this decrease in viscosity with increasing temperature reflects the molecular origins of viscous forces: the molecules in a liquid stick to one another, forming weak chemical bonds that require energy to break. In a hot liquid, the molecules have more thermal energy, so they break these bonds more easily in order to move past one another (see ■).

■ Your car's engine is protected by motor oil with a carefully chosen viscosity. If that oil were too thin, it would flow out from between surfaces and wouldn't keep them from rubbing against one another. If that oil were too thick, the engine would waste power moving its parts through the oil. Years ago, you had to change your motor oil for the season. Thick, 40 weight motor oil was used in summer because hot weather made it thinner; thin, 10 weight oil was used in winter because cold weather made it thicker. Now, a modern, multigrade oil maintains a nearly constant viscosity over a wide range of temperatures and need not be changed with the seasons. This oil contains tiny molecular chains that ball up when cold but straighten out when hot. These chains thicken hot oil so that 10W-40 oil resembles 10 weight oil in winter and 40 weight oil in summer.

Check Your Understanding #1: Keeping Warm on a Windy Day

A loosely woven wool sweater has many tiny air passages between the wool fibers, yet it dramatically reduces the rate at which air flows through to your skin when you stand in a breeze. Why doesn't air flow easily through the gaps between the fibers?

Answer: The air at the surfaces of the fibers is stationary, and the air's viscosity slows the motion of air in the vicinity of the fibers.

Why: Although air trying to pass through the gaps may not directly touch the fibers, viscous forces tend to keep all of the air moving together at the same velocity. As soon as some air is held up by a fiber, the air nearby is slowed by viscous forces. The fibers of a sweater are close enough together that viscous forces slow all the air trying to pass through the sweater. Imagine trying to pour honey through a sweater.

Flow in a Straight Hose: The Effect of Viscosity

Viscosity slows the flow of water through your hose. Chemical forces between the hose and the outermost layer of water hold that layer of water stationary, and this motionless layer exerts viscous forces on the layer of moving water inside it. As this second layer slows, it exerts viscous forces on yet another layer. Layer by layer, viscous forces hold back the moving water until even water at the center of the hose feels viscosity's slowing effects (Fig. 6.1.1). Although water at the center of the hose moves faster than water in any other layer, it's still affected by the stationary hose.

These viscous forces impede water delivery. Instead of coasting effortlessly through the straight, level hose, real water needs a pressure gradient to push it steadily forward. Like the file cabinet sliding on the sidewalk in Section 2.2, water must be pushed through the hose if it's to maintain a continuous flow. Also like that file cabinet, the water becomes hotter as the work done pushing it forward is wasted and becomes thermal energy.

However, unlike the forces of ordinary sliding friction—which don't depend on relative velocities—viscous forces become larger as the relative velocities within a fluid increase. That's because as two layers of water slide past one another faster, their molecules collide harder and more frequently. Since it experiences stronger viscous forces, fast-moving water wastes more energy per meter and needs a larger pressure gradient to keep it moving steadily through a hose than does slow-moving water.

Because of viscous forces, the amount of water flowing steadily through a hose depends on four factors:

1. It's inversely proportional to the water's viscosity. The more viscous the water, the more difficulty it has flowing through the hose.
2. It's inversely proportional to the length of the hose. The longer the hose, the more opportunity viscous forces have to slow the water down.

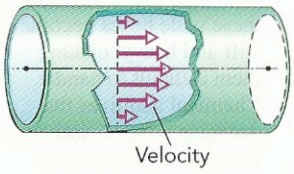


Fig. 6.1.1 The speed of water flowing through a pipe is not constant across the pipe. The water near the walls is stationary, while the water at the center of the pipe moves the fastest. The differences in velocity are the result of viscous forces.

3. It's proportional to the pressure difference between the hose's inlet and its outlet. This pressure difference determines the water's pressure gradient and thus how hard the water is pushed forward through the hose.
4. It's proportional to the fourth power of the diameter of the hose. Tripling the hose's diameter provides the water with nine times as much room and also allows water near the hose's center to move nine times faster.

We can turn all these proportional relationships into an equation by adding the correct numerical constant ($\pi/128$). The final relationship is called **Poiseuille's law** and can be written as a word equation:

$$\text{volume} = \frac{\pi \cdot \text{pressure difference} \cdot \text{pipe diameter}^4}{128 \cdot \text{pipe length} \cdot \text{fluid viscosity}}, \tag{6.1.1}$$

in symbols:

$$\frac{\Delta V}{\Delta t} = \frac{\pi \cdot \Delta p \cdot D^4}{128 \cdot L \cdot \eta},$$

and in everyday language:

It's hard to squeeze honey through a long, thin tube.

Poiseuille's Law

The volume of fluid flowing through a cylindrical pipe each second is equal to ($\pi/128$) times the pressure difference (Δp) across that pipe times the pipe's diameter to the fourth power, divided by the pipe's length times the fluid's viscosity (η).

■ To deliver large amounts of water at high pressure or velocity, fire hoses must have large diameters. When filled with high-pressure water, these wide hoses become stiff and heavy, making them difficult to handle. Chemical additives that decrease water's viscosity allow firefighters to use narrower, lighter, and more flexible hoses.

■ Very large diameter pipes are required to transport crude oil across the Alaskan wilderness. The distances are long and the fluid is viscous, although it is heated to lower its viscosity.

It's hardly surprising that the flow rate depends in this manner on the pressure difference, pipe length, and viscosity; we've all observed that low water pressure or a long hose lengthens the time needed to fill a bucket with water and that viscous syrup pours slowly from a bottle. However, the dependence of the flow rate on the fourth power of pipe diameter may come as a surprise. Even a small change in the diameter of a hose significantly changes the amount of water that hose delivers each second. The two most common garden hoses in the United States have diameters of 5/8 inch and 3/4 inch, and while these hoses differ by a seemingly insignificant 20% or a factor of 1.2 in diameter, the 3/4-inch hose can carry about 1.2^4 or 2 times as much water as the 5/8-inch hose (see ■, ■).

We can also look at viscous forces in terms of total energy. By opposing the flow of water through a hose, viscous forces do negative work on it and reduce its total energy—the energy considered in Bernoulli's equation, which doesn't include thermal energy. Just how much total energy the water retains depends on how fast it moves inside the hose. If you allow lots of water to leave the hose, water will move through it quickly and encounter large viscous forces. In the process, most of the water's total energy will be wasted as thermal energy and the water will pour gently out of the end of the hose.

However, if you partially block the hose's opening with your thumb and reduce the flow, water will travel slowly through the hose and encounter smaller viscous forces. As a result, the water will retain most of its total energy and will still be at high pressure when it reaches your thumb. This high-pressure water will then accelerate to enormous speed as it passes through the narrow opening and sprays out into the air.

We can now explain why water delivery systems normally use the widest pipes that are practical and affordable. In contrast to a narrow hose, wide pipes can carry large amounts of water while letting that water travel slowly, experience weak viscous forces, and waste little of its total energy. In such energy-efficient water delivery systems, friction is insignificant and Bernoulli's equation (Eq. 5.2.4) accurately predicts water's properties throughout its trip.

Check Your Understanding #2: Air Ducts

The long air ducts used to ventilate homes and businesses usually have very large diameters. These ducts are often visible near the ceilings of modern warehouse-style stores and restaurants as pipes roughly 0.5 m across. Why must the ducts be so large in diameter?

Answer: Air's viscosity slows its flow through ductwork. Moving large volumes of air rapidly without a large pressure difference between inlet and outlet requires a large diameter pipe.

Why: The airflow through long ductwork is dominated by viscous forces. The volume of air moved through ductwork is often enormous, and the pressure difference between the inlet and outlet is normally only a fraction of an atmosphere. To allow the air to move quickly through the ducts, their diameters must be large.

Check Your Figures #1: Old Plumbing

When your friend's house was new, the kitchen faucet could deliver 0.50 liter per second (0.50 L/s). Over the years, mineral deposits have built up in the pipes and reduced their effective diameters by 20%. How much water can the faucet deliver now?

Answer: It can deliver about 0.20 L/s.

Why: Water flow in pipes obeys Poiseuille's law (Eq. 6.1.1) and is proportional to the pipe diameter to the fourth power. Reducing the diameter by 20%, a factor of 0.8, while leaving the pipe length, pressures, and viscosity unchanged, will reduce the volume flow rate by a factor of 0.8^4 or 0.41. The pipes now deliver about 0.20 L/s (the product of 0.50 L/s times 0.41). It clearly doesn't take much mineral accumulation to dramatically reduce the flow through a pipe.

Flow in a Bent Hose: Dynamic Pressure Variations

On reaching your garden, let's suppose the hose bends toward the right and the flowing water bends with it. That water is accelerating as it turns and, as we observed in Chapter 5, water accelerates horizontally only in response to unbalanced pressures. Since the hose is motionless, the unbalanced pressures inside it must be caused by the water itself; the water is experiencing dynamic pressure variations.

To understand these dynamic pressure variations, let's follow the streamlines as water traverses this bend. Although we've just introduced viscous forces, we're going to ignore them here for clarity and simplicity. Although viscous forces are certainly important in the long, narrow hose, the bend is so short that viscous forces have little effect on what happens to the water passing through it.

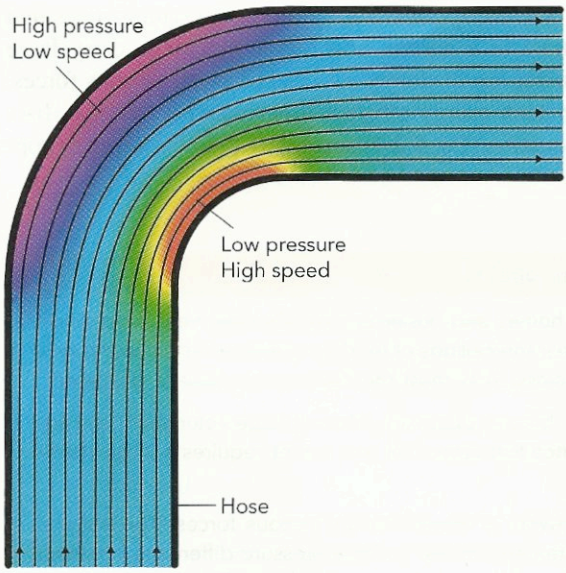


Fig. 6.1.2 Water in a bent hose experiences changes in speed and pressure. The black streamlines show the paths the water takes as it flows around the bend. The spacing between streamlines indicates flow speed (wider space is slower flow), and the background color indicates pressure (violet is higher pressure; red is lower pressure).

Neglecting viscous forces, the water's total energy is constant along each streamline and we can observe the interchanges of energy allowed by Bernoulli's equation (Eq. 5.2.4). However, since the hose rests on level ground, water's gravitational potential energy can't vary, and the only interchanges we'll see are between pressure potential energy and kinetic energy.

Figure 6.1.2 shows the water's steady-state flow pattern near the bend. We're looking down on the hose in this calculated drawing and, as indicated by the black streamlines, water that is initially flowing straight ahead arcs rightward at the bend and eventually continues directly toward the right.

Water approaches the bend through a straight section of hose in which it travels at constant velocity and has a uniform pressure. Its velocity is constant because the straight hose directs all the streamlines forward and because the water moving along a given streamline can't change its speed; if it tried to speed up, it would leave an empty space behind it; if it tried to slow down, it would cause a "traffic jam." The water's pressure is uniform throughout this straight section because constant velocities mean no accelerations and thus no pressure differences.

The water's constant velocity and uniform pressure are represented visually in Fig. 6.1.2. You can see the local water velocity by looking at the direction and spacing of the streamlines. Streamlines always point in the direction of the local water velocity, and their spacing varies inversely with the local water speed. Streamlines that become more widely spaced denote decreasing speed—water that slows down spreads out sideways and its streamlines separate from one another. Streamlines that become more narrowly spaced denote increasing speed—water that speeds up stretches out along its path and its streamlines draw toward one another. Since the streamlines leading up to the bend are straight and evenly spaced, we know that water moves along each streamline at a constant velocity.

You can see the local water pressure in Fig. 6.1.2 by looking for the colors of the rainbow. Colors toward the violet end of the spectrum denote higher pressures, while those toward the red end of the spectrum denote lower pressures. Since the straight section has a uniform blue-green color, the water there has a uniform, moderate pressure.

Once the water starts bending toward the right, its velocities and pressures begin to vary. Since the water is accelerating toward the inside of the bend, there must be a pressure imbalance pushing it in that direction. Sure enough, the turning stream of water develops higher local pressure (violet) near the outside of the bend and lower local pressure near the inside of the bend (red). A similar pressure imbalance accompanies any bend in a fluid's path: the pressure is always higher on the outside of the bend than it is on the inside of that bend. After all, that pressure imbalance is what causes the fluid to bend!

Bends and Pressure Imbalances

When the path of a fluid in steady-state flow bends, the pressure on the outside of the bend is always higher than the pressure on the inside of the bend.

To keep the total energy constant along a streamline, each decrease in the water's local pressure is accompanied by an increase in the water's local speed and vice versa. Water arcing around the outside of the bend slows down (the streamline spacing widens) as its pressure rises, while the water arcing around the inside of the bend speeds up (the streamline spacing narrows) as its pressure drops.

As the hose straightens out beyond the bend, water's pressures and speeds return to what they were before the bend. Water from the outside of the bend speeds up and its pressure drops, while water from the inside of the bend slows down and its pressure rises. In the straight section following the bend, water's velocity is once again constant along each streamline and its pressure is uniform.

Odd as these pressure and speed changes may seem, they are quite real and have real consequences. If your hose were clear and you could introduce thin threads of dye into the flowing water, you'd see these dyed streamlines arc around the bend just as they do in Fig. 6.1.2. If the hose were weak and couldn't tolerate excessive pressure, it would be most likely to burst on the outside of the bend, where the local water pressure is highest.

You might wonder which causes which: does each pressure change cause a speed change or does each speed change cause a pressure change? The answer is that they occur together and are equally entitled to be called cause and effect. Once the steady-state flow pattern has established itself, water following a particular streamline experiences rises and falls in pressure at the same time that it experiences decreases and increases in speed. The two effects, pressure changes and speed changes, simply go hand in hand.

Check Your Understanding #3: Washing Your Shirt with a Spoon

You're washing dishes when the stream of water falling from the kitchen faucet follows the curve of a spoon and sprays up onto your shirt. As the stream bent upward, where was its pressure greatest?

Answer: Pressure was greatest at the surface of the spoon.

Why: The pressure in the stream of water must be higher on the outside of the bend—at the spoon's surface—than on the inside of the bend.

Flow through a Nozzle: From Pressure to Speed

When water finally flows through the nozzle at the end of your hose, it exchanges its remaining pressure potential energy for kinetic energy and sprays out into the garden. The nozzle's narrowing channel initiates this energy transformation so that low-speed, high-pressure water entering the nozzle becomes fast-moving, atmospheric-pressure water leaving the nozzle.

Figure 6.1.3 shows that as water passes through the nozzle, the narrowing channel herds all the streamlines together so that the water's local speed increases. The water following each streamline is speeding up in order to squirt through the bottleneck without causing a backup. This increase in water's local speed is accompanied by a decrease in water's local pressure, as indicated by the color shift toward the red end of the spectrum.

By the time the water leaves the hose nozzle, its pressure has dropped all the way to atmospheric pressure and it has turned all of its available pressure potential energy into kinetic energy. It emerges as a narrow stream of fast-moving water and arcs gracefully through the air. No wonder you can reach the farthest parts of your garden with water when you use a nozzle.

Common Misconceptions: Speed and Pressure in Fluids

Misconception: A fast-moving fluid always has a low pressure.

Resolution: The pressure of a specific portion of fluid depends on its circumstances and can take any value, high or low. However, if a fluid speeds up without descending as it flows along a streamline in steady-state flow, its pressure will decrease. In that special context, the *faster* moving fluid has a *lower* pressure.

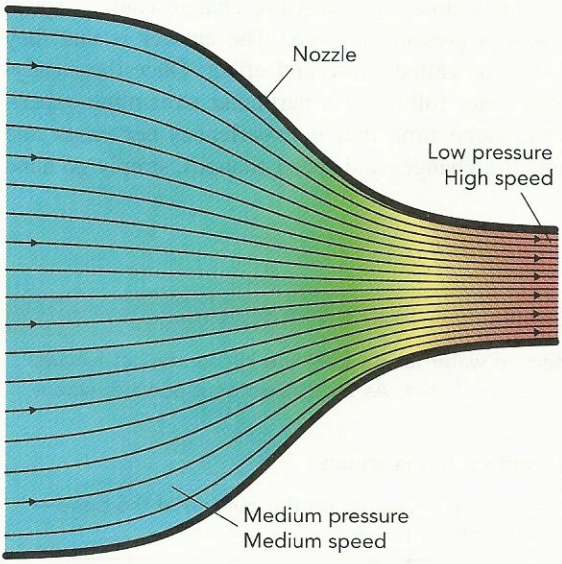


Fig. 6.1.3 Water flowing through a nozzle speeds up and its pressure drops. The narrowing spacing between streamlines indicates that the flow speed is increasing, while the color shift from violet toward red indicates that the pressure is dropping.

Check Your Understanding #4: Cleaning House

As air rushes steadily into the narrow opening of a vacuum cleaner attachment, it accelerates to high speed and its pressure drops well below atmospheric pressure. From where does the air's newfound kinetic energy come?

Answer: Even at atmospheric pressure, air has pressure potential energy. As it accelerates toward even lower pressure in the attachment, air converts some of that pressure potential energy into kinetic energy.

Why: Vacuum cleaners employ nozzles to get air moving very quickly. Fast-moving air rushing into the vacuum cleaner draws dust with it and cleans your home.

The Onset of Turbulence

As you direct the stream of water at the plants in your garden, you notice two interesting phenomena: first, the stream pushes on any surface that slows it down and, second, it tends to break up into fragments as it flows around obstacles. The pushing effect is another Bernoulli result: when the stream encounters a surface, it slows down and spreads out sideways. As the water slows close to the surface, its pressure there rises above atmospheric pressure and it is this elevated pressure that actually pushes the surface forward.

The breakup effect, however, is something new. In trying to go around the obstacle, the stream of water loses its orderly structure and disintegrates into a swirling, hissing froth. Actually, the hiss you hear is familiar; you heard it as you opened the faucet to start water flowing through the hose. That faucet uses a movable stopper to control the flow of water into the hose; as you opened the faucet, you gradually removed this stopper from the water pipe to allow water to flow more freely into the hose, and the faucet hissed. Whether water encounters a plant or a faucet stopper, there is something about high speeds and obstacles that upsets the smoothly flowing fluid.

Up until now, we've discussed only **laminar flow**—smooth, silent flow that's characterized by simple streamlines. In laminar flow, adjacent regions of a fluid always remain adjacent. For example, if you place two drops of dye near one another in a smoothly flowing stream, they will remain close together indefinitely as they follow streamlines in the laminar flow (Fig. 6.1.4). Laminar flow is the orderly result of viscous

Courtesy Lou Bloomfield

Fig. 6.1.4 Water flows slowly past rocks in the stream on the left, and its viscosity keeps it smooth and laminar. Water flows quickly past rocks in the stream on the right, and its inertia separates it into swirling, splashing pockets of turbulence.

forces, which tend to bring adjacent portions of fluid to the same velocity. When viscosity dominates a fluid's motion, the flow is usually laminar.

However, as the stream flows swiftly past rocks and obstacles, its streamlines break up into the eddies and churning "white water" that make rafting exciting. The dye is quickly dispersed in this frenzied **turbulence**. The stream is experiencing **turbulent flow**—roiling, noisy flow in which adjacent regions of fluid soon become separated from one another as they move independently in unpredictable directions. Turbulent flow is the disorderly consequence of inertia, which tends to propel each portion of fluid independently according to its own momentum. When inertia dominates a fluid's motion, the flow is usually turbulent.

The plants and faucet stopper are evidently initiating turbulence in what had been laminar flows; flows that were dominated by viscous forces are suddenly dominated by inertia instead. Whether a flow is laminar or turbulent depends on several characteristics of the fluid and its environment:

1. The fluid's viscosity. Viscous forces tend to keep nearby regions of fluid moving together, so high viscosity favors laminar flow (Fig. 6.1.5).
2. The fluid's speed past a stationary obstacle. The faster the fluid is moving, the more quickly two nearby regions of fluid can become separated and the harder it is for viscous forces to keep them together.
3. The size of the obstacle the fluid encounters. The larger the obstacle, the more likely that it will cause turbulence because viscous forces will be unable to keep the fluid ordered over such a long distance.
4. The fluid's density. The denser the fluid, the less it responds to viscous forces and the more likely it is to become turbulent.

Rather than keeping track of all four physical quantities independently, English mathematician and engineer Osborne Reynolds (1842–1912) found that they could be combined

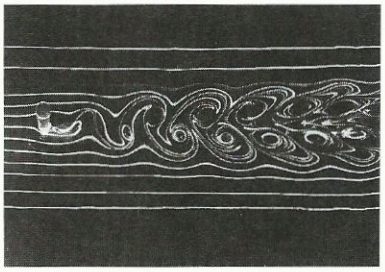
Courtesy Lou Bloomfield

Fig. 6.1.5 Honey's large viscosity keeps it flowing smoothly (laminar flow) when you pour it. Water's small viscosity allows it to splash about (turbulent flow) in a fountain. In both cases, the effective obstacle length is the width of the flowing fluid, about 1 cm.

into a single number that permits a comparison of seemingly different flows. The **Reynolds number** is defined as

$$\text{Reynolds number} = \frac{\text{density} \cdot \text{obstacle length} \cdot \text{flow speed}}{\text{viscosity}}. \qquad (6.1.2)$$

The units on the right side of Eq. 6.1.2 cancel one another so that the Reynolds number is dimensionless; that is, it's just a simple number, such as 10 or 25,000. As the Reynolds number increases, the flow goes from viscous-dominated to inertia-dominated and therefore from laminar to turbulent. In his experiments, Reynolds found that turbulence usually appears when the Reynolds number exceeds roughly 2300. You can observe this transition by moving a 1-cm-thick (0.4-in-thick) stick through still water. If you move the stick slowly, about 10 cm/s (4 in/s), the Reynolds number will be about 1000 and the flow around the stick will be laminar. But if you speed the stick up to about 50 cm/s (20 in/s), the Reynolds number will rise to about 5000 and the flow will become turbulent.



Courtesy Peter Bradshaw, Stanford University

Fig. 6.1.6 When water flows rapidly around a cylinder, its flow becomes turbulent. A pattern of swirling vortices forms to the right of this cylinder.

One of the most common features of turbulent flows is the **vortex**, a swirling region of fluid that moves in a circle around a central cavity. A vortex resembles a miniature tornado, with its cavity created by inertia as the fluid spins. Vortices are easily visible behind a canoe paddle or in a mixing bowl. Once an object moves fast enough through a fluid to create turbulence, these vortices begin to form. Each vortex builds up behind the object but is soon whisked away to form a wake of *shed vortices*—vortices that have broken free of the object that made them (Fig. 6.1.6).

While laminar flow is fully predictable, turbulent flow exhibits chaotic behavior or **chaos**: you can no longer predict exactly where any particular drop of water will go. The study of chaos is a relatively new field of science. Because a **chaotic system**—a system exhibiting chaos—is exquisitely sensitive to initial conditions, even the slightest change in those conditions may produce profound changes in its situation later on.

Even when you can't see turbulent water flow, you can usually hear it. The churning motion of turbulence converts some of the water's total energy into thermal energy and sound. The turbulence near the faucet slightly reduces the water's total energy as it enters the hose and therefore its speed as it emerges from the nozzle and sprays toward your garden.

A different sound occurs when you abruptly close the nozzle and stop the flow of water. Moving water has momentum, and stopping it suddenly requires an enormous backward force. Since the slowing flow is not steady state, Bernoulli's equation doesn't apply, and the pressure can surge to astronomical values near the front of the moving water. This pressure surge is what accelerates the water backward to slow it down and also what leads to the loud "thump" sound you hear as the water stops. Known as **water hammer**, the surging pressure in front of stopping water jerks the nozzle, swells the hose, and may even rattle the pipes in your home.

Check Your Understanding #5: Urban Windstorms

On a windy day in a city with many tall buildings, leaves and papers can be seen swirling about in the air or on the sidewalks. What causes these whirling air currents?

Answer: The air flowing through the "canyons" created by the buildings becomes turbulent and forms vortices that swirl the leaves and papers.

Why: Whether an object moves through a fluid or a fluid moves past an object, a Reynolds number is associated with the situation. When the Reynolds number becomes

high enough that viscosity is unable to keep the fluid flowing in an orderly fashion, turbulence appears. In wind blowing through a big city, turbulence and its whirling vortices are everywhere.

Check Your Figures #2: **Wind on the Open Road**

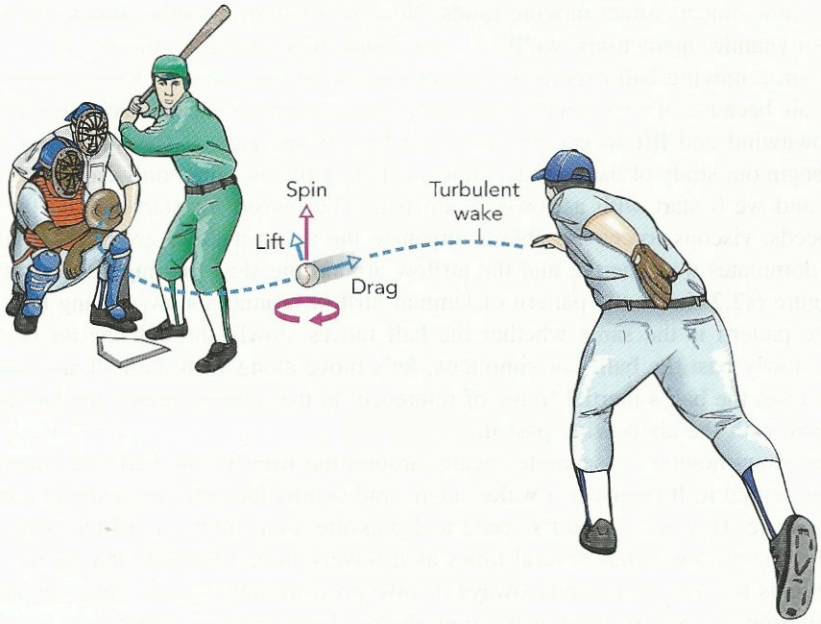
Is the flow of air around a convertible laminar or turbulent as the convertible cruises down the highway? (Air's viscosity is given in Table 6.1.1.)

Answer: The flow is turbulent.

Why: To calculate the Reynolds number for the airflow around the car, you need air's viscosity from Table 6.1.1 (0.0000183 Pa · s or 0.0000183 kg/m · s), air's density from Section 4.1 (1.25 kg/m^3), the car's size (roughly 3 m), and its speed through the air (roughly 55 mph or 25 m/s). You can then calculate its approximate Reynolds number, using Eq. 6.1.2:

$$\text{Reynolds number} = \frac{1.25\,\text{kg/m}^3 \cdot 3\,\text{m} \cdot 25\,\text{m/s}}{0.0000183\,\text{kg/m} \cdot \text{s}} = 5.1\,\text{million}$$

The convertible's Reynolds number is far above the threshold for turbulence (2300), so the air swirls chaotically around the vehicle. That explains why your hair flies around wildly.



SECTION 6.2 Ball Sports: Air

Much of the subtlety and nuance in games such as baseball and golf come from the way balls interact with air. If baseball were played on the moon, which has no air, the sinking fastball would be the only interesting pitch. Moon golfers wouldn't have to worry about hooks or slices. In this section we will investigate how air affects the flight of balls and other related objects.

Questions to Think About: *Why can you throw a real baseball so much farther than a hollow plastic one? Why does a long fly ball appear to drop straight down when you try to catch it in deep center field? What kind of force could make a curveball curve? What makes a well-hit golf ball hang in the air before falling to the green? How can a knuckleball or spitball jitter about in flight?*

Experiments to Do: *To make air's effects most apparent, you need a ball that weighs little but has lots of surface area. A beach ball is ideal, but a whiffle ball or hollow plastic ball will also do nicely. See how far you can throw it. How does it stop? Does it slow down and lose height gradually, or does it stop rapidly and fall to the ground? Now make the ball spin as you throw it. Why does the ball curve in flight? Does a fast spin make the ball curve more or less? Which way is the ball spinning, and how is the spin related to the direction of its curve? Change the direction of spin. Which way does the ball curve now?*

When a Ball Moves Slowly: Laminar Airflow

One of the first things you might notice if you joined a new baseball franchise on the moon is that pitched balls reach home plate faster than back at home. Since the moon has no atmosphere, there is no air resistance to slow a ball down. In the previous section,

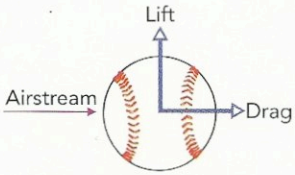


Fig. 6.2.1 The two types of aerodynamic forces exerted on objects by air are drag and lift. Drag is exerted parallel to the onrushing airstream and slows the object's motion through the air. Lift is exerted perpendicular to that airstream so that it pushes the object to one side or the other. Lift is not necessarily in the upward direction.

we saw how objects affect moving fluids. Now as we study **aerodynamics**, the science of air's dynamic interactions, we'll see how fluids affect moving objects.

In air, a moving ball experiences **aerodynamic forces**—that is, forces exerted on it by the air because of their relative motion. These consist of **drag forces** that push the ball downwind and **lift forces** that push the ball to one side or the other (Fig. 6.2.1). We'll begin our study of ball aerodynamics with drag forces, commonly called "air resistance," and we'll start with a slow-moving ball. The reason for starting slow is that at low speeds, viscous forces are able to organize the air as it flows around the ball; viscosity dominates over inertia, and the airflow around the slow-moving ball is laminar.

Figure 6.2.2 shows the pattern of laminar airflow around a slow-moving ball. Actually, the pattern is the same whether the ball moves slowly through the air or the air moves slowly past the ball. For simplicity, let's move along with the ball and study the airflow from the ball's inertial frame of reference. In that inertial frame, the ball appears stationary with the air flowing past it.

The slow-moving air separates neatly around the front of the ball and comes back together behind it. It produces a **wake**, an air trail behind the ball, that's smooth and free of turbulence. However, the air's speed and pressure aren't uniform all the way around the ball. The airflow bends several times as it travels around the ball and, as we saw in the previous section, such bends always involve pressure imbalances. Since the air pressure far from the ball is steadfastly atmospheric, those pressure imbalances are always caused by pressure variations near the ball's surface. Whenever air bends away from the ball, so that the ball is on the outside of a bend, the pressure near the ball must be higher than atmospheric. Whenever the air bends toward the ball, so that the ball is on the inside of a bend, the pressure near the ball must be lower than atmospheric.

With that introduction, let's examine the slow-moving airflow around the ball. Air heading toward the ball's front bends away from it, so the pressure near the front of the ball must be higher than atmospheric. This rise in air pressure is accompanied by a decrease in **airspeed**—the air's speed relative to the ball. Figure 6.2.2 indicates the pressure rise by a color shift toward the violet end of the spectrum and the decrease in airspeed by the widening separation of the streamlines.

Air rounding the ball's sides bends toward it, so the pressure near those sides of the ball must be below atmospheric. This drop in air pressure is accompanied by an increase

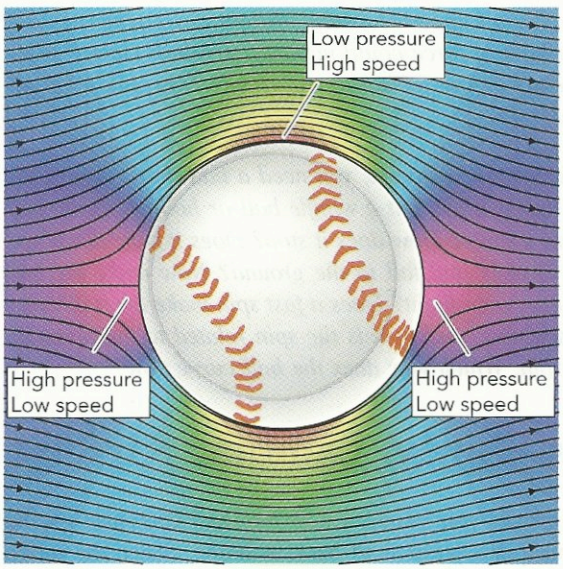


Fig. 6.2.2 The airflow around a slowly moving ball is laminar. Air slows down in front of and behind the ball (widely spaced streamlines), and its pressure increases (shifts toward the violet end of the spectrum). Air speeds up at the sides of the ball (narrowly spaced streamlines), and its pressure decreases (shifts toward the red end of the spectrum). However, the pressure forces on the ball balance one another perfectly, and it experiences no pressure drag. Only viscous drag is present to affect the ball.

in airspeed. Figure 6.2.2 indicates the pressure drop by a color shift toward the red end of the spectrum and the increase in airspeed by the narrowing separation of the streamlines.

The laminar airflow continues around to the back of the ball and then trails off behind it. Since the departing air again bends away from the ball, the pressure near the back of the ball must be higher than atmospheric. As before, the shift toward violet in Figure 6.2.2 indicates this pressure rise, and the widening separation of the streamlines points out the accompanying decrease in airspeed.

It may seem strange that the air pressure can be different at different points on the ball, but that's what happens in a flowing stream of air. It's particularly remarkable that low-pressure air at the sides of the ball is able to flow around to the back of the ball, where the pressure is higher. This air is experiencing a pressure imbalance that pushes it backward, opposite its direction of travel. But a pressure imbalance causes acceleration, not velocity, and the low-pressure air flowing past the sides of the ball has enough energy and forward momentum to carry it all the way to the back of the ball. Although this air slows as it flows into the rising pressure, it manages to complete its journey.

The airflow around the ball is symmetric, and the forces that air pressure exerts on the ball are also symmetric. These pressure forces cancel one another perfectly so that the ball experiences no overall force due to pressure. Most important, the high pressure in front of the ball is balanced by the high pressure behind it. As a result of this symmetric arrangement, the only aerodynamic force acting on the ball is **viscous drag**—the downstream frictional force caused by layers of viscous air sliding across the ball's surface (see ■).

Though we'll soon see that viscous drag is only a small fraction of the air resistance experienced by sports balls, it's the force that suspends dust in the air for hours and is an important issue for airplane wings. It's also a force that we've encountered before: viscous drag slowed water in your garden hose in the previous section!

■ When the airflow around an object is laminar, the pressure forces on it cancel perfectly and it experiences no drag due to pressure imbalances—no *pressure* drag. The absence of pressure drag was a great puzzlement to early aerodynamicists, who knew that the airflow around dust is laminar and that it experiences a drag force. This mystery was named d'Alembert's paradox, after Jean Le Rond d'Alembert (1717–1783), the French mathematician who first recognized it. D'Alembert and his contemporaries didn't know about the viscous drag force, which is what really slows dust's motion through the air.

Check Your Understanding #1: Smooth Flow in a Stream

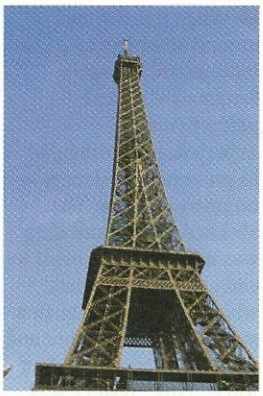
When water in a stream flows slowly past a small rock, the water in front of the rock slows down and its increased pressure lifts the water level slightly. The water level behind the rock also rises slightly. Explain.

Answer: The slow flow of water around the rock is laminar, so its pressure is highest at the front and back of the rock. The increased pressure behind the rock lifts the water level there.

Why: Laminar flow around an obstacle tends to create high-pressure regions at the front and back and low-pressure regions on the sides. In the case of our small rock, the pressure differences are visible as changes in the water level. At the front and back of the rock, the relatively high pressures push the water level upward, while at the sides of the rock, the water level is depressed.

When a Ball Moves Fast: Turbulent Airflow

Balls don't always experience laminar airflow. Turbulence is common, particularly in sports, and brings with it a new type of drag force. When the air flowing around a ball is turbulent, the air pressure distribution is no longer symmetric, and the ball experiences



Courtesy Lou Bloomfield

Fig. 6.2.4 Early experiments in aerodynamics were performed by Gustave Eiffel (French engineer, 1832–1923), who designed the tower that bears his name. In the 1890s, Eiffel dropped objects of various sizes and shapes from his tower and measured the drag that they experienced. His work was used by Prandtl to explain the reduction in drag that accompanies the appearance of turbulent boundary layers.

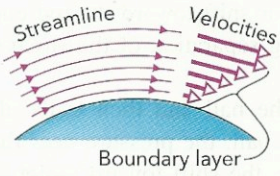


Fig. 6.2.3 As air flows past a surface, a thin layer of it is slowed by viscous drag forces. This boundary layer is laminar at low Reynolds numbers and doesn't become turbulent until the Reynolds number exceeds about 100,000.

pressure drag—the downstream force exerted by unbalanced pressures in the moving air. These unbalanced pressures exert an overall force on the ball that slows its motion through the air.

A ball can experience turbulent airflow and pressure drag when the Reynolds number exceeds about 2000. The Reynolds number, introduced in the previous section, combines the ball's size and speed with the air's density and viscosity to give an indication of whether the airflow is dominated by viscosity or inertia. At low Reynolds numbers, the air's viscosity dominates over its inertia and the airflow is laminar. At high Reynolds numbers, however, air's inertia dominates over its viscosity and the airflow tends to become turbulent. This turbulence, however, won't start until something triggers it, and viscosity provides that trigger.

To understand viscosity's role, we must look at the air near the ball's surface. Even in a strong wind, viscous forces slow down a thin **boundary layer** of air near the ball's surface (Fig. 6.2.3). Discovered by Ludwig Prandtl ■ with help from Gustave Eiffel (Fig. 6.2.4), this boundary layer moves more slowly and has less total energy than the freely flowing air farther from the surface.

■ Among Ludwig Prandtl's (German engineer, 1875–1953) many pivotal contributions to aerodynamic theory is the concept of boundary layers in fluid motion. Prandtl was so engrossed in establishing Göttingen as the world's foremost aerodynamic research facility that he did not have time to court a wife. Deciding he should be married, Prandtl wrote his former advisor's wife, asking to marry one of her two daughters but not specifying which one. The family selected the eldest daughter, and the wedding took place.

As air flows toward the back of the ball, it travels through an **adverse pressure gradient**—a region of rising pressure that pushes backward on the air and causes it to decelerate. While the freely flowing airstream outside the boundary layer has enough energy and forward momentum to continue onward and reach the back of the ball on its own, air in the boundary layer does not. It needs a forward push.

At low Reynolds numbers, the entire airstream helps to push that boundary layer all the way to the back of the ball and the airflow remains laminar. At high Reynolds numbers, however, viscous forces between the freely flowing airstream and the boundary layer are too weak to keep the boundary layer moving forward into the rising pressure behind the ball.

Without adequate help, the boundary layer eventually **stalls**—it comes to a stop and thereby spoils steady-state flow. More horrible still, this stalled boundary layer air is pushed backward by the adverse pressure gradient and returns all the way to the ball's sides. As it does, it cuts like a wedge between the ball and the freely flowing airstream. The result is an aerodynamic catastrophe: the airstream separates from the ball, leaving a huge turbulent wake or air pocket behind the ball (Fig. 6.2.5).

Because of this turbulent wake, air no longer bends smoothly away from the back of the ball and there is no rise in pressure there. Instead, the pressure behind the ball is roughly atmospheric. The absence of a high-pressure region behind the ball spoils the symmetry of pressure forces on the ball and those forces no longer cancel. The ball experiences an overall pressure force downwind—the force of pressure drag. In effect, the ball is transferring forward momentum to the air in its turbulent wake and dragging that wake along with it.

Pressure drag slows the flight of almost any ball moving faster than a snail's pace. The pressure drag force is roughly proportional to the cross-sectional area of the turbulent air pocket and to the square of the ball's speed through the air. For a ball moving at a moderate speed, the air pocket is about as wide as the ball and the ball experiences a large pressure drag force.

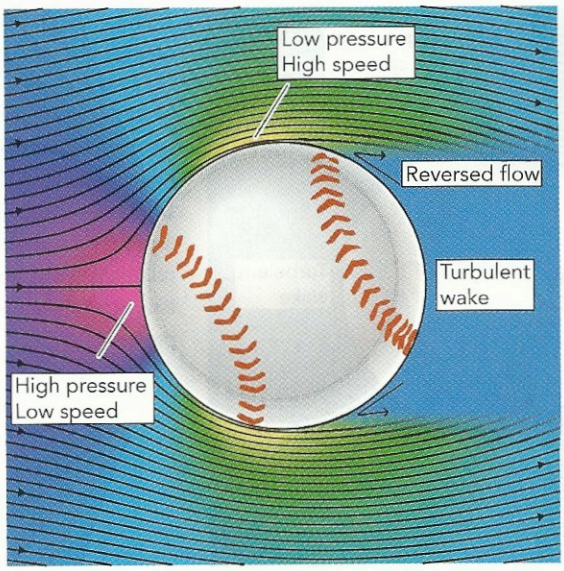


Fig. 6.2.5 When a ball's speed gives it a Reynolds number between about 2000 and 100,000, its laminar boundary layer stalls in the rising pressure behind the ball. The resulting reversed flow causes the main airflow to separate from the ball's surface, leaving a large, turbulent wake. The average pressure behind the ball remains low, and the ball experiences a large pressure drag.

Check Your Understanding #2: Leaving No Trace

When your canoe coasts extremely slowly across the water of a still lake, it leaves almost no trail in the water behind it. When you paddle it swiftly through the water, however, the canoe leaves a swirling wake. Explain this difference.

Answer: The slow-moving canoe experiences laminar flow in the water, while the fast-moving canoe experiences turbulent flow.

Why: If the canoe's speed is less than about 1 cm/s, its Reynolds number will be less than 2000 and the water flow around it will be laminar. The water will pass smoothly around the canoe's sides and join back together behind it. However, when the canoe is moving fast enough that its Reynolds number exceeds 2000, the water flow becomes turbulent and the canoe leaves a churning wake in the water behind it. This wake produces pressure drag on the canoe and extracts energy from it. Anyone who has paddled a canoe knows that overcoming this pressure drag can be exhausting.

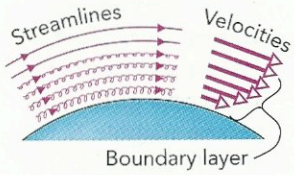


Fig. 6.2.6 When the Reynolds number exceeds about 100,000, the boundary layer of air flowing past a surface becomes turbulent. This whirling fluid brings in extra energy and momentum from the freely flowing airstream and can travel deep into a region of increasing pressure.

The Dimples on a Golf Ball

If this were the whole story, you would never hit a home run at a baseball game or a 250-yard drive on the golf course. But inertia has yet another card to play.

At very high Reynolds numbers the boundary layer itself becomes turbulent (Fig. 6.2.6). It loses its laminar streamlines and begins to mix rapidly within itself and with the freely flowing airstream nearby. This mixing brings additional energy and forward momentum into the boundary layer and makes it both harder to stop and more resistant to reversed flow. Although this turbulent boundary layer still stalls before reaching the back of the ball, the stalled air flows upstream only a short distance. Although the freely flowing

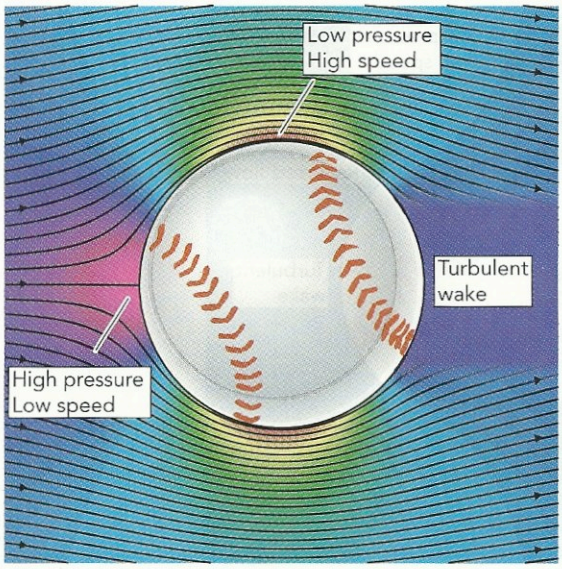
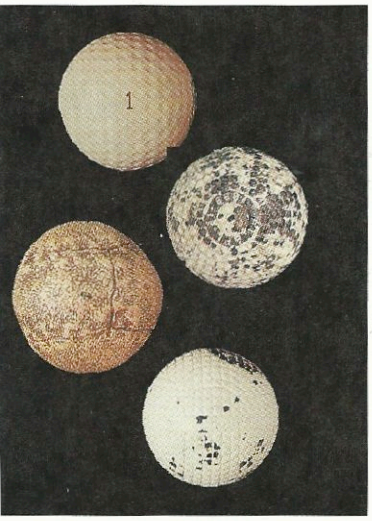


Fig. 6.2.7 When a ball travels fast enough that its Reynolds number exceeds 100,000, its boundary layer becomes turbulent. This turbulent layer travels much of the way around the back of the ball before it separates from the surface. The freely flowing air follows it, and the two leave a relatively small turbulent wake. The ball experiences only a modest pressure drag.



Courtesy Rebus, Inc.

Fig. 6.2.8 Early golf balls (*left*) were handmade of leather and stuffed with feathers. Golf became popular when cheap balls made of a hard rubber called gutta-percha became available. New, smooth "gutties" didn't travel very far, though; they flew better when they were nicked and worn. Manufacturers soon began to produce balls with various patterns of grooves on them (*bottom and right*), and those balls traveled dramatically farther than smooth ones. Modern golf balls (*top*) have dimples instead of grooves.

airstream still separates from the ball, that separation occurs far back on the ball and the resulting turbulent wake is relatively small (Fig. 6.2.7).

As a result of this smaller air pocket, the pressure drag is reduced from what it would be without the turbulent boundary layer. The effect of replacing the laminar boundary layer with a turbulent one is enormous; it's the difference between a golf drive of 70 yards and one of 250 yards! The effects of the Reynolds number on the airflow around a ball are summarized in Table 6.2.1.

Delaying the airflow separation behind the back of the ball is so important to distance and speed that the balls of many sports are designed to encourage a turbulent boundary layer (Fig. 6.2.8). Rather than waiting for the Reynolds number to exceed 100,000, the point near which the boundary layer spontaneously becomes turbulent, these balls "trip" the boundary layer deliberately (Fig. 6.2.9). They introduce some impediment to laminar flow, such as hair or surface irregularities, which causes the air near the ball's surface to tumble about and become turbulent. The drop in pressure drag more than makes up for the small increase in viscous drag, which is why a golf ball has dimples. A tennis ball's fuzz, however, creates more drag than it eliminates, so shaving a tennis ball would help it maintain its speed.

How much does drag affect balls in various sports? For those that involve rapid movements through air or water, the answer is quite a bit. Drag forces increase dramatically with speed; as soon as a turbulent wake and pressure drag appear, the drag force increases as the square of a ball's speed. As a result, baseball pitches slow significantly during their

Table 6.2.1 Effects of Reynolds Number on the Airflow around a Ball or Other Object

REYNOLDS NUMBER	BOUNDARY LAYER	TYPE OF WAKE	MAIN DRAG FORCE
<2000	Laminar	Small laminar	Viscous
2000–100,000	Laminar	Large turbulent	Pressure
$>100{,}000$	Turbulent	Small turbulent	Pressure

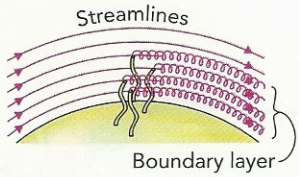


Fig. 6.2.9 The boundary layer can be made turbulent at Reynolds numbers below 100,000 by "tripping" it with obstacles such as fuzz or dimples.

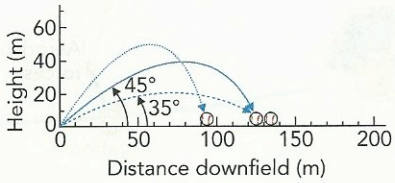


Fig. 6.2.10 Air drag slows the flight of a batted ball so that the ideal angle at which to hit it isn't the theoretical 45° of Fig. 1.2.7. An angle of roughly 35° above horizontal will achieve the maximum distance.

flights to home plate, and the faster they're thrown, the more speed they lose. A 90-mph fastball loses about 8 mph en route, while a 70-mph curveball loses only about 6 mph.

A batted ball fares slightly better because it travels fast enough for the boundary layer around it to become turbulent, an effect that appears at around 160 km/h (100 mph). While the resulting reduction in drag explains why it's possible to hit a home run, the presence of air drag still shortens the distance the ball travels by as much as 50%. Without air drag, a routine fly ball would become an out-of-the-park home run. To compensate for air drag, the angle at which the ball should be hit for maximum distance isn't the theoretical 45° above horizontal discussed in Section 1.2. Because of the ball's tendency to lose downfield velocity, it should be hit at a little lower angle, about 35° above horizontal (Fig. 6.2.10).

Since the ball loses much of its horizontal component of velocity during its trip to the outfield, a long fly ball tends to drop almost straight down as you catch it. Gravity causes it to move downward, but drag almost stops its horizontal motion away from home plate. Drag also limits the downward speed of a falling ball to about 160 km/h (100 mph). That's the baseball's **terminal velocity**, the downward velocity at which the upward drag force exactly balances its downward weight and it stops accelerating. Even dropped from a plane, its velocity won't exceed this value.

Check Your Understanding #3: Designing a Great Sports Car

As an automobile designer, your job is to minimize the aerodynamic drag experienced by the car on which you are working. Where should you try to locate the point at which the airflow separates from the car?

Answer: The point should be located as far back on the car as possible.

Why: As for all large, fast-moving objects in air, pressure drag is the main source of air resistance. You want to minimize this drag by keeping the air flowing smoothly over the car until it leaves the rear around a small turbulent wake. The smaller the air pocket behind a car, the better. Aerodynamically designed production cars leave a turbulent wake that is only about one-third as large in area as the thickest cross section of the car. Although there is still room for improvement, these cars experience far less drag than the boxy cars of earlier times.

Curveballs and Knuckleballs

The drag forces on a ball push it downstream, parallel to the onrushing air. In some cases, though, the ball may also experience lift forces—forces that are exerted perpendicular to the airflow (Fig. 6.2.1). To experience drag, the ball only has to slow the airflow

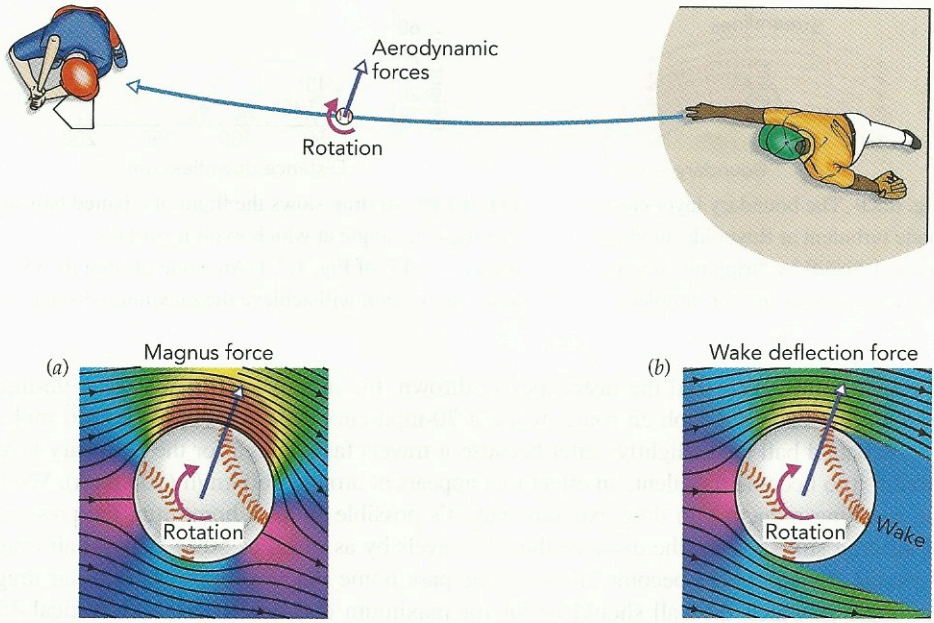


Fig. 6.2.11 A rapidly rotating baseball experiences two lift forces that cause it to curve in flight. (*a*) The Magnus force occurs because air flowing around the ball in the direction of its rotation bends mostly toward it, while air flowing opposite its rotation bends mostly away from it. (*b*) The wake deflection force occurs because air flowing around the ball in the direction of its rotation remains attached to the ball longer and the ball's wake is deflected.

down; to experience lift, the ball must deflect the airflow to one side or the other. Although its name implies an upward force, lift can also push the ball toward the side or even downward.

Curveballs and knuckleballs both use lift forces. In each of these famous baseball pitches, the ball deflects the airstream toward one side and the ball accelerates toward the other. Again we have action and reaction—the air and the ball push off one another. Getting the air to push the ball sideways is no small trick. Explaining it isn't easy either, but here we go.

A curveball is thrown by making the ball spin rapidly about an axis perpendicular to its direction of motion. The choice of this axis determines which way the ball curves. In Fig. 6.2.11, the ball is spinning clockwise, as viewed from above. With this choice of rotation axis, the ball curves to the pitcher's right because the ball experiences two lift forces to the right. One is the Magnus force, named after the German physicist H. G. Magnus (1802–1870), who discovered it. The other is a force we will call the wake deflection force.

The **Magnus force** occurs because the spinning ball carries some of the viscous air around with it (Fig. 6.2.11*a*). The steady-state flow pattern that forms around this ball is asymmetric: the airstream that moves with the turning surface is much longer than the airstream that moves opposite that surface. Since the longer airstream bends mostly toward the baseball, the average pressure on that side of the ball must be below atmospheric. The shorter airstream bends mostly away from the ball, so the average pressure on that side of the ball must be above atmospheric. Because the pressure forces on the ball's sides don't balance one another, the ball experiences the Magnus force toward the low-pressure side—the side turning toward the pitcher—and deflects in that direction. The airflow deflects in the opposite direction.

In laminar flow, the Magnus force is the only lift force acting on a spinning object. But a pitched baseball has a turbulent wake behind it and is also acted on by the **wake deflection force**. This force appears when the ball's rapid rotation deforms the wide, symmetric wake (Fig. 6.2.5) that develops behind it at high Reynolds numbers. When the ball isn't spinning, the freely flowing airstream separates from the ball approximately at its side and that separation is symmetric all the way around the ball's middle. However, when the ball is spinning (Fig. 6.2.11*b*), the moving surface pushes on the airstream with viscous forces. As a result, airstream separation is delayed on one side of the ball and hastened on the other. The overall wake of air behind the ball is thus deflected to one side and the ball experiences the wake deflection force toward the opposite side—the side turning toward the pitcher. The wake deflection force and the Magnus force both push the ball in the same direction.

Of these two forces, the wake deflection force is probably the more important for a curveball, although the Magnus force is usually given all the credit. A skillful pitcher can make a baseball curve about 0.3 m (12 in) during its flight from the mound to home plate—the more spin, the more curve. The pitcher counts on this change in direction to confuse the batter. The pitcher can also choose the *direction* of the curve by selecting the axis of the ball's rotation. The ball will always curve toward the side of the ball that is turning toward the pitcher. When thrown by a right-handed pitcher, a proper curveball curves down and to the left, a slider curves horizontally to the left, and a screwball curves down and to the right.

When the pitcher throws a ball with backspin, so that the top of the ball turns toward the pitcher, the ball experiences an upward lift force. In baseball this force isn't strong enough to overcome gravity, but it does make the pitch hang in the air unusually long and appear to "hop." Not surprisingly, a fastball thrown with strong backspin is called a hanging fastball. A fastball thrown with relatively little spin falls naturally and is called a sinking fastball. In golf, where the club can give the ball enormous backspin, the ball really does lift itself upward so that it flies down the fairway like a glider.

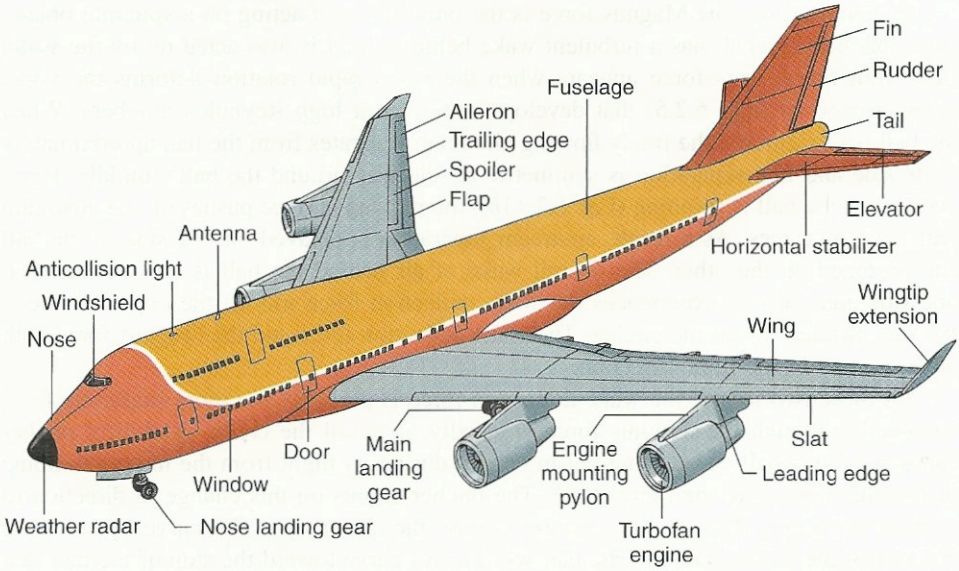
There are, however, some interesting cases when a ball's behavior stems from its *lack* of spin. In baseball, for example, a knuckleball is thrown by giving the ball almost no rotation. Its seams are then very important. As air passes over a seam, the flow is disturbed so that the ball experiences a sideways aerodynamic force: a lift force. The ball flutters about in a remarkably erratic manner. Releasing the ball without making it spin is difficult and requires great skill. Pitchers who are unable to throw a knuckleball legally sometimes resort to lubricating their fingers so that the ball slips out of their hands without spinning. Like its legal relative, this so-called spitball dithers about and is hard to hit. The same is true for a scuffed ball.

Check Your Understanding #4: **Center Court**

One of the most difficult and effective strokes in tennis is the topspin lob, in which the top of the ball spins away from the player who hit it. Which way is the lift force on this ball directed?

Answer: The lift force is directed downward, so the ball accelerates downward faster than it would by gravity alone.

Why: A ball with topspin falls faster than it would without a spin. In tennis, the topspin strokes appear to dive downward once they cross the net. Their downward curve means that they can travel very fast and still remain inside the court and are thus very hard to return.



SECTION 6.3 Airplanes

We have now set the stage for the ultimate aerodynamic machines—airplanes. Freed from contact with the ground, airplanes are affected only by aerodynamic forces and gravity, hopefully in that order. Despite their complex appearances, airplanes employ physical principles that we have already successfully examined. While this section revisits many familiar concepts, it also explores new territory. For example, you may have already figured out what type of aerodynamic force holds an airplane up, but what type of aerodynamic force keeps it moving forward?

Questions to Think About: *Why are the wings of small, propeller-driven aircraft relatively large and bowed in comparison to those of jets? Why does a commercial airplane extend slats and flaps from its wings during takeoffs and landings? What pushes airplanes forward in flight? How can some airplanes fly upside down? Why do most fast commercial aircraft employ jet engines and not propellers?*

Experiments to Do: *The best experiment for this section is to take a plane flight or at least to visit the airport and watch the planes.*

As you sit in the plane during takeoff, feel the plane accelerating forward. If you're on a commercial jet, notice that the slats and flaps on the airplane's wings are extended during takeoff, making the wings wider and more curved. How could this increased width and curvature help the plane take off? The pilot holds the plane on the ground until it reaches the proper speed, then quickly tips it upward into the air. An invisible vortex of air peels away from the trailing edge of the wing and the plane lifts off the ground.

Once airborne, the airplane retracts its landing gear, slats, and flaps. Watch the trailing edge of each wing as the plane turns or changes altitudes; you'll see various surfaces there move up or down. Similar motions occur on the tail. How do these surfaces control the plane's orientation?

Near its destination, the airplane prepares for landing. Again the slats and flaps are extended. Watch as spoilers on the tops of the wings pop up and down noisily. How do these surfaces affect the drag force on the plane? The plane's landing gear extends, and it touches down on the runway. The propellers or jet engines abruptly begin to slow the airplane, assisted by the spoilers on the wings. Feel the plane accelerating backward. Another invisible vortex of air peels away from the trailing edge of the wing, rotating in the opposite direction from the first vortex, and the flight is over.

Airplane Wings: Streamlining

By now you've probably realized that an airplane is supported in flight by an upward lift force on its wings and that this lift force comes from deflecting the passing airflow downward. Each wing is an **airfoil**, an aerodynamically engineered surface that's designed to obtain particular lift and drag forces from the air flowing past it. More specifically, each wing is shaped and oriented so that, during flight, the airstream flowing over the wing bends downward toward its top surface while the airstream under the wing bends downward away from its bottom surface. These bends are associated with pressure changes near the wing itself and are responsible for the upward lift force that suspends the airplane in the sky.

However, to get a more complete understanding of how the wing develops this lift, let's go for a flight. Imagine yourself in an airplane that has just begun rolling down the runway. From your perspective, air is beginning to flow past each of the airplane's wings. When this moving air encounters the wing's *leading edge*, it separates into two airstreams: one traveling over the wing and the other under it (Fig. 6.3.1). These airstreams continue onward until they leave the wing's *trailing edge*. Since the airplane's nose is still on the ground, the wing is essentially horizontal and the airflow around it is simple and symmetric.

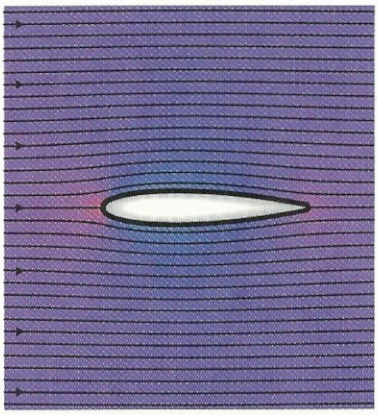


Fig. 6.3.1 An airplane wing is a streamlined airfoil and the airflow around it is laminar. This horizontal wing is symmetric, top and bottom, and the airflow splits evenly into airstreams above and below it. Since it doesn't deflect the airflow, it experiences no lift.

Since the wing isn't deflecting the airflow yet, it's experiencing no lift, only drag. But while this drag pushes the airplane downwind and thus opposite its forward motion along the runway, it's unusually weak. The wing produces almost no turbulent wake and thus experiences almost no pressure drag. What little drag it does experience is mostly viscous drag, essentially surface friction with the passing air.

Although the wing's near lack of air resistance should surprise you, you probably take it for granted. That's because you've often observed that such "streamlined" objects cut through the air particularly well. Having a long, tapered tail allows the wing to avoid the flow separation and turbulent wake that occur behind an unstreamlined ball.

What makes the horizontal wing **streamlined** is the extremely gradual rise in air pressure after its widest point. While this gently rising pressure pushes the wing's boundary layer backward, opposite the direction of flow, the force it exerts is so weak that the layer doesn't stall. Driven onward by viscous forces from the freely flowing airstream, the wing's boundary layer manages to keep moving forward all the way to the wing's trailing edge and never triggers flow separation. The wing produces almost no turbulent wake and experiences almost no pressure drag.

Check Your Understanding #1: Slicing through the Air

The fastest bicycles are those with fairings—streamlined shells that reduce air resistance dramatically. How do those fairings work?

Answer: A fairing delays airstream separation in the airflow around a bicycle and thereby reduces pressure drag.

Why: Without a fairing, a bicycle racer must struggle against severe pressure drag. The sharply rising pressure gradients that follow wide parts of his body trigger flow separation and he develops a huge turbulent wake. A fairing makes the vehicle streamlined: the gently rising pressure gradient following its widest part doesn't trigger flow separation.

Airplane Wings: Producing Lift

With so little air resistance, the airplane accelerates forward rapidly and soon reaches takeoff speed. The pilot then raises the airplane's nose so that its wings are no longer horizontal and they begin to experience upward lift forces. The airplane's total lift soon exceeds its weight and it begins to accelerate upward into the air. The airplane is flying!

Let's take a closer look at the moment of takeoff. If you could see the airflow and were paying close attention, you'd notice a remarkable sequence of events that begins when the wings tilt upward.

At first, the airflow around the tilted wings continues to travel horizontally on average, although it develops a peculiar shape (Fig. 6.3.2*a*). The two airstreams, one over the tilted wing and one under it, each bend twice—once up and once down. As we saw while studying balls, when an airstream bends toward the wing, the pressure near the wing is below atmospheric and when an airstream bends away from the wing, the pressure near the wing is above atmospheric. Since each airstream bends equally toward and away from the wing, it experiences no overall deflection or average pressure change and provides the wing with no overall lift.

The lower airstream, however, is making a sharp bend around the wing's trailing edge, essentially an upward kink. Air's inertia makes such a kink unstable and it soon blows away from the wing's trailing edge as a swirling horizontal vortex of air (Fig. 6.3.2*b*). After shedding that vortex, the wing establishes a new, stable flow pattern in which both airstreams pass smoothly away from the wing's trailing edge (Fig. 6.3.2*c*), a situation named the *Kutta condition* after the German mathematician M. Wilhelm Kutta (1867–1944).

In this new pattern, the airstream flowing over the wing is longer than the airstream flowing under it and both bend downward (Fig. 6.3.3). The upper airstream bends primarily toward the wing, so the air's pressure just above the wing is below atmospheric

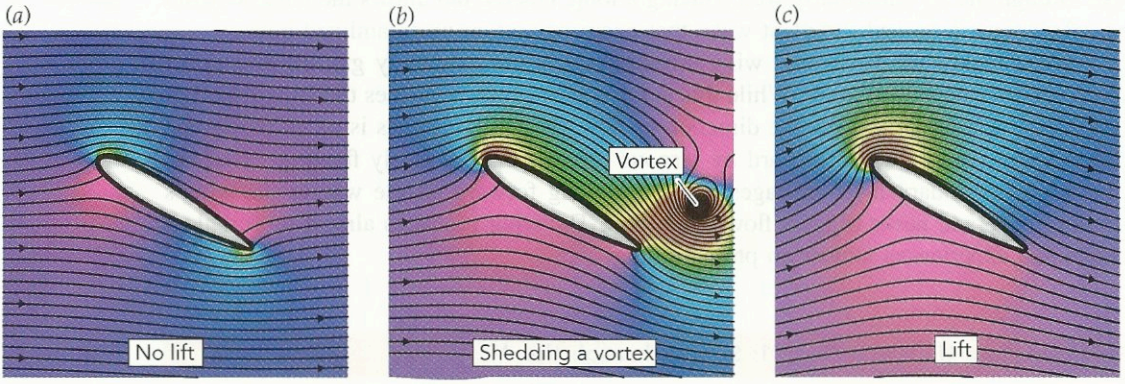
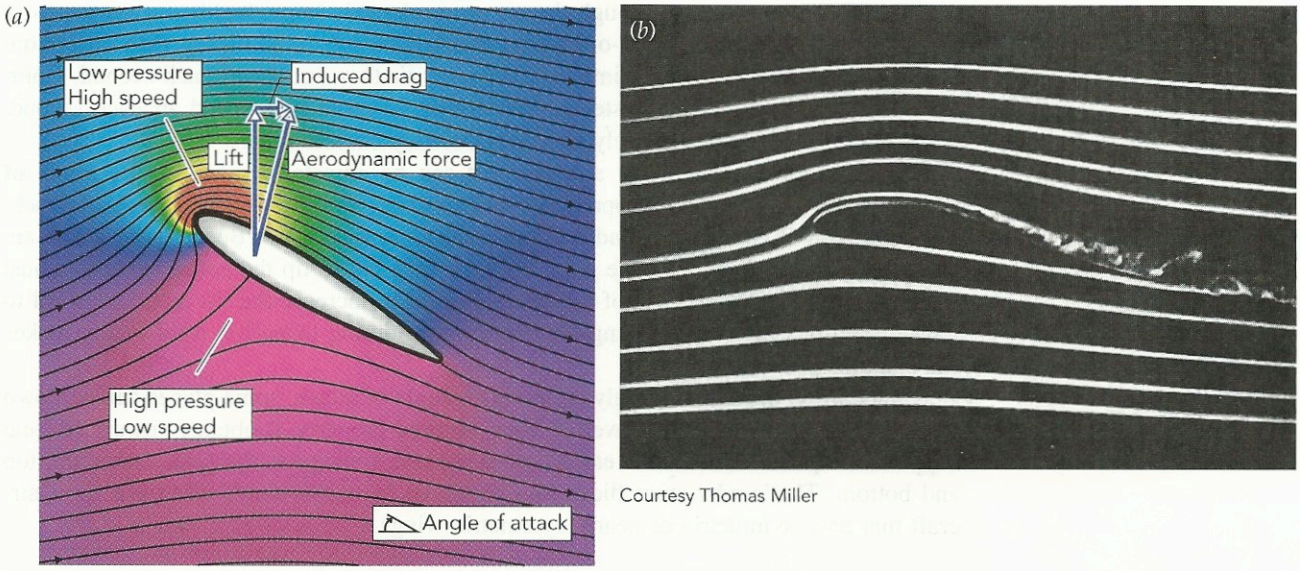


Fig. 6.3.2 (*a*) Although this wing's leading edge has been tipped upward, giving it a positive angle of attack, the airflow around it is relatively symmetric and produces no lift. (*b*) The kink at the trailing edge of the wing is unstable and is blown away or *shed* as a horizontal vortex. (*c*) The resulting airflow is deflected downward and the wing experiences an upward lift force.



Courtesy Thomas Miller

Fig. 6.3.3 (*a*) This airplane wing is shaped and oriented so that both airstreams, over it and under it, bend downward. The wing experiences a large aerodynamic force that points upward and slightly downstream. The upward component of this force is lift. The downstream component is induced drag. (*b*) Smoke trails in a wind tunnel show the airflow past a wing.

(a shift toward red) and its speed is increased (narrowly spaced streamlines). In contrast, the lower airstream bends primarily away from the wing, so the air's pressure just below the wing is above atmospheric (a shift toward violet) and its speed is decreased (widely spaced streamlines). The air pressure is now higher under the wing than over it, so this new flow pattern produces upward lift. The air now supports your plane and up you go.

Another way to think about this lift is as a deflection of the airflow. Air approaches the wing horizontally but leaves heading somewhat downward. To cause this deflection, the wing must push the airflow downward. In reaction, the airflow pushes the wing upward and produces lift. In other words, the wing transfers downward momentum to the air and is left with upward momentum as a result. These two explanations for lift—the Bernoullian view that lift is caused by a pressure difference above and below the wing and the Newtonian view that lift is caused by a transfer of momentum to the air—are perfectly equivalent and equally valid.

However, the overall aerodynamic force on the wing isn't quite perpendicular to the onrushing air; it tilts slightly downwind. The perpendicular component of this aerodynamic force is lift, but the downwind component is a new type of drag force—induced drag. **Induced drag** is a consequence of energy conservation: in addition to transferring momentum to the passing air, the wing also transfers some energy to it. The air extracts that energy from the wing by pushing the wing downwind with induced drag and thereby doing negative work on it. Since induced drag is undesirable, the airplane minimizes it by using as much air mass as possible to obtain its lift. A larger mass of air carries away the airplane's unwanted downward momentum while moving downward less quickly and with less kinetic energy. Since larger wings obtain their lift from larger air masses, they experience less induced drag.

Unfortunately, larger wings also have more surface area and experience more viscous drag, so bigger isn't always better. Also, because wing shape and airspeed affect aerodynamic forces, too, wings must be carefully matched to their airplanes. Small propeller

airplanes that move slowly through the air need relatively large, highly curved wings to support them. Those wings are often asymmetric—more curved on top than on bottom to make maximum use of the limited, low-speed air they encounter each second. Commercial and military jets fly faster and encounter far more high-speed air each second, so they can get by with relatively small, moderately curved wings.

Even at constant airspeed, a wing's lift can be adjusted by varying its **angle of attack**—the angle at which it approaches the onrushing air. The larger the angle of attack, the more the two airstreams bend and the greater the wing's lift. Because the wings are rigidly attached to the plane, the pilot has no choice but to tip the entire plane to adjust its lift. The pilot tips the nose of the plane upward to increase the lift and downward to reduce the lift. That's why raising the plane's nose during takeoff is what finally makes the plane leap up into the air.

Since lift depends so strongly on a wing's angle of attack, some planes can be flown upside down. As long as the inverted wing is tilted properly, it obtains upward lift and supports the plane. This feat is easiest when a plane's wing has the same curvature, top and bottom. That's why stunt fliers who regularly fly upside down often use sport aircraft that have symmetric or nearly symmetric wings.

Check Your Understanding #2: **Blowing in the Wind**

The sail of a small sailboat bows forward and outward so that wind traveling around the sail's outside surface bends toward the sail, while wind traveling across its inside surface bends away from the sail. How does this arrangement propel the sailboat across the water?

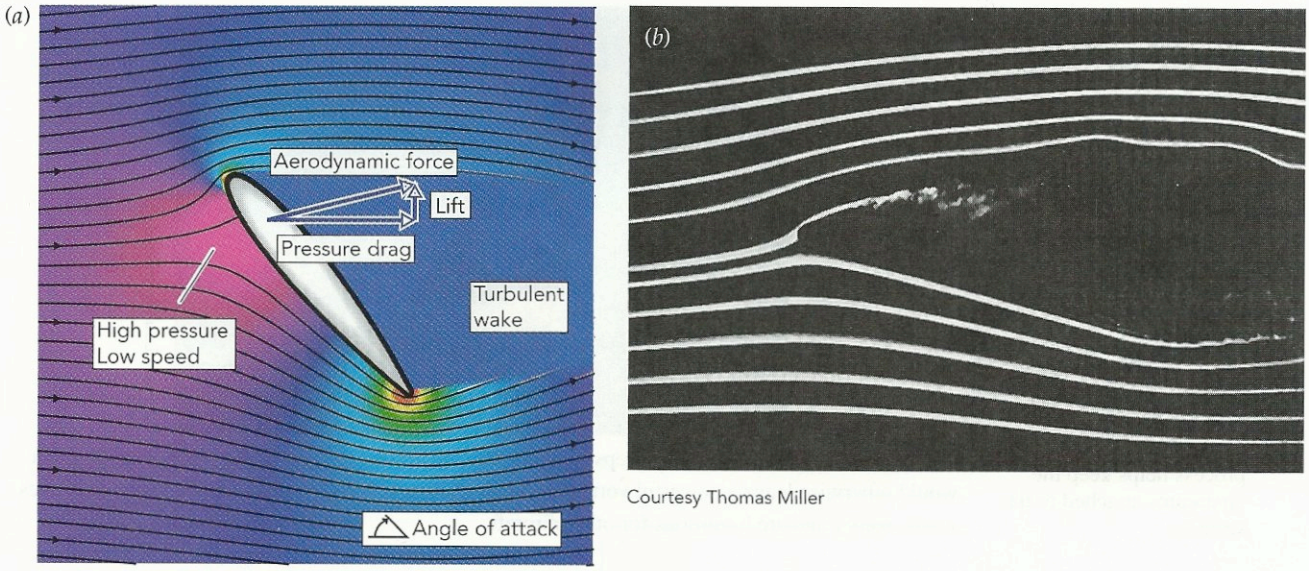
Answer: The air traveling around the outside of the sail has a lower pressure than that traveling across the inside of the sail. The sail experiences a lift force that pushes it and the boat across the water.

Why: Sails experience both lift and drag forces. The sail experiences an aerodynamic force that pushes it outward (lift) and slightly downwind (drag) just as an airplane wing experiences an aerodynamic force upward (lift) and slightly downwind (drag). The sailboat's keel, or centerboard, and its rudder provide additional forces so that the net force on the sailboat can be controlled and it can travel in a variety of directions.

Lift Has Its Limits: Stalling a Wing

There's a limit to how much lift the pilot can obtain by increasing the wing's angle of attack because tilting the wing gradually transforms it from streamlined to **blunt**—that is, to having a rapid rise in air pressure after its widest point. As we saw for balls, blunt objects generally experience airflow separation and pressure drag. Indeed, beyond a certain angle of attack, the airstream over the top of a wing separates from its surface and the wing stalls. This separation starts when air in the upper boundary layer is brought to a standstill by the rapidly rising pressure beyond the wing's widest point. Once this boundary layer stalls, it shaves most of the airstream away from the wing's upper surface.

The separated airstream over the top of the stalled wing leaves a billowing storm of turbulence beneath it (Fig. 6.3.4). This airstream separation is an aerodynamic catastrophe for the airplane. Because the average pressure above the wing increases, the wing loses much of its lift. Also, the appearance of a turbulent wake heralds the arrival of severe pressure drag. The plane slows dramatically and drops like a rock.



Courtesy Thomas Miller

Fig. 6.3.4 (*a*) A wing stalls when the airstream over the top of the wing separates from its surface. A turbulent air pocket forms above the wing, making it much less efficient. The wing's lift decreases because the average pressure above the thickest part of the wing becomes higher, and the drag increases because the average pressure above the trailing edge becomes lower. (*b*) Smoke trails in a wind tunnel show that the air separates from the surface and becomes turbulent as it flows over a stalled wing.

To avoid stalling, pilots keep the angle of attack within a safe range. The possibility of stalling also limits the minimum speed at which the airplane will fly. As the airplane slows down, the pilot must increase its angle of attack to maintain adequate lift. Below a certain speed, the airplane can't obtain that lift without tilting its wings until they stall. It can no longer fly.

To avoid stalling, a plane must never fly slower than this minimum speed, particularly during landings and takeoffs. For a small, propeller-driven plane with highly curved wings, the minimum flight speed is so low that it's rarely an issue. For a commercial jet, however, the minimum airspeed is about 220 km/h (140 mph). Airplanes taking off or landing this fast would require very long runways on which to build up or get rid of speed. Instead, commercial jets have wings that can change shape during flight. Slats move forward and down from the leading edges of the wings, and flaps move back and down from the trailing edges (Fig. 6.3.5). With both slats and flaps extended, the wing becomes larger and more strongly curved, similar to the wings of a small propeller plane, and the minimum safe airspeed drops to a reasonable 150 km/h (95 mph). Vanes near the flaps also emerge during landings to direct high-energy air from beneath the wings onto the flaps. These jets of air keep the boundary layers moving downstream and help prevent stalling. (For another approach to stall prevention, see ■).

Once a commercial jet lands, flat panels on the top surfaces of its wings are tilted upward and cause the airflow to separate from the tops of the wings. The resulting turbulence created by these spoilers reduces the lift of the wings and increases their drag, so that the plane doesn't accidentally start flying again. Even before landing, the spoilers are sometimes used to slow the plane and help it descend rapidly toward an airport.

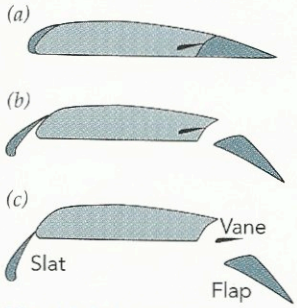


Fig. 6.3.5 At cruising speed, an airplane's wings are moderately curved airfoils (*a*). During takeoffs (*b*) and landings (*c*), slats are extended from the leading edges and flaps from the trailing edges. The airfoils become much more highly curved, generating more lift at low speeds. During landing, a vane is also extended for boundary layer control to prevent stalling.

■ Airplane designers can reduce the dangers of stalling by adding special boundary layer control devices to their aircraft. Narrow metal strips called *vortex generators*, which stick up from the surfaces of wings, introduce turbulence into the boundary layers over the wings. This turbulent flow allows higher energy air to mix with the boundary layers so that they can continue forward into rising pressure. This process helps keep the airstreams attached to the surfaces.

Courtesy Lou Bloomfield

Fig. 6.3.6 This vertical wingtip keeps air from flowing around the end of the wing, a motion that would otherwise leave a powerful vortex in the air trailing behind the plane. Such wingtip vortices waste energy and are hazardous for other aircraft.

In flight, a wing does more than just push the passing air downward; it also twists the air near its tip. Since the air pressure below the wing is greater than the air pressure above it, air tends to flow around the wing's tip from bottom to top. The plane soon leaves this air behind, but not before the air has acquired lots of angular momentum and kinetic energy.

A swirling vortex thus emerges from each wingtip and trails behind the plane for several kilometers, like an invisible tornado. You can occasionally see them behind a plane that's landing or taking off in humid air. A wingtip vortex from a jumbo jet can flip over a small aircraft that flies through it or give passengers in a much larger plane an unexpected thrill. Entered from behind, one of these vortices feels like a horizontal blender; from the side, it feels like a speed hump that you might drive over in a car.

For safety, air traffic controllers are careful to keep planes from flying through one another's wakes and schedule them at least 90 seconds apart on runways. Many modern airplanes have vertical wingtip extensions that reduce these vortices, both to save energy and to diminish the hazard (Fig. 6.3.6).

Check Your Understanding #3: **Stunt Flying**

A pilot normally tips the plane's nose upward in order to gain altitude. If the pilot tries to make the plane rise too quickly, the plane will suddenly begin to drop. What is happening?

Answer: The plane's wings are stalling.

Why: Tipping the plane's nose upward increases the wings' angle of attack. While this action increases lift up to a point, it can also cause the airflow to separate from the top surface of the wing. The sudden reduction in lift and increase in drag that accompany stalling can cause the plane to drop. A stall during takeoff or landing is extremely dangerous.

Propellers

For a plane to obtain lift, it needs airspeed; air must flow across its wings. And since drag forces push it downwind, a plane in level flight can't maintain its airspeed unless something pushes it upwind. That's why a plane has propellers or jet engines: to push the air backward so that the air pushes the plane forward, action and reaction.

A propeller is an assembly of rotating wings. Extending from its central hub are two or more blades that together form a sophisticated fan (Fig. 6.3.7). These blades have airfoil cross sections and are designed to create forward lift forces when the propeller turns and the blades move through the air.

As a propeller blade slices through the air, the airstreams bending around that blade experience pressure variations (Fig. 6.3.8). The forward airstream bends toward the blade's front surface, so the pressure in front of the blade drops below atmospheric. The rearward airstream bends away from the blade's rear surface, so the pressure behind the blade rises above atmospheric. The resulting pressure difference exerts a forward lift or *thrust* force on the propeller.

The propeller blades have all the features, good and bad, of airplane wings. Their thrust increases with size, front-surface curvature, *pitch* (i.e., angle of attack), and airspeed; in other words, the larger the propeller, the faster it turns, and the more its blades are angled into the wind, the more thrust it produces. The blades themselves have a twisted shape to accommodate the variations in airspeed along their lengths, from hub to tip.

Like a wing, a propeller stalls when the airflow separates from the front surfaces of its blades; it suddenly becomes more of an air mixer than a propeller. This stalled-wing behavior was the standard operating condition for air and marine propellers (see ■) before the work of Wilbur Wright in 1902 (see ■). The Wrights were among the first people to study aerodynamics with a wind tunnel (Fig. 6.3.9), and their methodical and scientific approach to aeronautics allowed them to achieve the first powered flight (Fig. 6.3.10). Since the Wrights' work, propellers have experienced almost no pressure drag.

A propeller does, however, experience induced drag. As the propeller's thrust pushes the plane through the air, induced drag extracts energy from the propeller. To keep the propeller turning steadily, an engine must do work on the propeller. Propellers are driven by high-performance reciprocating (piston-based) engines, like those found in automobiles, or the turbojet engines that we'll discuss later.

Propellers aren't perfect; they have three serious limitations. First, a propeller exerts a torque on the passing air, so that air exerts a torque on the propeller. This reaction

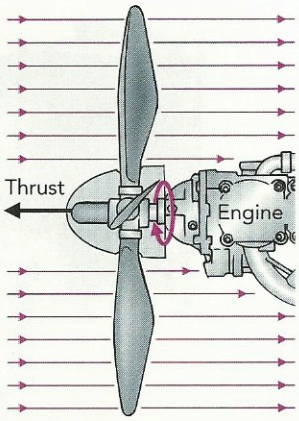


Fig. 6.3.7 A propeller behaves like a rotating wing. As the propeller turns, its blades create lift in the forward direction. This lift pushes the engine and the aircraft forward through the air, so that it's called thrust.

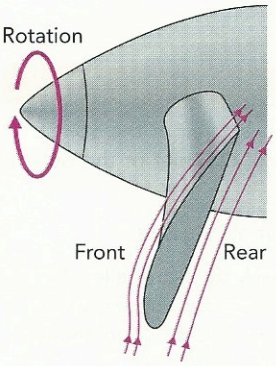


Fig. 6.3.8 As the propeller blade rotates, the flow of air around it creates a low pressure in front of it (left) and a high pressure behind it (right). The blade experiences a lift force that pushes the propeller and plane forward (toward the left). Induced drag tends to slow the rotation of the propeller.

■ One of the principal sources of noise in submarines is the turbulence created by their propellers. To reduce this turbulence, the propellers of modern nuclear submarines are designed to avoid water flow separation and stalling.

■ In addition to achieving the first self-propelled flight of an airplane in 1903, Orville (1871–1948) and Wilbur (1867–1912) Wright (American aviators) were exceptionally accomplished aerodynamicists. In 1902, Wilbur was the first person to recognize that a propeller is actually a rotating wing. Propellers up until his time were little more than rotating paddles, more effective at stirring the air than propelling the plane. Wilbur's aerodynamically redesigned propeller made flight possible and dominated aircraft design for a decade.

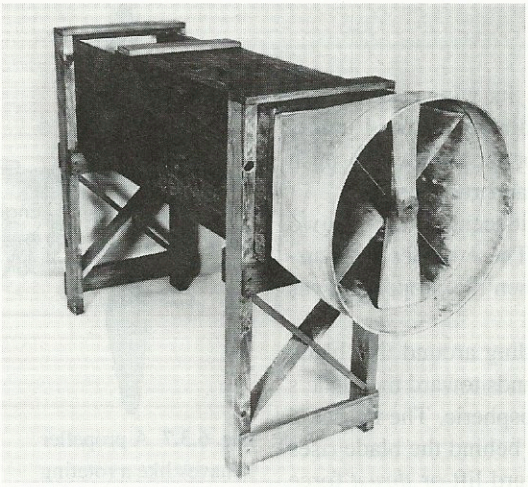


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Fig. 6.3.9 The Wright brothers were accomplished aerodynamicists, using this wind tunnel to study and perfect wings and propellers for their airplanes.

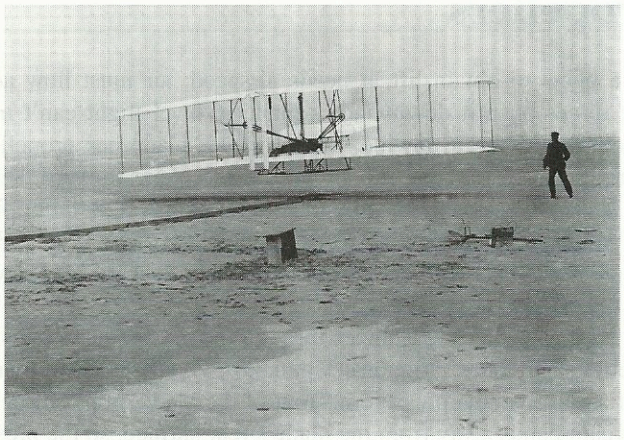

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Fig. 6.3.10 The era of powered flight began at 10:35 A.M. on Dec. 17, 1903, when the Wright Flyer lifted Orville Wright into the air over Kitty Hawk, North Carolina. His brother Wilbur stands beside him in this unique photograph of that first powered flight.

torque can flip a small plane. To minimize torque problems, some planes use pairs of oppositely turning propellers, and single-propeller planes usually locate their propellers in front, so that the spinning air can return angular momentum to them while passing over their wings.

A second problem with a propeller is that its thrust diminishes as the plane's forward speed increases. When the airplane is stationary, a propeller blade moves through motionless air (Fig. 6.3.11*a*). When the airplane is traveling fast, though, the air approaches that same propeller blade from the front of the plane (Fig. 6.3.11*b*). To retain its thrust at higher airspeeds, the propeller blade must increase its pitch—that is, its angle of attack. It must swivel forward to meet the onrushing air.

The third and most discouraging problem with propellers, especially in high-speed aircraft, is drag. To keep up with the onrushing air at high airspeeds, the propellers must turn at phenomenal rates. The tips of the blades must travel so fast that they exceed the **speed of sound**—the fastest speed at which a fluid such as air can convey forces from one place to another. When the blade tip exceeds this speed, the air near the tip doesn't accelerate until the tip actually hits it. Instead of flowing smoothly around the tip, the air forms a **shock wave**—a narrow region of high pressure and temperature caused by the supersonic impact—and the propeller stalls. That's why propellers aren't useful on high-speed aircraft.

Check Your Understanding #4: Circulating the Air

The only difference between a fan and a propeller is what moves—the air or the object. Which side of each fan blade experiences the lowest air pressure, the inlet or the outlet side?

Answer: The inlet side of each fan blade experiences the lowest air pressure.

Why: Air blowing toward you from a fan is like the air blown back by a propeller. The lowest pressures experienced by a propeller are on its forward surfaces. Similarly, the lowest pressures experienced by a fan are on its inlet side surfaces. This pressure imbalance pushes the fan away from you while the fan pushes the air toward you.

Jet Engines

Unlike propellers, jet engines work well at high speeds. While a propeller tries to operate directly in the high-speed air approaching the plane, a jet engine first slows this air down to a manageable speed. To achieve this change in speeds, the jet engine makes wonderful use of Bernoulli's equation.

A turbojet engine is depicted in Fig. 6.3.12. During flight, air rushes into the engine's inlet duct or *diffuser* at about 800 km/h (500 mph), the speed of the plane. Once inside that diffuser, the air slows down and its pressure increases, but its total energy is unchanged. The air then passes through a series of fanlike compressor blades that push it deeper into the engine, doing work on it and increasing both its pressure and its total energy. By the time the air arrives at the combustion chamber, its pressure is many times atmospheric.

Now fuel is added to the air and the mixture is ignited. Since hot air is less dense than cold air, the hot exhaust gas takes up more space than it did before combustion. Furthermore, combustion subdivides the fuel molecules into smaller pieces that therefore take up still more volume. This hot exhaust gas pours out of the combustion chamber, traveling faster than when it entered.

The pressure of the exhaust gas is still very high as it streams through a windmill-like turbine. The air does work on that turbine and thereby spins the compressor for the incoming air. After the turbine, the high-pressure gas finally accelerates through the engine's outlet nozzle and emerges into the open sky at atmospheric pressure and extraordinarily high speed.

Overall, the engine slows the air down, adds energy to it, and then lets it accelerate back to high speed. Because the engine has added energy to the air, the air leaves the engine traveling faster than when it arrived. The air's increased backward velocity means that the jet engine has pushed it backward and the air has reacted by exerting a forward thrust force on the jet engine. In other words, the airplane has obtained forward momentum by giving the departing air backward momentum.

The turbojet is less energy efficient than it could be. Since it gives backward momentum to a relatively small mass of air, that air ends up traveling overly fast and

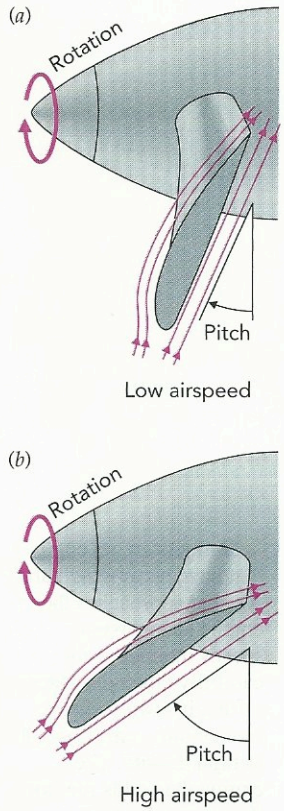

Fig. 6.3.11 At low airspeeds (*a*), the propeller blade approaches nearly stationary air as it rotates. At high airspeeds (*b*), air rushes past the propeller, so the blade must swivel forward to meet it. The blade's angle of attack is called its pitch.

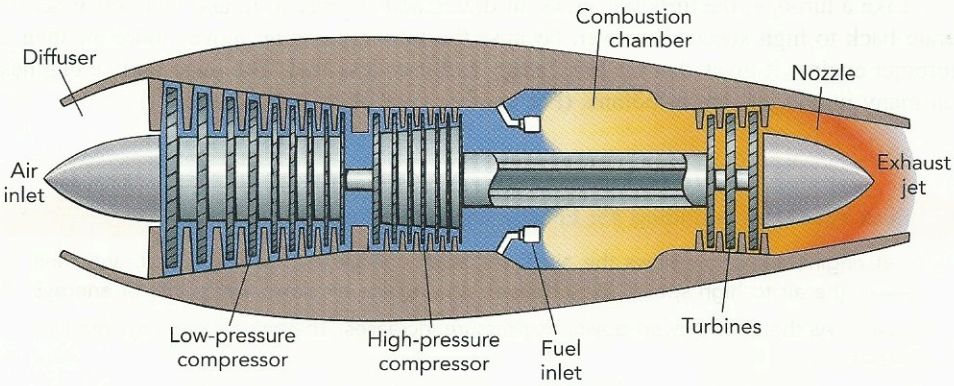

Fig. 6.3.12 The turbojet engine operates by compressing incoming air with a series of fanlike blades. Fuel is mixed with the high-pressure air and the mixture is ignited. The high-energy, high-pressure air accelerates out the rear of the jet, does work on the turbines, and leaves at a greater speed than it had when it arrived. The engine has accelerated the air backward and experiences a thrust forward.

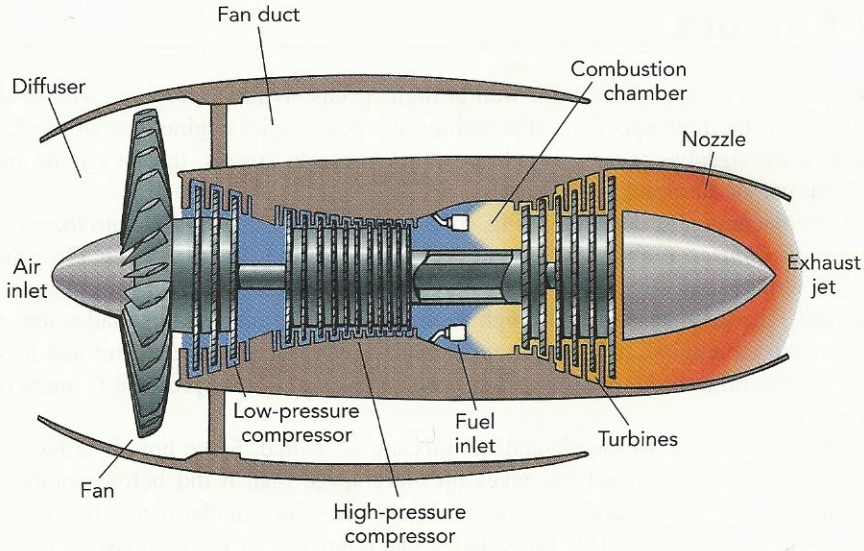

Fig. 6.3.13 The turbofan engine adds a giant fan to the shaft of a normal turbojet engine. Most of the air passing through the fan bypasses the turbojet and returns directly to the airstream around the engine. Because the fan does work on this air, it leaves the engine at a higher speed than it had when it arrived. The air has transferred forward momentum to the engine and the plane.

Ramjets are jet engines that have no moving parts. Air that approaches the engine at supersonic speeds interacts with carefully tapered surfaces so that its own forward momentum compresses it to high density. The engine then adds fuel to this pressurized air, ignites the mixture, and allows the hot burned gas to expand out of a nozzle. The engine pushes this exhaust backward, and the exhaust propels the engine and airplane forward. Although the air enters the engine at supersonic speeds, it passes through the combustion chamber much more slowly. In a supersonic combustion ramjet or "scramjet," the fuel and air mixture flows through the combustion chamber at supersonic speeds. This motion makes it extremely difficult to keep the fuel burning because the flame tends to flow downstream and out of the engine. The flame can't advance through the mixture faster than the speed of sound, so it won't spread upstream fast enough to stay in the engine on its own.

with excessive kinetic energy. To make the engine more efficient, it should give backward momentum to a larger mass of air.

The turbofan engine solves this problem by using a turbojet engine to spin a huge fan (Fig. 6.3.13). Since this fan is located in the engine's inlet duct, the air's speed decreases and its pressure increases before it enters the fan. The fan then does work on the air and further increases its pressure. While about 5% of this air then enters the turbojet engine, the vast majority of it accelerates out the back of the fan duct and emerges into the open sky at atmospheric pressure and increased speed. Overall, the fan has pushed the air backward and the air has pushed the fan forward, producing forward thrust.

Like a turbojet, the turbofan slows air down, adds energy to it, and then lets it accelerate back to high speed. However, because the turbofan engine moves more air than a turbojet engine, it gives that air less energy and uses less fuel. The huge fanlike engines on many jumbo jets are turbofans. (For another type of jet engine, see .)

Check Your Understanding #5: Energy and a Jet Engine

A jet engine somehow slows the air down, adds energy to it at low speed, and then returns the air to high speed. Why doesn't slowing the air down waste lots of energy?

Answer: As the air is slowed down, its pressure increases. The air's total energy remains constant.

Why: The remarkable result of Bernoulli's effect is that you can slow the air down without squandering its kinetic energy. That energy becomes pressure potential energy, and it passes through the jet engine in that form. As the air leaves the jet engine, its pressure potential energy becomes kinetic energy once again, so that no energy is wasted.

Epilogue for Chapter 6

In this chapter, we looked at a number of objects that use moving fluids to perform their tasks. In *garden watering*, we saw how water moves through openings and channels. We looked at the effects of viscosity and the importance of Bernoulli's equation in describing the conversion of pressure potential energy into kinetic energy and vice versa. Two types of fluid flow appeared—laminar and turbulent. While laminar flow is smooth and predictable, we saw that turbulent flow involves unpredictability and chaos, a common behavior in our complicated universe.

In the section on *balls and air*, we examined the ways in which moving air exerts forces on larger objects, both in the downstream direction as drag and in a perpendicular direction as lift. We learned about two different types of drag forces and how these can be controlled or reduced by choosing the shapes or motions of the balls.

Finally, in *airplanes*, we explored the aerodynamics of those remarkable machines. We saw how they use air to support and propel themselves. We also examined the limitations of wings and saw what can go wrong if those limitations are exceeded. We studied propulsion in propeller planes and in jet aircraft and saw that these systems involve Bernoulli's equation and the forward force that comes from pushing air backward.

Explanation: A Vortex Cannon

The vortex cannon creates ring vortices—tiny tornadoes that are bent into loops so that they have no beginnings or ends. Air swirls forward in the middle of each ring and backward on its outer edge. This circular tornado structure is created when air flows through the hole of the vortex cannon. Air flows forward in the middle of the hole, while the hole's edges create the backward flow around the outside of the ring. After it leaves the cannon, each ring vortex crawls forward through the surrounding air until its kinetic energy has been exhausted and it slows to a stop. It finishes its existence swirling in place until viscous forces bring its moving air to rest.

Chapter Summary

How Garden Watering Works: As water flows through a hose, viscous forces in the hose limit its speed, particularly near the walls of the hose. Each time the hose bends, the water pressure rises on the outside of the bend and drops on the inside of the bend. When the water reaches the nozzle, it accelerates through the narrow opening, increasing in speed and decreasing in pressure until it emerges at atmospheric pressure and arcs gracefully into the garden. Whenever the water flows rapidly around obstacles, both in the garden and at the faucet leading the hose, the flow becomes turbulent and noisy.

How Balls and Air Work: A ball traveling through the air experiences two major types of aerodynamic force—drag and lift. For a nonspinning ball traveling very slowly, the only drag force is viscous drag; it experiences no lift force. As the ball's speed through the air increases, a large turbulent wake appears behind the ball and the ball experiences

pressure drag. At a still higher speed, the boundary layer of air near the ball's surface becomes turbulent and the size of the wake behind the ball shrinks. A ball with a turbulent boundary layer experiences less drag than one with a laminar boundary layer, which is why balls are designed to encourage turbulent boundary layers.

Rotating balls experience lift forces. These forces occur because bending and deflecting airstreams push asymmetrically on these balls. Lift forces can cause a ball to curve in flight or take surprisingly long to fall.

How Airplanes Work: An airplane is supported in flight by air passing across its wings. Air bending toward the top surface of a wing experiences a drop in pressure, while air bending away from the bottom surface of a wing experiences a rise in pressure. As a result of this pressure difference, the wing experiences an upward lift force. The airplane also experiences drag, which tends to slow it down. To keep the airplane moving forward, the plane employs propellers or jet engines. These devices push the air backward and the air reacts by pushing them forward. A propeller works directly in the oncoming air, increasing the air's energy and pushing it backward with rotating blades. A jet engine first slows the air, then increases its energy by burning fuel in it, and finally lets it accelerate backward to high speed.

Important Laws and Equations

1. Poiseuille's Law: The volume of fluid flowing through a pipe each second is equal to ($\pi/128$) times the pressure difference across that pipe times the pipe's diameter to the fourth power, divided by the pipe's length times the fluid's viscosity, or

$$\text{volume} = \frac{\pi \cdot \text{pressure difference} \cdot \text{pipe diameter}^4}{128 \cdot \text{pipe length} \cdot \text{fluid viscosity}} \quad (6.1.1)$$

2. Bends and Pressure Imbalances: When the path of a fluid in steady-state flow bends, the pressure on the outside of the bend is always higher than the pressure on the inside of the bend.

3. Reynolds Number: A measure of the relative importances of inertia and viscosity in the fluid flow around an obstacle is given by the Reynolds number:

$$\frac{\text{density} \cdot \text{obstacle length} \cdot \text{flow speed}}{\text{viscosity}}. \quad (6.1.2)$$

Exercises

1. A favorite college prank involves simultaneously flushing several toilets while someone is in the shower. The cold water pressure to the shower drops and the shower becomes very hot. Why does the cold water pressure suddenly drop?

2. On hot days in the city, people sometimes open up fire hydrants and play in the water. Why does this activity reduce the water pressure in nearby hydrants?

3. Why does a relatively modest narrowing of the coronary arteries, the blood vessels supplying blood to the heart, cause a dramatic drop in the amount of blood flowing through them?

4. Why does hot maple syrup pour more easily than cold maple syrup?

5. Why is "molasses in January" slower than "molasses in July," at least in the northern hemisphere?

6. Why is it so difficult to squeeze ketchup through a very small hole in its packet?

7. A baker is decorating a cake by squeezing frosting out of a sealed paper cone with the tip cut off. If the baker makes the hole at the tip of the cone too small, it's extremely difficult to get any frosting to flow out of it. Why?

8. Why is the wind stronger several meters above a flat field than it is just above the ground?

9. Pedestrians on the surface of a windswept bridge don't feel the full intensity of the wind because the air is moving relatively slowly near the bridge's surface. Explain this effect in terms of a boundary layer.

10. An electric valve controls the water for the lawn sprinklers in your backyard. Why do the pipes in your home shake whenever this valve suddenly stops the water but not when the valve suddenly starts the water?

11. If you drop a full can of applesauce and it strikes a cement floor squarely with its flat bottom, what happens to the pressures at the top and bottom of the can?

12. When you mix milk or sugar into your coffee, you should move the spoon quickly enough to produce turbulent flow around the spoon. Why does this turbulence aid mixing?

13. If you start two identical paper boats from the same point, you can make them follow the same path down a quiet stream. Why can't you do the same on a brook that contains eddies and vortices?

14. When you swing a stick slowly through the air, it's silent, but when you swing it quickly, you hear a "whoosh" sound. What behavior of the air is creating that noise?

15. If you try to fill a bucket by holding it in a waterfall, you will find the bucket pushed downward with enormous force. How does the falling water exert such a huge downward force on the bucket?

16. You sometimes see paper pressed tightly against the front of a moving car. What holds the paper in place?

17. Fish often swim just upstream or downstream from the posts supporting a bridge. How does the water's speed in these regions compare with its speed in the open stream and at the sides of the posts?

18. Why do flyswatters have many holes in them?

19. You have two golf balls that differ only in their surfaces. One has dimples on it while the other is smooth. If you drop these two balls simultaneously from a tall tower, which one will hit the ground first?

20. If you ride your bicycle directly behind a large truck, you will find that you don't have to pedal very hard to keep moving forward. Why?

21. How does running directly behind another runner reduce the wind resistance you experience?

22. When a car is stopped, its flexible radio antenna points straight up. But when the car is moving rapidly down a highway, the antenna arcs toward the rear of the car. What force is bending the antenna?

23. To drive along a level road at constant velocity, your car's engine must be running and friction from the ground must be pushing your car forward. Since the net force on an object at constant velocity is zero, why do you need this forward force from the ground?

24. Racing bicycles often have smooth, disk-shaped covers over the spokes of their wheels. Why would these thin wire spokes be a problem for a fast-moving bicycle?

25. A bullet slows very quickly in water but a spear doesn't. What force acts to slow these two objects, and why does the spear take longer to stop?

26. If you hang a tennis ball from a string, it will deflect downwind in a strong breeze. But if you wet the ball so that the fuzz on its surface lies flat, it will deflect even more than before. Why does smoothing the ball increase its deflection?

27. Explain why a parachute slows your descent when you leap out of an airplane.

28. Bicycle racers sometimes wear teardrop-shaped helmets that taper away behind their heads. Why does having this smooth taper behind them reduce the drag forces they experience relative to those they would experience with more ball-shaped helmets?

29. If you want the metal tubing in your bicycle to experience as little drag as possible while you're riding in a race, is cylindrical tubing the best shape? How should the tubing be shaped?

30. In 1971, astronaut Alan Shepard hit a golf ball on the moon. How did the absence of air affect the ball's flight?

31. A water-skier skims along the surface of a lake. What types of forces is the water exerting on the skier, and what is the effect of these forces?

32. How would a Frisbee fly on the airless moon?

33. You can buy special golf tees that wrap around behind the ball to prevent you from giving it any spin when you hit it. These tees are guaranteed to prevent hooks and slices (i.e., curved flights). How do these tees affect the distance the ball travels? Why?

34. A hurricane or gale force wind can lift the roof off a house, even when the roof has no exposed eaves. How can wind blowing across a roof produce an upward force on it?

35. A skillful volleyball player can serve the ball so that it barely spins at all. The ball dithers slightly from side to side as it flies over the net and is hard to return. What causes the ball to accelerate sideways?

36. Why does an airplane have a "flight ceiling," a maximum altitude above which it can't obtain enough lift to balance the downward force of gravity?

37. If you let a stream of water from a faucet flow rapidly over the curved bottom of a spoon, the spoon will be drawn into the stream. Explain this effect.

38. If you put your hand out the window of a moving car, so that your palm is pointing directly forward, the force on your hand is directly backward. Explain why the two halves of the airstream, passing over and under your hand, don't produce an overall up or down force on your hand.

39. If instead of holding your hand palm forward (see Exercise 38), you tip your palm slightly downward, the force on your hand will be both backward and upward. How is the airstream exerting an upward force on your hand?

40. When a hummingbird hovers in front of a flower, what forces are acting on it and what is the net force it experiences?

41. A poorly designed household fan stalls, making it inefficient at moving air. Describe the airflow through the fan when its blades stall.

42. When a plane enters a steep dive, the air rushes toward it from below. If the pilot pulls up suddenly from such a dive, the wings may abruptly stall, even though the plane is oriented horizontally. Explain why the wings stall.

Problems

1. About how fast can a small fish swim before experiencing turbulent flow around its body?

2. How much higher must your blood pressure get to compensate for a 5% narrowing in your blood vessels? (The pressure difference across your blood vessels is essentially equal to your blood pressure.)

3. If someone replaced the water in your home plumbing with olive oil, how much longer would it take you to fill a bathtub?

4. You are trying to paddle a canoe silently across a still lake and know that turbulence makes noise. How quickly can the canoe and the paddle travel through water without causing turbulence?

5. The pipes leading to the showers in your locker room are old and inadequate. Although the city water pressure is 700,000 Pa, the pressure in the locker room when one shower is on is only 600,000 Pa. Use Eq. 6.1.1 to calculate the approximate pressure if three showers are on.

6. If the plumbing in your dorm carried honey instead of water, filling a cup to brush your teeth could take awhile. If the faucet takes 5 s to fill a cup with water, how long will it take to fill your cup with honey, assuming all the pressures and pipes remain unchanged?

7. How quickly would you have to move a 1-cm-diameter stick through olive oil to reach a Reynolds number of 2000, so that you would begin to see turbulence around the stick? (Olive oil has a density of 918 kg/m^3.)

8. The effective obstacle length of a blimp is its width—the distance to which the air is separated as it flows around the blimp. How slowly would a 15-m-wide blimp have to move in order to keep the airflow around it laminar? (Air has a density of 1.25 kg/m^3.)