Chapter 15. Fluids and Elasticity

In this chapter we study macroscopic systems: systems with many particles, such as the water the kayaker is paddling through. We will introduce the concepts of density, pressure, fluid statics, fluid dynamics, and the elasticity of solids.

Chapter Goal: To understand macroscopic systems that flow or deform.

Chapter 15. Fluids and Elasticity

Topics:

- Fluids
- Pressure
- Measuring and Using Pressure
- Buoyancy
- Fluid Dynamics
- Elasticity

Chapter 15. Quizzes

What is the SI unit of pressure?

A. Pascal
B. Atmosphere
C. Bernoulli
D. Young
E. p.s.i.

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

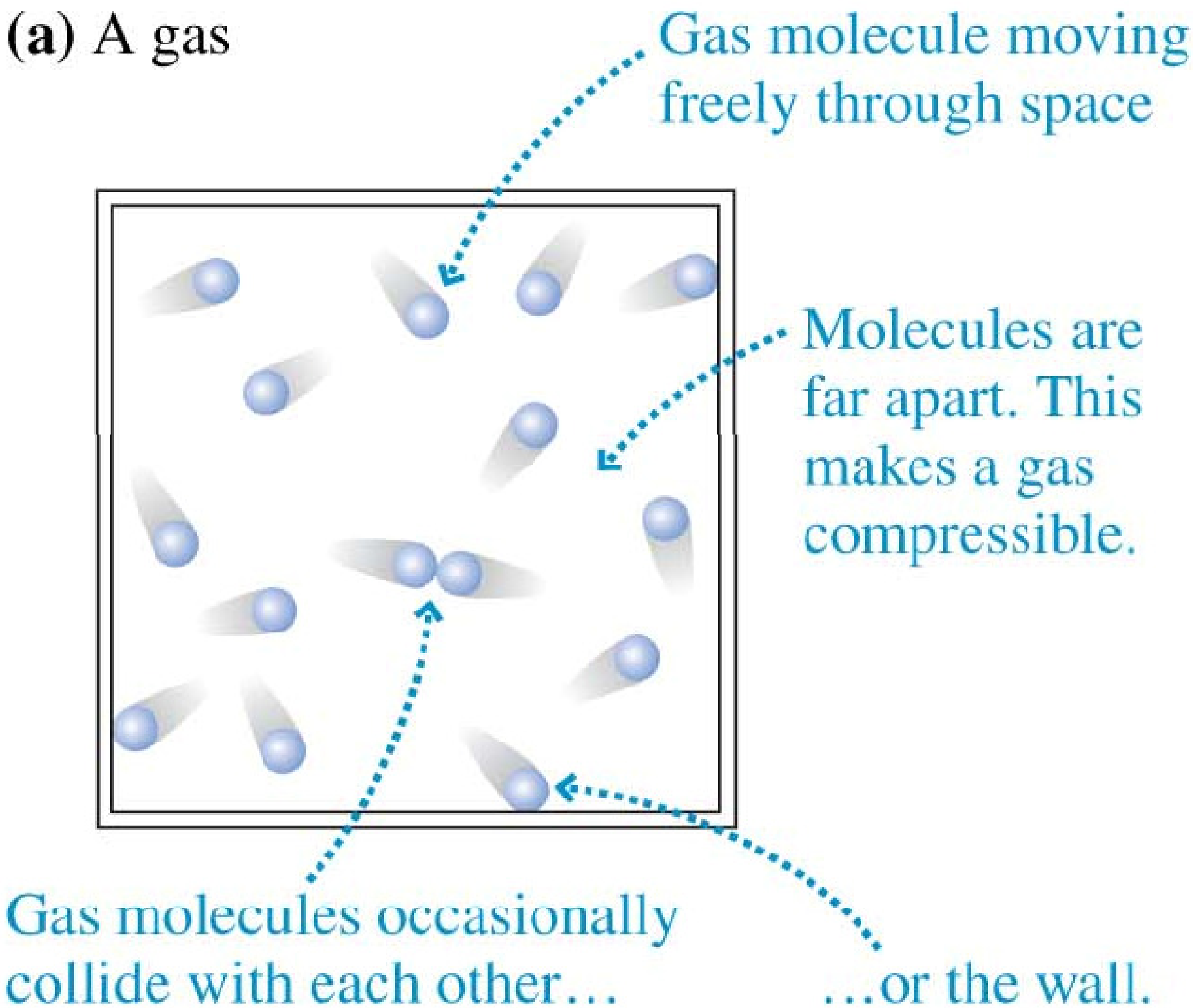
A. the object’s mass.
B. the object’s volume.
C. the density of the liquid.
D. both A and B.
E. both B and C.

The elasticity of a material is characterized by the value of

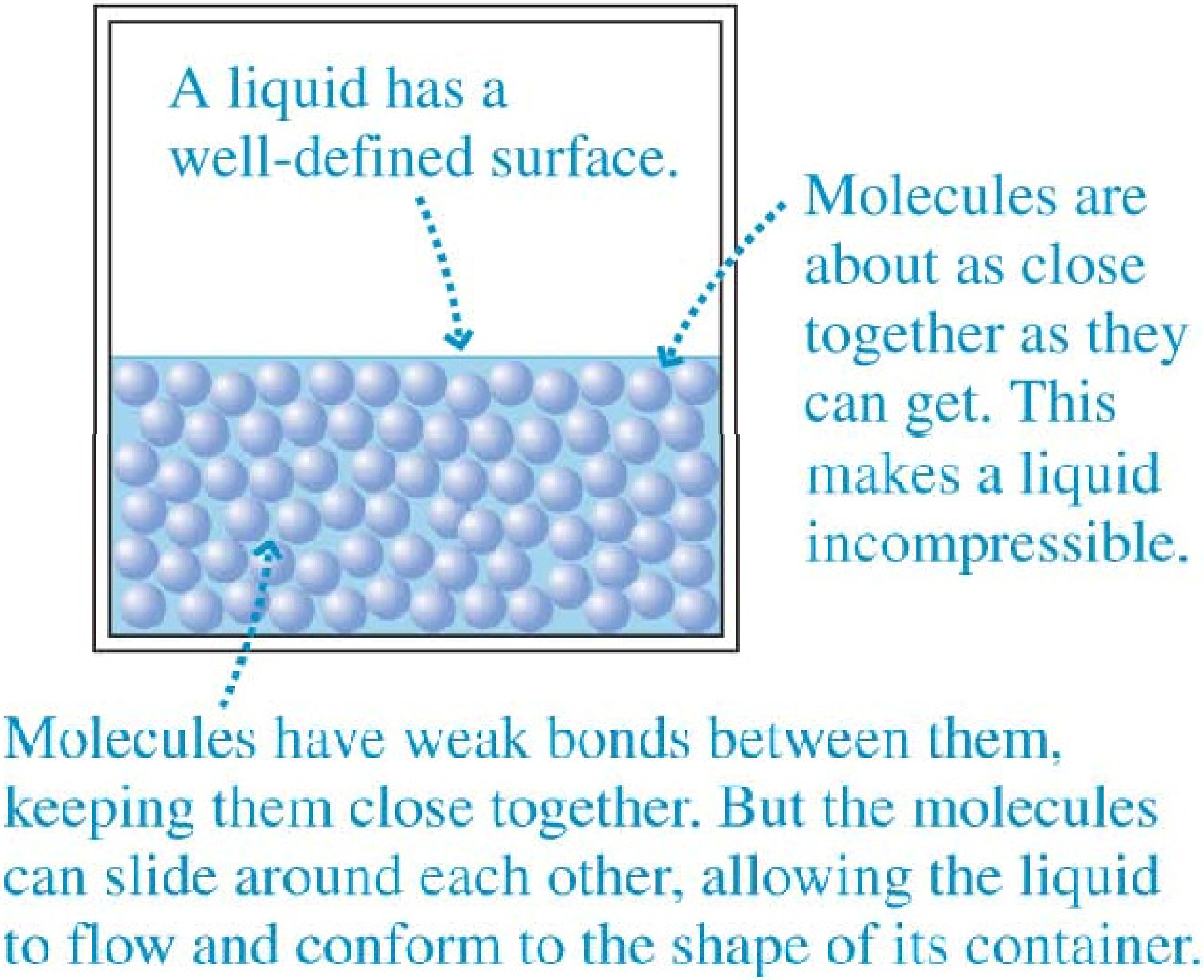
A. the elastic constant.
B. Young's modulus.
C. the spring constant.
D. Hooke's modulus.
E. Archimedes' modulus.

Chapter 15. Basic Content and Examples

FIGURE 15.1 Simple atomic models of gases and liquids.



(b) A liquid


A liquid has a well-defined surface.
Molecules are about as close together as they can get. This makes a liquid incompressible.
Molecules have weak bonds between them, keeping them close together. But the molecules can slide around each other, allowing the liquid to flow and conform to the shape of its container.

Density

The ratio of an object's or material's mass to its volume is called the **mass density**, or sometimes simply "the density."

$$\rho = \frac{m}{V} \qquad \text{(mass density)}$$

The SI units of mass density are kg/m^3.

TABLE 15.1 Densities of fluids at standard temperature (0°C) and pressure (1 atm)

Substance	ρ (kg/m^3)
Air	1.28
Ethyl alcohol	790
Gasoline	680
Glycerin	1260
Helium gas	0.18
Mercury	13,600
Oil (typical)	900
Seawater	1030
Water	1000

Pressure

A fluid in a container presses with an outward force against the walls of that container. The **pressure** is defined as the ratio of the force to the area on which the force is exerted.

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

The SI units of pressure are N/m^2, also defined as the pascal, where 1 pascal = 1 Pa = 1 N/m^2.

FIGURE 15.4 The fluid presses against area A with force $\vec{F}$.

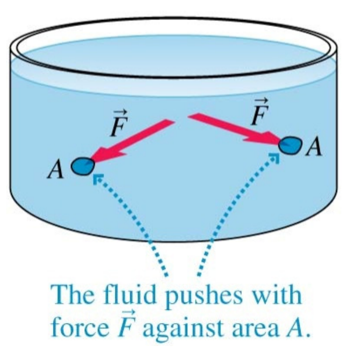
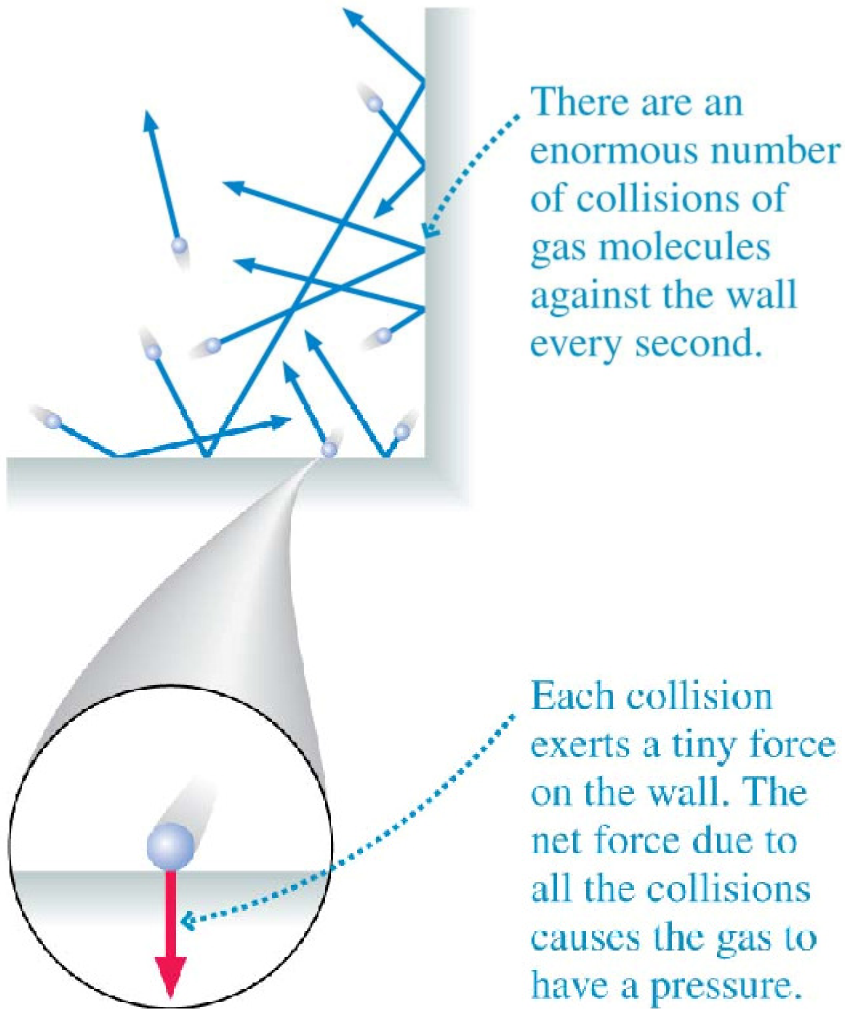


FIGURE 15.7 The pressure in a gas is due to the net force of the molecules colliding with the walls.

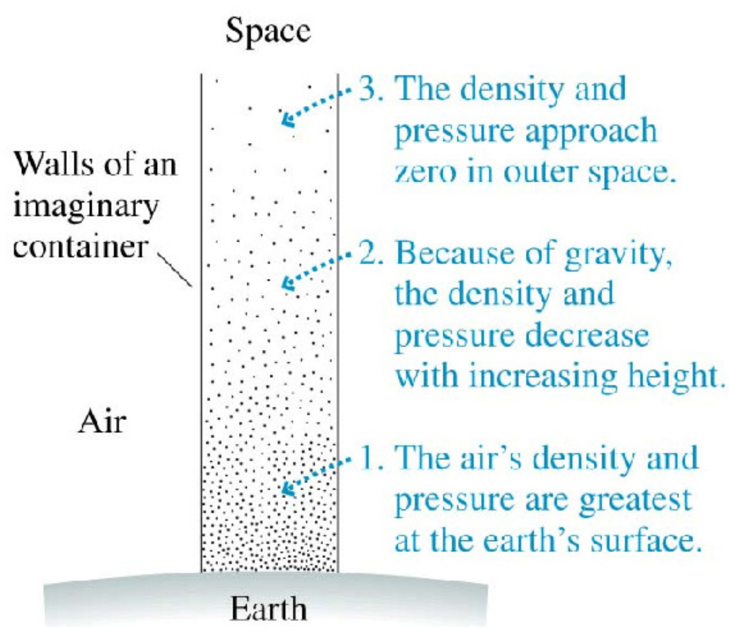


Atmospheric Pressure

The global average sea-level pressure is 101,300 Pa. Consequently we define the **standard atmosphere** as

$$1 \text{ standard atmosphere} = 1 \text{ atm} \equiv 101{,}300 \text{ Pa} = 101.3 \text{ kPa}$$

FIGURE 15.9 The pressure and density decrease with increasing height in the atmosphere.



EXAMPLE 15.2 A suction cup

QUESTION:

EXAMPLE 15.2 A suction cup

A 10.0-cm-diameter suction cup is pushed against a smooth ceiling. What is the maximum mass of an object that can be suspended from the suction cup without pulling it off the ceiling? The mass of the suction cup is negligible.

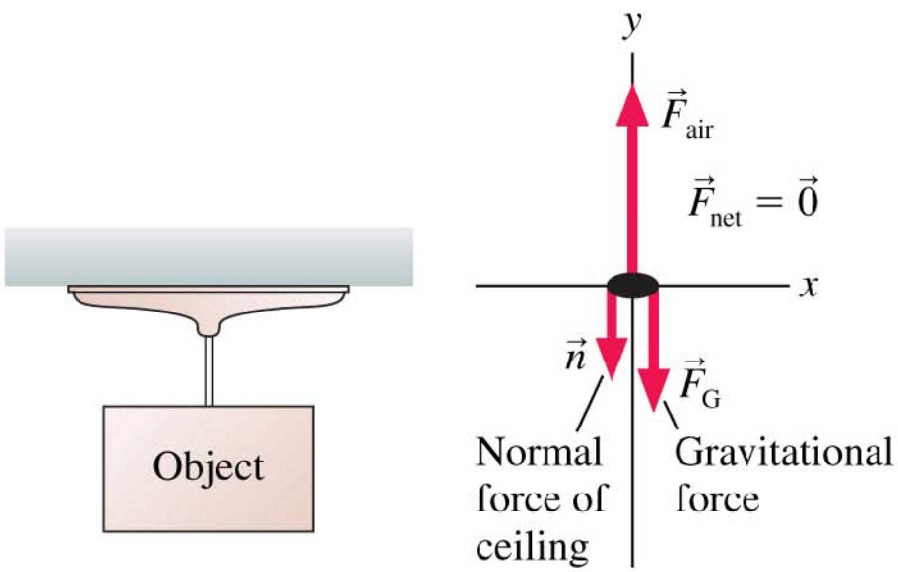
EXAMPLE 15.2 A suction cup

MODEL Pushing the suction cup against the ceiling pushes the air out. We'll assume that the volume enclosed between the suction cup and the ceiling is a perfect vacuum with $p = 0$ Pa. We'll also assume that the pressure in the room is 1 atm.

EXAMPLE 15.2 A suction cup

VISUALIZE **FIGURE 15.11** shows a free-body diagram of the suction cup stuck to the ceiling. The downward normal force of the ceiling is distributed around the rim of the suction cup, but in the particle model we can show this as a single force vector.

FIGURE 15.11 A suction cup is held to the ceiling by air pressure pushing upward on the bottom.



EXAMPLE 15.2 A suction cup

SOLVE The suction cup remains stuck to the ceiling, in static equilibrium, as long as $F_{\text{air}} = n + F_G$. The magnitude of the upward force exerted by the air is

$$F_{\text{air}} = pA = p\pi r^2 = (101{,}300\ \text{Pa})\pi(0.050\ \text{m})^2 = 796\ \text{N}$$

There is no downward force from the air in this case because there is no air inside the cup. Increasing the hanging mass decreases the normal force n by an equal amount. The maximum weight has been reached when n is reduced to zero. Thus

$$(F_G)_{\text{max}} = mg = F_{\text{air}} = 796\ \text{N}$$

$$m = \frac{796\ \text{N}}{g} = 81\ \text{kg}$$

Hence this suction cup can support a mass of up to 81 kg.

Pressure in Liquids

The pressure at depth d in a liquid is

$$p = p_0 + \rho g d \qquad \text{(hydrostatic pressure at depth } d\text{)}$$

where ρ is the liquid's density, and p_0 is the pressure at the surface of the liquid. Because the fluid is at rest, the pressure is called the **hydrostatic pressure**. The fact that g appears in the equation reminds us that there is a gravitational contribution to the pressure.

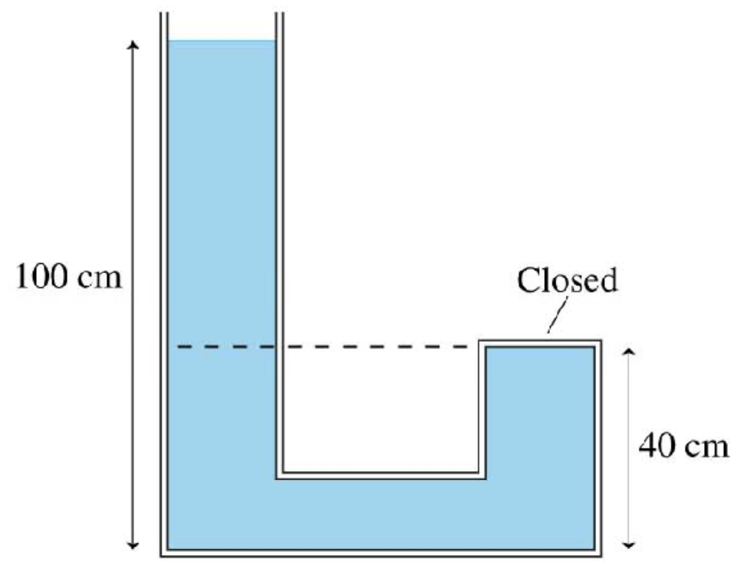
EXAMPLE 15.4 Pressure in a closed tube

QUESTION:

EXAMPLE 15.4 Pressure in a closed tube

Water fills the tube shown in FIGURE 15.15. What is the pressure at the top of the closed tube?

FIGURE 15.15 A water-filled tube.



EXAMPLE 15.4 Pressure in a closed tube

MODEL 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 $p_0 = 1.00$ atm.

EXAMPLE 15.4 Pressure in a closed tube

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

$$p = p_0 + \rho g d = 1.013 \times 10^5 \text{ Pa} + (1000 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(0.60 \text{ m})$$
$$= 1.072 \times 10^5 \text{ Pa} = 1.06 \text{ atm}$$

This is the pressure at the top of the closed tube.

EXAMPLE 15.4 Pressure in a closed tube

ASSESS The water in the open tube *pushes* the water in the closed tube up against the top of the tube, which is why the pressure is greater than 1 atm.

Gauge Pressure

Many pressure gauges, such as tire gauges and the gauges on air tanks, measure not the actual or absolute pressure p but what is called **gauge pressure** p_g.

$$p_g = p - 1\ \text{atm}$$

where 1 atm = 101.3 kPa.

A tire-pressure gauge reads the gauge pressure p_g, not the absolute pressure p. The gauge reads zero when the tire is flat, but this doesn't mean there is a vacuum inside. Zero gauge pressure means the inside pressure is 1 atm.

Tactics: Hydrostatics

TACTICS BOX 15.1 **Hydrostatics**

MP

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 at surfaces.**
   - **Surface open to the air:** $p_0 = p_{\text{atmos}}$, usually 1 atm.
   - **Surface covered by a gas:** $p_0 = p_{\text{gas}}$.
   - **Closed surface:** $p = F/A$ where F is the force the surface, such as a piston, exerts on the fluid.

Tactics: Hydrostatics

3. **Use horizontal lines.** Pressure in a connected fluid 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.** $p = p_0 + \rho g d$.

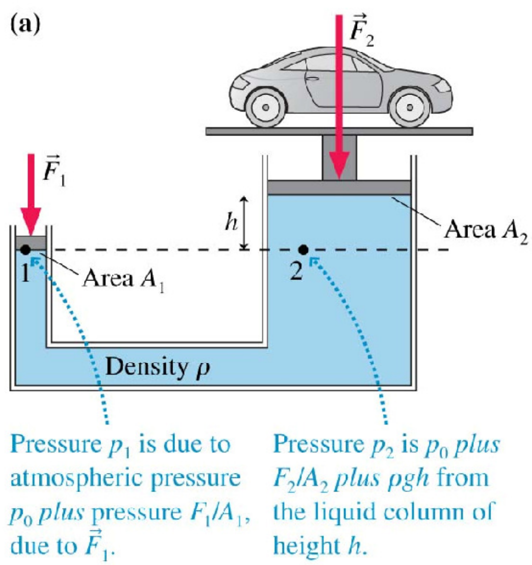
Exercises 4–13

Hydraulics

Consider a hydraulic lift, such as the one that lifts your car at the repair shop. The system is in static equilibrium if

$$F_2 = \frac{A_2}{A_1}F_1 - \rho g h A_2$$

FIGURE 15.19 A hydraulic lift.



EXAMPLE 15.7 Lifting a car

QUESTIONS:

EXAMPLE 15.7 Lifting a car

The hydraulic lift at a car repair shop is filled with oil. The car rests on a 25-cm-diameter piston. To lift the car, compressed air is used to push down on a 6.0-cm-diameter piston.

a. What air-pressure force will support a 1300 kg car level with the compressed-air piston?

b. By how much must the air-pressure force be increased to lift the car 2.0 m?

EXAMPLE 15.7 Lifting a car

MODEL Assume that the oil is incompressible. Its density, from Table 15.1, is 900 kg/m^3.

EXAMPLE 15.7 Lifting a car

SOLVE a. The weight of the car pressing on the piston is $F_2 = mg = 12{,}700\text{ N}$. The piston areas are $A_1 = \pi(0.030\text{ m})^2 = 0.00283\text{ m}^2$ and $A_2 = \pi(0.125\text{ m})^2 = 0.0491\text{ m}^2$. The force required to hold the car level with the compressed air piston, with $h = 0\text{ m}$, is

$$F_1 = \frac{F_2}{A_2/A_1} = \frac{12{,}700\text{ N}}{(0.0491\text{ m}^2)/(0.00283\text{ m}^2)} = 730\text{ N}$$

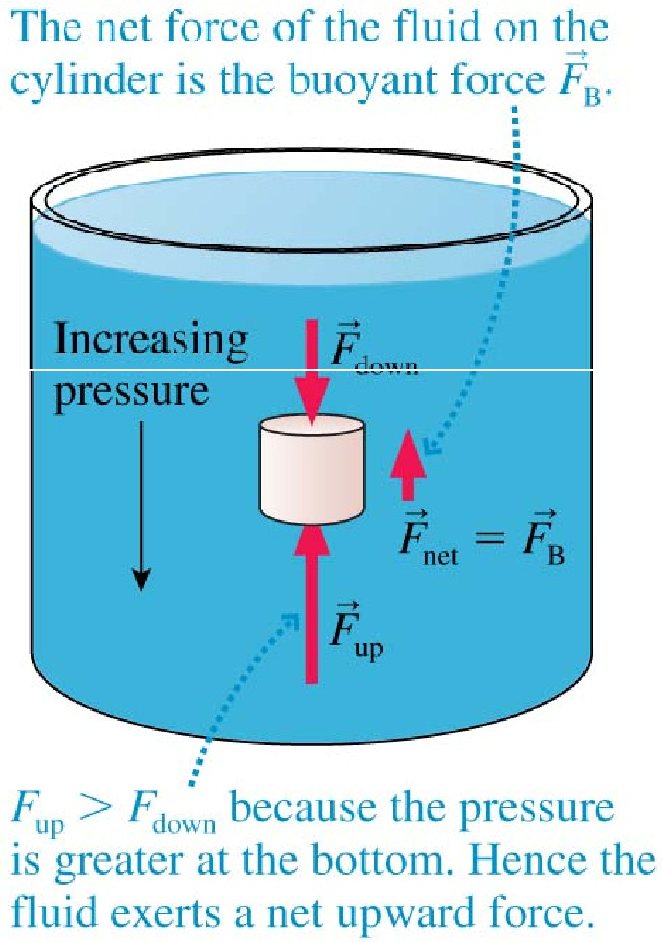
b. To raise the car $d_2 = 2.0\text{ m}$, the air-pressure force must be increased by

$$\Delta F = \rho g(A_1 + A_2)d_2 = 920\text{ N}$$

EXAMPLE 15.7 Lifting a car

ASSESS 730 N is roughly the weight of an average adult man. The multiplication factor $A_2/A_1 = (25\text{ cm}/6\text{ cm})^2 = 17$ makes it quite easy to hold up the car.

FIGURE 15.20 The buoyant force arises because the fluid pressure at the bottom of the cylinder is larger than at the top.



Buoyancy

When an object (or portion of an object) is immersed in a fluid, it displaces fluid. The **displaced fluid's** volume equals the volume of the portion of the object that is immersed in the 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.

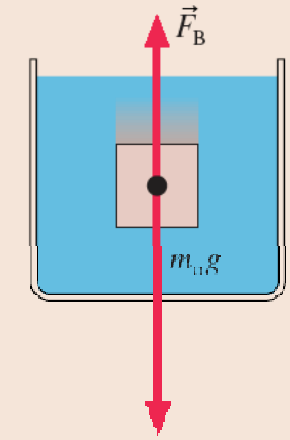
Suppose the fluid has density ρ_f and the object displaces volume V_f of fluid. Archimedes' principle in equation form is

$$F_B = \rho_f V_f g$$

Tactics: Finding whether an object floats or sinks

TACTICS BOX 15.2 **Finding whether an object floats or sinks**

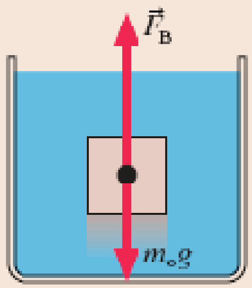
1 Object sinks



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:

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

Tactics: Finding whether an object floats or sinks

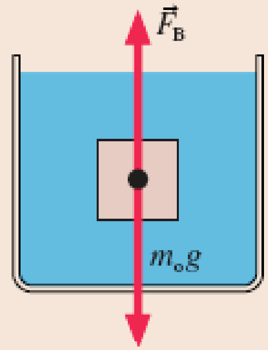


An object floats on the surface if it weighs less than the fluid it displaces—that is, if its average density is less than the density of the fluid:

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

Tactics: Finding whether an object floats or sinks

3 Neutral buoyancy



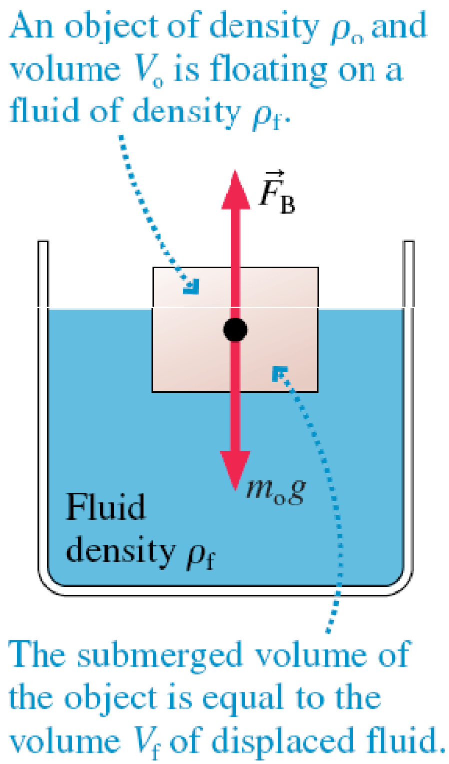
An object hangs motionless if it weighs exactly the same as the fluid it displaces—that is, if its average density equals the density of the fluid:

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

Exercises 14–18

Float or Sink?

FIGURE 15.23 A floating object is in static equilibrium.



The volume of fluid displaced by a floating object of uniform density is

$$F_B = \rho_f V_f g = m_o g = \rho_o V_o g$$

Fluid Dynamics

Comparing two points in a flow tube of cross section A_1 and A_2, we may use the **equation of continuity**

$$\boxed{v_1 A_1 = v_2 A_2}$$

where v_1 and v_2 are the fluid speeds at the two points. The flow is faster in narrower parts of a flow tube, slower in wider parts. This is because the volume flow rate Q, in m^3/s, is constant.

$$Q = vA$$

EXAMPLE 15.10 Gasoline through a pipe

QUESTIONS:

EXAMPLE 15.10 Gasoline through a pipe

An oil refinery pumps gasoline into a 1000 L holding tank through an 8.0-cm-diameter pipe. The tank can be filled in 2.0 min.

a. What is the speed of the gasoline through the pipe?
b. Farther upstream, the pipe's diameter is 16 cm. What is the flow speed in this section of pipe?

EXAMPLE 15.10 Gasoline through a pipe

MODEL Treat the gasoline as an ideal fluid. The pipe is a flow tube, so the equation of continuity applies.

EXAMPLE 15.10 Gasoline through a pipe

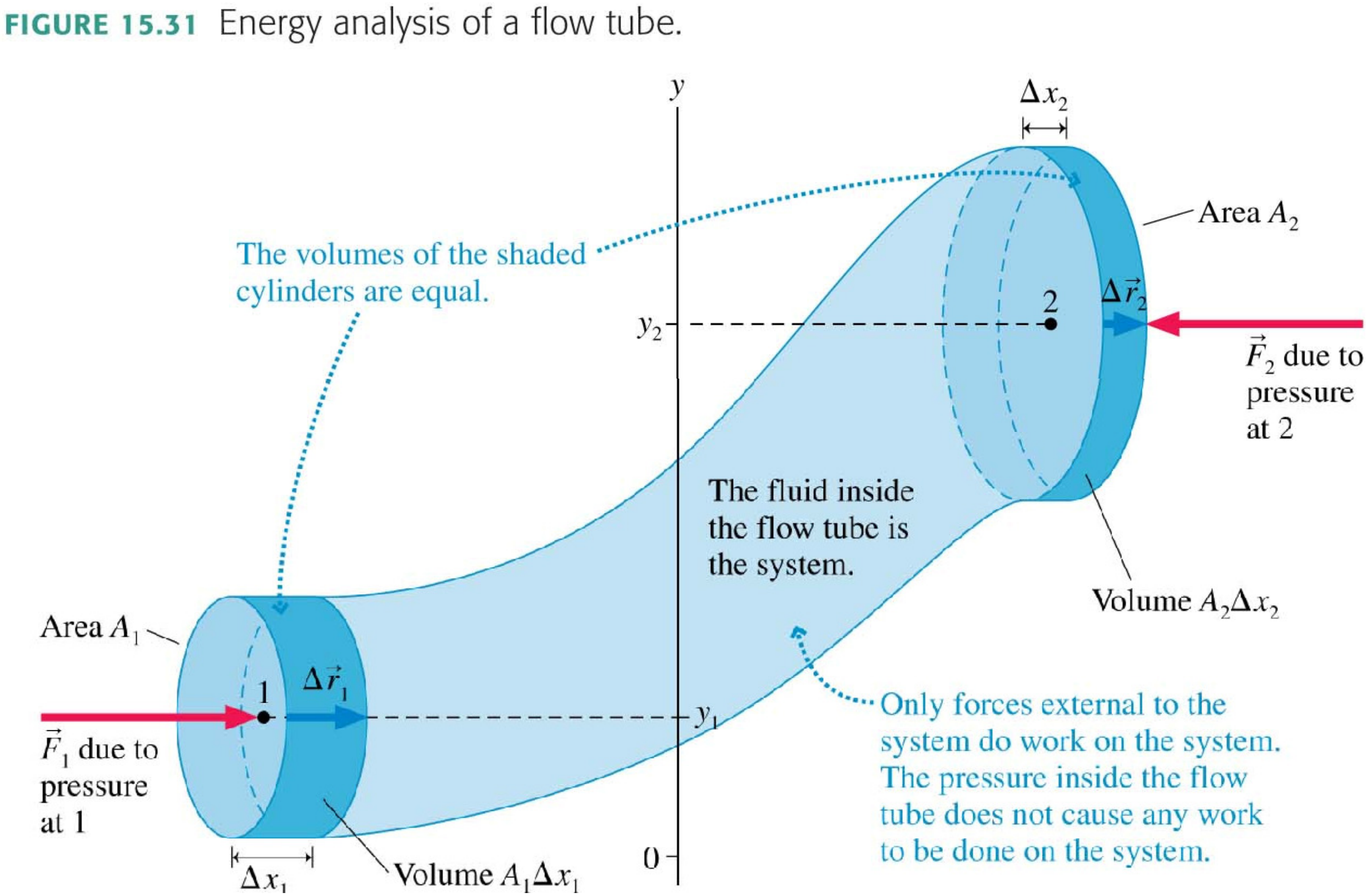
SOLVE a. The volume flow rate is $Q = (1000\ \text{L})/(120\ \text{s}) = 8.33\ \text{L/s}$. To convert this to SI units, recall that $1\ \text{L} = 10^{-3}\ \text{m}^3$. Thus $Q = 8.33 \times 10^{-3}\ \text{m}^3/\text{s}$. We can find the speed of the gasoline from Equation 15.20:

$$v = \frac{Q}{A} = \frac{Q}{\pi r^2} = \frac{8.33 \times 10^{-3}\ \text{m}^3/\text{s}}{\pi (0.040\ \text{m})^2} = 1.66\ \text{m/s}$$

EXAMPLE 15.10 Gasoline through a pipe

b. $Q = vA$ remains constant. The cross-section area depends on the square of the radius, so the pipe's cross-section area upsteam is a factor of 4 larger. Consequently, the flow speed must be a factor of 4 smaller, or 0.41 m/s.

Bernoulli's Equation



Bernoulli's Equation

The energy equation for fluid in a flow tube is

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

An alternative form of **Bernoulli's equation** is

$$p + \frac{1}{2}\rho v^2 + \rho g y = \text{constant}$$

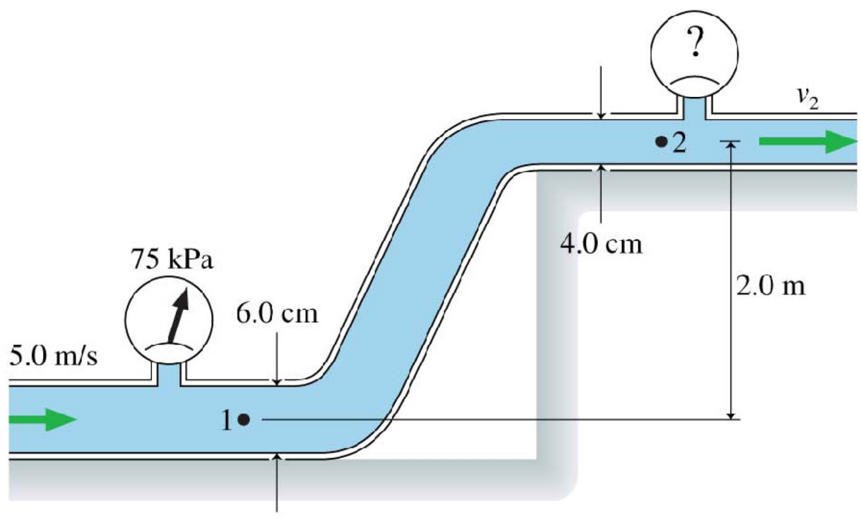
EXAMPLE 15.11 An irrigation system

QUESTION:

EXAMPLE 15.11 An irrigation system

Water flows through the pipes shown in **FIGURE 15.33**. 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?

FIGURE 15.33 The water pipes of an irrigation system.



EXAMPLE 15.11 An irrigation system

MODEL 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 15.11 An irrigation system

SOLVE Bernoulli's equation, Equation 15.28, relates the pressure, fluid speed, and heights at points 1 and 2. It is easily solved for the pressure p_2 at point 2:

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

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

All quantities on the right are known except v_2, and that is where the equation of continuity will be useful.

EXAMPLE 15.11 An irrigation system

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

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

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 $p_2 = 105{,}900\text{ Pa}$. This is the absolute pressure; the pressure gauge on the upper pipe will read

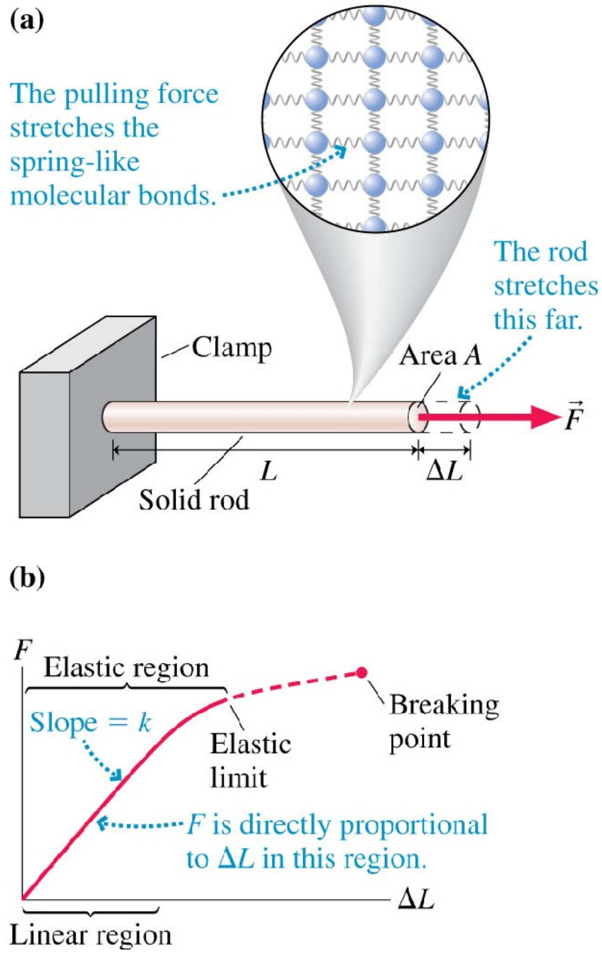
$$p_2 = 105{,}900\text{ Pa} - 1\text{ atm} = 4.6\text{ kPa}$$

EXAMPLE 15.11 An irrigation system

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

Elasticity

FIGURE 15.37 Stretching a solid rod.



Elasticity

F/*A* is proportional to $\Delta L/L$. We can write the proportionality as

$$\frac{F}{A} = Y\frac{\Delta L}{L}$$

• The proportionality constant *Y* is called **Young's modulus**.

• The quantity *F*/*A* is called the **tensile stress**.

• The quantity $\Delta L/L$, the fractional increase in length, is called **strain**.

With these definitions, we can write

$$\text{stress} = Y \times \text{strain}$$

TABLE 15.3 Elastic properties of various materials

Substance	Young's modulus (N/m^2)	Bulk modulus (N/m^2)
Aluminum	7×10^{10}	7×10^{10}
Concrete	3×10^{10}	–
Copper	11×10^{10}	14×10^{10}
Mercury	–	3×10^{10}
Plastic (polystyrene)	0.3×10^{10}	–
Steel	20×10^{10}	16×10^{10}
Water	–	0.2×10^{10}
Wood (Douglas fir)	1×10^{10}	–

EXAMPLE 15.13 Stretching a wire

QUESTIONS:

EXAMPLE 15.13 Stretching a wire

A 2.0-m-long, 1.0-mm-diameter wire is suspended from the ceiling. Hanging a 4.5 kg mass from the wire stretches the wire's length by 1.0 mm. What is Young's modulus for this wire? Can you identify the material?

EXAMPLE 15.13 Stretching a wire

MODEL The hanging mass creates tensile stress in the wire.

EXAMPLE 15.13 Stretching a wire

SOLVE The force pulling on the wire, which is simply the weight of the hanging mass, produces tensile stress

$$\frac{F}{A} = \frac{mg}{\pi r^2} = \frac{(4.5\text{ kg})(9.80\text{ m/s}^2)}{\pi(0.0005\text{ m})^2} = 5.6 \times 10^7\text{ N/m}^2$$

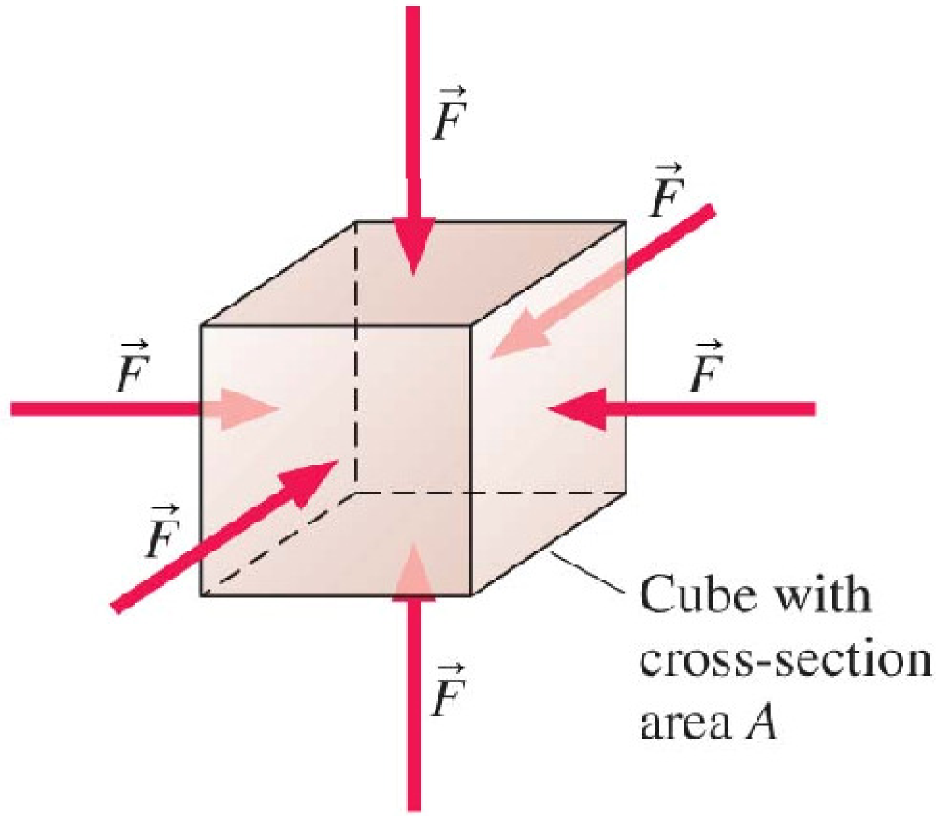
The resulting stretch of 1.0 mm is a strain of $\Delta L/L = (1.0\text{ mm})/(2000\text{ mm}) = 5.0 \times 10^{-4}$. Thus Young's modulus for the wire is

$$Y = \frac{F/A}{\Delta L/L} = 11 \times 10^{10}\text{ N/m}^2$$

Referring to Table 15.3, we see that the wire is made of copper.

Volume Stress and the Bulk Modulus

FIGURE 15.39 An object is compressed by pressure forces pushing equally on all sides.



Volume Stress and the Bulk Modulus

- A volume stress applied to an object compresses its volume slightly.
- The volume strain is defined as $\Delta V/V$, and is negative when the volume decreases.
- Volume stress is the same as the pressure.

$$\frac{F}{A} = p = -B\frac{\Delta V}{V}$$

where B is called the **bulk modulus**. The negative sign in the equation ensures that the pressure is a positive number.

Chapter 15. Summary Slides

General Principles

Fluid Statics

Gases

- Freely moving particles
- Compressible
- Pressure primarily thermal
- Pressure is constant in a laboratory-size container

Liquids

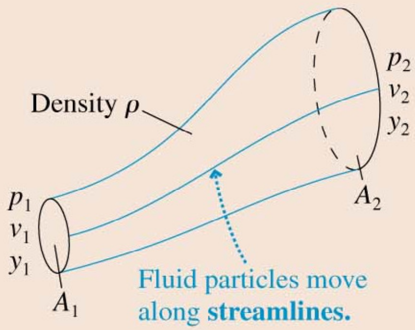
- Loosely bound particles
- Incompressible
- Pressure primarily gravitational
- Hydrostatic pressure at depth d is $p = p_0 + \rho g d$

General Principles

Fluid Dynamics

Ideal-fluid model

- Incompressible
- Smooth, laminar flow
- Nonviscous



Equation of continuity

$$v_1 A_1 = v_2 A_2$$

Bernoulli's equation

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

Bernoulli's equation is a statement of energy conservation.

Important Concepts

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

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

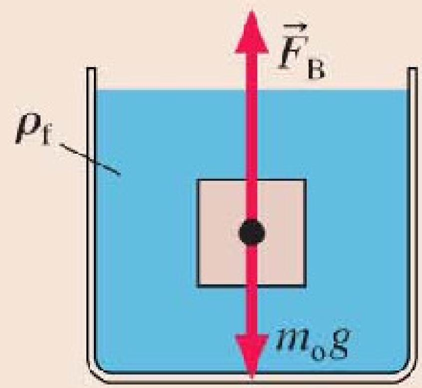
- Pressure exists at all points in a fluid.
- Pressure pushes equally in all directions.
- Pressure is constant along a horizontal line.
- Gauge pressure is $p_g = p - 1$ atm.

Applications

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

Archimedes' principle

The magnitude of the buoyant force equals the weight of the fluid displaced by the object.



Sink	$\rho_{avg} > \rho_f$	$F_B < m_o g$
Rise to surface	$\rho_{avg} < \rho_f$	$F_B > m_o g$
Neutrally buoyant	$\rho_{avg} = \rho_f$	$F_B = m_o g$

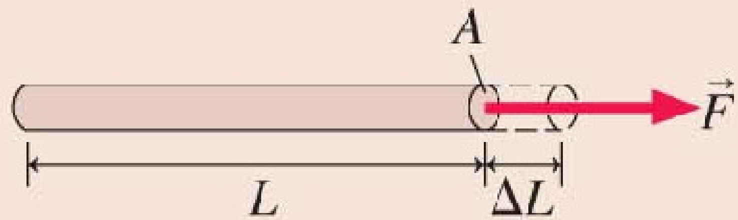
Applications

Elasticity describes the deformation of solids and liquids under stress.

Linear stretch and compression

$$(F/A) = Y(\Delta L/L)$$

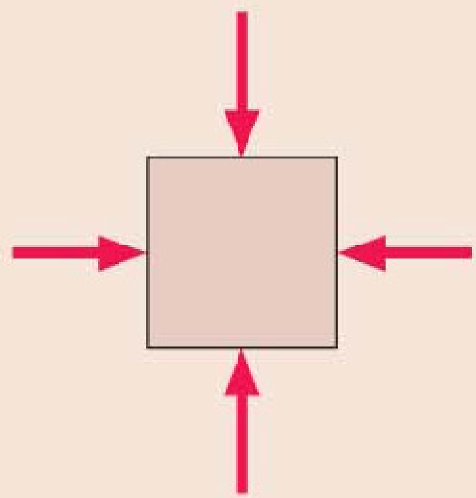
Tensile stress — Young's modulus — Strain



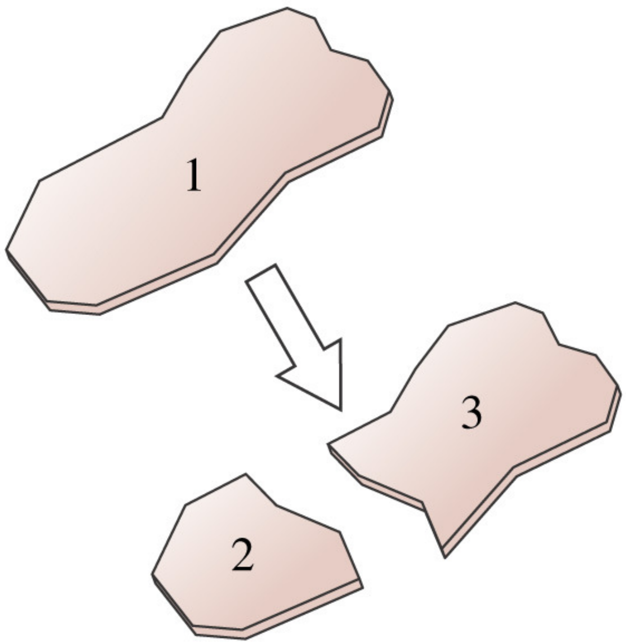
Volume compression

$$p = -B(\Delta V/V)$$

Bulk modulus — Volume strain



Chapter 15. Questions



A piece of glass is broken into two pieces of different size. Rank order, from largest to smallest, the mass densities of pieces 1, 2, and 3.

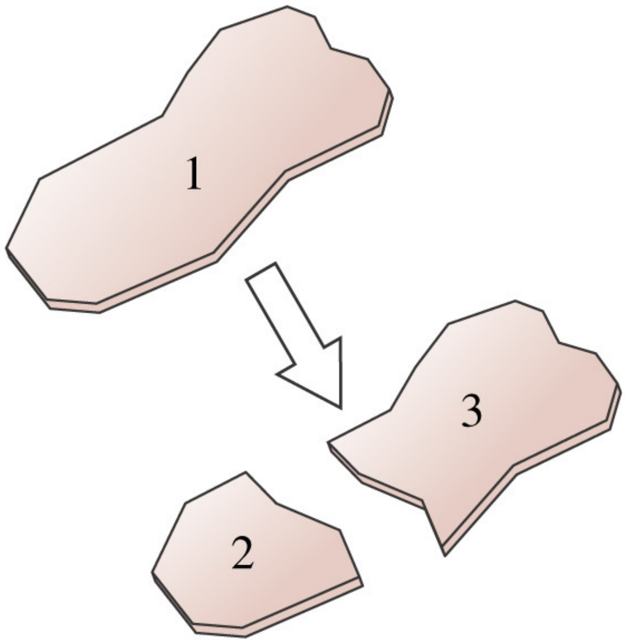
A. $\rho_1 > \rho_3 > \rho_2$

B. $\rho_2 > \rho_3 > \rho_1$

C. $\rho_1 > \rho_2 = \rho_3$

D. $\rho_2 = \rho_3 > \rho_1$

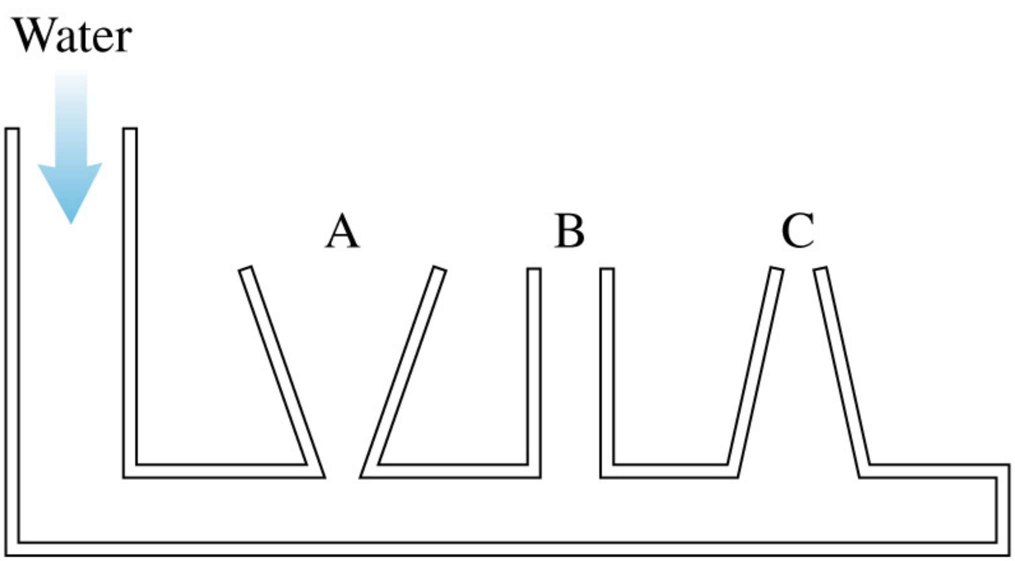
E. $\rho_1 = \rho_2 = \rho_3$



A piece of glass is broken into two pieces of different size. Rank order, from largest to smallest, the mass densities of pieces 1, 2, and 3.

A. $\rho_1 > \rho_3 > \rho_2$
B. $\rho_2 > \rho_3 > \rho_1$
C. $\rho_1 > \rho_2 = \rho_3$
D. $\rho_2 = \rho_3 > \rho_1$
✔ **E.** $\rho_1 = \rho_2 = \rho_3$

Water is slowly poured into the container until the water level has risen into tubes A, B, and C. The water doesn't overflow from any of the tubes. How do the water depths in the three columns compare to each other?



A. $d_A = d_C > d_B$

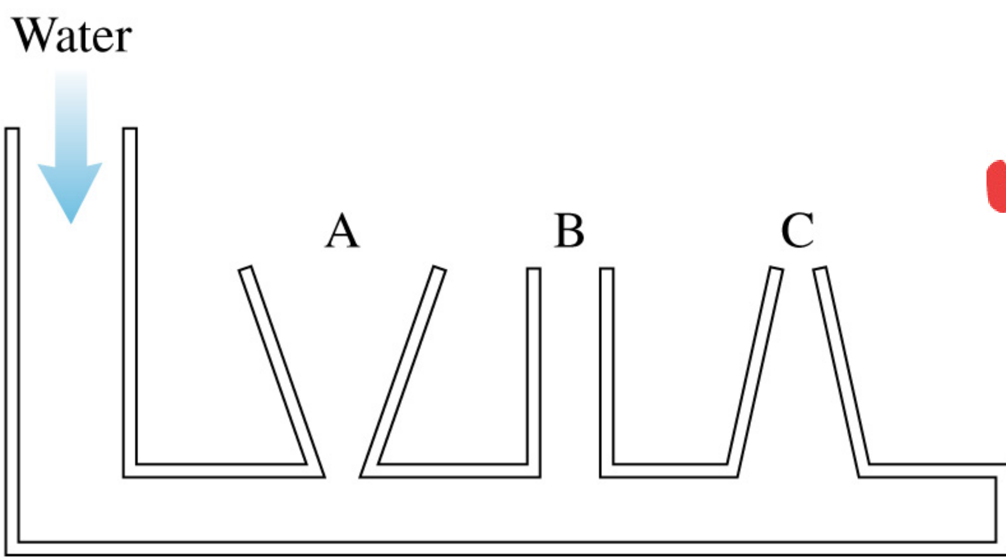
B. $d_A > d_B > d_C$

C. $d_A = d_B = d_C$

D. $d_A < d_B < d_C$

E. $d_A = d_C < d_B$

Water is slowly poured into the container until the water level has risen into tubes A, B, and C. The water doesn't overflow from any of the tubes. How do the water depths in the three columns compare to each other?



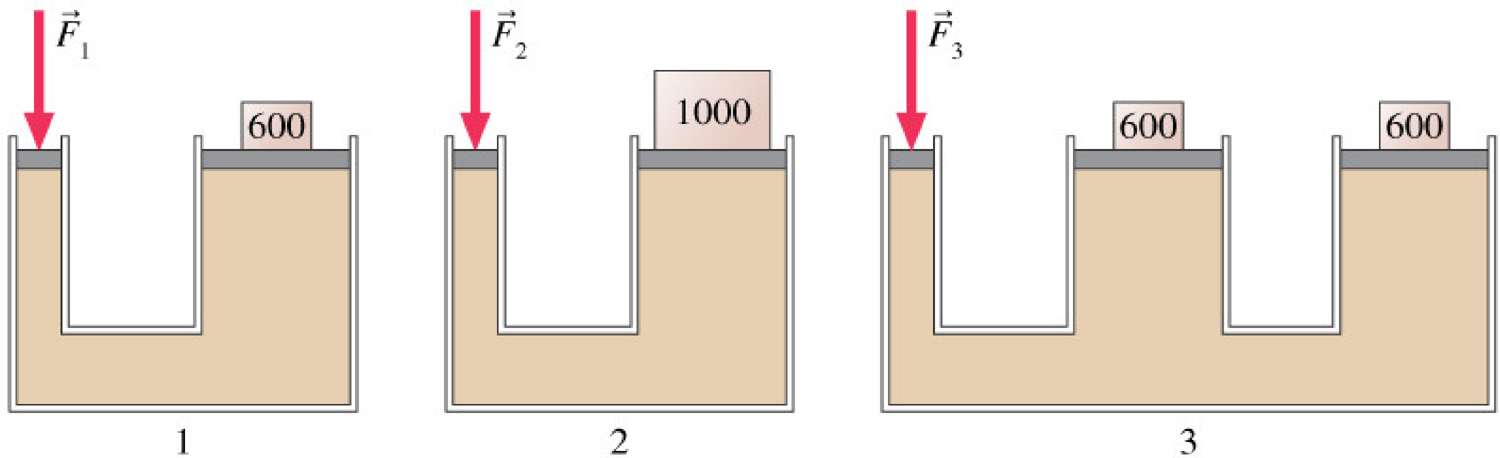
A. $d_A = d_C > d_B$

B. $d_A > d_B > d_C$

C. $\boldsymbol{d_A = d_B = d_C}$

D. $d_A < d_B < d_C$

E. $d_A = d_C < d_B$



Rank in order, from largest to smallest, the magnitudes of the forces $\vec{F}_1$, $\vec{F}_2$ and $\vec{F}_3$ required to balance the masses. The masses are in kilograms.

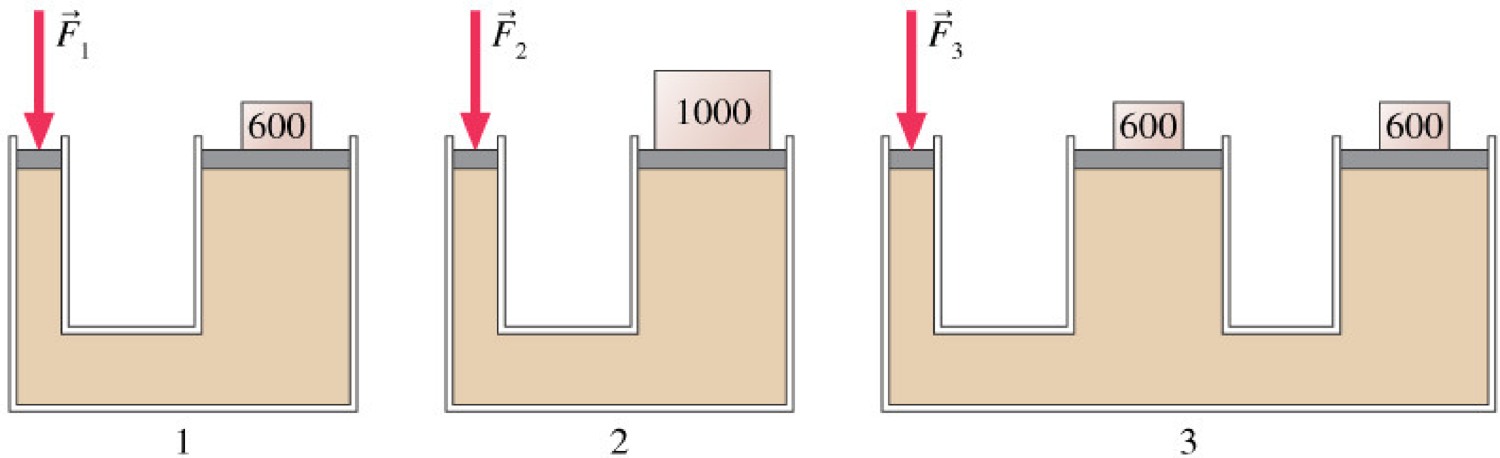
A. $F_1 = F_2 = F_3$

B. $F_3 > F_2 > F_1$

C. $F_3 > F_1 > F_2$

D. $F_2 > F_1 > F_3$

E. $F_2 > F_1 = F_3$



Rank in order, from largest to smallest, the magnitudes of the forces $\vec{F}_1$, $\vec{F}_2$ and $\vec{F}_3$ required to balance the masses. The masses are in kilograms.

A. $F_1 = F_2 = F_3$

B. $F_3 > F_2 > F_1$

C. $F_3 > F_1 > F_2$

D. $F_2 > F_1 > F_3$

✔ **E.** $\boldsymbol{F_2 > F_1 = F_3}$

An ice cube is floating in a glass of water that is filled entirely to the brim. When the ice cube melts, the water level will

A. rise, causing the water to spill.
B. fall.
C. stay the same, right at the brim.

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A. rise, causing the water to spill.
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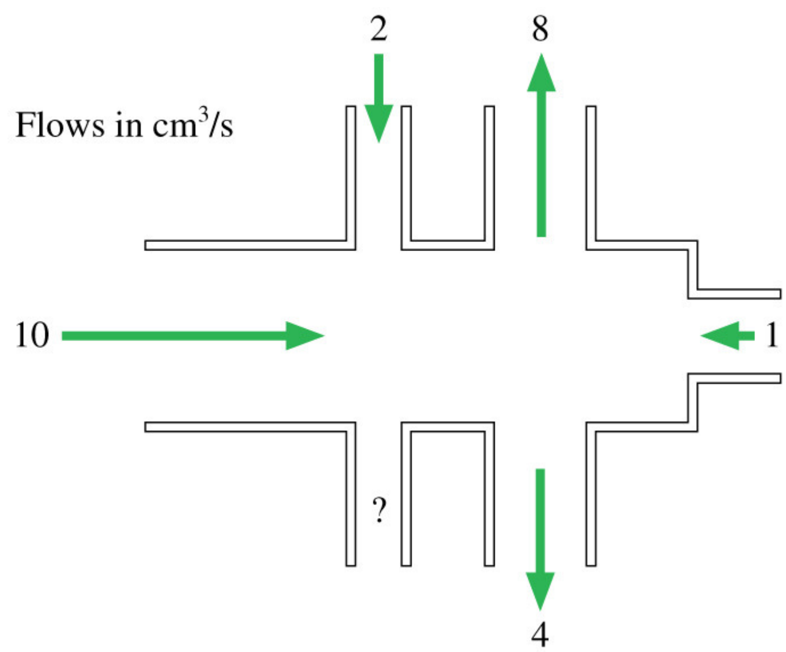
✔ **C. stay the same, right at the brim.**

The figure shows volume flow rates (in cm^3/s) for all but one tube. What is the volume flow rate through the unmarked tube? Is the flow direction in or out?



A. 1 cm^3/s, in
B. 1 cm^3/s, out
C. 10 cm^3/s, in
D. 10 cm^3/s, out
E. It depends on the relative size of the tubes.

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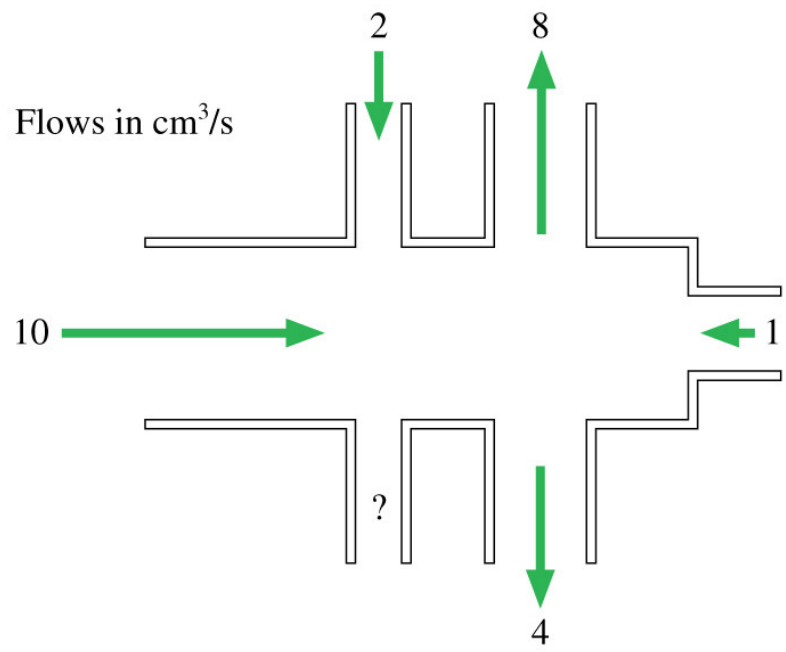


A. 1 cm^3/s, in

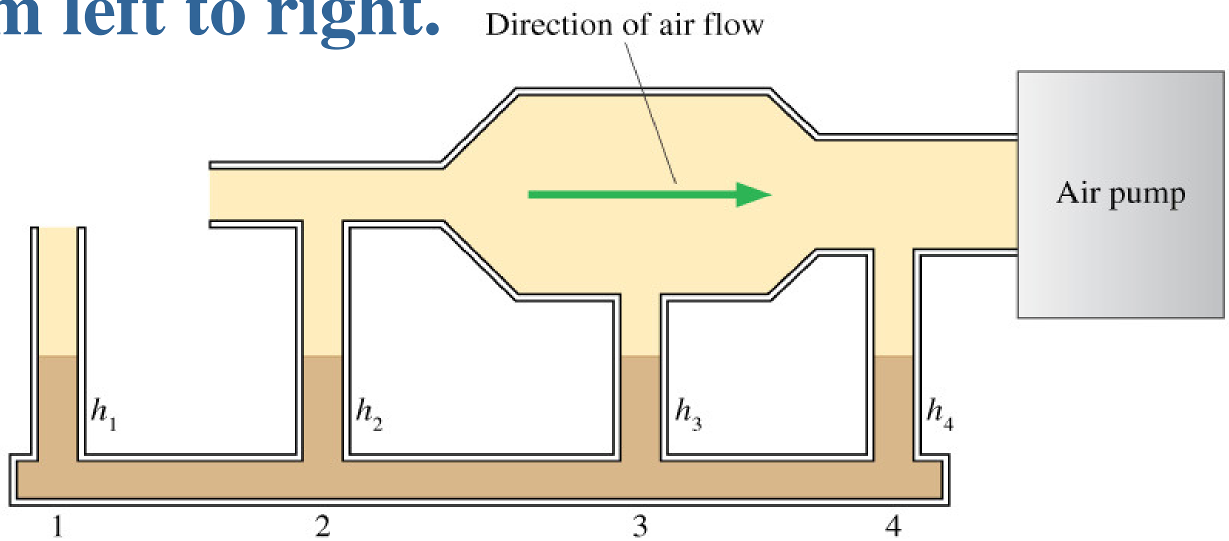
B. 1 cm^3/s, out

C. 10 cm^3/s, in

D. 10 cm^3/s, out

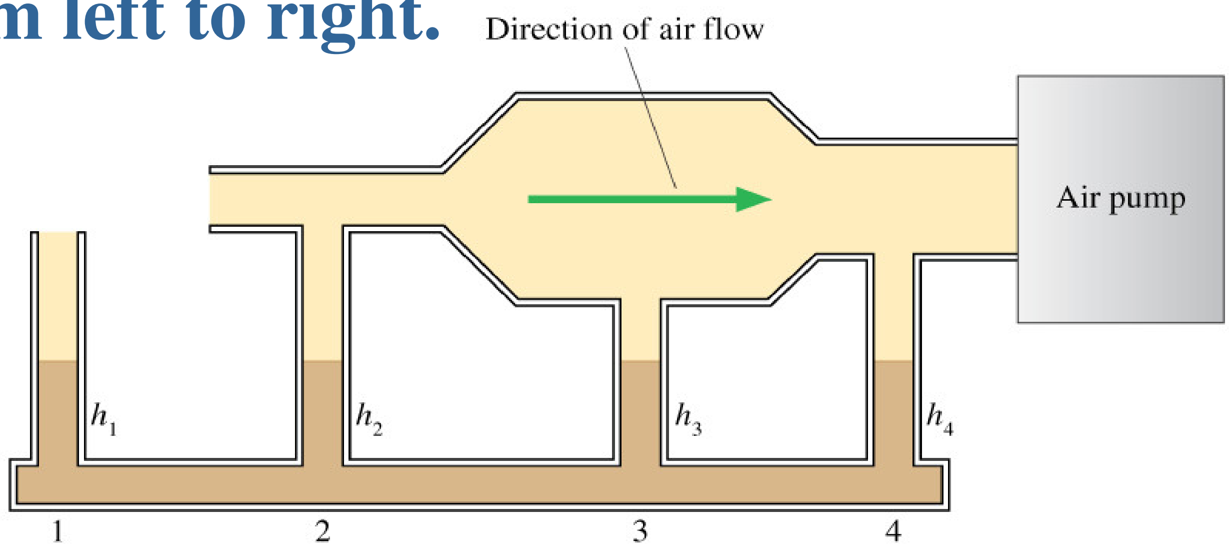
E. It depends on the relative size of the tubes.

Rank in order, from highest to lowest, the liquid heights h_1 to h_4 in tubes 1 to 4. The air flow is from left to right.



A. $h_1 > h_2 = h_3 = h_4$
B. $h_2 > h_4 > h_3 > h_1$
C. $h_2 = h_3 = h_4 > h_1$
D. $h_3 > h_4 > h_2 > h_1$
E. $h_1 > h_3 > h_4 > h_2$

Rank in order, from highest to lowest, the liquid heights h_1 to h_4 in tubes 1 to 4. The air flow is from left to right.



A. $h_1 > h_2 = h_3 = h_4$

B. $h_2 > h_4 > h_3 > h_1$

C. $h_2 = h_3 = h_4 > h_1$

D. $h_3 > h_4 > h_2 > h_1$

E. $h_1 > h_3 > h_4 > h_2$