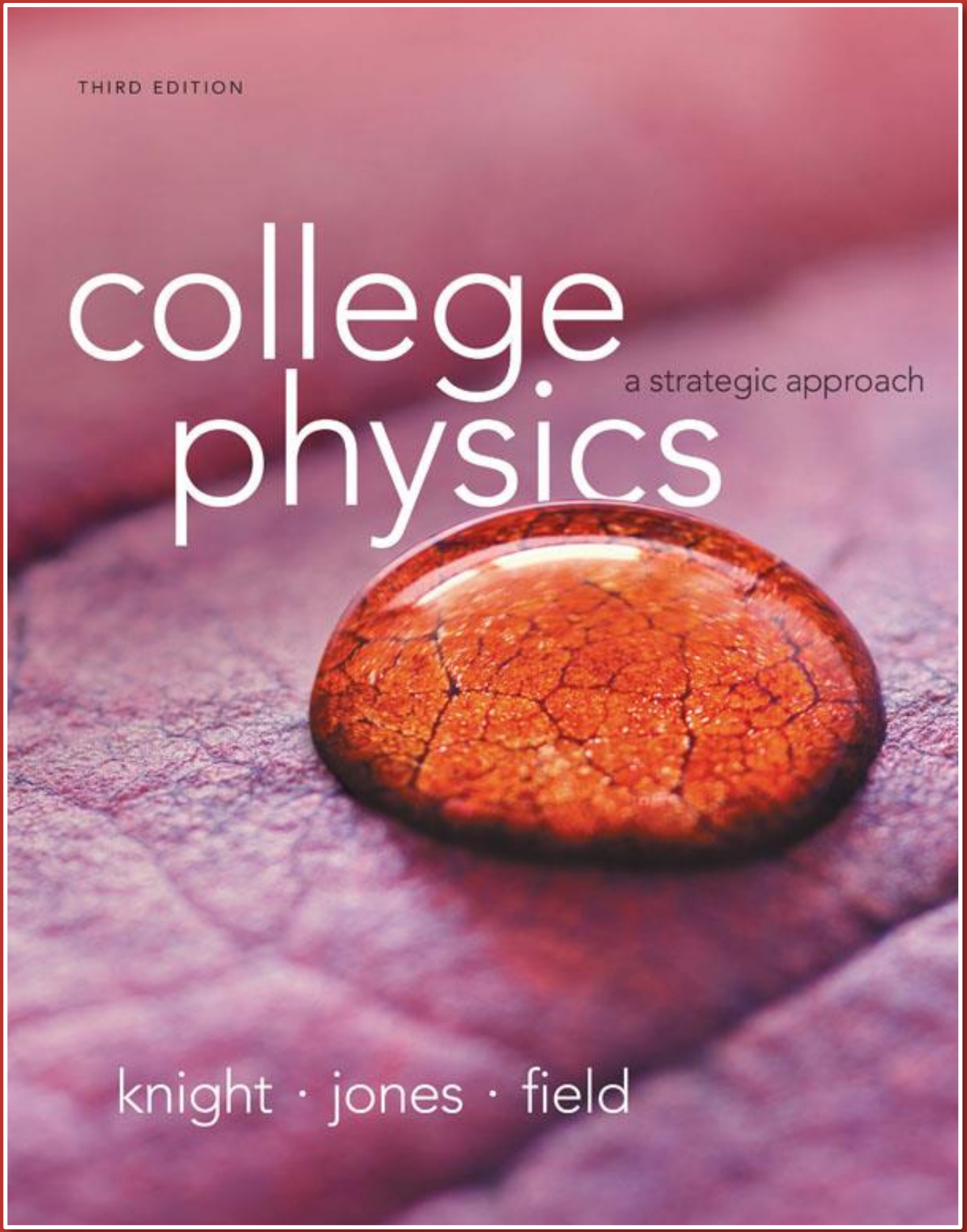


Lecture Presentation

Chapter 13

Fluids

Suggested Videos for Chapter 13

- **Prelecture Videos**
  - *Pressure in Fluids*
  - *Buoyancy*
- **Class Videos**
  - *Buoyancy and Density Part 1*
  - *Buoyancy and Density Part 2*
  - *Continuity*
- **Video Tutor Solutions**
  - *Fluids*
- **Video Tutor Demos**
  - *Pressure in Water and Alcohol*
  - *Water Level in Pascal's Vases*
  - *Weighing Weights in Water*
  - *Air Jet Blows between Bowling Balls*

Suggested Simulations for Chapter 13

- **PhETs**
  - *Gas Properties*
  - *States of Matter*
  - *Balloons & Buoyancy*

Chapter 13 Fluids

Chapter Goal: To understand the static and dynamic properties of fluids.

Chapter 13 Preview
Looking Ahead: Pressure in Liquids

- A liquid's pressure increases with depth. The high pressure at the base of this water tower pushes water throughout the city.

- You'll learn about **hydrostatics**—how liquids behave when they're in equilibrium.

Chapter 13 Preview
Looking Ahead: Buoyancy

- These students are competing in a concrete canoe contest. How can such heavy, dense objects stay afloat?

- You'll learn how to find the **buoyant force** on an object in a fluid using **Archimedes' principle**.

Chapter 13 Preview
Looking Ahead: Fluid Dynamics

- Moving fluids can exert large forces. The air passing this massive airplane's wings can lift it into the air.

- You'll learn to use **Bernoulli's equation** to predict the pressures and forces due to moving fluids.

Chapter 13 Preview
Looking Ahead

Pressure in Liquids

A liquid's pressure increases with depth. The high pressure at the base of this water tower pushes water throughout the city.

You'll learn about **hydrostatics**–how liquids behave when they're in equilibrium.

Buoyancy

These students are competing in a concrete canoe contest. How can such heavy, dense objects stay afloat?

You'll learn how to find the **buoyant force** on an object in a fluid using **Archimedes' principle.**

Fluid Dynamics

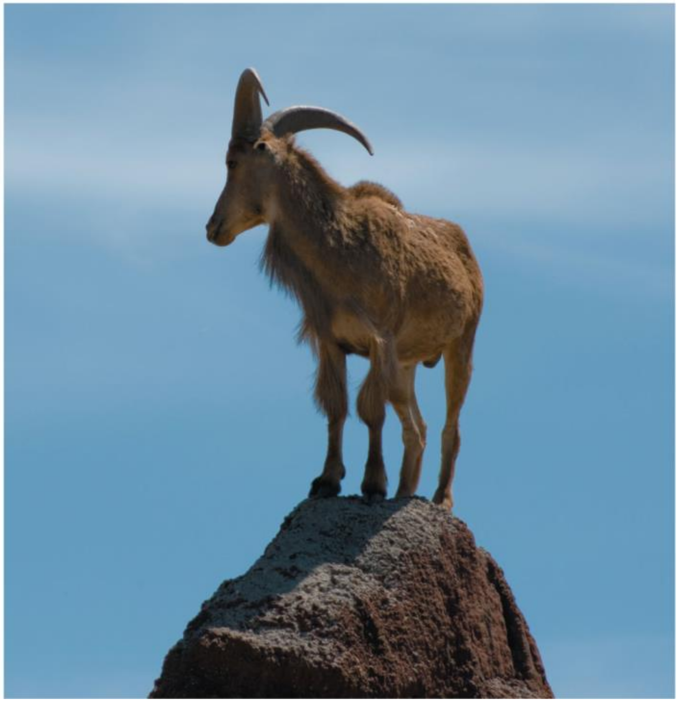
Moving fluids can exert large forces. The air passing this massive airplane's wings can lift it into the air.

You'll learn to use **Bernoulli's equation** to predict the pressures and forces due to moving fluids.

Text: p. 398

Chapter 13 Preview
Looking Back: Equilibrium

- In Section 5.1, you learned that for an object to be at rest—in *static equilibrium*—the net force on it must be zero. We'll use the principle of equilibrium in this chapter to understand how an object floats.

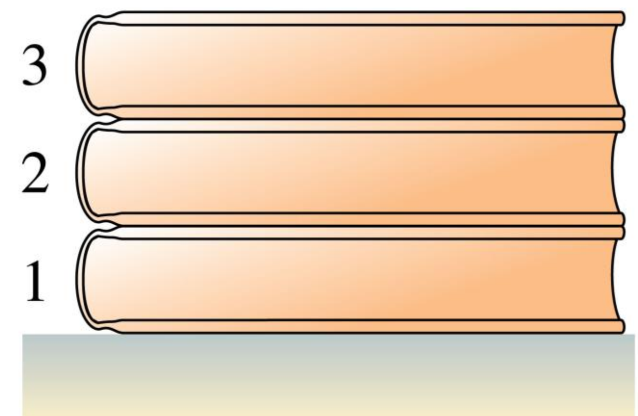


- This mountain goat is in equilibrium: Its weight is balanced by the normal force of the rock.

Chapter 13 Preview
Stop to Think

Three identical books are stacked vertically. The normal force of book 1 on book 2 is

A. Equal to the weight of one book.
B. Less than the weight of one book.
C. Greater than the weight of one book.



Reading Question 13.1

What is the SI unit of pressure?

A. The newton
B. The erg
C. The pascal
D. The poise

Reading Question 13.1

What is the SI unit of pressure?

A. The newton
B. The erg
C. The pascal
D. The poise

Reading Question 13.2

Is *gauge pressure* larger, smaller, or the same as absolute pressure?

A. Greater
B. Smaller
C. The same

Reading Question 13.2

Is *gauge pressure* larger, smaller, or the same as absolute pressure?

A. Greater
✔ B. Smaller
C. The same

Reading Question 13.3

The buoyant force on an object submerged in a liquid depends on

A. The object's mass.
B. The object's volume.
C. The density of the liquid.
D. All of the above.

Reading Question 13.3

The buoyant force on an object submerged in a liquid depends on

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B. The object's volume.
✔ C. The density of the liquid.
D. All of the above.

Reading Question 13.4

Bernoulli's equation is a relationship between a fluid's

A. Temperature and volume.
B. Volume and pressure.
C. Mass and density.
D. Speed and pressure.

Reading Question 13.4

Bernoulli's equation is a relationship between a fluid's

A. Temperature and volume.
B. Volume and pressure.
C. Mass and density.
✔ D. Speed and pressure.

Reading Question 13.5

When a viscous fluid flows in a tube, its velocity is

A. Greatest at the wall of the tube.
B. Greatest at the center of the tube.
C. The same everywhere.

Reading Question 13.5

When a viscous fluid flows in a tube, its velocity is

A. Greatest at the wall of the tube.

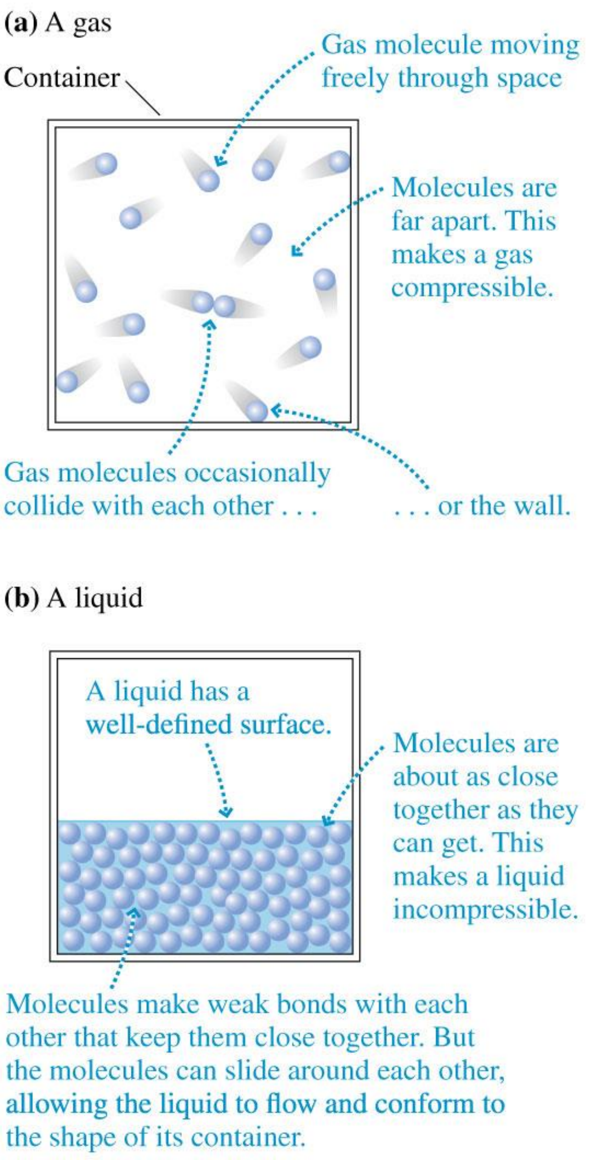
✔ B. Greatest at the center of the tube.

C. The same everywhere.

Section 13.1 Fluids and Density

Fluids and Density

- A **fluid** is a substance that flows.
- Liquids and gases are fluids.
- Gases are *compressible*; the volume of a gas is easily increased or decreased.
- Liquids are nearly *incompressible*; the molecules are packed closely, yet they can move around.



Density

- The **mass density** is the *ratio* of mass to volume:

$$\rho = \frac{m}{V}$$

Mass density of an object of mass m and volume V

- The SI units of mass density are kg/m^3.
- Gasoline has a mass density of 680 kg/m^3, meaning there are 680 kg of gasoline *for each* 1 cubic meter of the liquid.

Density

TABLE 13.1 Densities of fluids at 1 atm pressure

Substance	ρ (kg/m^3)
Helium gas (20°C)	0.166
Air (20°C)	1.20
Air (0°C)	1.28
Gasoline	680
Ethyl alcohol	790
Oil (typical)	900
Water	1000
Seawater	1030
Blood (whole)	1060
Glycerin	1260
Mercury	13,600

Example 13.1 Weighing the air in a living room

What is the mass of air in a living room with dimensions 4.0 m × 6.0 m × 2.5 m?

PREPARE Table 13.1 gives air density at a temperature of 20°C, which is about room temperature.

SOLVE The room's volume is

$$V = (4.0\text{ m}) \times (6.0\text{ m}) \times (2.5\text{ m}) = 60\text{ m}^3$$

The mass of the air is

$$m = \rho V = (1.20\text{ kg/m}^3)(60\text{ m}^3) = 72\text{ kg}$$

ASSESS This is perhaps more mass—about that of an adult person—than you might have expected from a substance that hardly seems to be there. For comparison, a swimming pool this size would contain 60,000 kg of water.

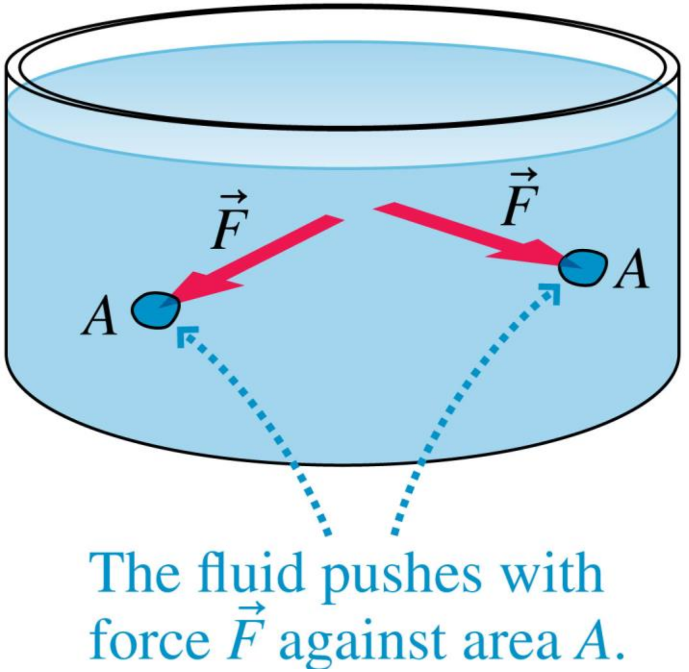
Section 13.2 Pressure

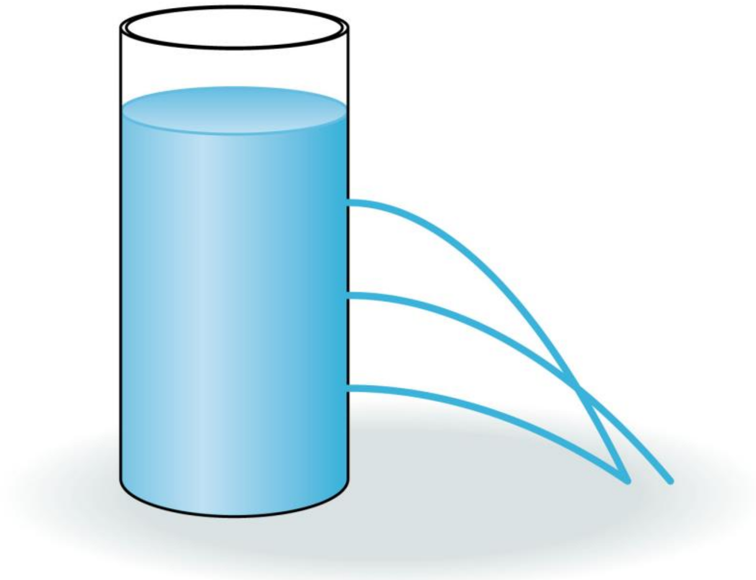
Pressure

- Liquids exert forces on the walls of their containers.
- The pressure is the ratio of the force to the area on which the force is exerted:

$$p = \frac{F}{A}$$

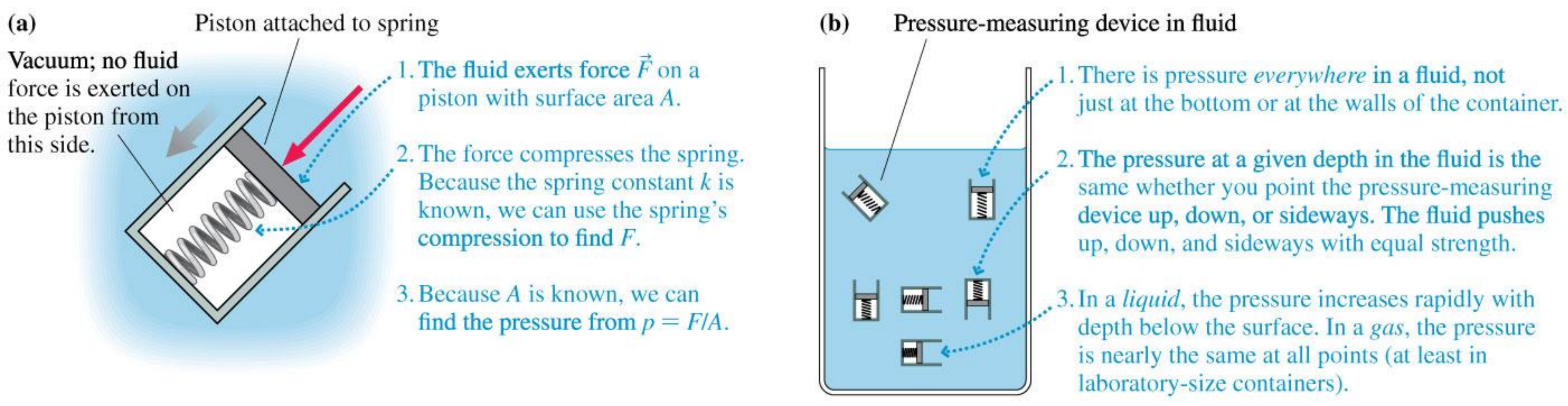
- The fluid's pressure pushes on *all* parts of the fluid itself, forcing the fluid out of a container with holes.





Pressure

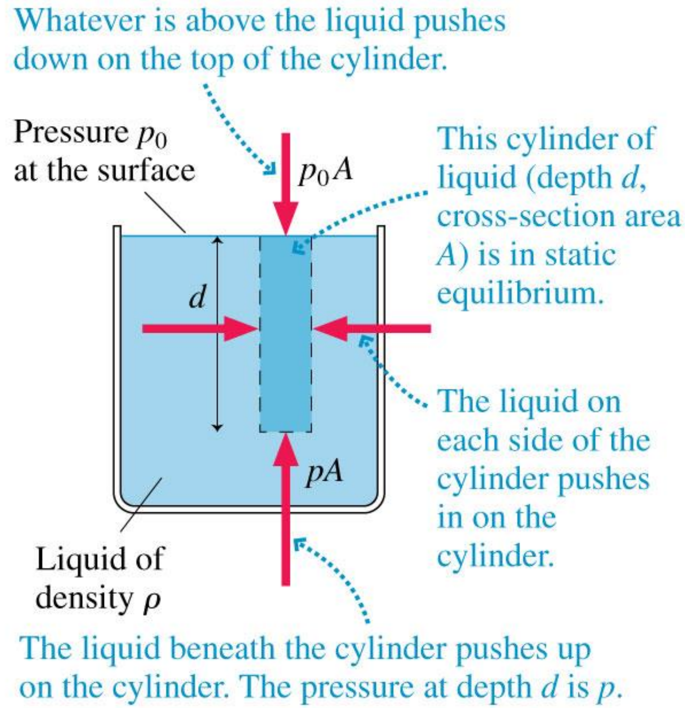
- We can measure the pressure in a liquid with a simple device. We find that pressure is *everywhere* in the fluid; different parts of a fluid are *pushing* against each other.

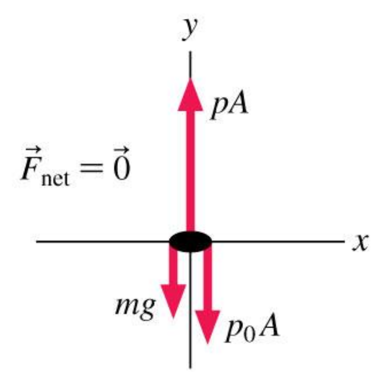


Pressure in Liquids

- The force of gravity (the weight of the liquid) is responsible for the pressure in the liquid.
- The horizontal forces cancel each other out.
- The vertical forces balance:

$$pA = p_0A + mg$$





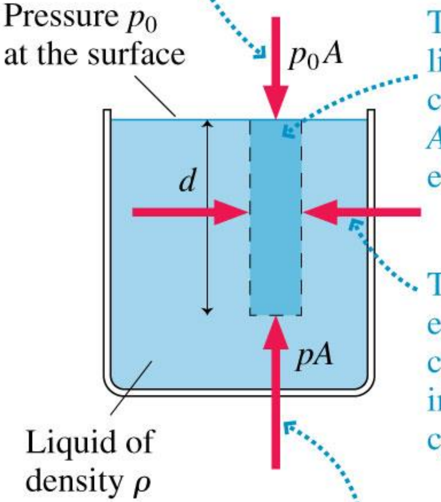
Free-body diagram of the column of liquid. The horizontal forces cancel and are not shown.

Pressure in Liquids

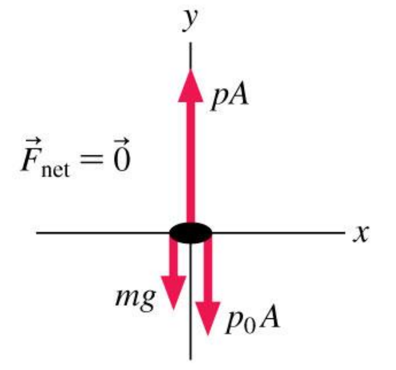
- The liquid is a cylinder of cross-section area A and height d. The mass is $m = \rho A d$. The pressure at depth d is

$$p = p_0 + \rho g d$$

Pressure of a liquid with density ρ at depth d



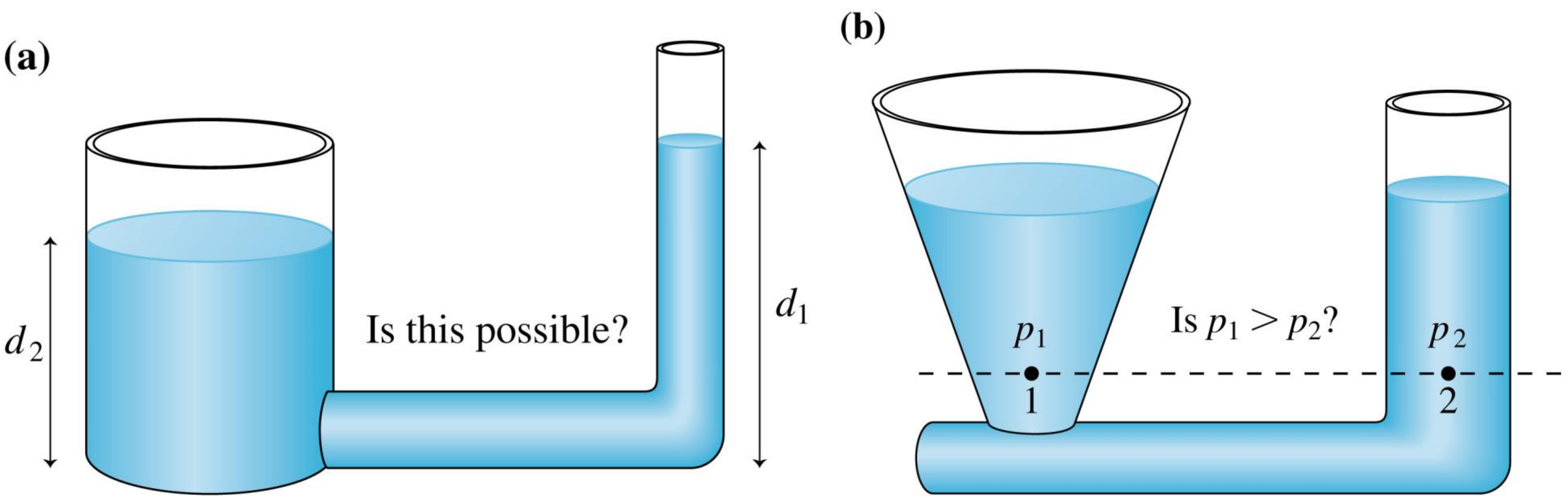
- Because we assumed that the fluid is at rest, this pressure is the **hydrostatic pressure.**



Free-body diagram of the column of liquid. The horizontal forces cancel and are not shown.

Pressure in Liquids

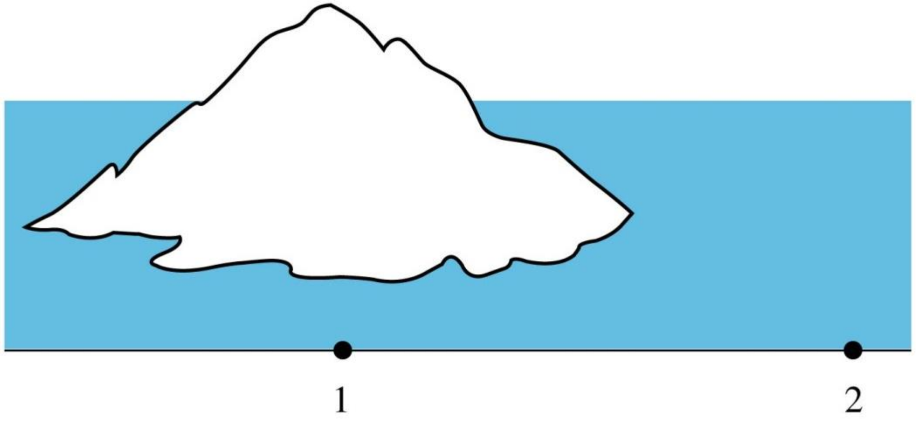
- **A connected liquid in hydrostatic equilibrium rises to the same height in all open regions of the container.**
- **In hydrostatic equilibrium, the pressure is the same at all points on a horizontal line through a connected liquid of a single kind.**



QuickCheck 13.1

An iceberg floats in a shallow sea. What can you say about the pressures at points 1 and 2?

A. $p_1 > p_2$
B. $p_1 = p_2$
C. $p_1 < p_2$



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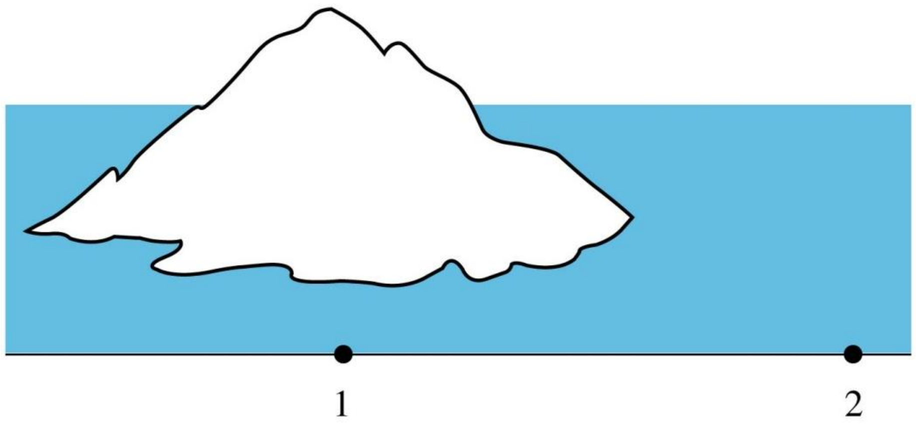
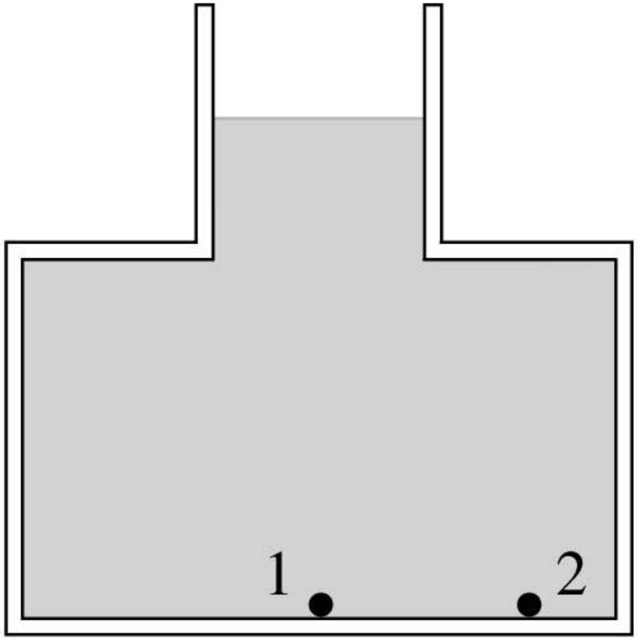


Hydrostatic pressure is the same at all points on a horizontal line through a connected fluid.

QuickCheck 13.2

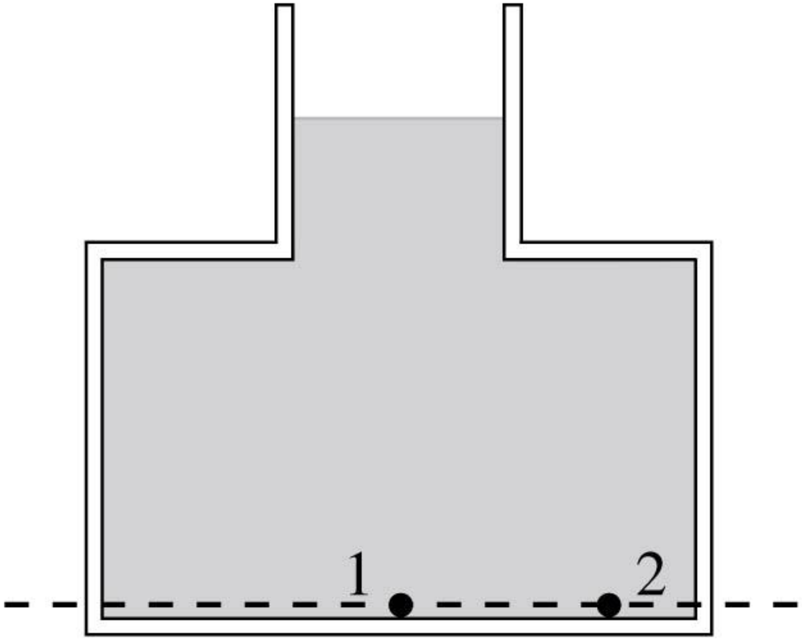
What can you say about the pressures at points 1 and 2?

A. $p_1 > p_2$
B. $p_1 < p_2$
C. $p_3 = p_1$



QuickCheck 13.2

What can you say about the pressures at points 1 and 2?



A. $p_1 > p_2$

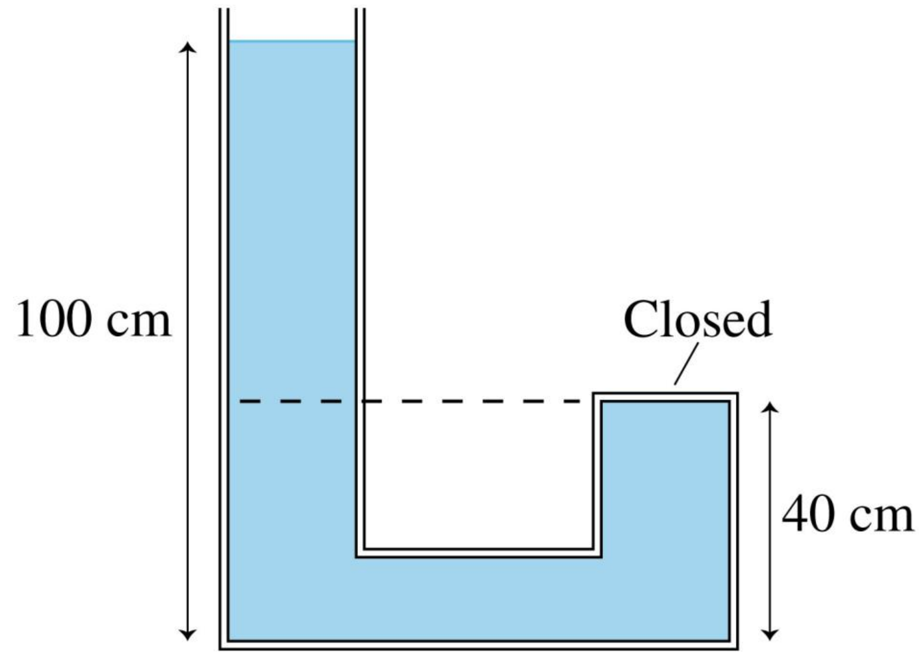
B. $p_1 < p_2$

✔ C. $p_3 = p_1$

Hydrostatic pressure is the same at all points on a horizontal line through a connected fluid.

Example 13.3 Pressure in a closed tube

Water fills the tube shown in **FIGURE 13.7**. What is the pressure at the top of the closed tube?



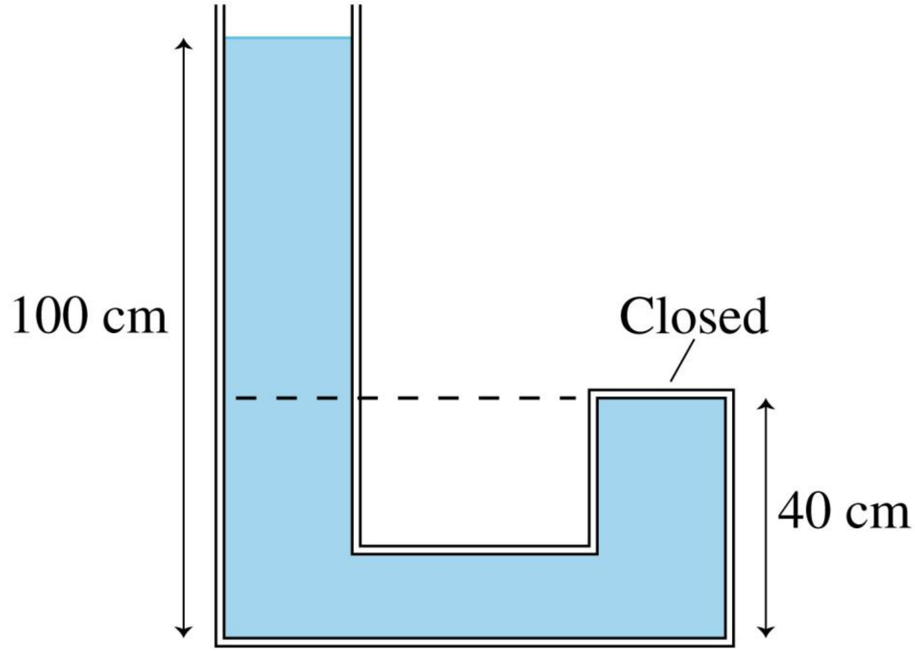
PREPARE This is a liquid in hydrostatic equilibrium. The closed tube is not an open region of the container, so the water cannot rise to an equal height. Nevertheless, the pressure is still the same at all points on a horizontal line. In particular, the pressure at the top of the closed tube equals the pressure in the open tube at the height of the dashed line. Assume $p_0 = 1$ atm.

Example 13.3 Pressure in a closed tube (cont.)

SOLVE A point 40 cm above the bottom of the open tube is at a depth of 60 cm. The pressure at this depth is

$$p = p_0 + \rho g d$$
$$= (1.01 \times 10^5 \text{ Pa}) + (1000 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(0.60 \text{ m})$$
$$= 1.07 \times 10^5 \text{ Pa} = 1.06 \text{ atm}$$

ASSESS The water column that creates this pressure is not very tall, so it makes sense that the pressure is only a little higher than atmospheric pressure.



QuickCheck 13.3

What can you say about the pressures at points 1, 2, and 3?

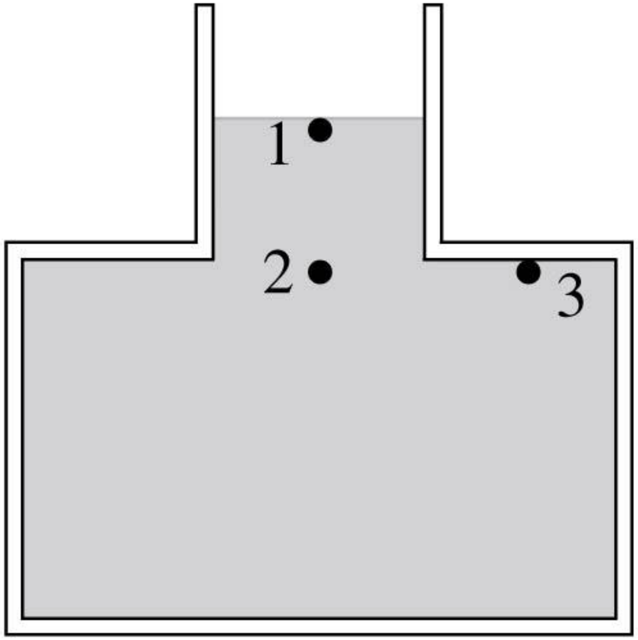
A. $p_1 = p_2 = p_3$

B. $p_1 = p_2 > p_3$

C. $p_3 > p_1 = p_2$

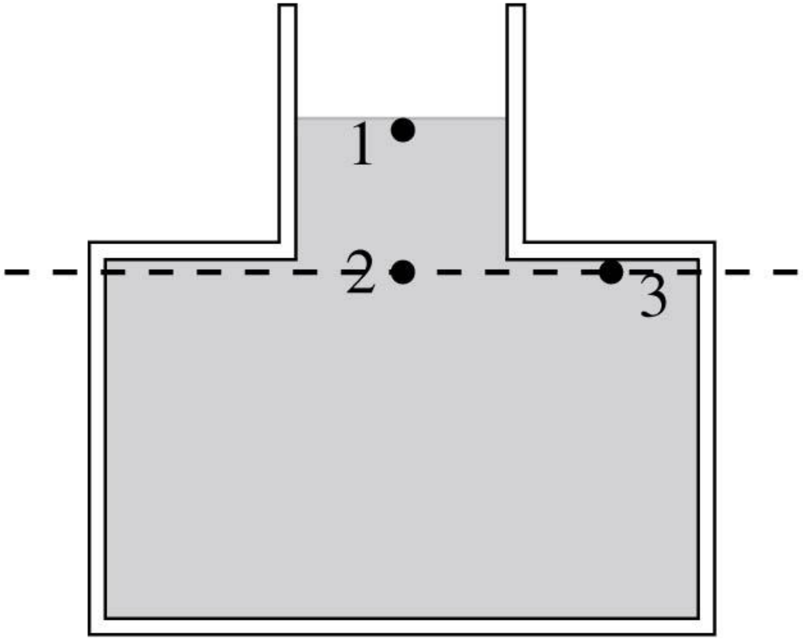
D. $p_3 > p_1 > p_2$

E. $p_1 = p_3 > p_2$



QuickCheck 13.3

What can you say about the pressures at points 1, 2, and 3?



A. $p_1 = p_2 = p_3$

B. $p_1 = p_2 > p_3$

C. $p_3 > p_1 = p_2$

D. $p_3 > p_1 > p_2$

✔ E. $p_1 = p_3 > p_2$

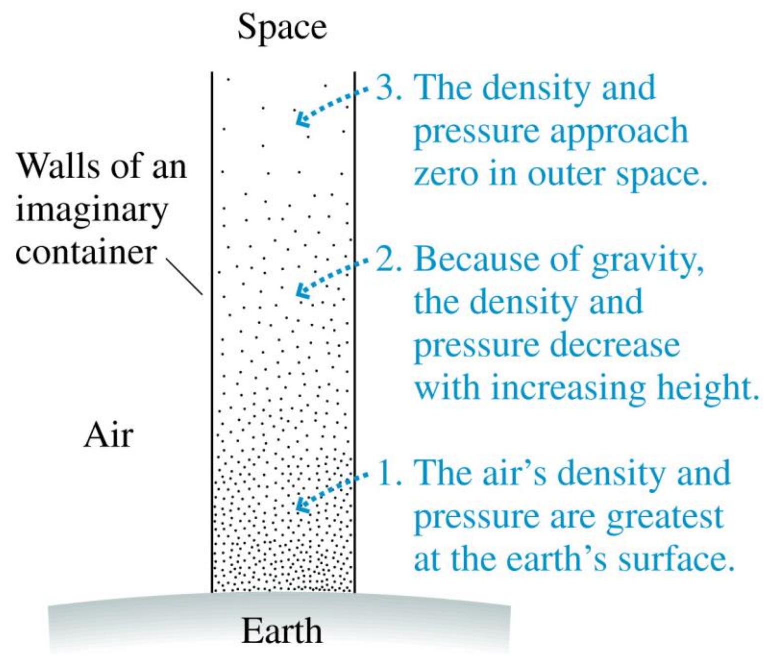
Hydrostatic pressure is the same at all points on a horizontal line through a connected fluid, and pressure increases with depth.

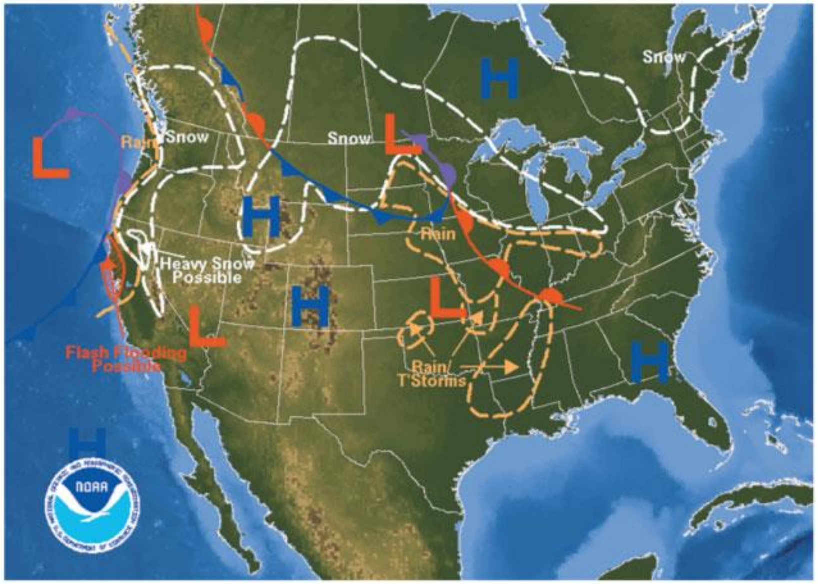
Pressure in Liquids

Pascal's principle If the pressure at one point in an incompressible fluid is changed, the pressure at every other point in the fluid changes by the same amount.

Atmospheric Pressure

- Gas is compressible, so the air in the atmosphere becomes less dense with increasing altitude.
- 99% of the air in our atmosphere is below 30 km.
- Atmospheric pressure varies with altitude and with changes in the weather.





Section 13.3 Measuring and Using Pressure

Measuring and Using Pressure

TACTICS BOX 13.1 Hydrostatics

1. **Draw a picture.** Show open surfaces, pistons, boundaries, and other features that affect pressure. Include height and area measurements and fluid densities. Identify the points at which you need to find the pressure.
2. **Determine the pressure p_0 at surfaces.**
   - **Surface open to the air:** $p_0 = p_{\text{atmos}}$, usually 1 atm.
   - **Surface in contact with a gas:** $p_0 = p_{\text{gas}}$.
   - **Closed surface:** $p_0 = F/A$, where F is the force that the surface, such as a piston, exerts on the fluid.
3. **Use horizontal lines.** The pressure in a connected fluid (of one kind) is the same at any point along a horizontal line.
4. **Allow for gauge pressure.** Pressure gauges read $p_g = p - 1$ atm.
5. **Use the hydrostatic pressure equation:** $p = p_0 + \rho g d$.

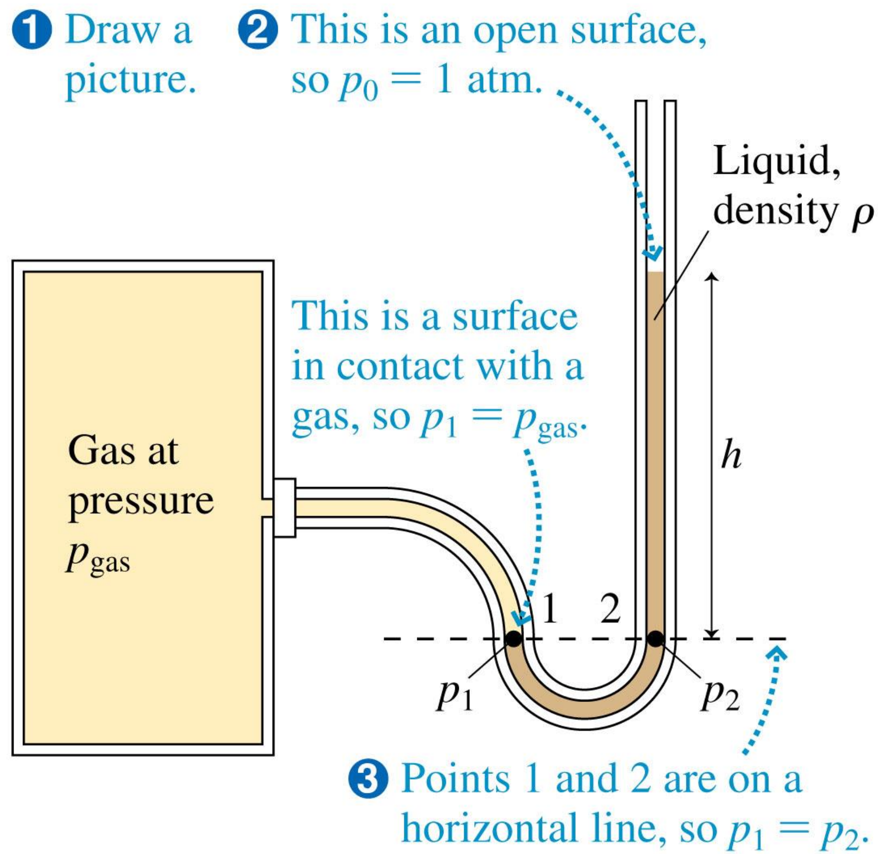
Exercises 5–7

Text: p. 404

Manometers and Barometers

- A *manometer* measures the gas pressure.
- The tube is filled with liquid (often mercury). Since pressures on a horizontal line are equal, p_1 is the gas pressure, p_2 is the hydrostatic pressure at depth $d = h$.
- Equating the two pressures gives

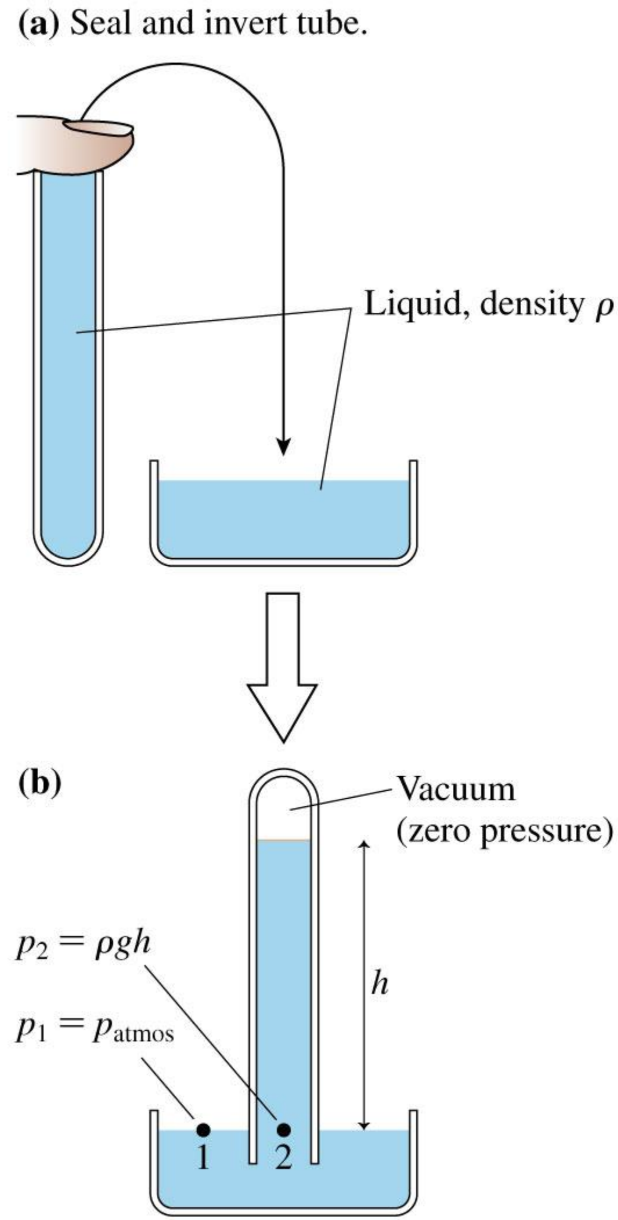
$$p_{gas} = 1\text{ atm} + \rho g\text{h}$$



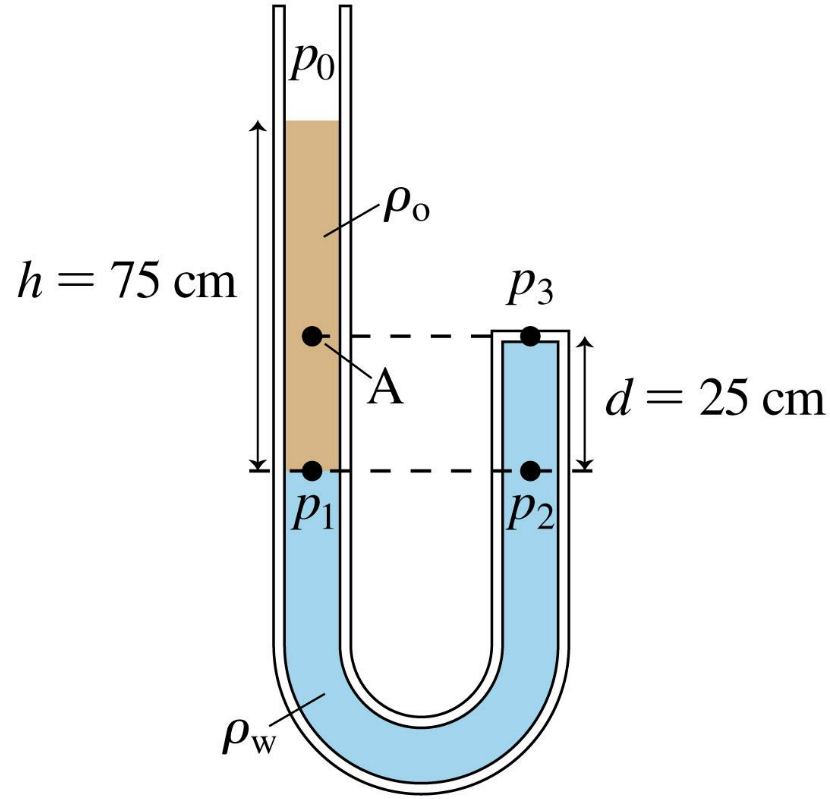
Manometers and Barometers

- A *barometer* measures the atmospheric pressure p_{atmos}.
- A glass tube is placed in a beaker of the same liquid. Some, but not all liquid leaves the tube.
- p_2 is the pressure due to the weight of the liquid in the tube and $p_1 = p_{atmos}$.
- Equating the two pressures gives

$$p_{atmos} = \rho g h$$

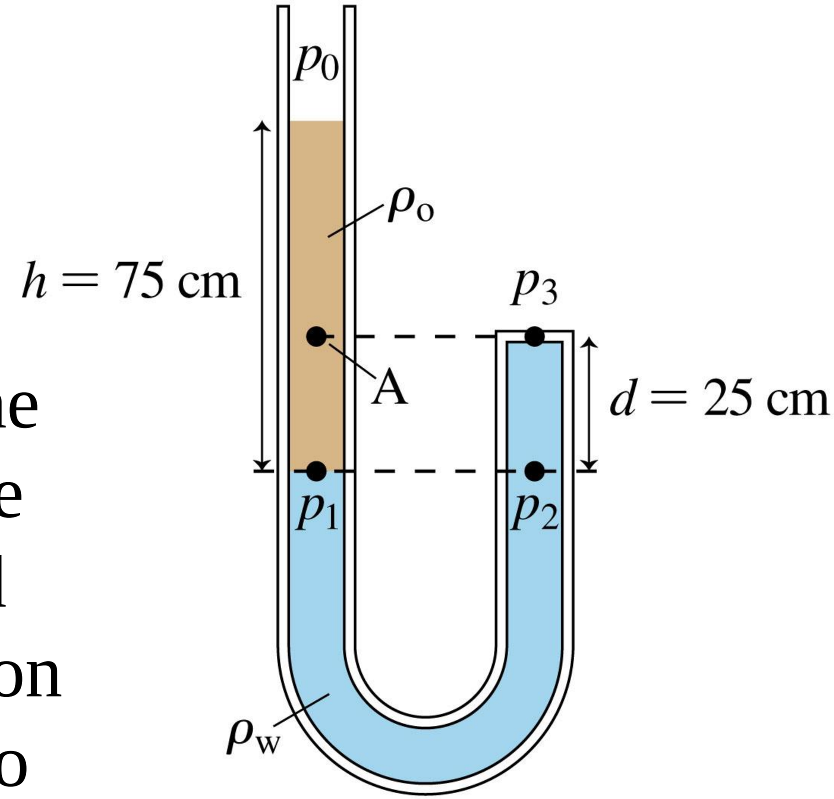


Example 13.4 Pressure in a tube with two liquids



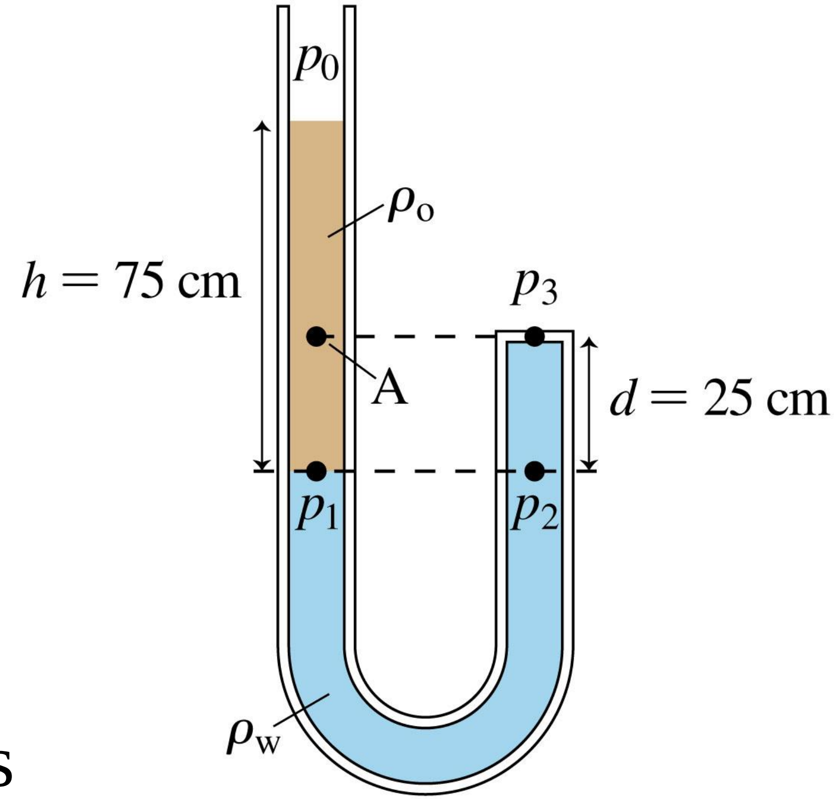
A U-shaped tube is closed at one end; the other end is open to the atmosphere. Water fills the side of the tube that includes the closed end, while oil, floating on the water, fills the side of the tube open to the atmosphere. The two liquids do not mix. The height of the oil above the point where the two liquids touch is 75 cm, while the height of the closed end of the tube above this point is 25 cm. What is the gauge pressure at the closed end?

Example 13.4 Pressure in a tube with two liquids (cont.)



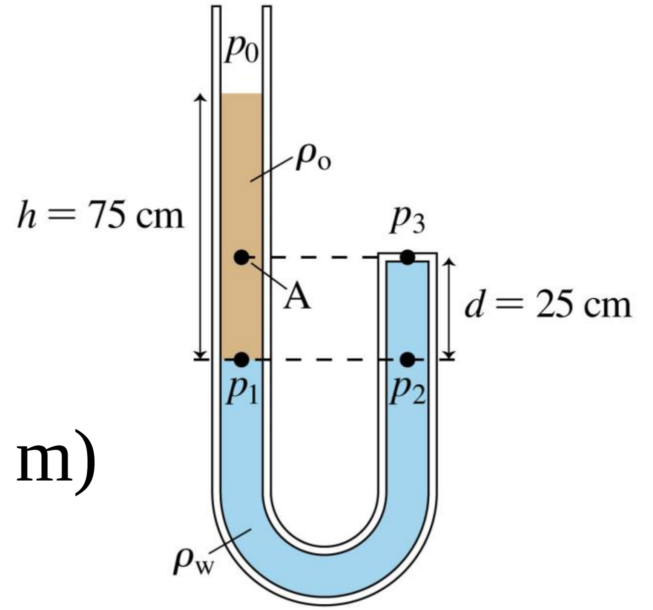
PREPARE Following the steps in Tactics Box 13.1, we start by drawing the picture shown in **FIGURE 13.12**. We know that the pressure at the open surface of the oil is $p_0 = 1$ atm. Pressures p_1 and p_2 are the same because they are on a horizontal line that connects two points in the *same* fluid. (The pressure at point A is *not* equal to p_3, even though point A and the closed end are on the same horizontal line, because the two points are in *different* fluids.)

Example 13.4 Pressure in a tube with two liquids (cont.)



We can apply the hydrostatic pressure equation twice: once to find the pressure p_1 by its known depth below the open end at pressure p_0, and again to find the pressure p_3 at the closed end once we know p_2 a distance d below it. We'll need the densities of water and oil, which are found in Table 13.1 to be $\rho_w = 1000$ kg/m^3 and $\rho_o = 900$ kg/m^3.

Example 13.4 Pressure in a tube with two liquids (cont.)



SOLVE The pressure at point 1, 75 cm below the open end, is

$$p_1 = p_0 + \rho_o g h$$
$$= 1 \text{ atm} + (900 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(0.75 \text{ m})$$
$$= 1 \text{ atm} + 6620 \text{ Pa}$$

(We will keep $p_0 = 1$ atm separate in this result because we'll eventually need to subtract exactly 1 atm to calculate the gauge pressure.)

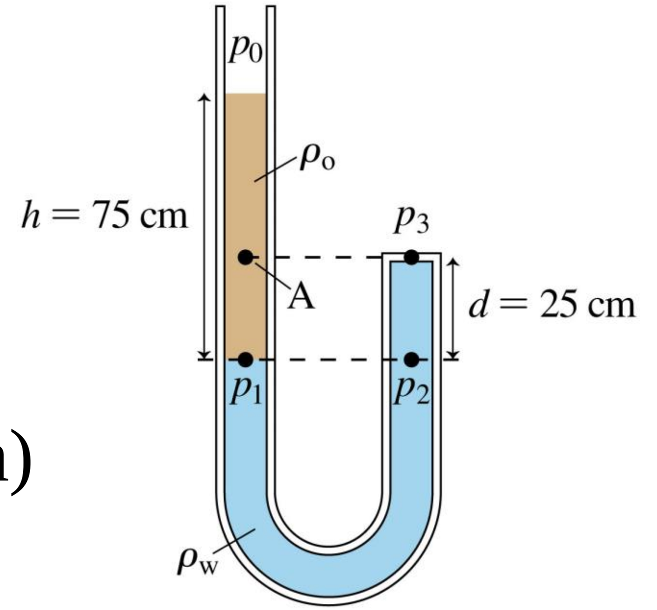
Example 13.4 Pressure in a tube with two liquids (cont.)

We can also use the hydrostatic pressure equation to find

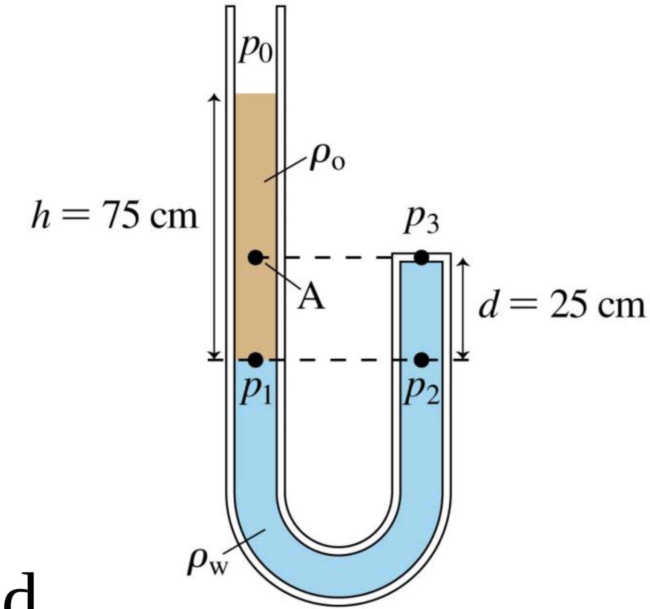
$$p_2 = p_3 + \rho_{\mathrm{w}} g d$$

$$= p_3 + (1000\ \mathrm{kg/m^3})(9.8\ \mathrm{m/s^2})(0.25\ \mathrm{m})$$

$$= p_3 + 2450\ \mathrm{Pa}$$



Example 13.4 Pressure in a tube with two liquids (cont.)



But we know that $p_2 = p_1$, so

$$p_3 = p_2 - 2450\text{ Pa} = p_1 - 2450\text{ Pa}$$

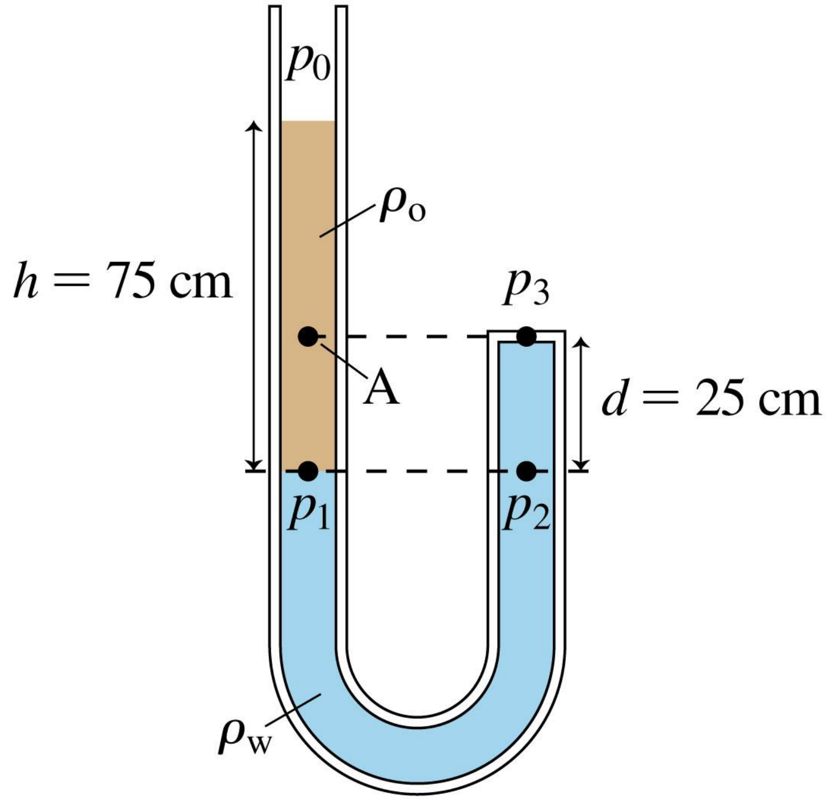
$$= 1\text{ atm} + 6620\text{ Pa} - 2450\text{ Pa}$$

$$= 1\text{ atm} + 4200\text{ Pa}$$

The gauge pressure at point 3, the closed end of the tube, is $p_3 - 1$ atm or 4200 Pa.

Example 13.4 Pressure in a tube with two liquids (cont.)

ASSESS The oil's open surface is 50 cm higher than the water's closed surface. Their densities are not too different, so we expect a pressure difference of roughly $\rho g(0.50 \text{ m}) = 5000$ Pa. This is not too far from our answer, giving us confidence that it's correct.



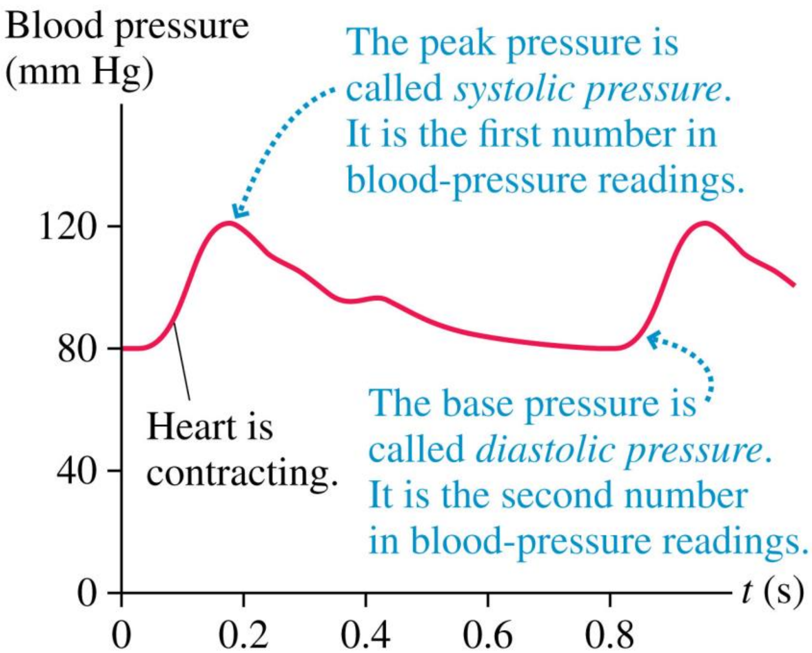
Pressure Units

TABLE 13.2 Pressure units

Unit	Abbreviation	Conversion to 1 atm	Uses
pascal	Pa	101.3 kPa	SI unit: 1 Pa = 1 N/m^2 used in most calculations
atmosphere	atm	1 atm	general
millimeters of mercury	mm Hg	760 mm Hg	gases and barometric pressure
inches of mercury	in	29.92 in	barometric pressure in U.S. weather forecasting
pounds per square inch	psi	14.7 psi	U.S. engineering and industry

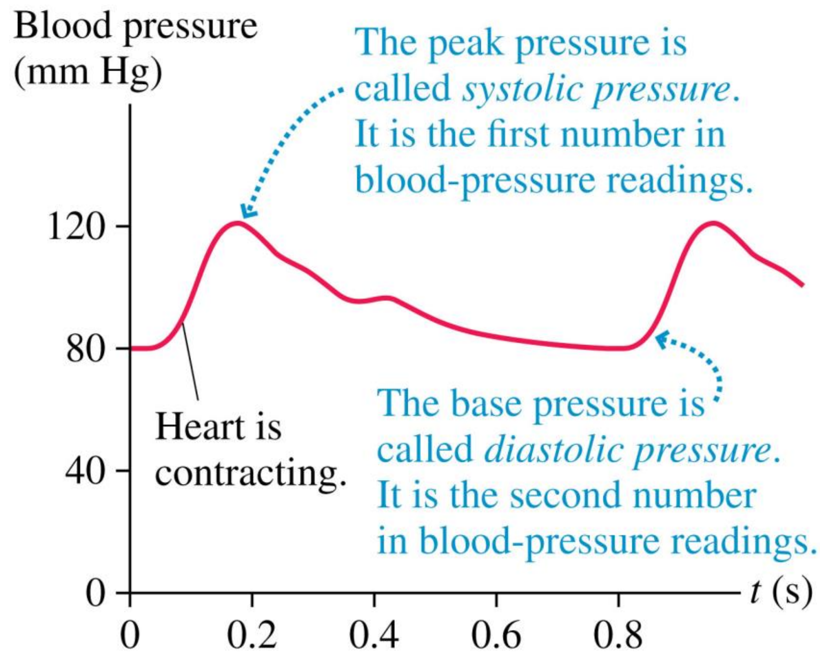
Blood Pressure

- Blood pressure is measured by pressurizing a cuff around a patient's arm.
- The cuff squeezes the artery shut. When the cuff pressure drops below the systolic (max) blood pressure, the artery pushes blood through in pulses, which can be heard through a stethoscope.
- When the cuff pressure drops below the diastolic pressure, blood flows smoothly.



Blood Pressure

- When a doctor or nurse gives you your blood pressure, the first number is the systolic blood pressure and the second number is the diastolic pressure.



Conceptual Example 13.5

In Figure 13.14, the patient's arm is held at about the same height as her heart. Why?

Conceptual Example 13.5

REASON The hydrostatic pressure of a fluid varies with height. Although flowing blood is not in hydrostatic equilibrium, it is still true that blood pressure increases with the distance below the heart and decreases above it. Because the upper arm when held beside the body is at the same height as the heart, the pressure here is the same as the pressure at the heart. If the patient held her arm straight up, the pressure cuff would be a distance $d \approx 25$ cm above her heart and the pressure would be *less* than the pressure at the heart by $\Delta p = \rho_{\text{blood}}\, gd \approx 20$ mm Hg.

Conceptual Example 13.5

ASSESS 20 mm Hg is a substantial fraction of the average blood pressure. Measuring pressure above or below heart level could lead to a misdiagnosis of the patient’s condition.

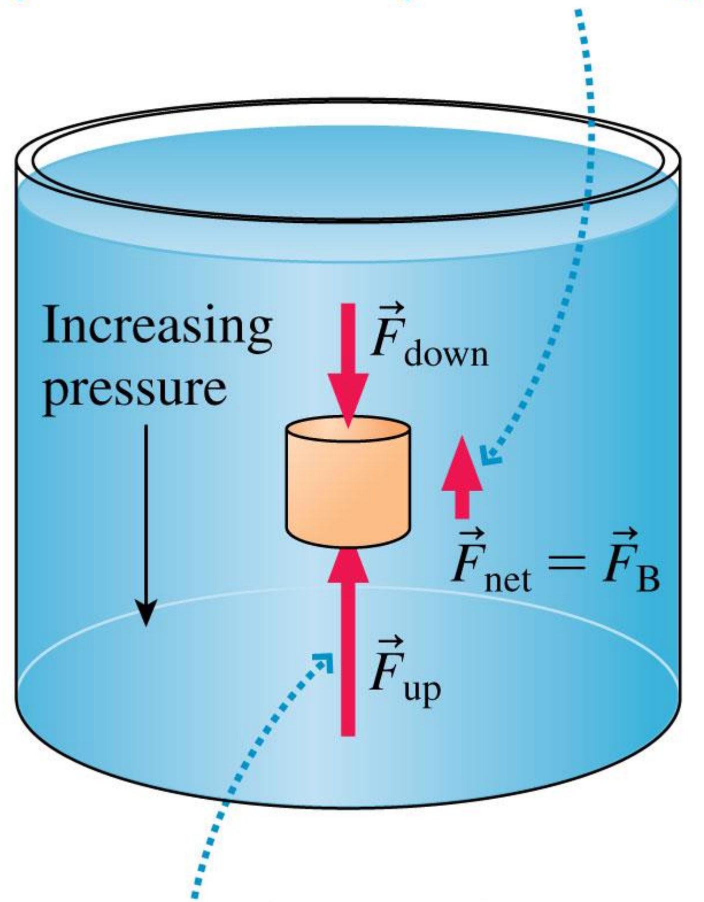
Section 13.4 Buoyancy

Buoyancy

- **Buoyancy** is the upward force of a liquid.
- The pressure in a liquid increases with depth, so the pressure in a liquid-filled cylinder is greater at the bottom than at the top.
- The pressure exerts a *net upward force* on a submerged cylinder of

$$F_{\text{net}} = F_{\text{up}} - F_{\text{down}}$$

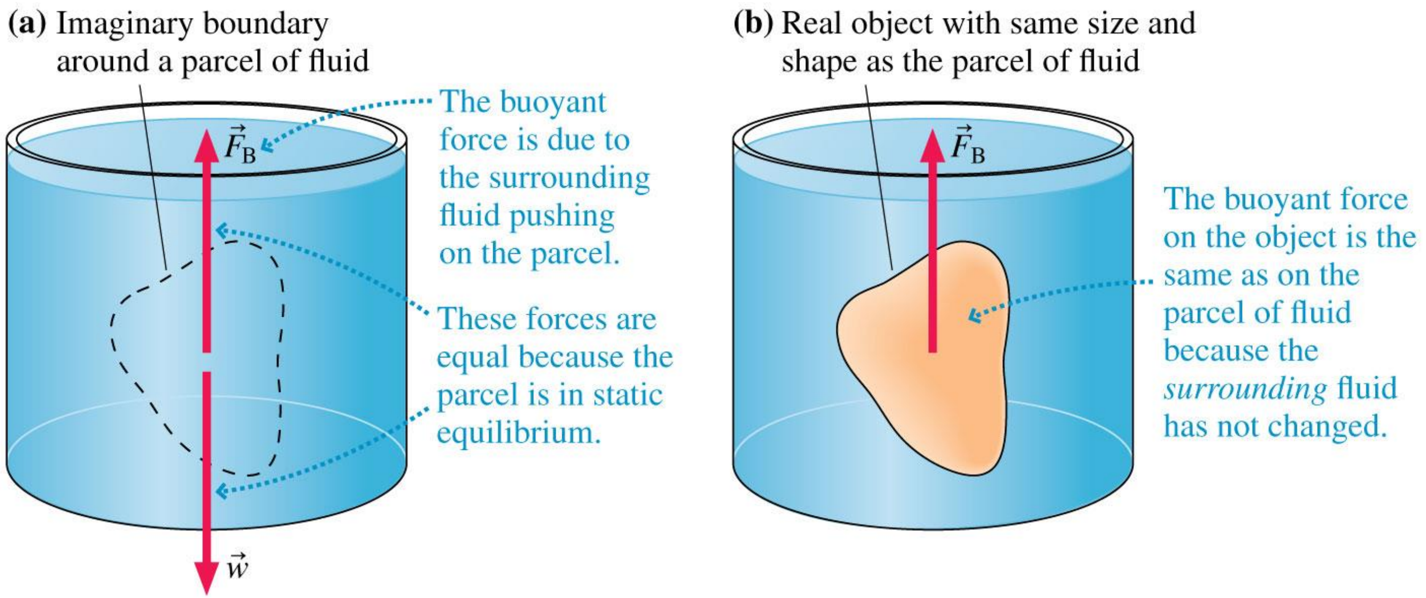
The net force of the fluid on the cylinder is the buoyant force $\vec{F}_B$.



$F_{\text{up}} > F_{\text{down}}$ because the pressure is greater at the bottom. Hence the fluid exerts a net upward force.

Buoyancy

- If an isolated parcel of a fluid is in static equilibrium, then the parcel's weight force pulling it down must be balanced by an upward force: the buoyant force $\vec{F}_B$.
- The buoyant force matches the fluid weight: $F_B = w$.
- If we replace the parcel of liquid with an object of the same shape and size, the buoyant force on the new object is *exactly the same* as before.



Buoyancy

- When an object is immersed in a fluid, it *displaces* the fluid that would otherwise fill that region of space. The fluid is called the **displaced fluid**:

> **Archimedes' principle** A fluid exerts an upward buoyant force $\vec{F}_B$ on an object immersed in or floating on the fluid. The magnitude of the buoyant force equals the weight of the fluid displaced by the object.

- Archimedes' principle in equation form is

$$F_B = \rho_f V_f g$$

QuickCheck 13.4

A heavy lead block and a light aluminum block of equal sizes are both submerged in water. Upon which is the buoyant force greater?

A. On the lead block
B. On the aluminum block
C. They both experience the same buoyant force.

QuickCheck 13.4

A heavy lead block and a light aluminum block of equal sizes are both submerged in water. Upon which is the buoyant force greater?

A. On the lead block
B. On the aluminum block
✔ C. They both experience the same buoyant force.

Same size ⇒ both displace the same volume and weight of water.

QuickCheck 13.5

Two blocks are of identical size. One is made of lead and sits on the bottom of a pond; the other is of wood and floats on top. Upon which is the buoyant force greater?

A. On the lead block
B. On the wood block
C. They both experience the same buoyant force

QuickCheck 13.5

Two blocks are of identical size. One is made of lead and sits on the bottom of a pond; the other is of wood and floats on top. Upon which is the buoyant force greater?

✔ A. On the lead block

B. On the wood block

C. They both experience the same buoyant force

The fully submerged lead block displaces more much water than the wood block.

QuickCheck 13.6

A barge filled with ore floats in a canal lock. If the ore is tossed overboard into the lock, the water level in the lock will

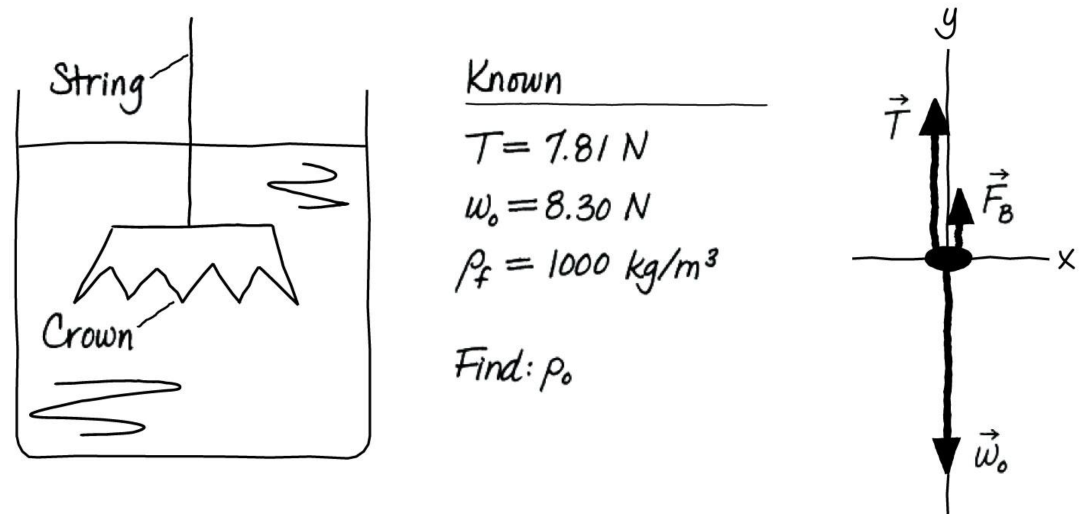
A. Rise.
B. Fall.
C. Remain constant.

QuickCheck 13.6

A barge filled with ore floats in a canal lock. If the ore is tossed overboard into the lock, the water level in the lock will

A. Rise.
✔ B. Fall.
C. Remain constant.

Example 13.6 Is the crown gold?



Legend has it that Archimedes was asked by King Hiero of Syracuse to determine whether a crown was of pure gold or had been adulterated with a lesser metal by an unscrupulous goldsmith. It was this problem that led him to the principle that bears his name. In a modern version of his method, a crown weighing 8.30 N is suspended underwater from a string. The tension in the string is measured to be 7.81 N. Is the crown pure gold?

Example 13.6 Is the crown gold? (cont.)

PREPARE To discover whether the crown is pure gold, we need to determine its density ρ_o and compare it to the known density of gold.

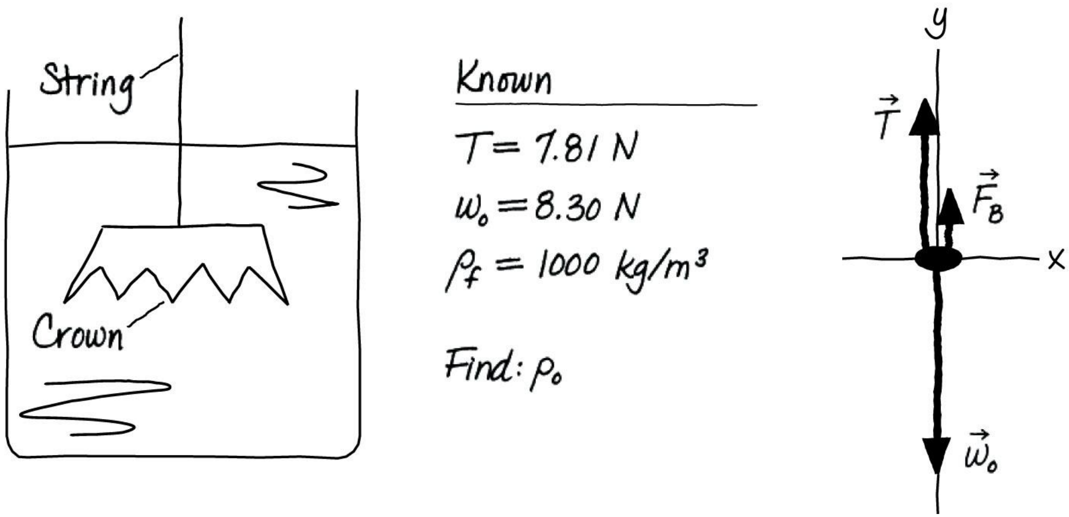
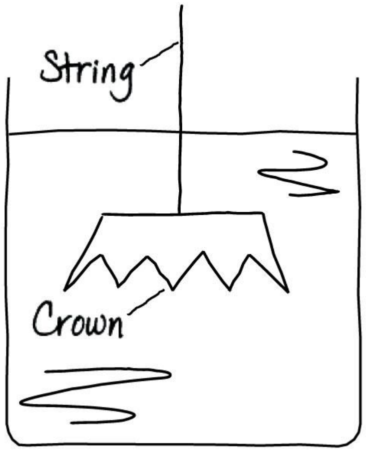
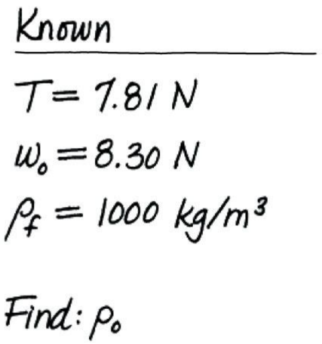


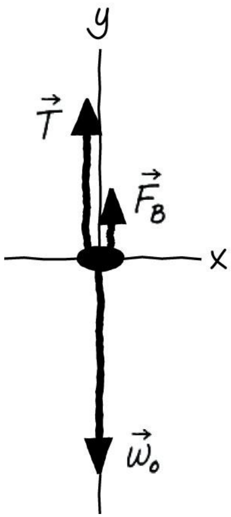
FIGURE 13.17 shows the forces acting on the crown. In addition to the familiar tension and weight forces, the water exerts an upward buoyant force on the crown. The size of the buoyant force is given by Archimedes' principle.

Example 13.6 Is the crown gold? (cont.)

SOLVE Because the crown acceleration and the net force on it are zero. Newton's second law then reads







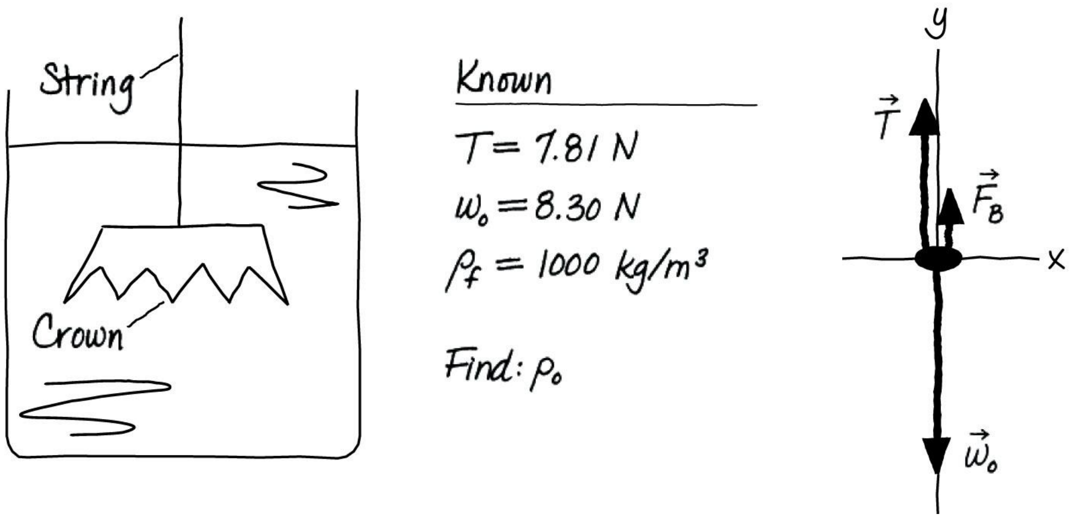
$$\Sigma F_y = F_B + T - w_o = 0$$

from which the buoyant force is

$$F_B = w_o - T = 8.30 \text{ N} - 7.81 \text{ N} = 0.49 \text{ N}$$

Example 13.6 Is the crown gold? (cont.)

According to Archimedes' principle, $F_B = \rho_f V_f\, g$, where V_f is the volume of the fluid displaced. Here, where the crown is completely submerged,



the volume of the fluid displaced is equal to the volume V_o of the crown. Now the crown's weight is $w_o = m_o g = \rho_o V_o g$, so its volume is

$$V_o = \frac{w_o}{\rho_o g}$$

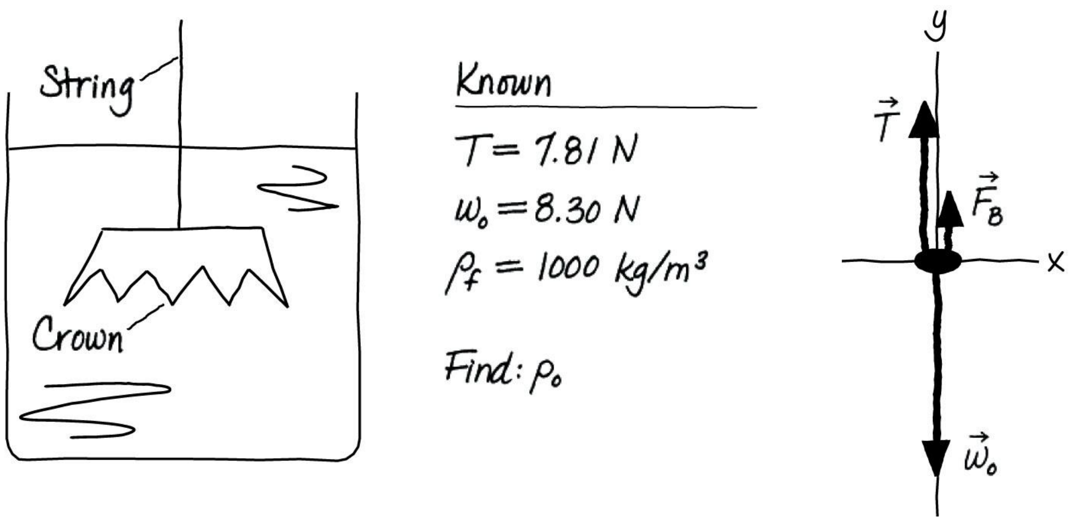
Example 13.6 Is the crown gold? (cont.)

Inserting this volume into Archimedes' principle gives

$$F_B = \rho_f V_o g = \rho_f \left(\frac{w_o}{\rho_o g}\right) g = \frac{\rho_f}{\rho_o} w_o$$

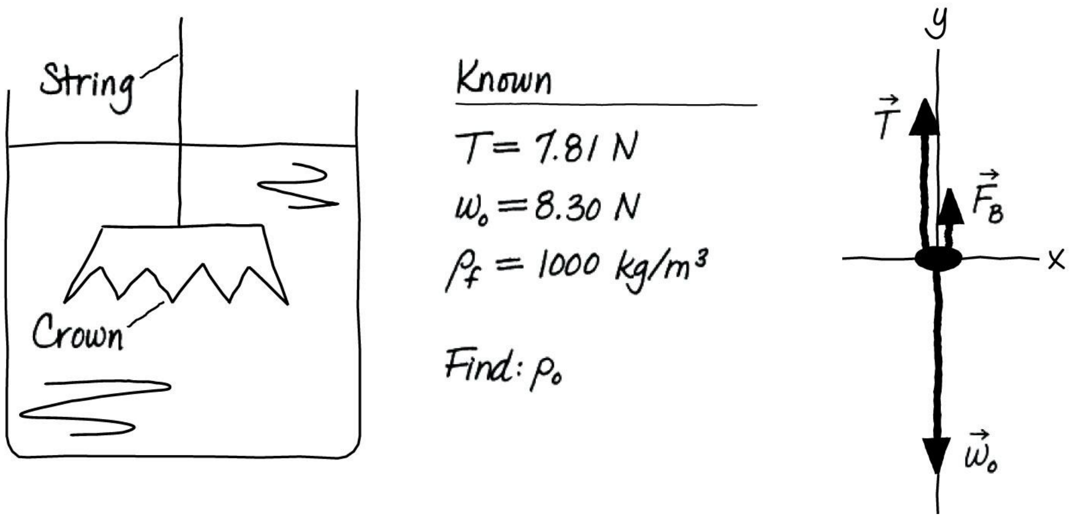
or, solving for ρ_o,

$$\rho_o = \frac{\rho_f w_o}{F_B} = \frac{(1000\ \text{kg/m}^3)(8.30\ \text{N})}{0.49\ \text{N}} = 17{,}000\ \text{kg/m}^3$$



Example 13.6 Is the crown gold? (cont.)

The crown's density is considerably lower than that of pure gold, which is 19,300 kg/m3. The crown is not pure gold.



ASSESS For an object made of a dense material such as gold, the buoyant force is small compared to its weight.

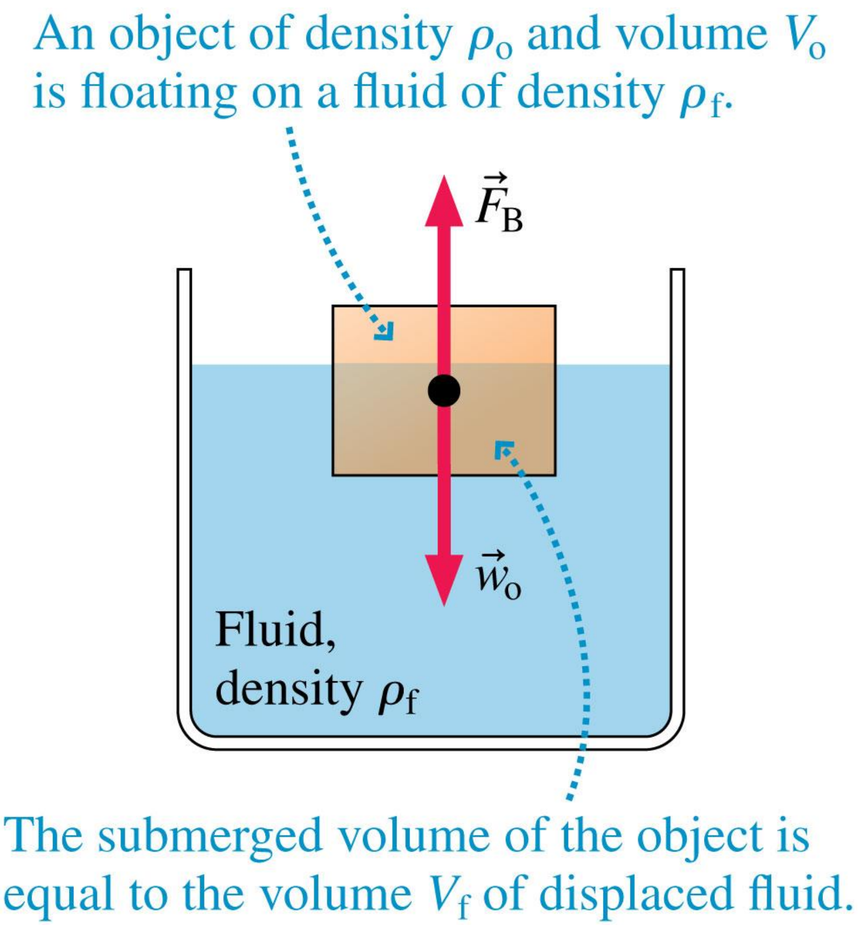
Float or Sink?

- Whether an object released underwater will head to the surface or to the bottom depends on whether the upward buoyant force on the object is larger or smaller than the downward weight force.

- Some objects are not uniform. We therefore define the **average density** to be $\rho_{avg} = m_o/V_o$. The weight of a compound object can be written as $w_o = \rho_{avg}V_o g$.

Float or Sink?

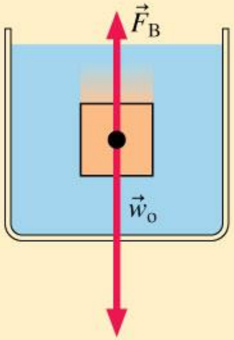
- An object will float or sink depending on whether the fluid density is larger or smaller than the object's average density.
- If the densities are equal, the object is in static equilibrium and hangs motionless. This is called **neutral buoyancy**.



Float or Sink?

TACTICS BOX 13.2 **Finding whether an object floats or sinks**

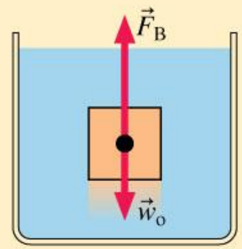
❶ Object sinks



An object sinks if it weighs more than the fluid it displaces—that is, if its average density is greater than the density of the fluid:

$$\rho_{avg} > \rho_f$$

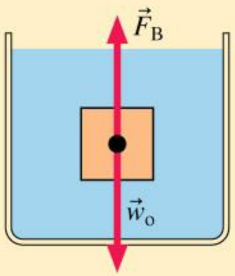
❷ Object floats



An object rises to the surface if it weighs less than the fluid it displaces—that is, if its average density is less than the density of the fluid:

$$\rho_{avg} < \rho_f$$

❸ Object has neutral buoyancy



An object hangs motionless if it weighs exactly the same as the fluid it displaces—that is, if its average density equals the density of the fluid:

$$\rho_{avg} = \rho_f$$

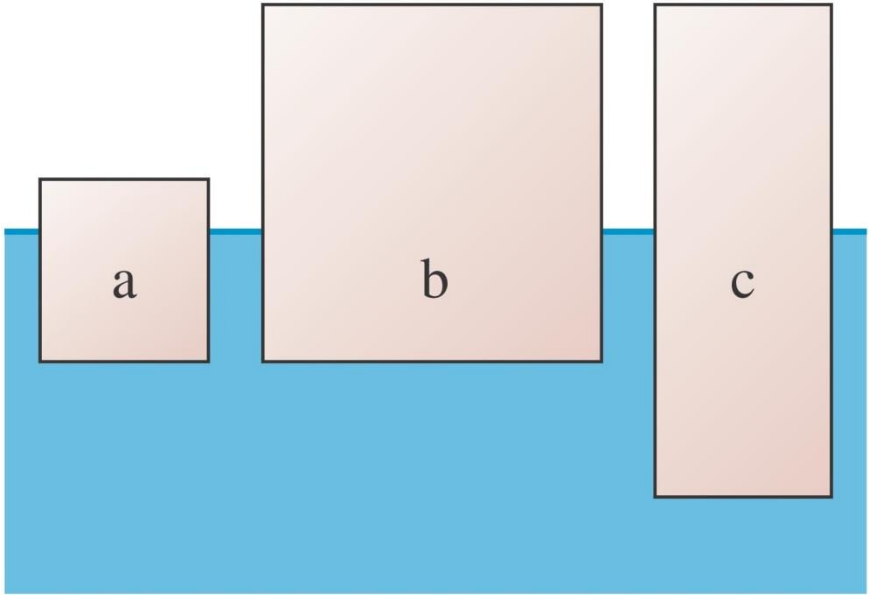
Exercises 10–12

Text: p. 410

QuickCheck 13.7

Which floating block is most dense?

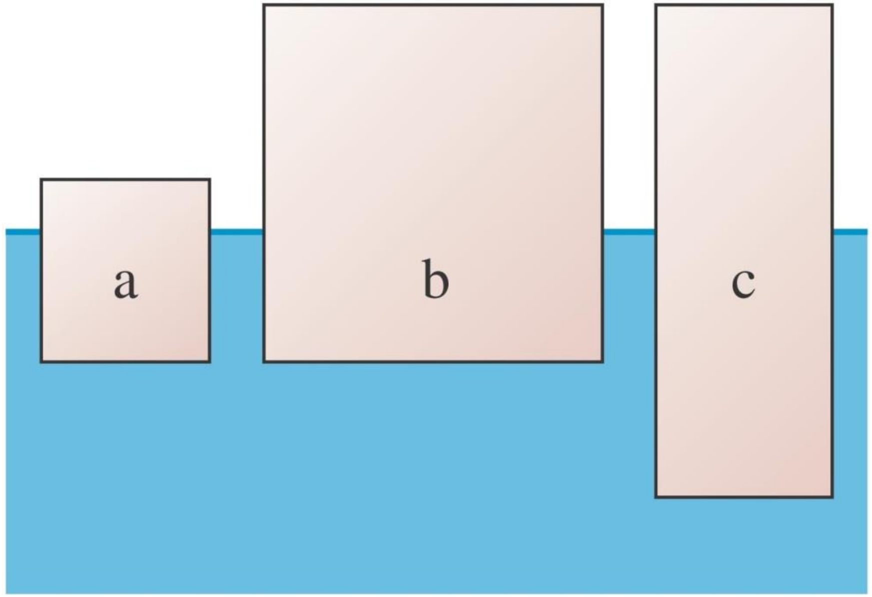
A. Block a
B. Block b
C. Block c
D. Blocks a and b are tied.
E. Blocks b and c are tied.



QuickCheck 13.7

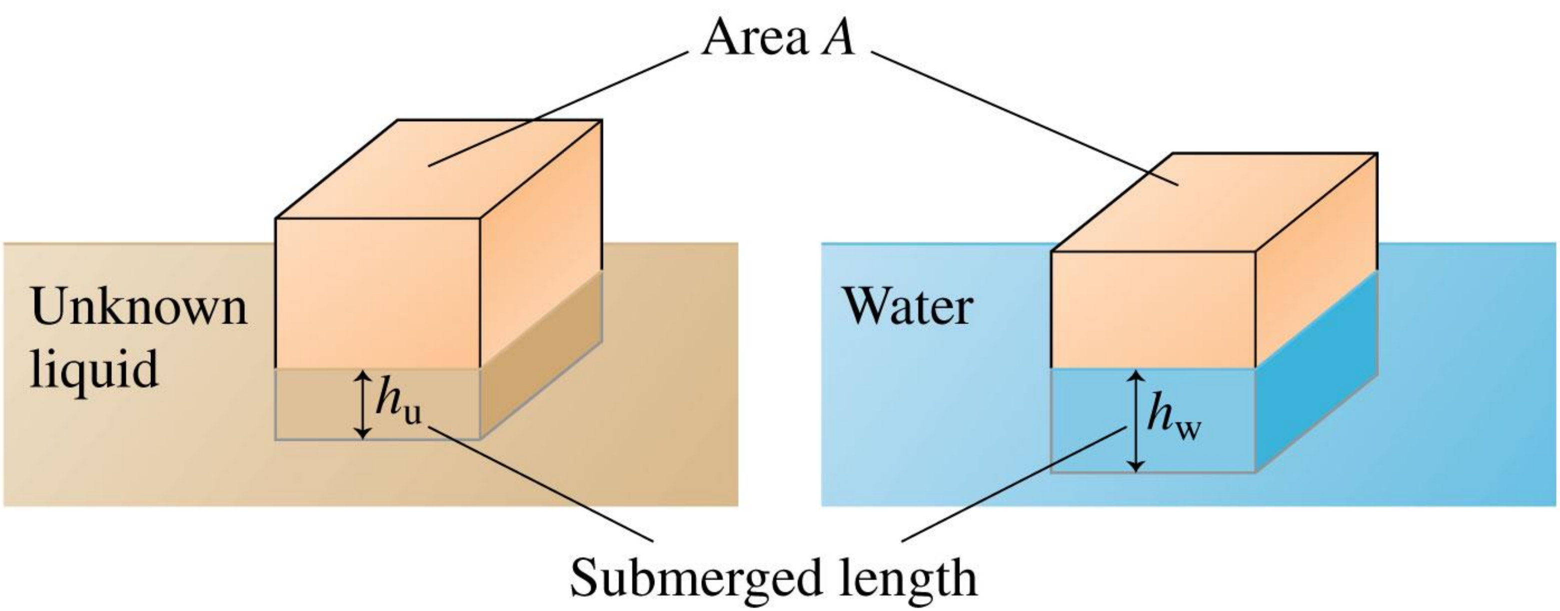
Which floating block is most dense?

A. Block a
B. Block b
C. Block c
D. Blocks a and b are tied.
E. Blocks b and c are tied.



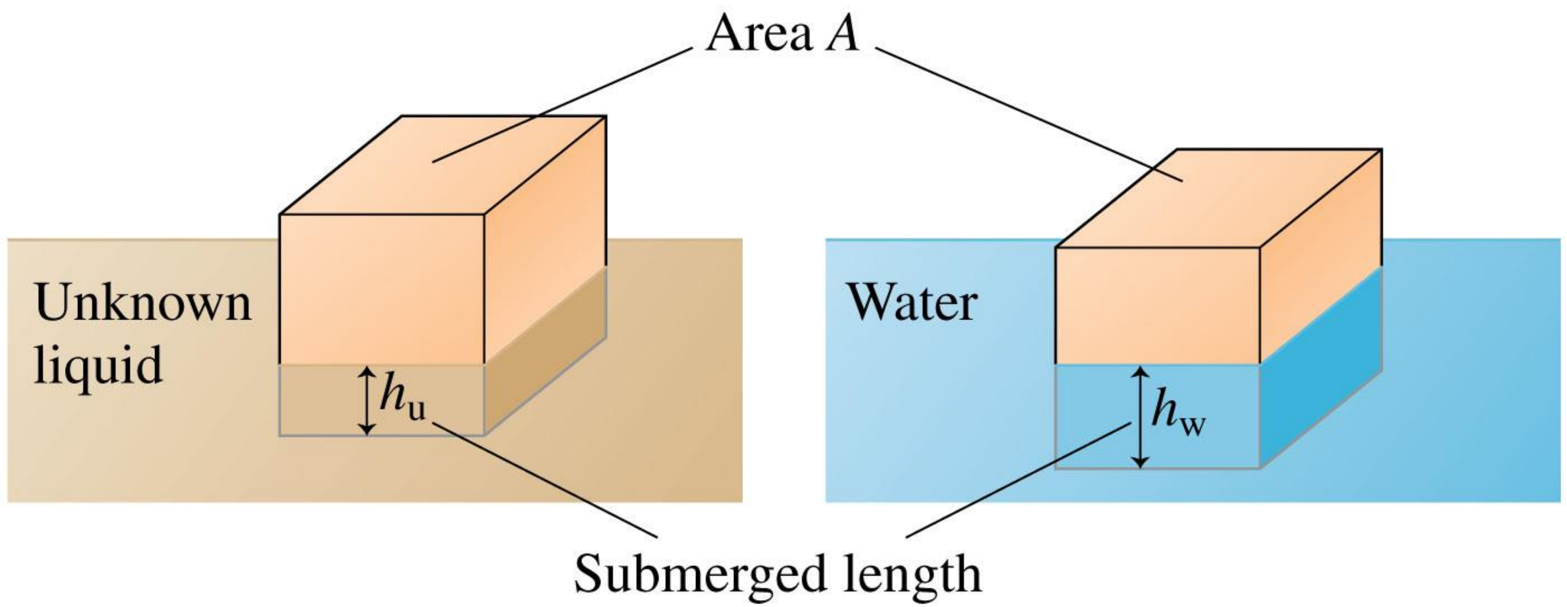
Example 13.8 Measuring the density of an unknown liquid

You need to determine the density of an unknown liquid. You notice that a block floats in this liquid with 4.6 cm of the side of the block submerged. When the block is placed in water, it also floats but with 5.8 cm submerged. What is the density of the unknown liquid?



Example 13.8 Measuring the density of an unknown liquid (cont.)

PREPARE Assume that the block is an object of uniform composition. **FIGURE 13.19** shows the block as well as the cross-section area A and submerged lengths h_u in the unknown liquid and h_w in water.



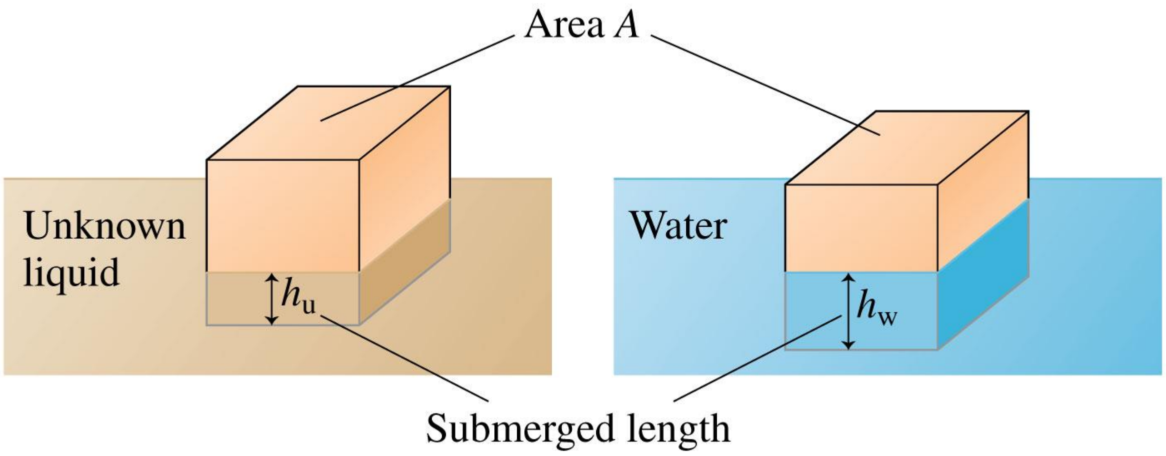
Example 13.8 Measuring the density of an unknown liquid (cont.)

SOLVE The block is floating, so Equation 13.10 applies. The block displaces volume $V_u = Ah_u$ of the unknown liquid. Thus

$$V_u = Ah_u = \frac{\rho_o}{\rho_u} V_o$$

Similarly, the block displaces volume $V_w = Ah_w$ of the water, leading to

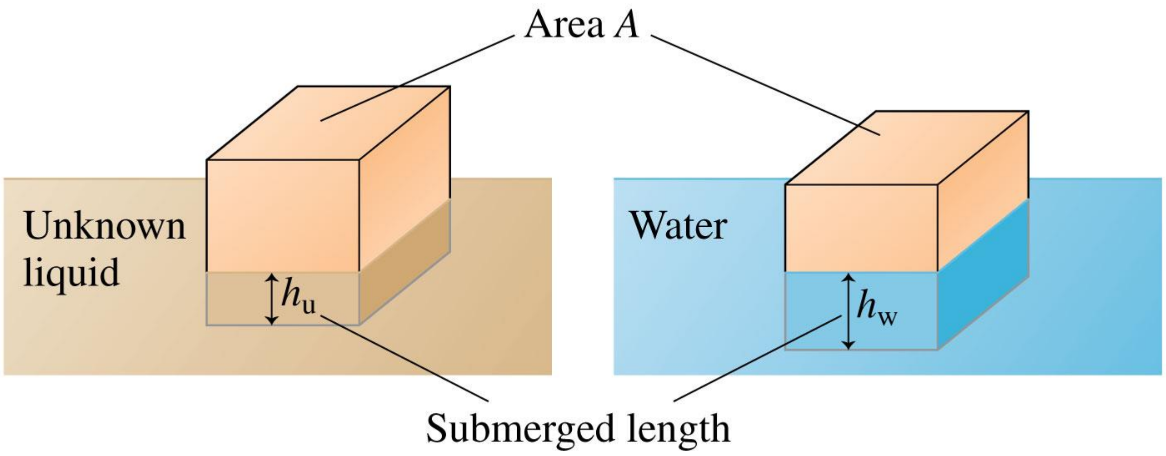
$$V_w = Ah_w = \frac{\rho_o}{\rho_w} V_o$$



Example 13.8 Measuring the density of an unknown liquid (cont.)

Because there are two fluids, we've used subscripts w for water and u for the unknown in place of the fluid subscript f. The product $\rho_o V_o$ appears in both equations. In the first $\rho_o V_o = \rho_u A h_u$, and in the second $\rho_o V_o = \rho_w A h_w$. Equating the right-hand sides gives

$$\rho_u A h_u = \rho_w A h_w$$

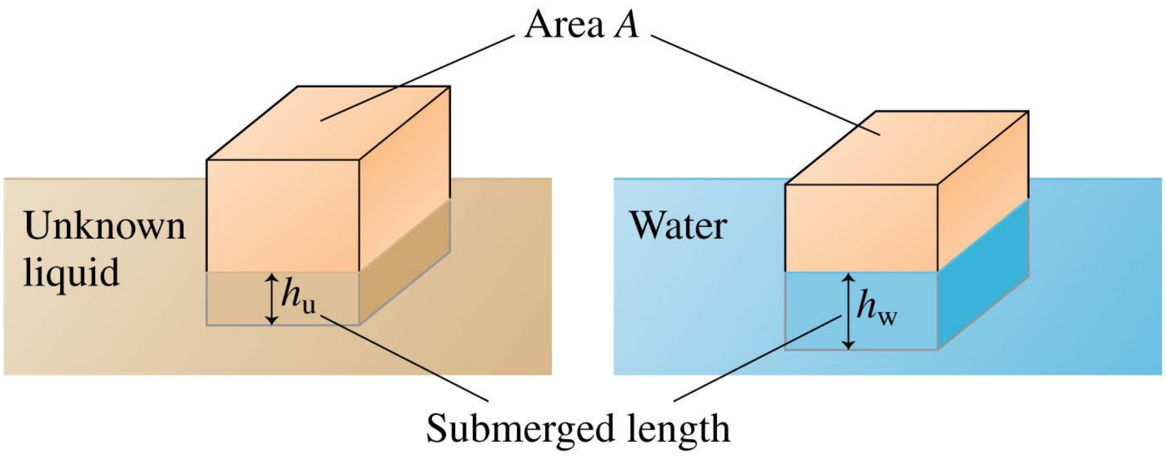


Example 13.8 Measuring the density of an unknown liquid (cont.)

The area A cancels, and the density of the unknown liquid is

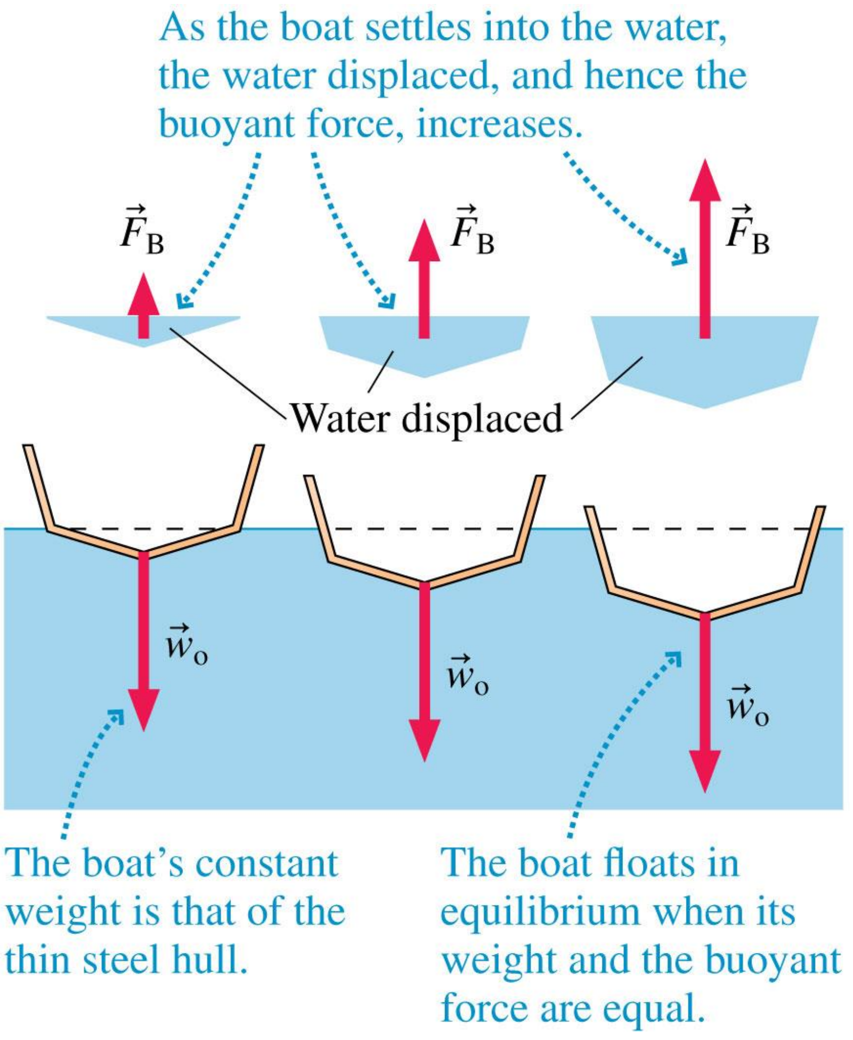
$$\rho_u = \frac{h_w}{h_u}\rho_w = \frac{5.8\text{ cm}}{4.6\text{ cm}}1000\text{ kg/m}^3 = 1300\text{ kg/m}^3$$

ASSESS Comparison with Table 13.1 shows that the unknown liquid is likely to be glycerin.



Boats and Balloons

- The hull of a boat is really a hollow shell, so the volume of water displaced by the shell is *much* larger than the volume of the hull itself.
- The boat sinks until the weight of the displaced water exactly matches the boat's weight. It is then in static equilibrium and floats.



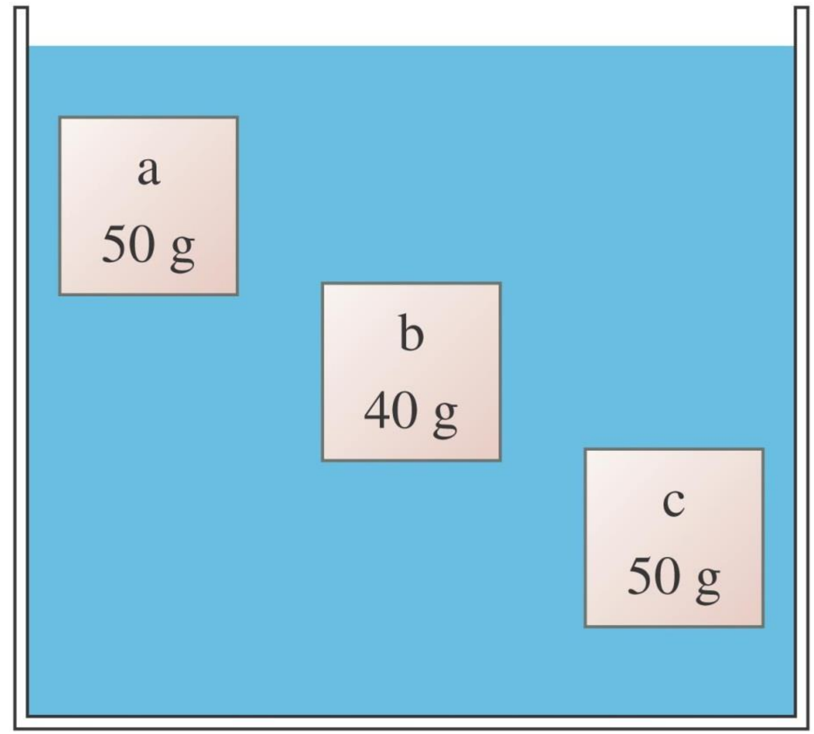
Boats and Balloons

- The density of air is low so the buoyant force is generally negligible.
- Balloons cannot be filled with regular air because it would weigh the same amount as the displaced air and therefore have no net upward force.

- For a balloon to float, it must be filled with a gas that has a *lower* density than that of air.

QuickCheck 13.8

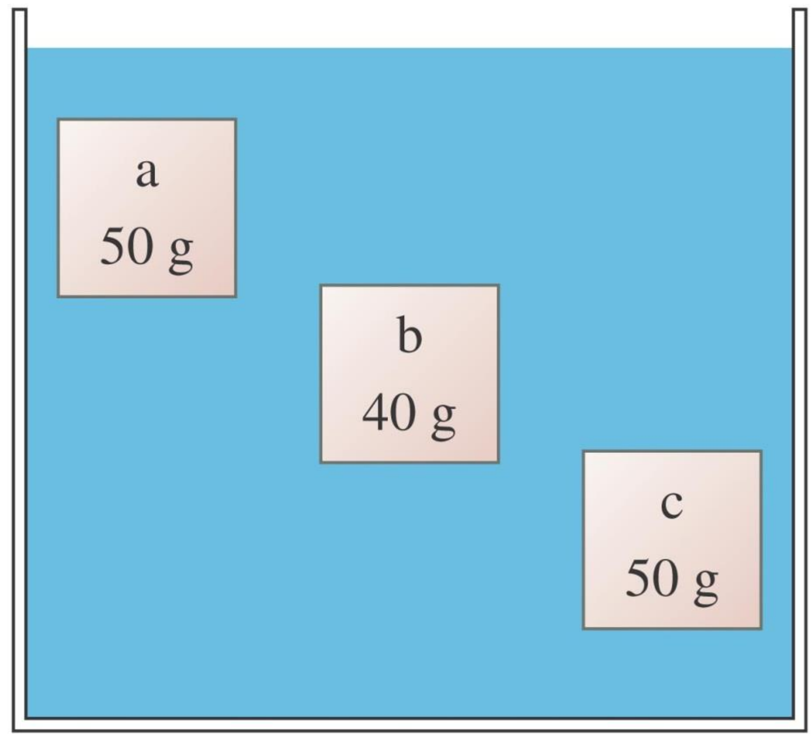
Blocks a, b, and c are all the same size. Which experiences the largest buoyant force?



A. Block a
B. Block b
C. Block c
D. All have the same buoyant force.
E. Blocks a and c have the same buoyant force, but the buoyant force on block b is different.

QuickCheck 13.8

Blocks a, b, and c are all the same size. Which experiences the largest buoyant force?

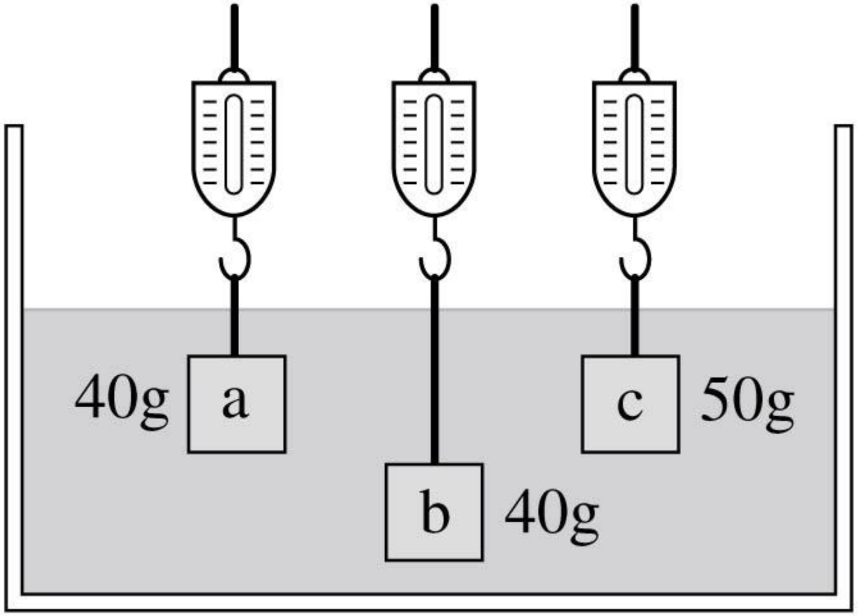


A. Block a
B. Block b
C. Block c
D. All have the same buoyant force.
E. Blocks a and c have the same buoyant force, but the buoyant force on block b is different.

QuickCheck 13.9

Blocks a, b, and c are all the same size. Which is the correct order of the scale readings?

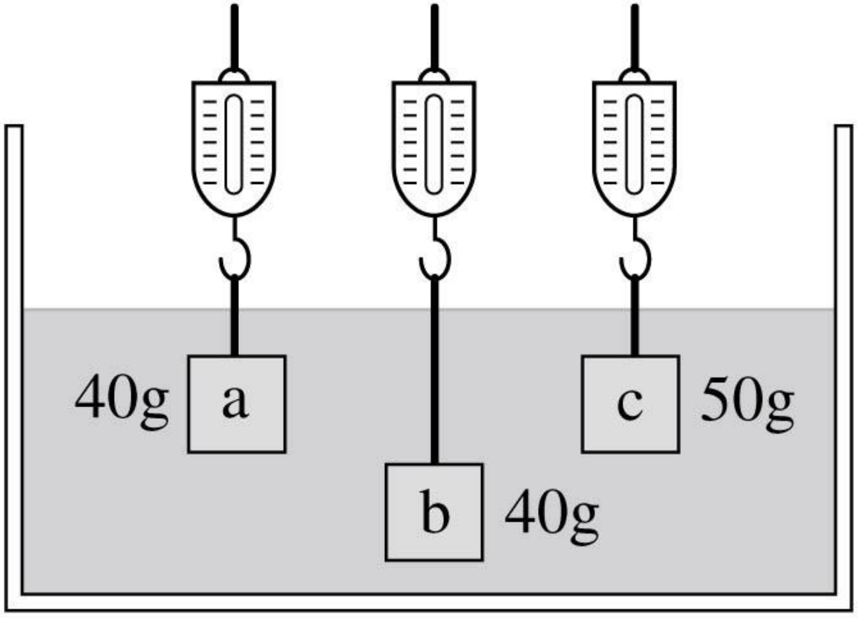
A. a = b = c
B. c > a = b
C. c > a > b
D. b > c > a
E. a = c > b



QuickCheck 13.9

Blocks a, b, and c are all the same size. Which is the correct order of the scale readings?

A. a = b = c
B. c > a = b
C. c > a > b
D. b > c > a
E. a = c > b



Example Problem

The envelope of a typical hot air balloon has a volume of 2500 m^3. Assume that such a balloon is flying in Fort Collins, Colorado, where the density of air is approximately 1.0 kg/m^3.

A. What mass of air does the balloon displace?
B. If heated to the maximum temperature, the air inside the balloon has a density of about 80% that of the surrounding air. What is the mass of air in the balloon?
C. How much mass can the balloon lift?

Section 13.5 Fluids in Motion

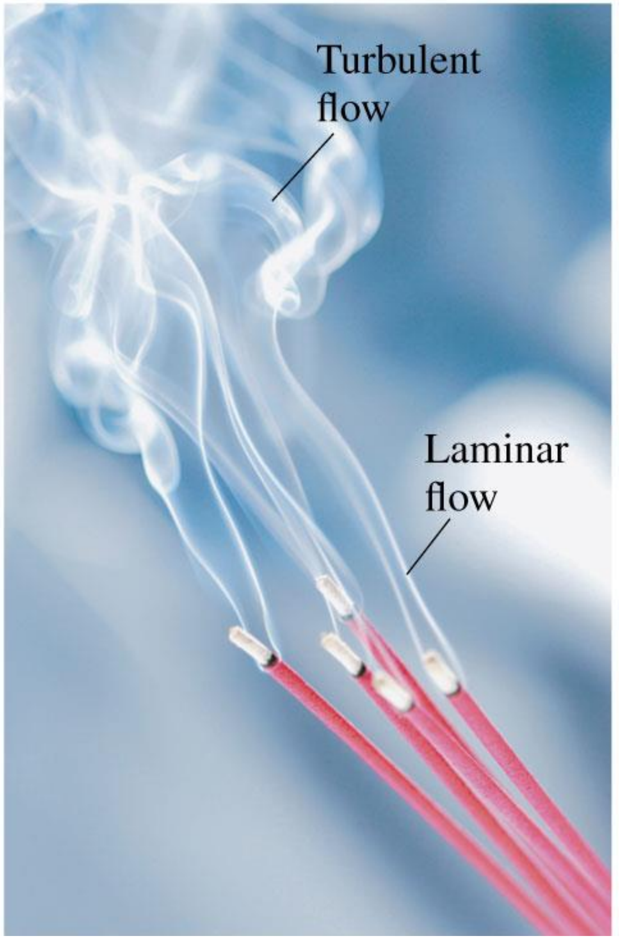
Fluids in Motion

For fluid *dynamics* we use a simplified *model* of an *ideal* fluid. We assume

1. The fluid is *incompressible*. This is a very good assumption for liquids, but it also holds reasonably well for a moving gas, such as air. For instance, even when a 100 mph wind slams into a wall, its density changes by only about 1%.
2. The flow is *steady*. That is, the fluid velocity at each point in the fluid is constant; it does not fluctuate or change with time. Flow under these conditions is called **laminar flow,** and it is distinguished from *turbulent flow*.
3. The fluid is *nonviscous*. Water flows much more easily than cold pancake syrup because the syrup is a very viscous liquid. Viscosity is resistance to flow, and assuming a fluid is nonviscous is analogous to assuming the motion of a particle is frictionless. Gases have very low viscosity, and even many liquids are well approximated as being nonviscous.

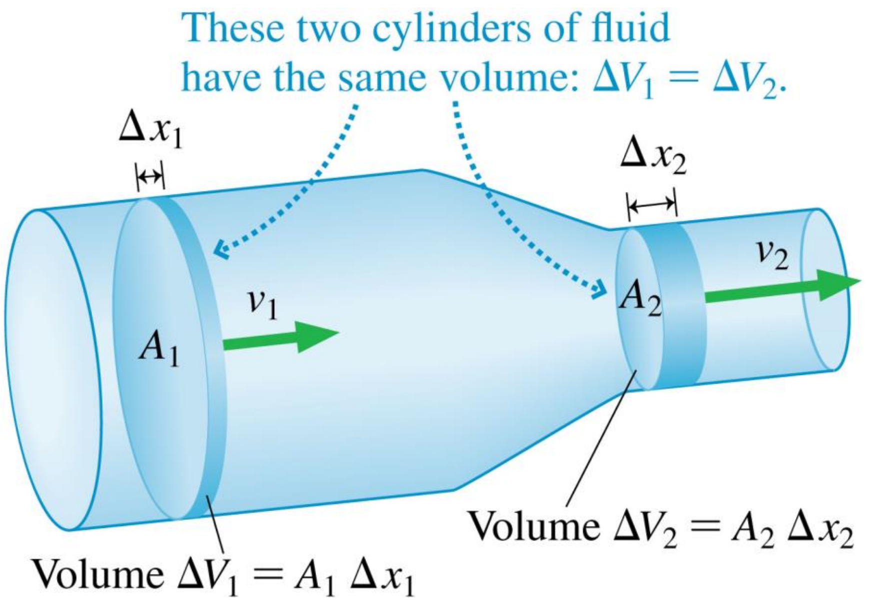
Fluids in Motion

- The rising smoke begins as laminar flow, recognizable by the smooth contours.
- At some point, the smoke undergoes a transition to turbulent flow.
- A laminar-to-turbulent transition is not uncommon in fluid flow.
- Our model of fluids can only be applied to laminar flow.



The Equation of Continuity

- When an incompressible fluid enters a tube, an equal volume of the fluid must leave the tube.
- The velocity of the molecules will change with different cross-section areas of the tube.



$$\Delta V_1 = A_1\,\Delta x_1 = A_1\,v_1\,\Delta t = \Delta V_2 = A_2\,\Delta x_2 = A_2\,v_2\,\Delta t$$

The Equation of Continuity

- Dividing both sides of the previous equation by Δt gives the **equation of continuity**:

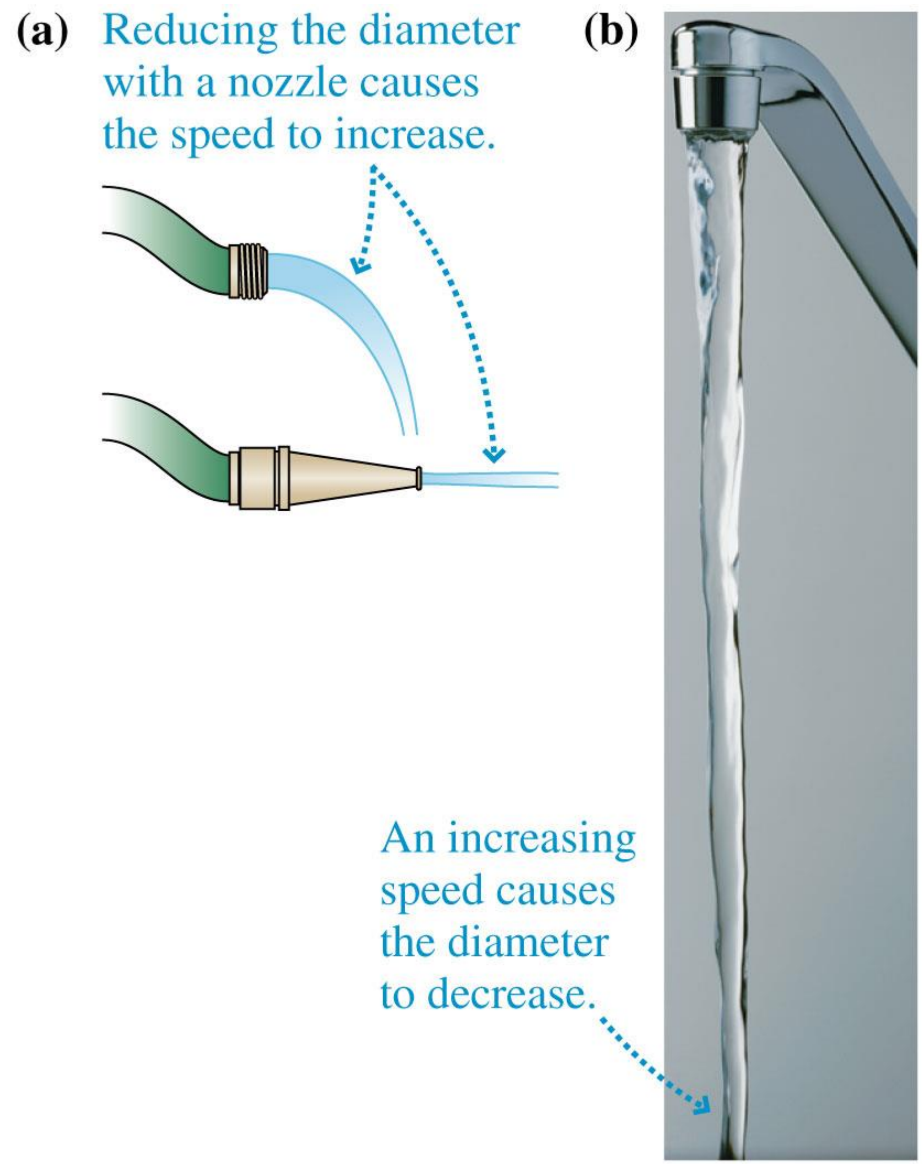
$$v_1 A_1 = v_2 A_2$$

The equation of continuity relating the speed v of an incompressible fluid to the cross-section area A of the tube in which it flows

- **The volume of an incompressible fluid entering one part of a tube or pipe must be matched by an equal volume leaving downstream.**
- A consequence of the equation of continuity is that **flow is faster in narrower parts of a tube, slower in wider parts.**

The Equation of Continuity

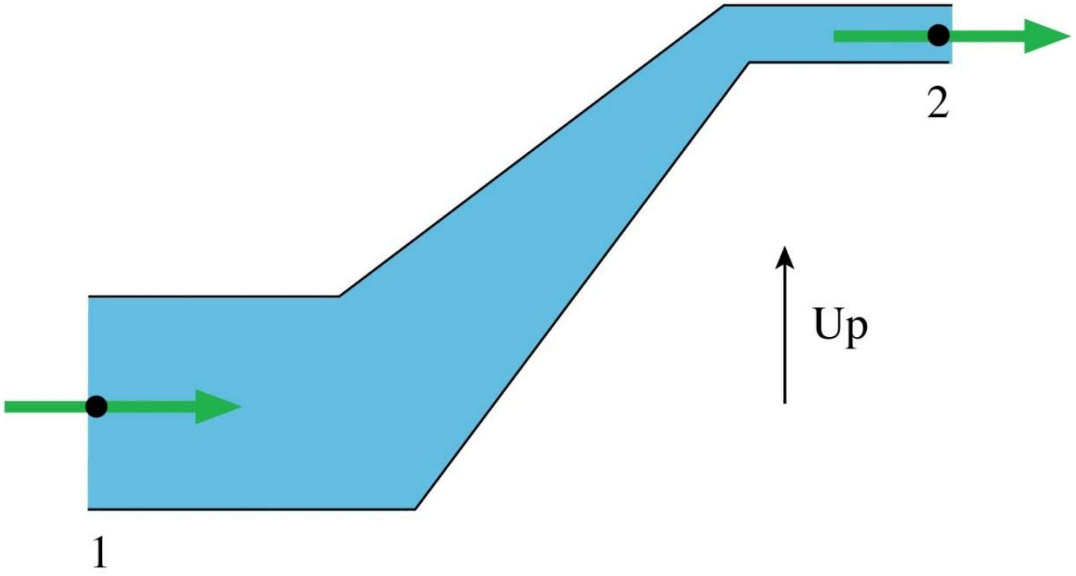
- The *rate* at which fluid flows through a tube (volume per second) is called the **volume flow rate** Q. The SI units of Q are m^3/s.
- Another way to express the meaning of the equation of continuity is to say that **the volume flow rate is constant at all points in the tube.**



QuickCheck 13.10

Water flows from left to right through this pipe. What can you say about the speed of the water at points 1 and 2?

A. $v_1 > v_2$
B. $v_1 = v_2$
C. $v_1 < v_2$

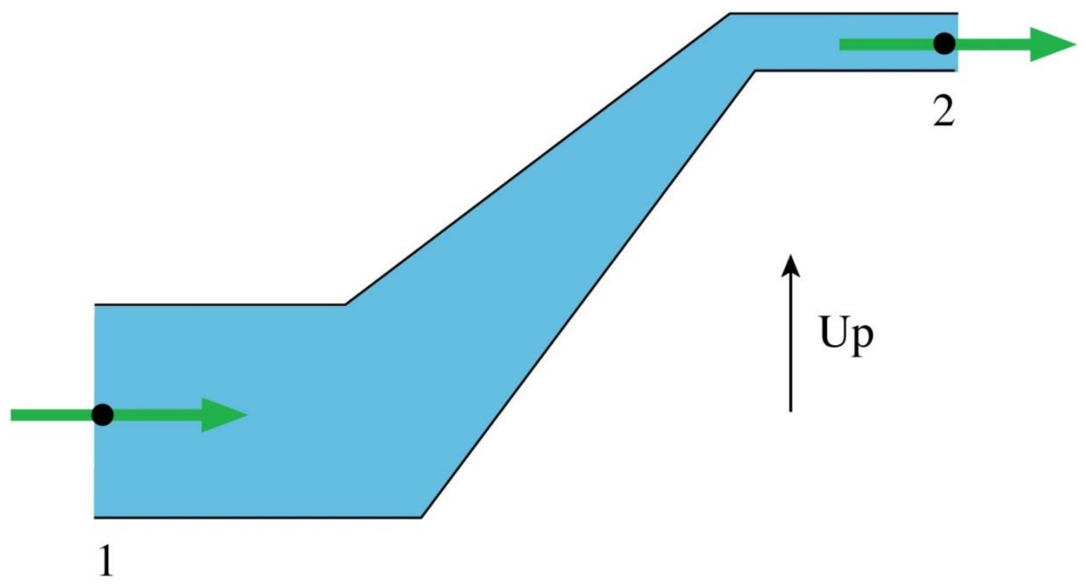


QuickCheck 13.10

Water flows from left to right through this pipe. What can you say about the speed of the water at points 1 and 2?

A. $v_1 > v_2$
B. $v_1 = v_2$
C. $v_1 < v_2$ ✔

Continuity: $v_1 A_1 = v_2 A_2$



Example 13.10 Speed of water through a hose

A garden hose has an inside diameter of 16 mm. The hose can fill a 10 L bucket in 20 s.

a. What is the speed of the water out of the end of the hose?

b. What diameter nozzle would cause the water to exit with a speed 4 times greater than the speed inside the hose?

PREPARE Water is essentially incompressible, so the equation of continuity applies.

Example 13.10 Speed of water through a hose (cont.)

SOLVE

a. The volume flow rate is $Q = \Delta V/\Delta t$ = (10 L)/(20 s) = 0.50 L/s. To convert this to SI units, recall that 1 L = 1000 mL = 10^3 cm^3 = 10^{-3} m^3. Thus Q = 5.0 × 10^{-4} m^3/s. We can find the speed of the water from Equation 13.13:

$$v = \frac{Q}{A} = \frac{Q}{\pi r^2} = \frac{5.0 \times 10^{-4}\ \mathrm{m^3/s}}{\pi(0.0080\ \mathrm{m})^2} = 2.5\ \mathrm{m/s}$$

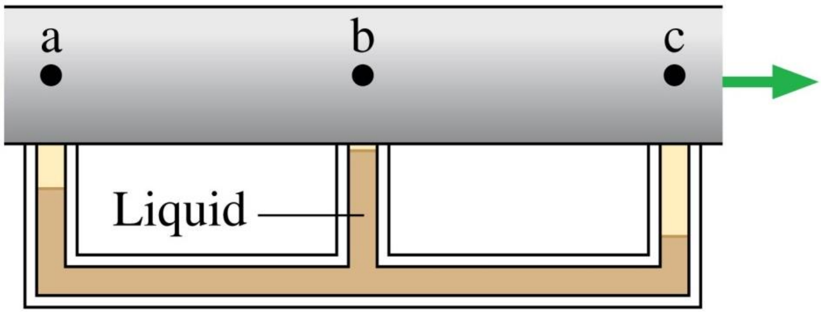
Example 13.10 Speed of water through a hose (cont.)

SOLVE

b. The quantity $Q = vA$ remains constant as the water flows through the hose and then the nozzle. To increase v by a factor of 4, A must be reduced by a factor of 4. The cross-section area depends on the square of the diameter, so the area is reduced by a factor of 4 if the diameter is reduced by a factor of 2. Thus the necessary nozzle diameter is 8 mm.

QuickCheck 13.11

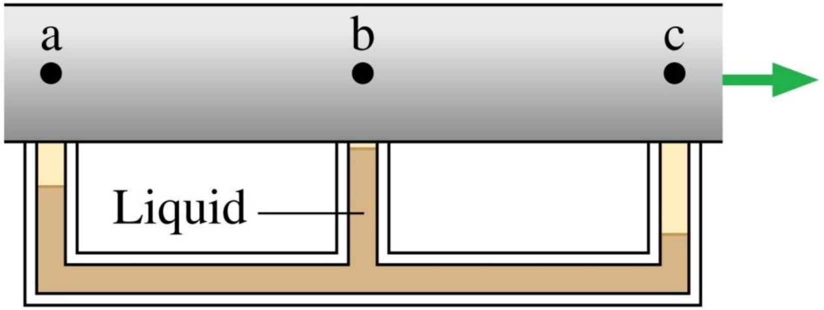
Gas flows from left to right through this pipe, whose interior is hidden. At which point does the pipe have the smallest inner diameter?



A. Point a
B. Point b
C. Point c
D. The diameter doesn't change.
E. Not enough information to tell.

QuickCheck 13.11

Gas flows from left to right through this pipe, whose interior is hidden. At which point does the pipe have the smallest inner diameter?



A. Point a

B. Point b

C. Point c

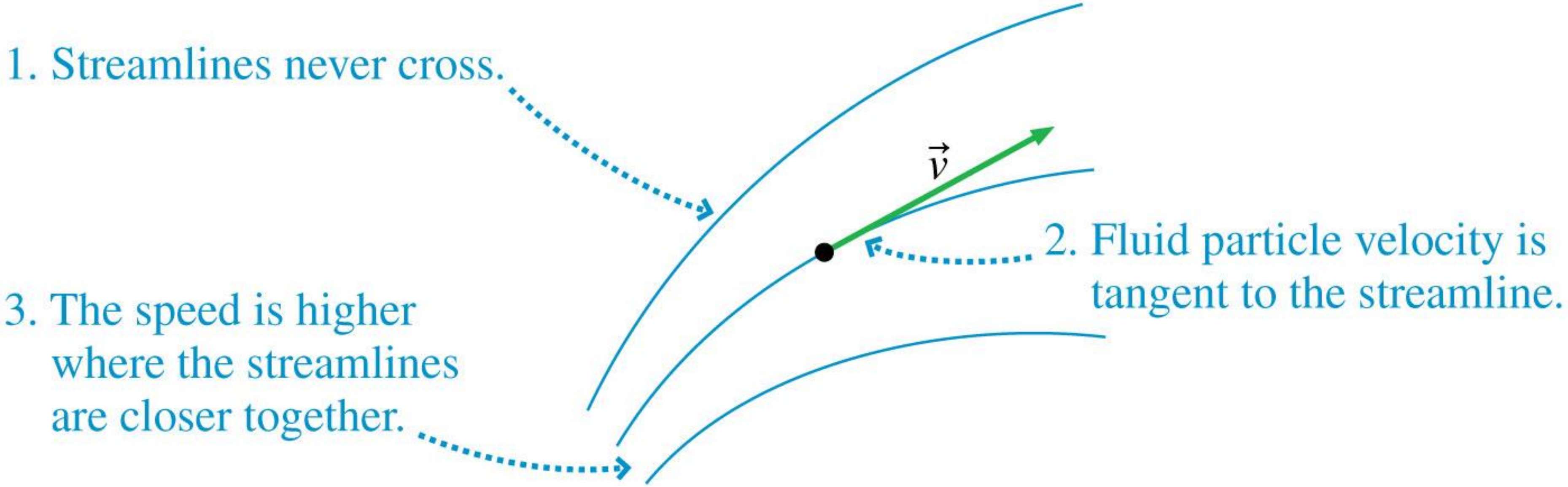
D. The diameter doesn't change.

E. Not enough information to tell.

Smallest pressure ⇨ fastest speed ⇨ smallest diameter

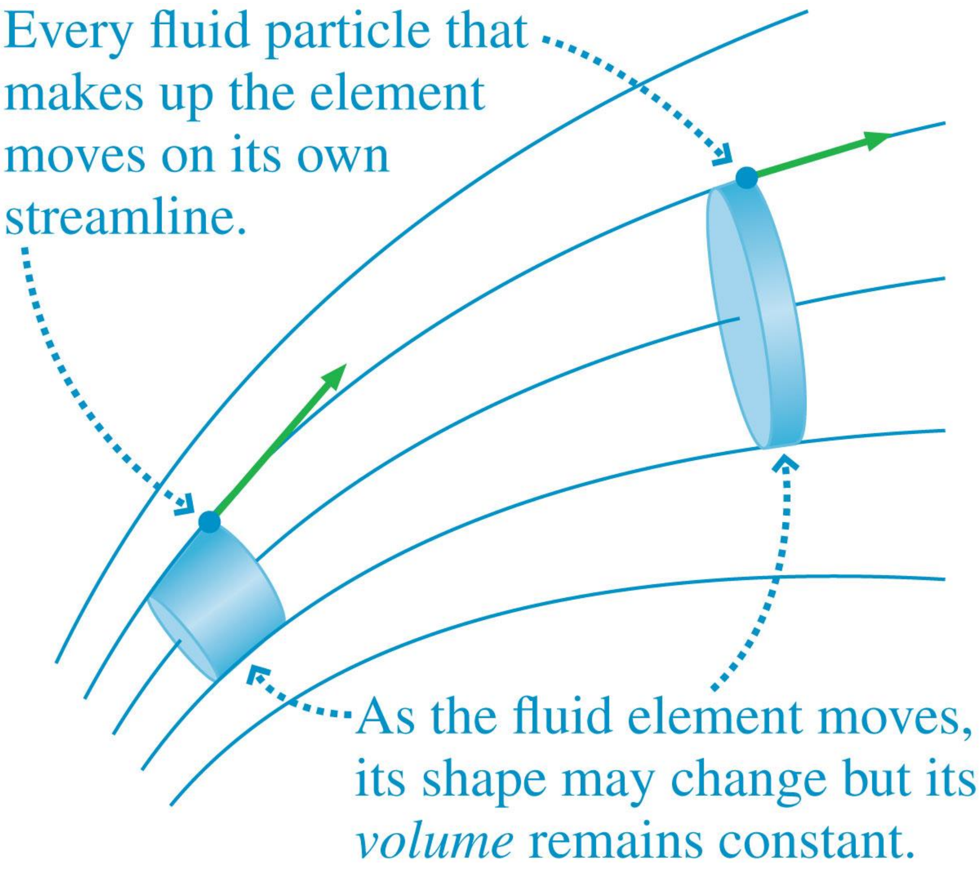
Representing Fluid Flow: Streamlines and Fluid Elements

- A **streamline** is the path or trajectory followed by a "particle of fluid".



Representing Fluid Flow: Streamlines and Fluid Elements

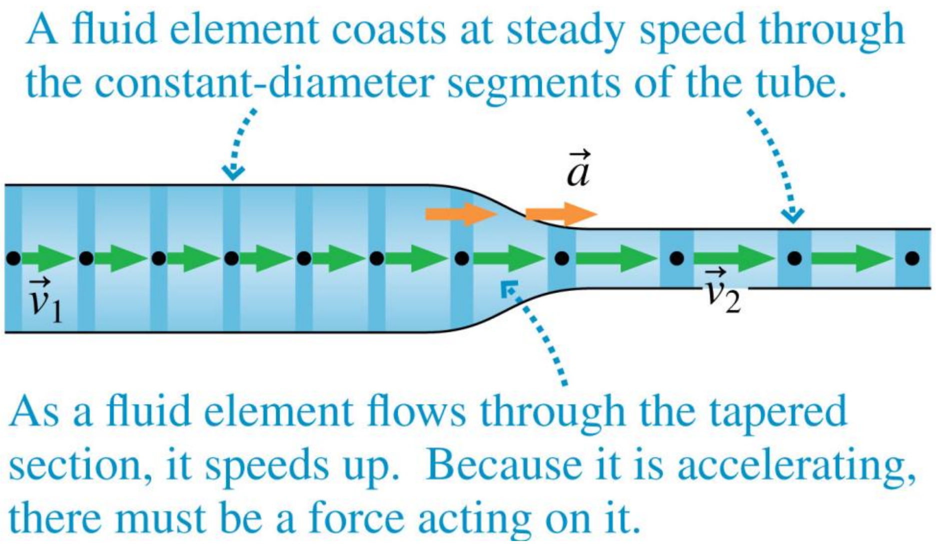
- A **fluid element** is a small *volume* of a fluid, a volume containing many particles of fluid.
- A fluid element has a shape and volume. The shape can change, but the volume is constant.



Section 13.6 Fluid Dynamics

Fluid Dynamics

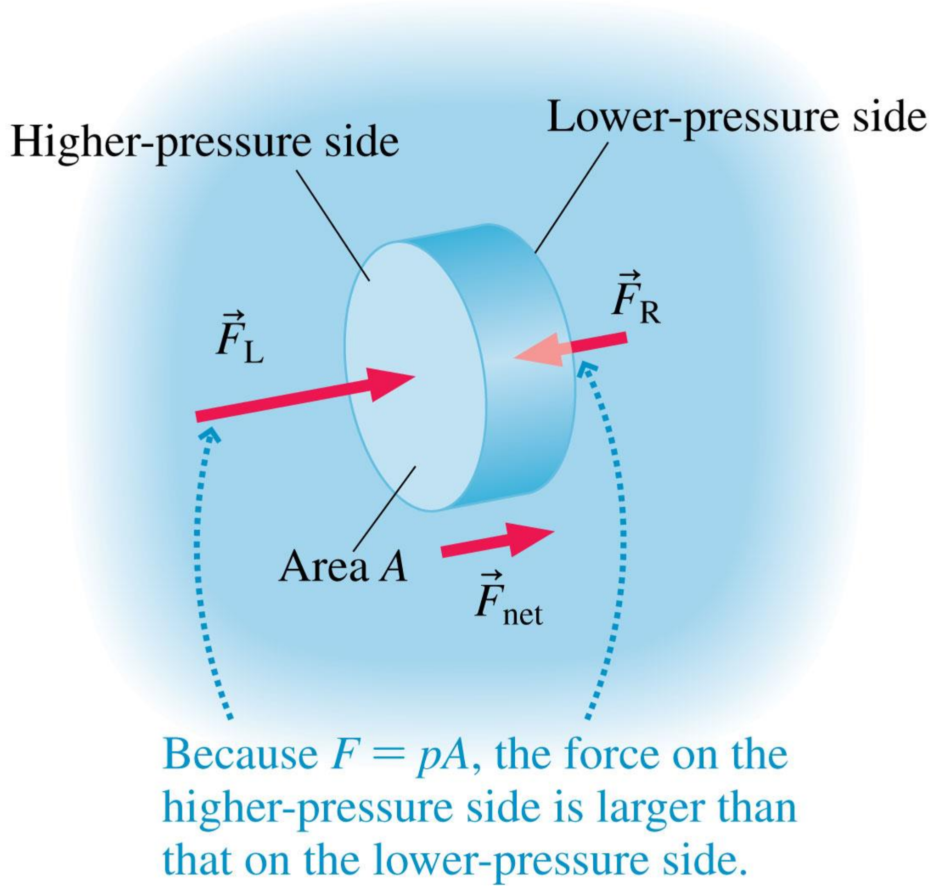
- A fluid element changes velocity as it moves from the wider part of a tube to the narrower part.
- This acceleration of the fluid element must be caused by a force.



- The fluid element is pushed from both ends by the *surrounding fluid*, that is, by *pressure forces*.

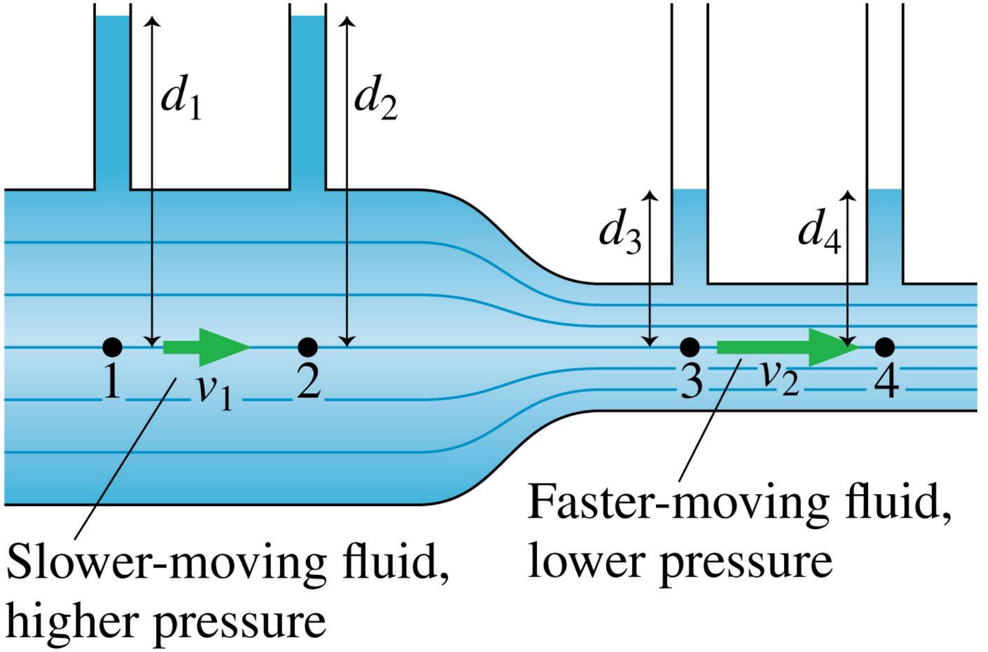
Fluid Dynamics

- To accelerate the fluid element, the pressure must be higher in the wider part of the tube.
- A **pressure gradient** is a region where there is a change in pressure from one point in the fluid to another.
- **An ideal fluid accelerates whenever there is a pressure gradient.**



Fluid Dynamics

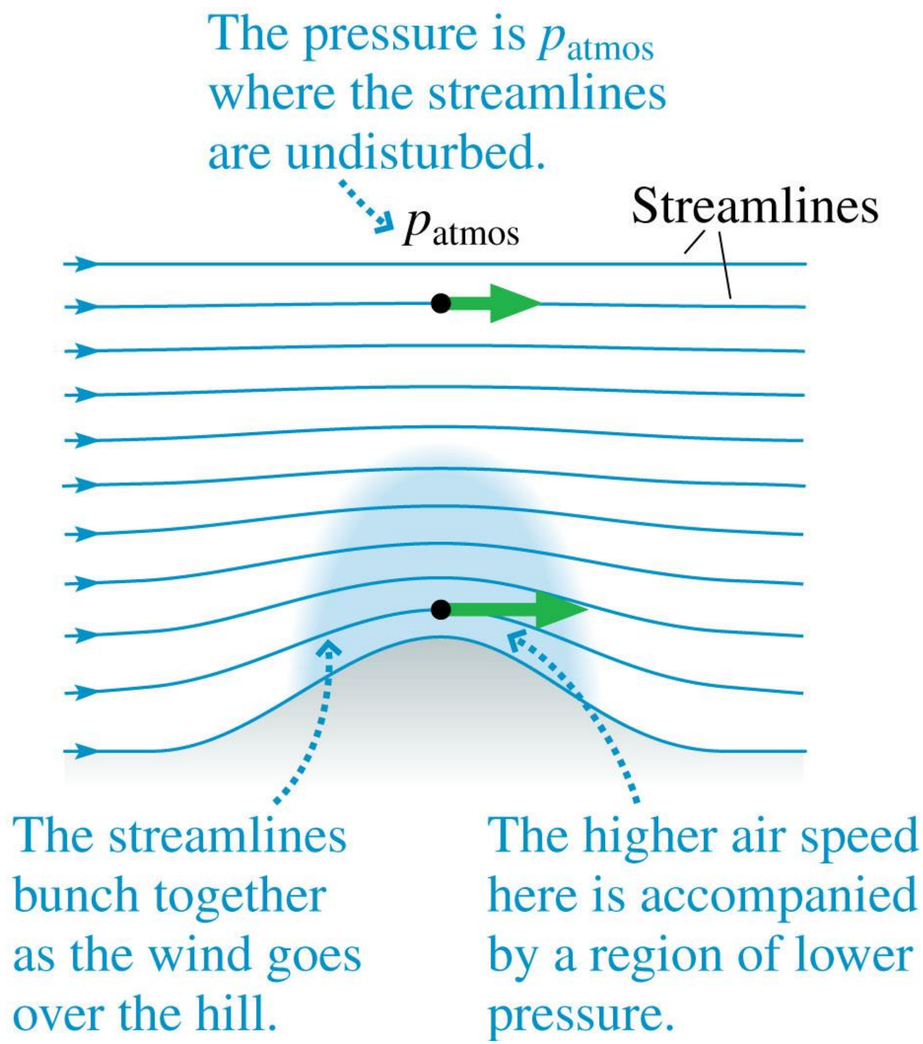
- **The pressure is higher at a point along a stream line where the fluid is moving slower, lower where the fluid is moving faster.**



- This property of fluids was discovered by Daniel Bernoulli and is called the **Bernoulli effect**.
- The speed of a fluid can be measured by a *Venturi tube*.

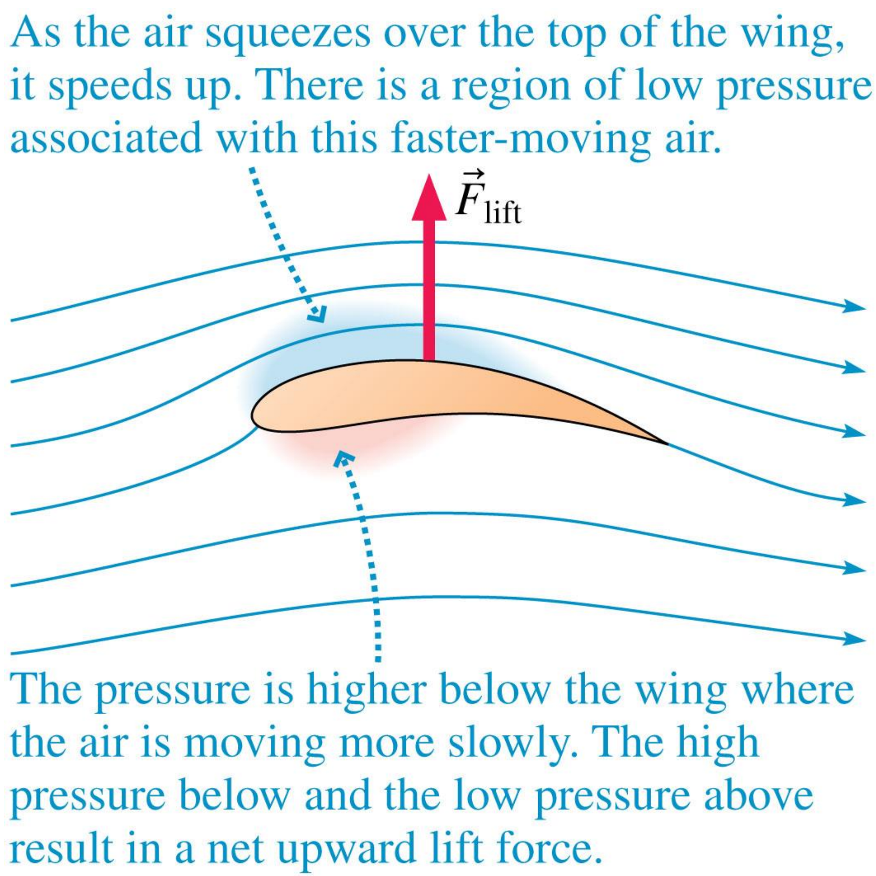
Applications of the Bernoulli Effect

- As air moves over a hill, the streamlines bunch together, so that the air speeds up. This means there must exist a zone of *low pressure* at the crest of the hill.



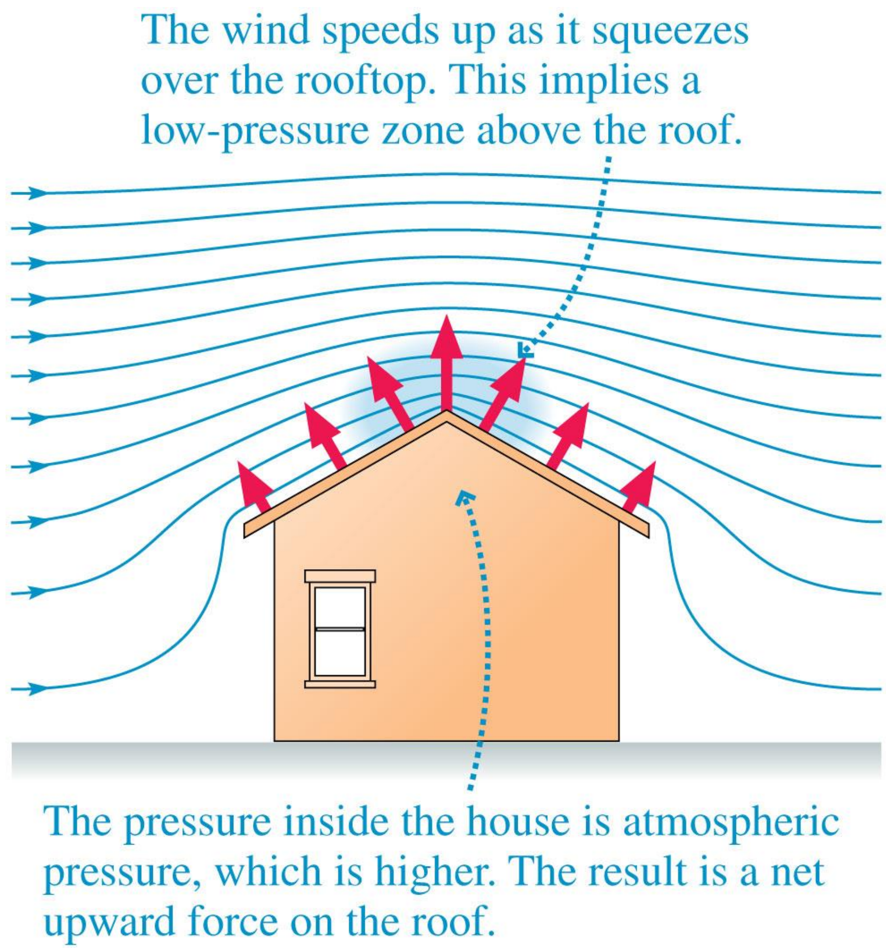
Applications of the Bernoulli Effect

- *Lift* is the upward force on the wing of an airplane that makes flight possible.
- The wing is designed such that above the wing the air speed increases and the pressure is low. Below the wing, the air is slower and the pressure is high.
- The high pressure below the wing pushes more strongly than the low pressure from above, causing lift.



Applications of the Bernoulli Effect

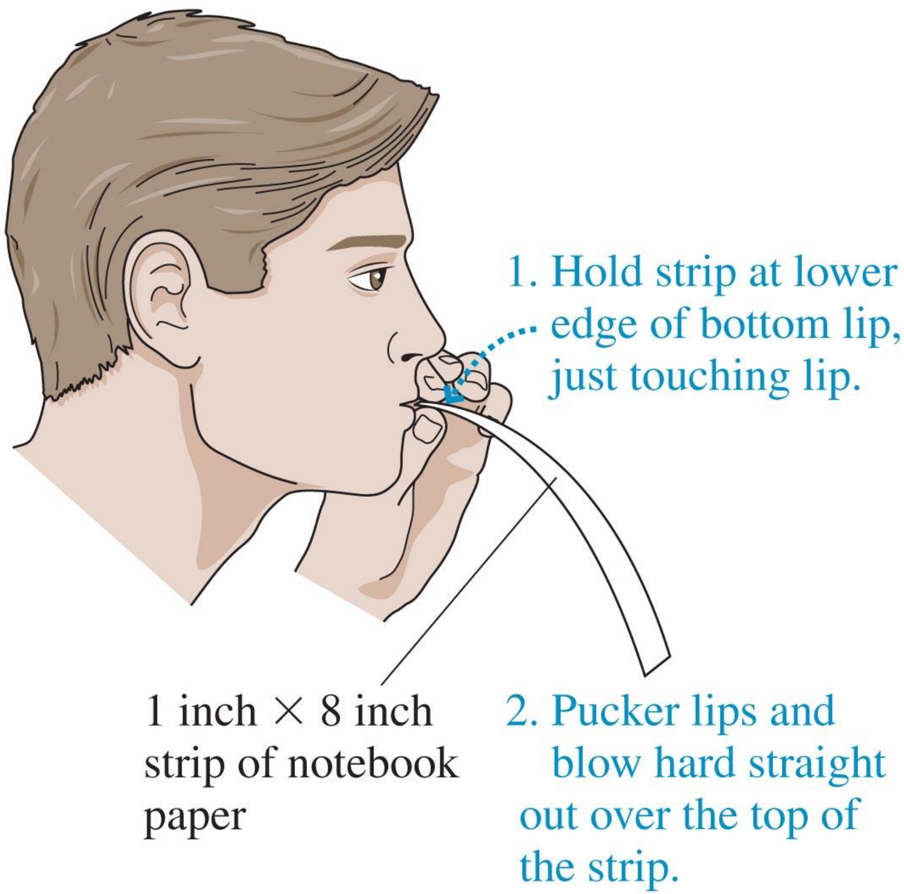
- In a hurricane, roofs are "lifted" off a house by pressure differences.
- The pressure differences are small but the force is proportional to the *area* of the roof.



Try It Yourself: Blowing Up

Try the experiment in the figure. You might expect the strip to be pushed *down* by the force of your breath, but you'll find that the strip actually *rises*.

Your breath moving over the curved strip is similar to wind blowing over a hill, and Bernoulli's effect likewise predicts a zone of lower pressure above the strip that causes it to rise.

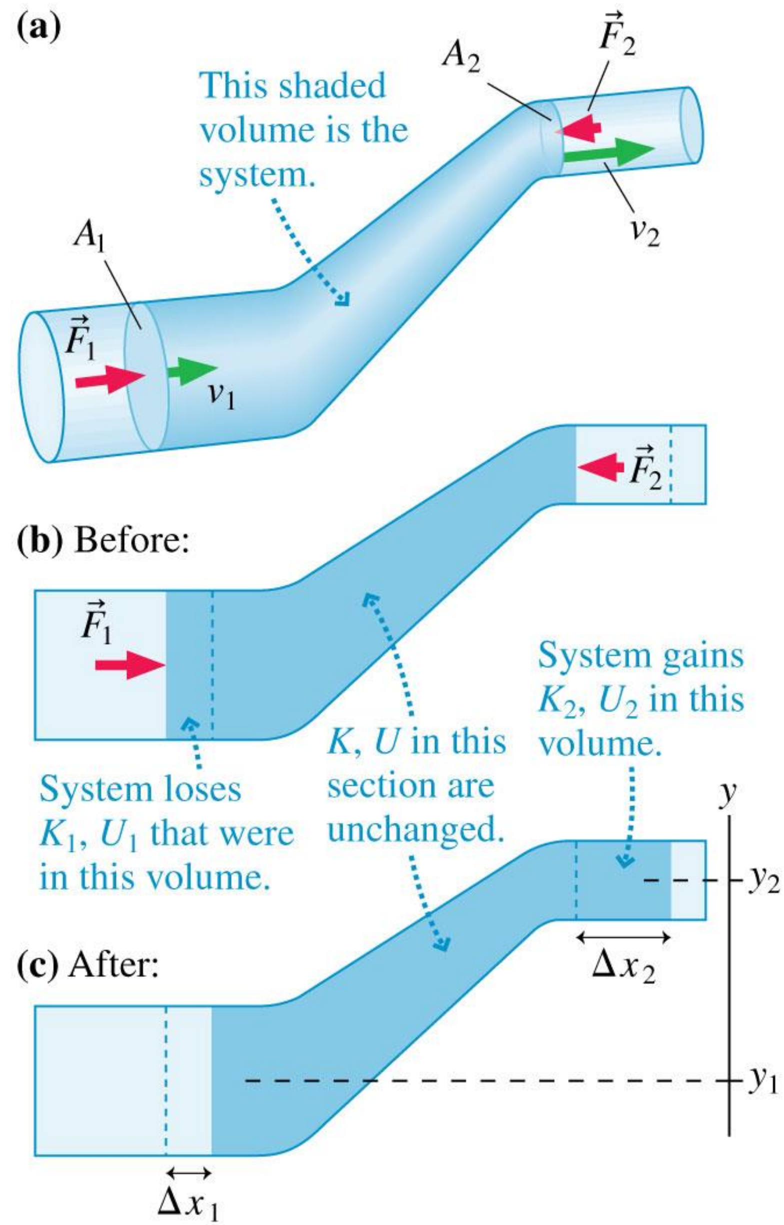


Bernoulli's Equation

- We can find a numerical relationship for pressure, height and speed of a fluid by applying conservation of energy:

$$\Delta K + \Delta U = W$$

- As a fluid moves through a tube of varying widths, parts of a segment of fluid will lose energy that the other parts of the fluid will gain.



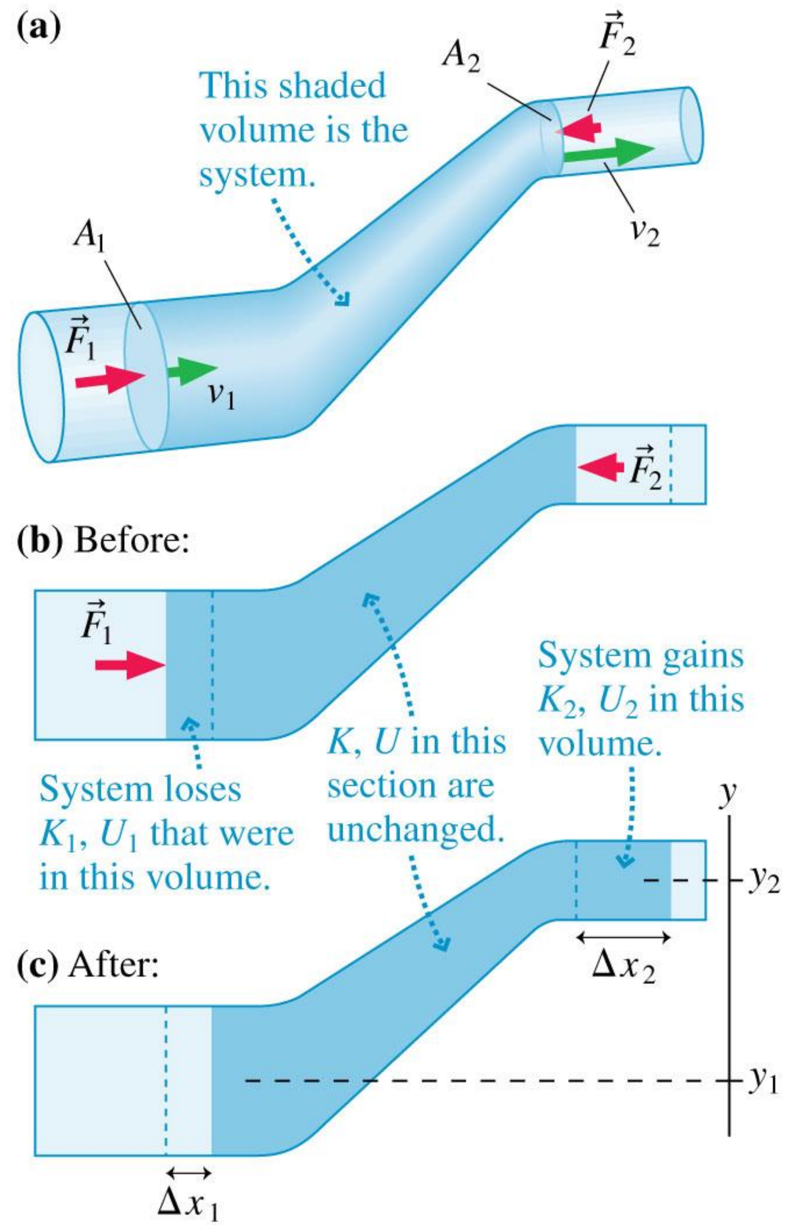
Bernoulli's Equation

- The system moves out of cylindrical volume V_1 and into V_2. The kinetic energies are

$$K_1 = \frac{1}{2}\underbrace{\rho\,\Delta V}_{m} v_1^2 \quad \text{and} \quad K_2 = \frac{1}{2}\underbrace{\rho\,\Delta V}_{m} v_2^2$$

- The *net* change in kinetic energy is

$$\Delta K = K_2 - K_1 = \frac{1}{2}\rho\,\Delta V v_2^2 - \frac{1}{2}\rho\,\Delta V v_1^2$$



Bernoulli's Equation

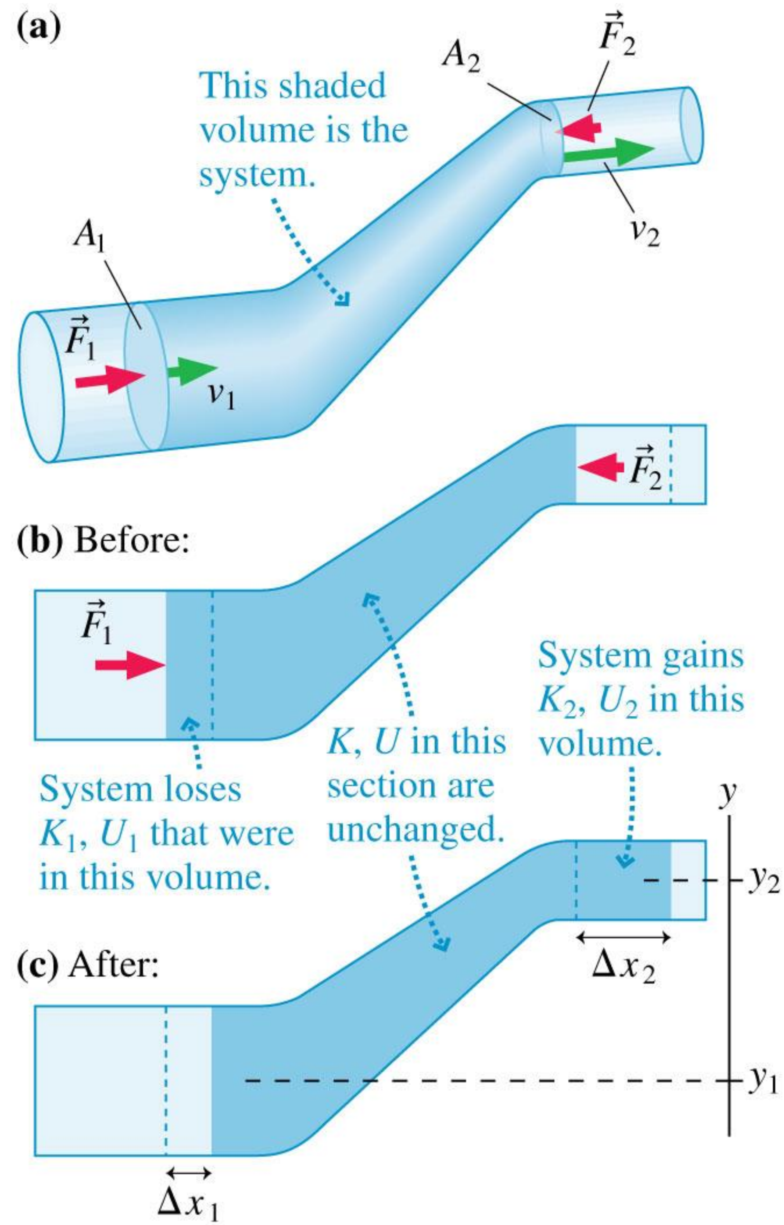
- The net change in gravitational potential energy is

$$\Delta U = U_2 - U_1 = \rho\,\Delta V g y_2 - \rho\,\Delta V g y_1$$

- The positive and negative work done are

$$W_1 = F_1\,\Delta x_1 = (p_1 A_1)\,\Delta x_1$$
$$= p_1\,(A_1\,\Delta x_1) = p_1\,\Delta V$$

$$W_2 = -F_2\,\Delta x_2 = -(p_2 A_2)\,\Delta x_2$$
$$= -p_2\,(A_2\,\Delta x_2) = -p_2\,\Delta V$$



Bernoulli's Equation

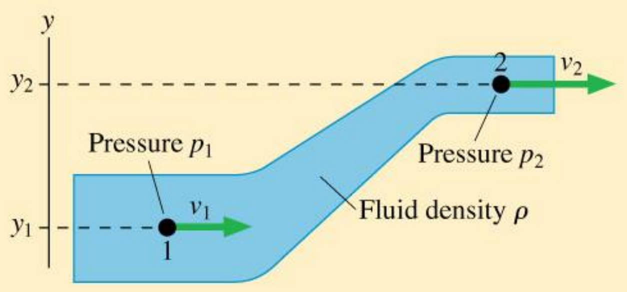
- The *net* work done on the system is:

$$W = W_1 + W_2 = p_1 \Delta V - p_2 \Delta V = (p_1 - p_2) \Delta V$$

- We combine the equations for kinetic energy, potential energy, and work done:

$$\underbrace{\frac{1}{2}\rho \Delta V v_2^2 - \frac{1}{2}\rho \Delta V v_1^2}_{\Delta K} + \underbrace{\rho \Delta V g y_2 - \rho \Delta V g y_1}_{\Delta U} = \underbrace{(p_1 - p_2) \Delta V}_{W}$$

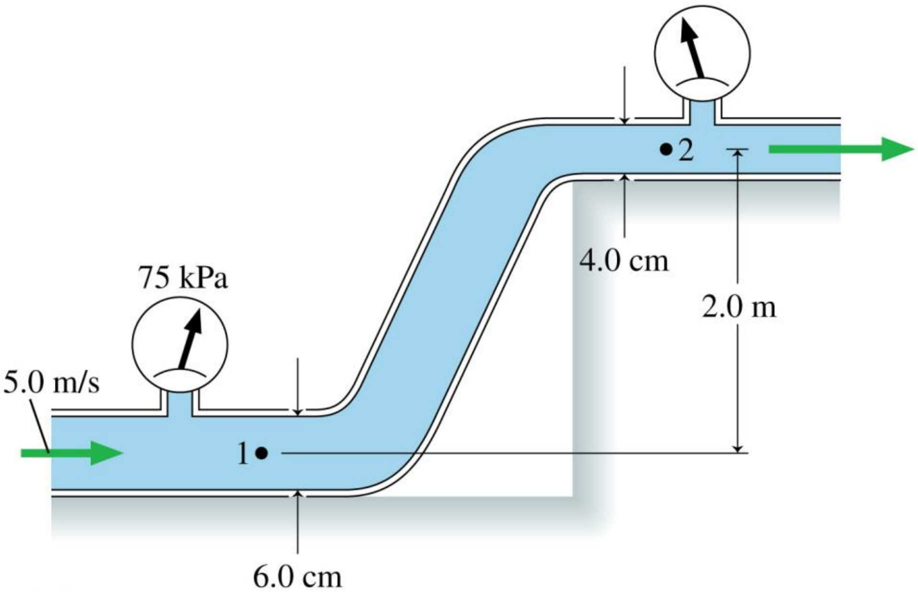
- Rearranged, this equation is **Bernoulli's equation**, which relates ideal-fluid quantities at two points along a streamline:



$$\underbrace{p_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2}_{\text{Pressure, speed, and height at point 2 are related to . . .}} = \underbrace{p_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1}_{\text{. . . pressure, speed, and height at point 1.}}$$

Example 13.12 Pressure in an irrigation system

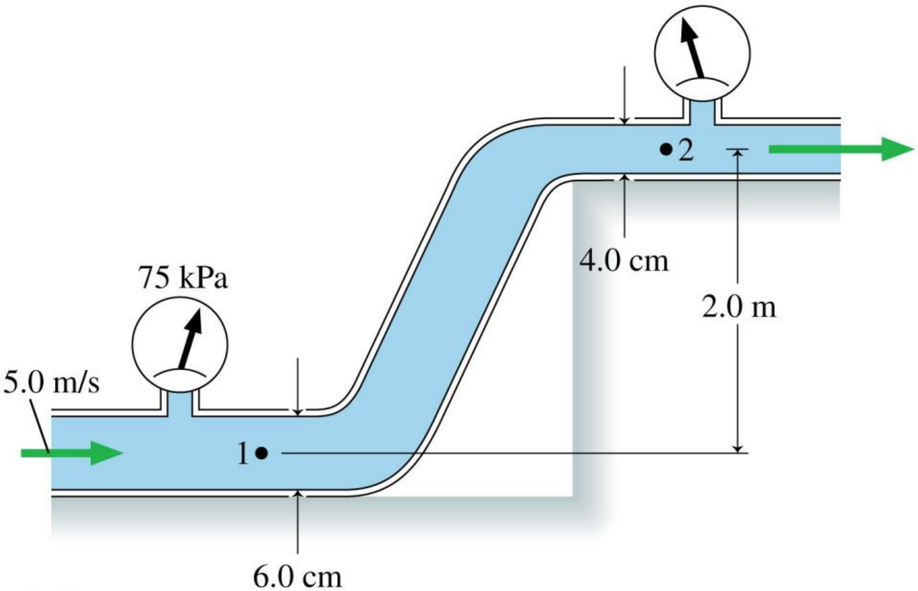
Water flows through the pipes shown in **FIGURE 13.35**. The water's speed through the lower pipe is 5.0 m/s, and a pressure gauge reads 75 kPa. What is the reading of the pressure gauge on the upper pipe?



PREPARE Treat the water as an ideal fluid obeying Bernoulli's equation. Consider a streamline connecting point 1 in the lower pipe with point 2 in the upper pipe.

Example 13.12 Pressure in an irrigation system (cont.)

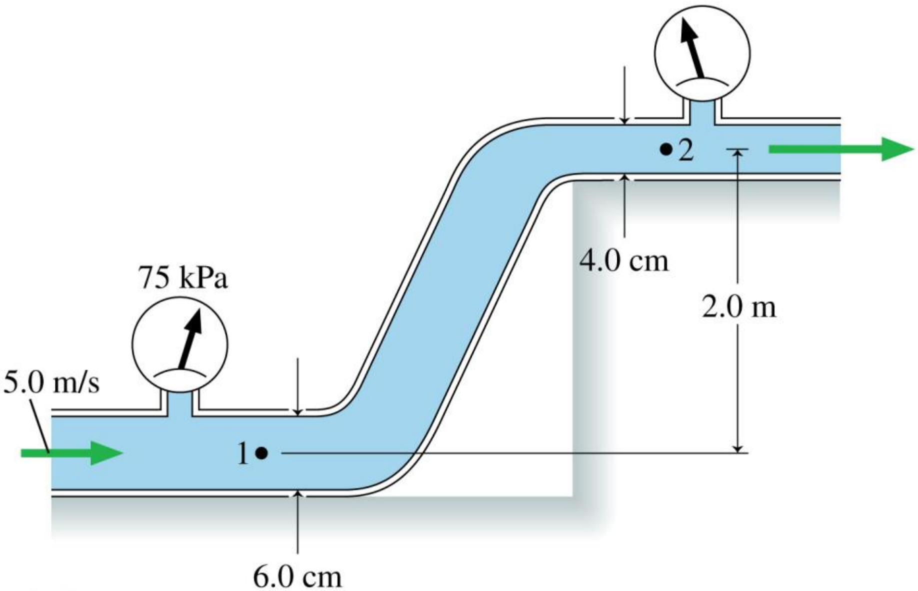
SOLVE Bernoulli's equation, Equation 13.14, relates the pressures, fluid speeds, and heights at points 1 and 2. It is easily solved for the pressure p_2 at point 2:



$$p_2 = p_1 + \frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2 + \rho g y_1 - \rho g y_2$$
$$= p_1 + \frac{1}{2}\rho(v_1^2 - v_2^2) + \rho g(y_1 - y_2)$$

Example 13.12 Pressure in an irrigation system (cont.)

All quantities on the right are known except v_2, and that is where the equation of continuity will be useful. The cross-section areas and water speeds at points 1 and 2 are related by



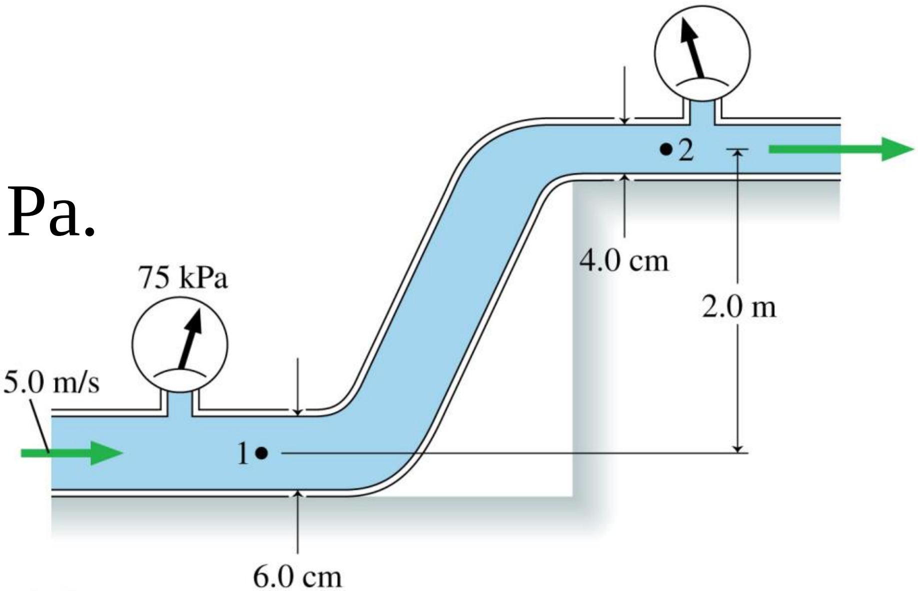
$$v_1 A_1 = v_2 A_2$$

from which we find

$$v_2 = \frac{A_1}{A_2} v_1 = \frac{r_1^2}{r_2^2} v_1 = \frac{(0.030\ \text{m})^2}{(0.020\ \text{m})^2}(5.0\ \text{m/s}) = 11.25\ \text{m/s}$$

Example 13.12 Pressure in an irrigation system (cont.)

The pressure at point 1 is
$p_1 = 75\text{ kPa} + 1\text{ atm} = 176{,}300\text{ Pa}$.
We can now use the above expression for p_2 to calculate $p_2 = 105{,}900$ Pa. This is the absolute pressure; the pressure gauge on the upper pipe will read



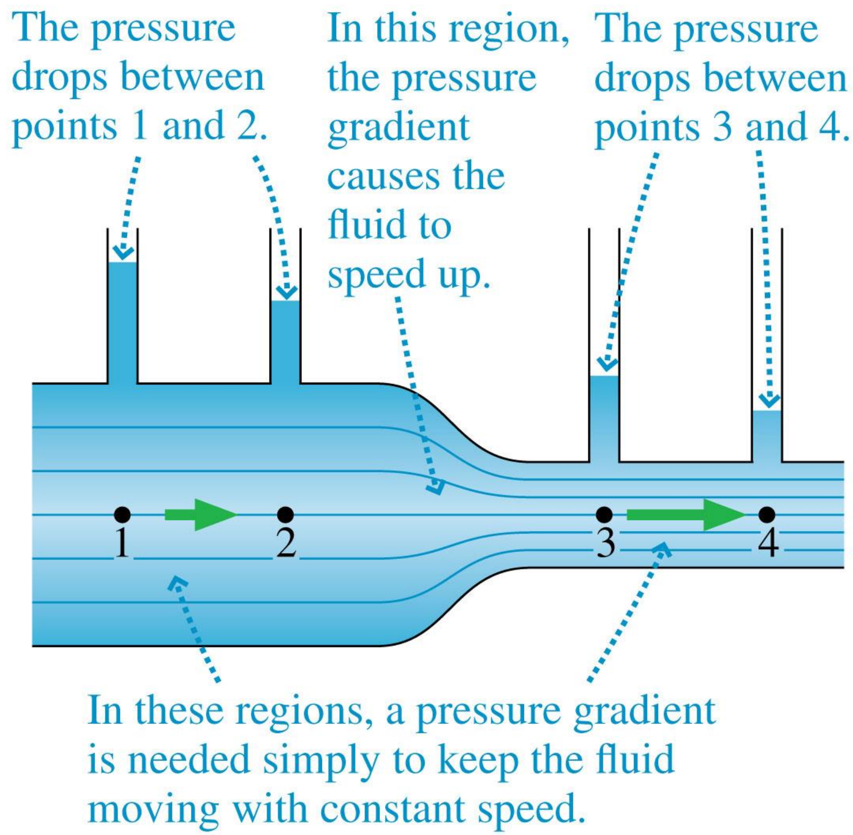
$$p_2 = 105{,}900\text{ Pa} - 1\text{ atm} = 4.6\text{ kPa}$$

ASSESS Reducing the pipe size decreases the pressure because it makes $v_2 > v_1$. Gaining elevation also reduces the pressure.

Section 13.7 Viscosity and Poiseuille's Equation

Viscosity and Poiseuille's Equation

- **Viscosity** is the measure of a fluid's resistance to flow.
- A very viscous fluid flows slowly when poured.
- Real fluids (viscous fluids) require a *pressure difference* in order to flow at a constant speed.

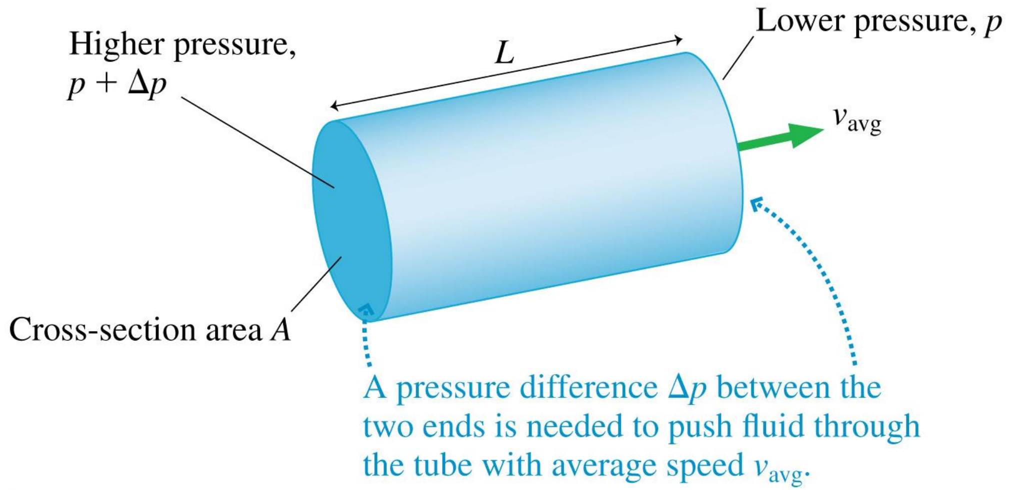


Viscosity and Poiseuille's Equation

- The pressure difference needed to keep a fluid moving is proportional to v_{avg} and to the tube length L, and inversely proportional to cross-section area A.

$$\Delta p = 8\pi\eta\frac{Lv_{avg}}{A}$$

- η is the coefficient of viscosity. The units are $N \cdot s/m^2$ or $Pa \cdot s$.



Viscosity and Poiseuille's Equation

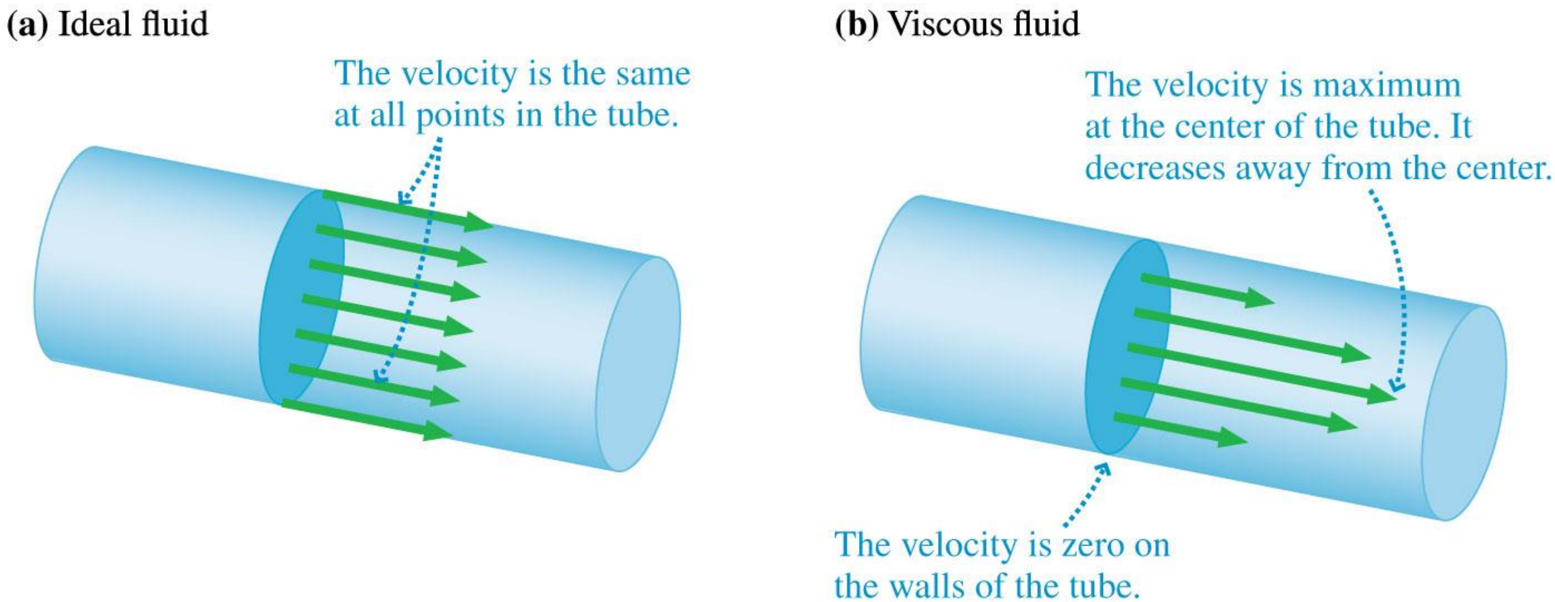
The viscosity of many liquids decreases *very* rapidly with temperature.

TABLE 13.3 Viscosities of fluids

Fluid	η (Pa · s)
Air (20°C)	1.8×10^{-5}
Water (20°C)	1.0×10^{-3}
Water (40°C)	0.7×10^{-3}
Water (60°C)	0.5×10^{-3}
Whole blood (37°C)	2.5×10^{-3}
Motor oil (−30°C)	3×10^{5}
Motor oil (40°C)	0.07
Motor oil (100°C)	0.01
Honey (15°C)	600
Honey (40°C)	20

Poiseuille's Equation

- In an ideal fluid, all fluid particles move with the same speed.
- For a viscous fluid, the fluid moves fastest in the center of the tube. The speed decreases as you move away from the center towards the walls of the tube, where speed is 0.



Poiseuille's Equation

- The average speed of a viscous fluid is

$$v_{\text{avg}} = \frac{R^2}{8\eta L}\Delta p$$

- The volume flow rate for a viscous fluid is

$$Q = v_{\text{avg}} A = \frac{\pi R^4 \Delta p}{8\eta L}$$

Poiseuille's equation for viscous flow through a tube of radius R and length L

- The viscous flow rate equation is called the **Poiseuille's Equation** after the person who first performed this calculation.

Example 13.14 Pressure drop along a capillary

In Example 13.11 we examined blood flow through a capillary. Using the numbers from that example, calculate the pressure "drop" from one end of a capillary to the other.

PREPARE Example 13.11 gives enough information to determine the flow rate through a capillary. We can then use Poiseuille's equation to calculate the pressure difference between the ends.

Example 13.14 Pressure drop along a capillary (cont.)

SOLVE The measured volume flow rate leaving the heart was given as 5 L/min = 8.3×10^{-5} m^3/s. This flow is divided among all the capillaries, which we found to number $N = 3 \times 10^9$. Thus the flow rate through each capillary is

$$Q_{\text{cap}} = \frac{Q_{\text{heart}}}{N} = \frac{8.3 \times 10^{-5}\ \text{m}^3/\text{s}}{3 \times 10^9} = 2.8 \times 10^{-14}\ \text{m}^3/\text{s}$$

Example 13.14 Pressure drop along a capillary (cont.)

Solving Poiseuille's equation for Δp, we get

$$\Delta p = \frac{8\eta L Q_{\text{cap}}}{\pi R^4} = \frac{8(2.5 \times 10^{-3}\ \text{Pa} \cdot \text{s})(0.001\ \text{m})(2.8 \times 10^{-14}\ \text{m}^3/\text{s})}{\pi(3 \times 10^{-6}\ \text{m})^4} = 2200\ \text{Pa}$$

If we convert to mm of mercury, the units of blood pressure, the pressure drop across the capillary is $\Delta p = 16$ mm Hg.

Example 13.14 Pressure drop along a capillary (cont.)

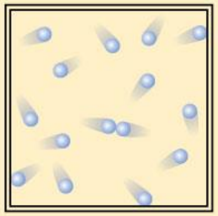
ASSESS The average blood pressure provided by the heart (the average of the systolic and diastolic pressures) is about 100 mm Hg. A physiology textbook will tell you that the pressure has decreased to 35 mm by the time blood enters the capillaries, and it exits from capillaries into the veins at 17 mm. Thus the pressure drop across the capillaries is 18 mm Hg. Our calculation, based on the laws of fluid flow and some simple estimates of capillary size, is in almost perfect agreement with measured values.

Summary: General Principles

Fluid Statics

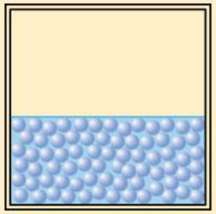
Gases

- Freely moving particles
- Compressible
- Pressure mainly due to particle collisions with walls



Liquids

- Loosely bound particles
- Incompressible
- Pressure due to the weight of the liquid
- Hydrostatic pressure at depth d is $p = p_0 + \rho g d$
- The pressure is the same at all points on a horizontal line through a liquid (of one kind) in hydrostatic equilibrium



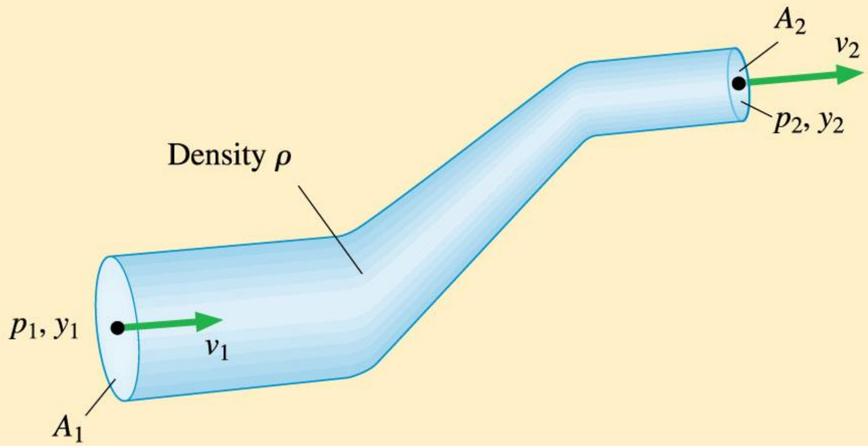
Text: p. 424

Summary: General Principles

Fluid Dynamics

Ideal-fluid model

- Incompressible
- Smooth, laminar flow
- Nonviscous



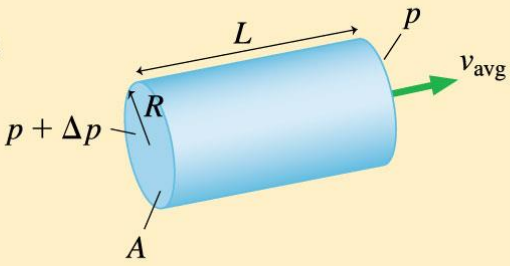
Equation of continuity

Volume flow rate $Q = \dfrac{\Delta V}{\Delta t} = v_1 A_1 = v_2 A_2$

Bernoulli's equation is a statement of energy conservation:

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2$$

Poiseuille's equation governs viscous flow through a tube:



$$Q = v_{avg} A = \frac{\pi R^4 \Delta p}{8 \eta L}$$

Text: p. 424

Summary: Important Concepts

Density $\rho = m/V$, where m is mass and V is volume.

Pressure $p = F/A$, where F is force magnitude and A is the area on which the force acts.

- Pressure exists at all points in a fluid.
- Pressure pushes equally in all directions.
- Gauge pressure $p_g = p - 1\text{ atm}$.

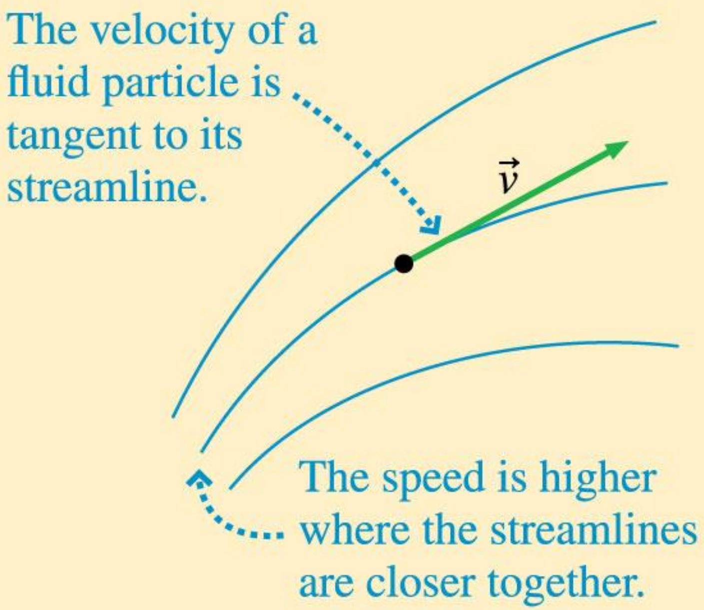
Viscosity η is the property of a fluid that makes it resist flowing.

Text: p. 424

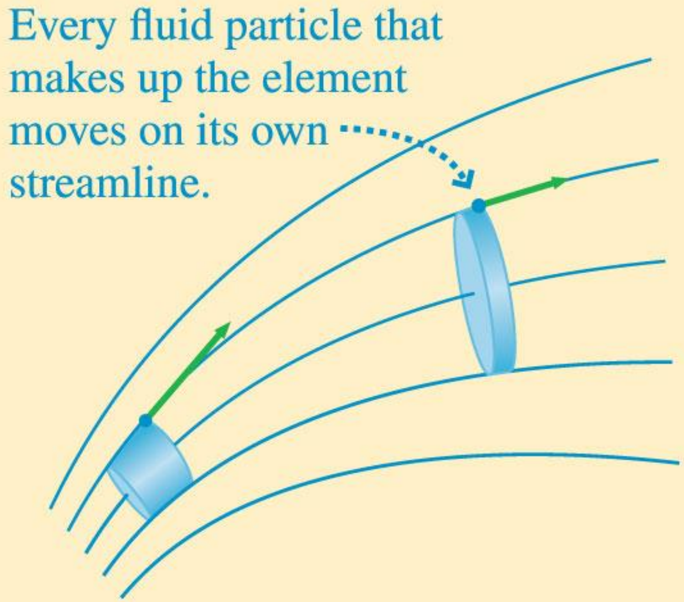
Summary: Important Concepts

Representing fluid flow

Streamlines are the paths of individual fluid particles.



Fluid elements contain a fixed volume of fluid. Their shape may change as they move.



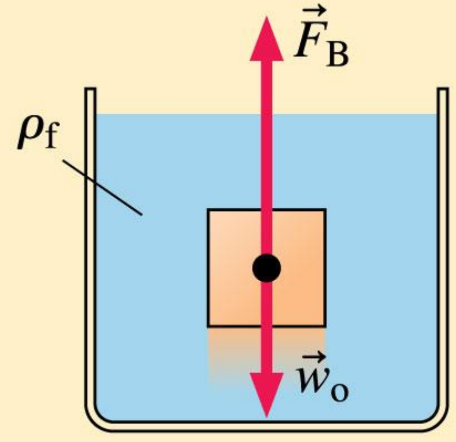
Text: p. 424

Summary: Applications

Buoyancy is the upward force of a fluid on an object immersed in the fluid.

Archimedes' principle: The magnitude of the buoyant force equals the weight of the fluid displaced by the object.

Sink:	$\rho_{avg} > \rho_f$	$F_B < w_o$
Float:	$\rho_{avg} < \rho_f$	$F_B > w_o$
Neutrally buoyant:	$\rho_{avg} = \rho_f$	$F_B = w_o$



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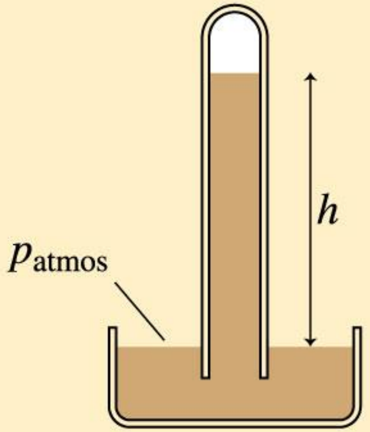
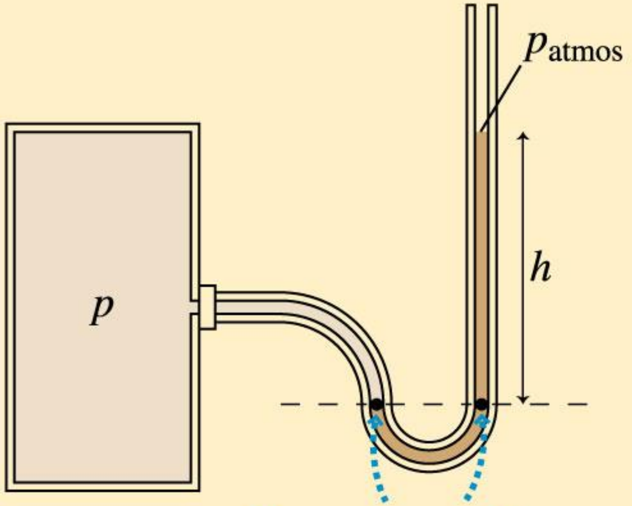
Summary: Applications

Barometers measure atmospheric pressure. Atmospheric pressure is related to the height of the liquid column by $p_{\text{atmos}} = \rho g h$.



Manometers measure pressure. The pressure at the closed end of the tube is $p = 1 \text{ atm} + \rho g h$.



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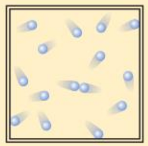

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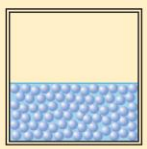

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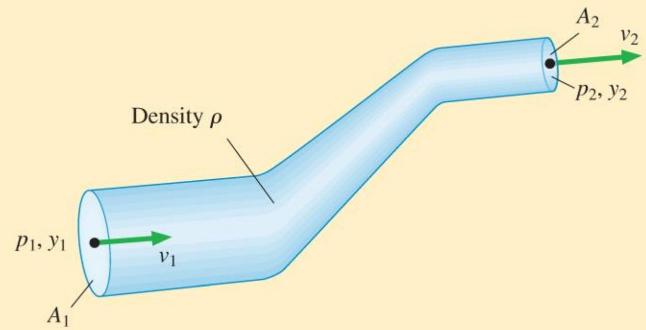

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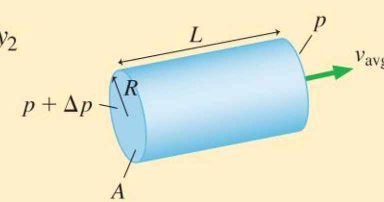

Text: p. 424

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- Gauge pressure $p_g = p - 1$ atm.

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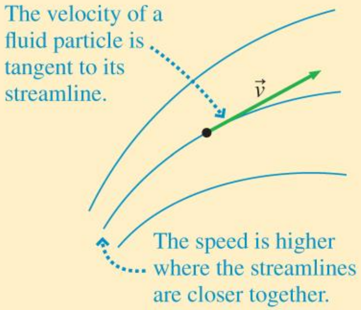

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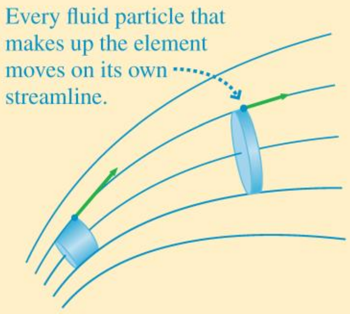

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Summary

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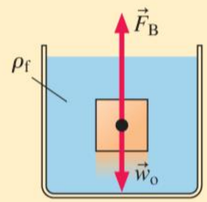
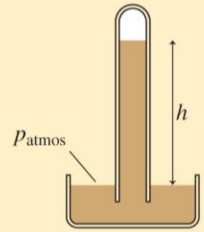
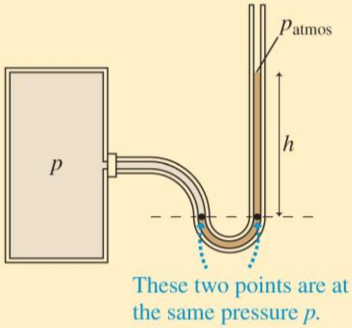
Float:	$\rho_{avg} < \rho_f$	$F_B > w_o$
Neutrally buoyant:	$\rho_{avg} = \rho_f$	$F_B = w_o$



Barometers measure atmospheric pressure. Atmospheric pressure is related to the height of the liquid column by $p_{atmos} = \rho g h$.



Manometers measure pressure. The pressure at the closed end of the tube is $p = 1\ \text{atm} + \rho g h$.



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