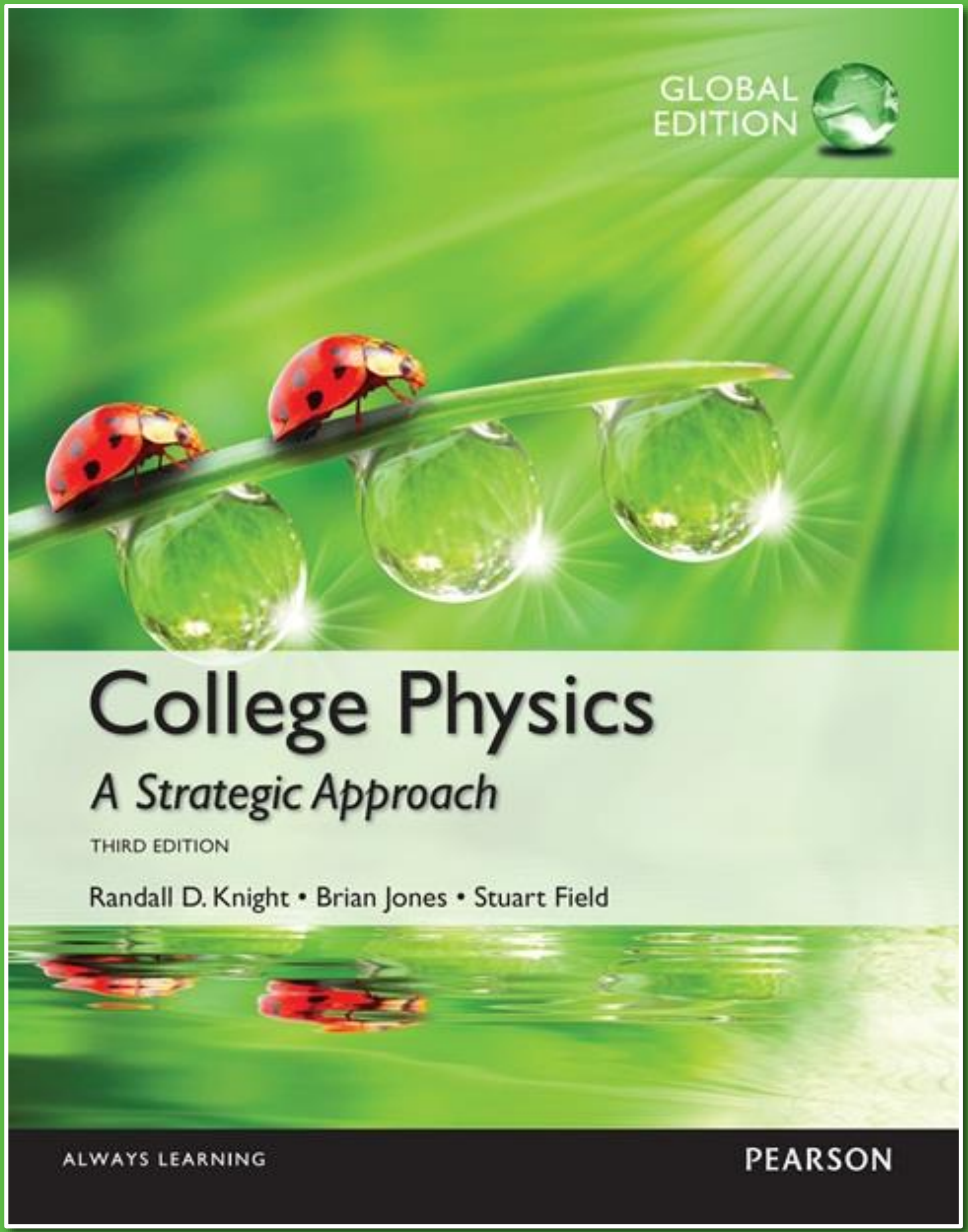


Lecture Presentation

Chapter 13

Fluids

Chapter 13 Fluids

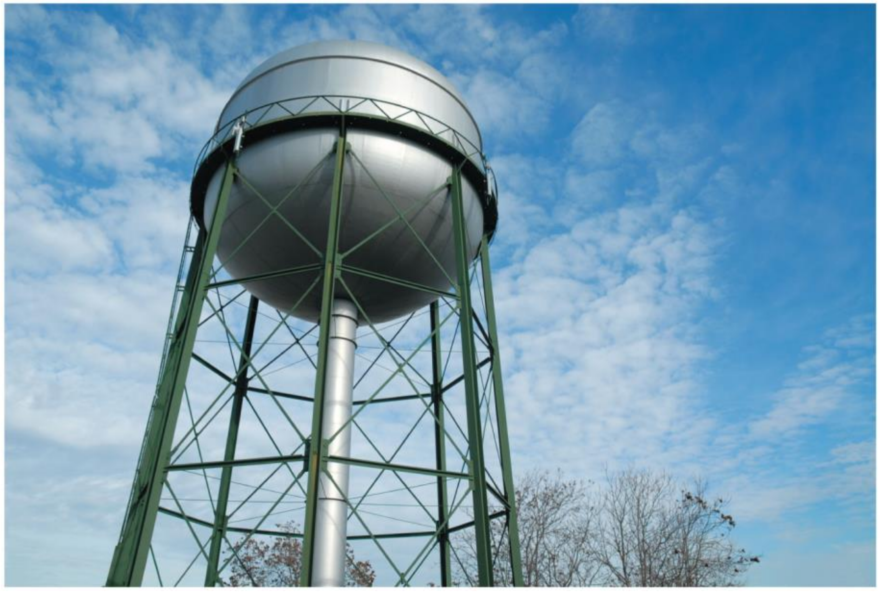
Section 13.1 Fluids and Density
Section 13.2 Pressure
Section 13.3 Measuring and Using Pressure
Section 13.5 Fluids in Motion
Section 13.6 Fluid Dynamics

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: 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.

Fluid Dynamics

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

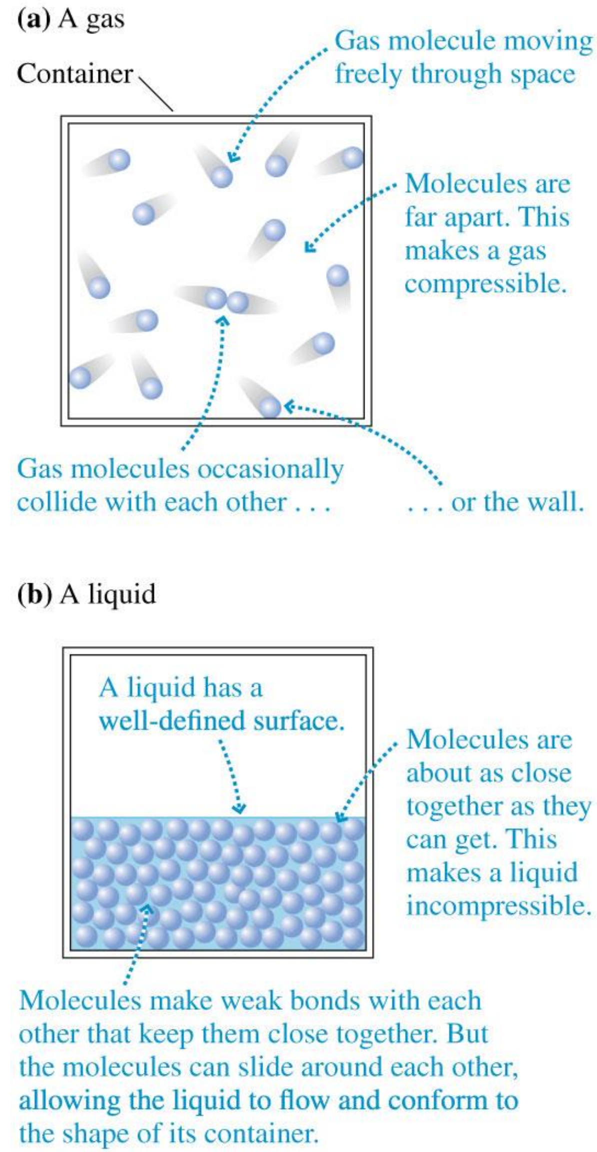
You'll learn to use **Bernoulli's equation** to predict the pressures and forces due to moving fluids.

Text: p. 432

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.

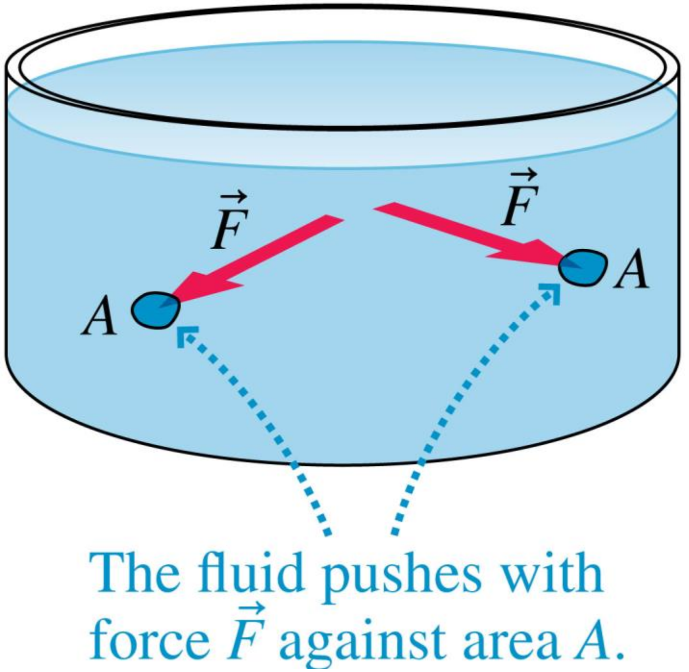
Section 13.2 Pressure

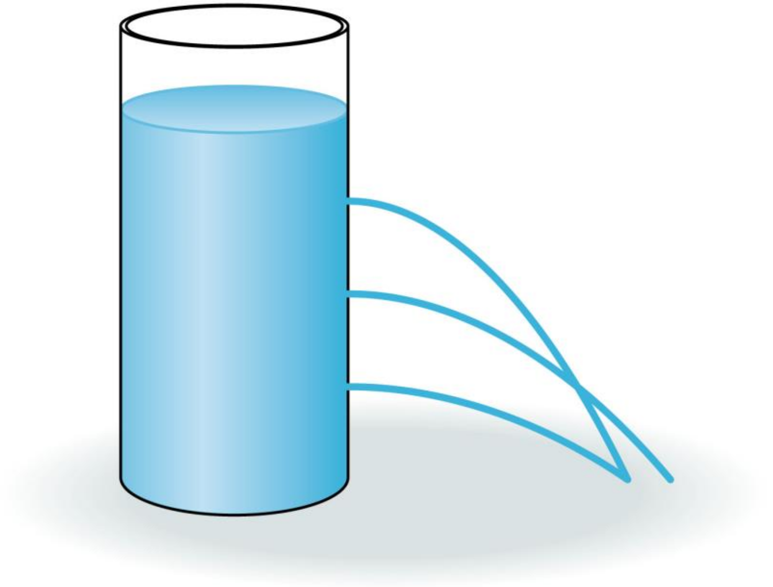
Pressure

- 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 Units

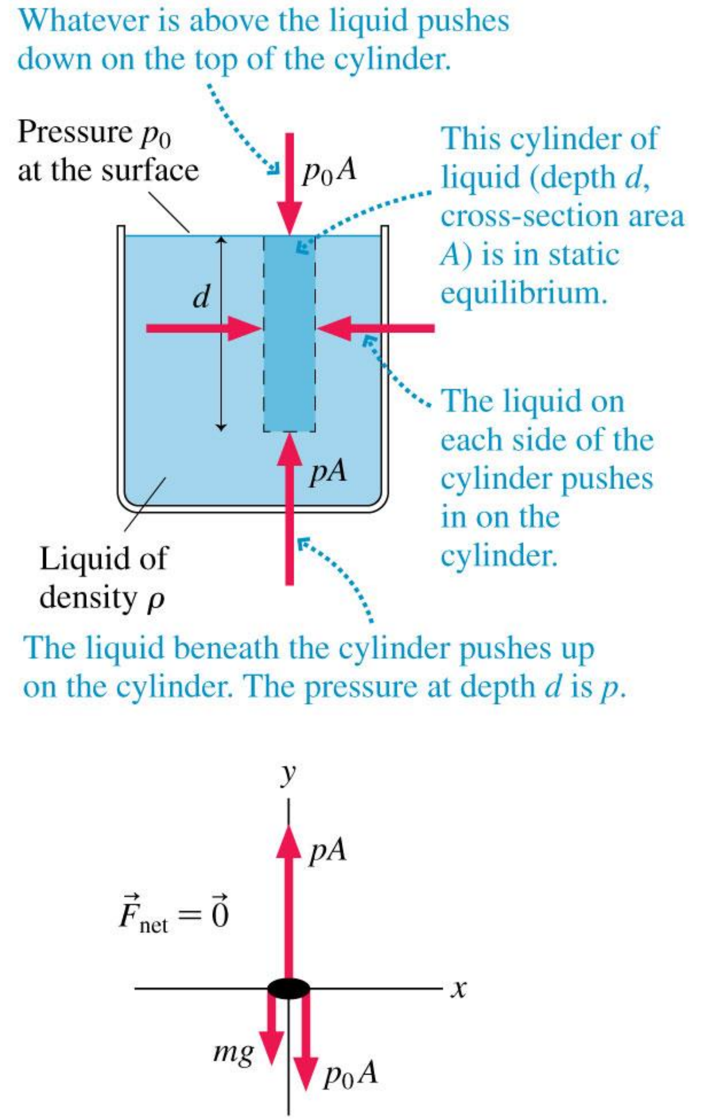
TABLE 13.2 Pressure units

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

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

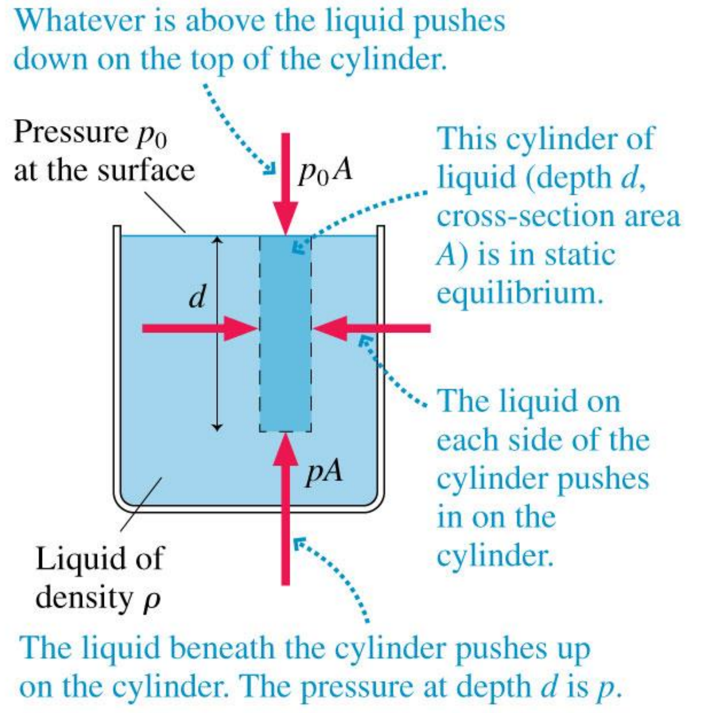
- The liquid is a cylinder of cross-section area A and height d. The mass is $m = \rho A d$. The pressure at depth d is

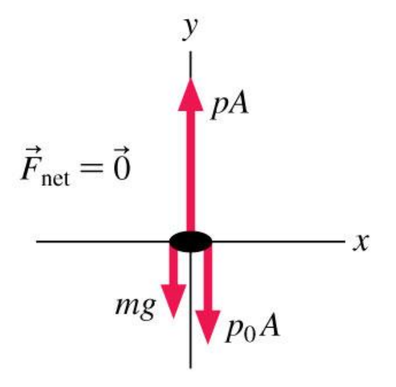
$$p = p_0 + \rho g d$$

Pressure of a liquid with density ρ at depth d

- Gauge Pressure

$$P_{gauge} = P - P_0 = \rho g d$$





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

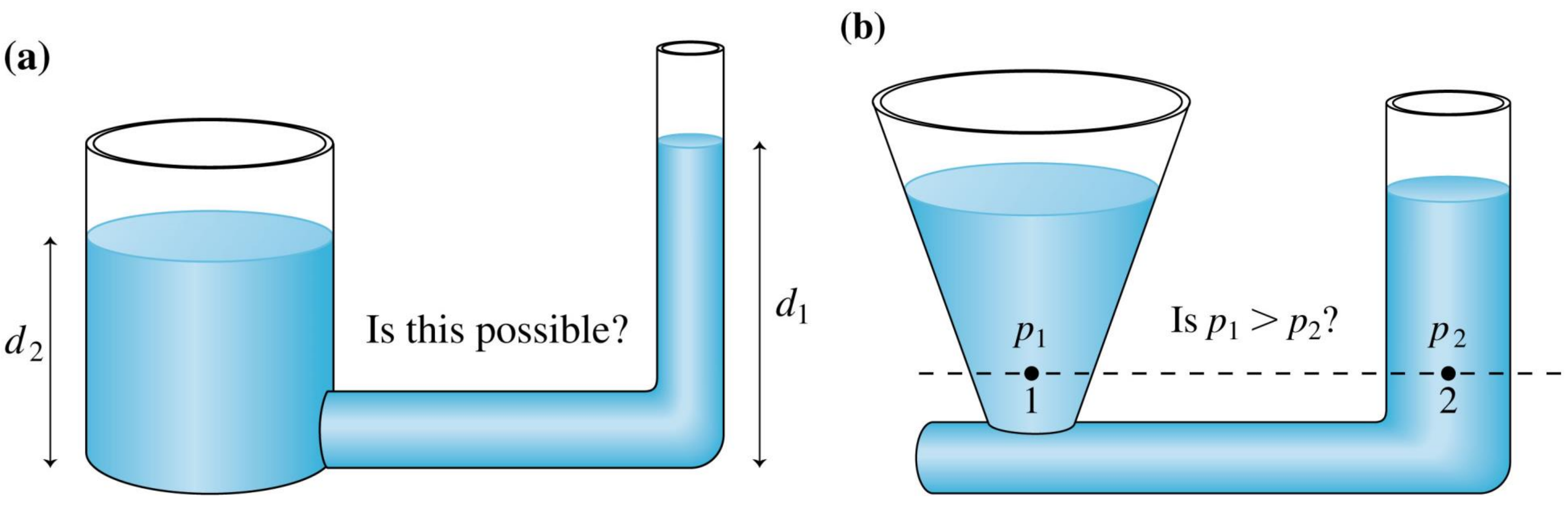
Pressure in Liquids

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.

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

Pressure in Liquids

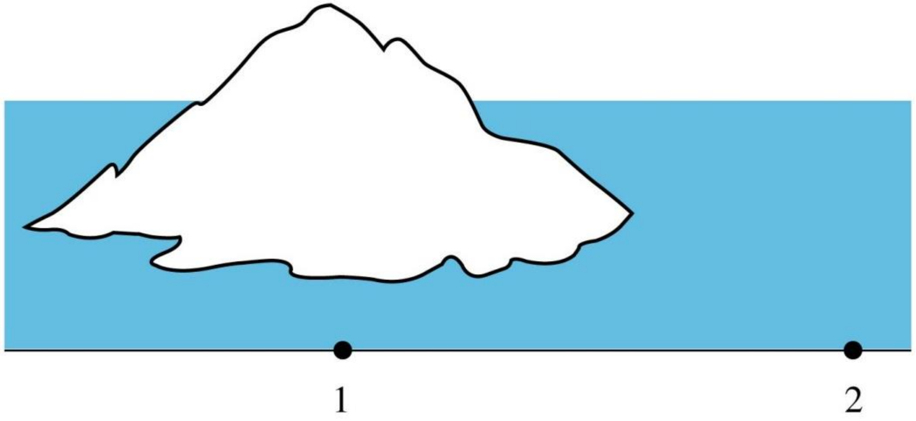
- **A connected liquid in hydrostatic equilibrium rises to the same height in all open regions of the container.**
- **In hydrostatic equilibrium, the pressure is the same at all points on a horizontal line through a connected liquid of a single kind.**



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. $p_1 < p_2$



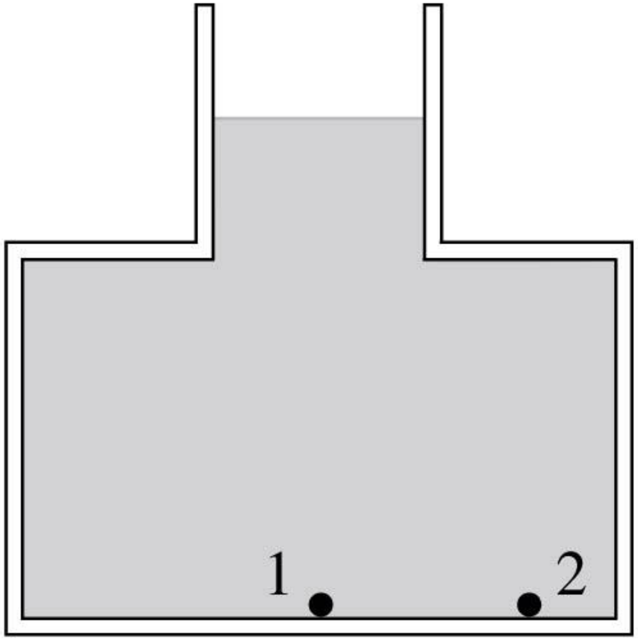
QuickCheck 13.2

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

A. $p_1 > p_2$

B. $p_1 < p_2$

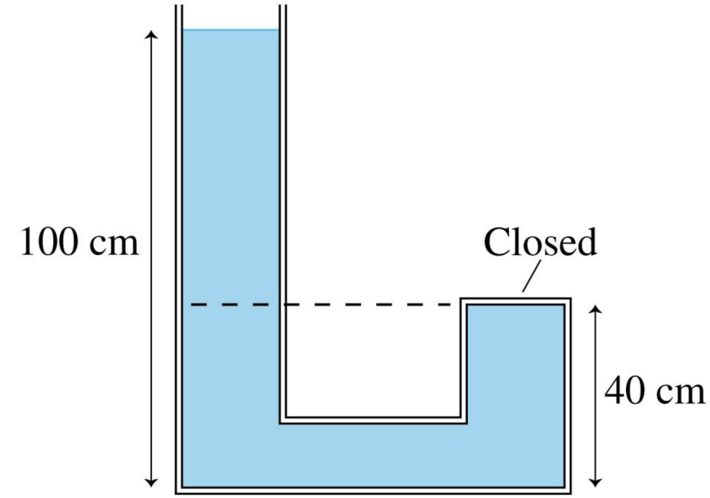
C. $p_1 = p_2$



Example 13.3 Pressure in a closed tube

Water fills the tube shown in the figure.

What is the pressure at the top of the closed tube?



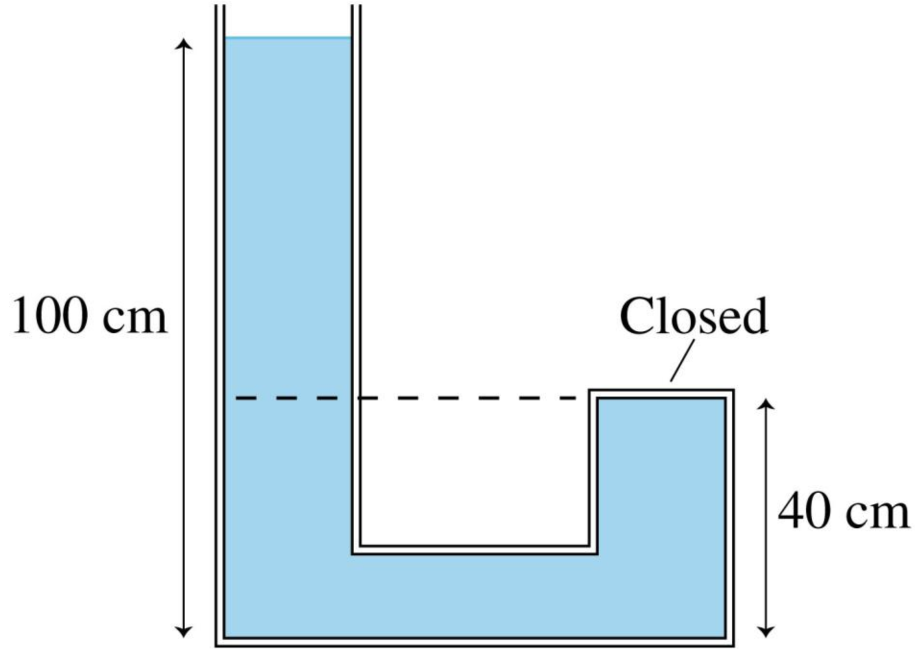
PREPARE This is a liquid in hydrostatic equilibrium. The closed tube is not an open region of the container, so the water cannot rise to an equal height. Nevertheless, the pressure is still the same at all points on a horizontal line. In particular, the pressure at the top of the closed tube equals the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

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

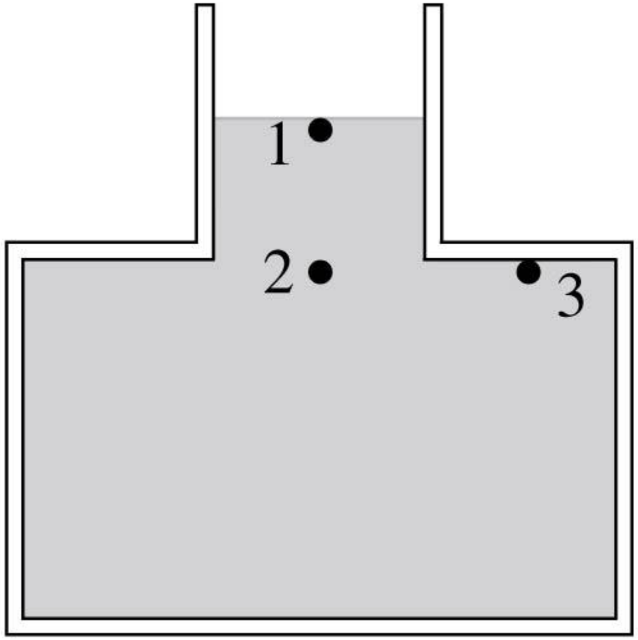
ASSESS The water column that creates this pressure is not very tall, so it makes sense that the pressure is only a little higher than atmospheric pressure.



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. $p_2 = p_3 > p_1$



Section 13.3 Measuring and Using Pressure

Measuring and Using Pressure

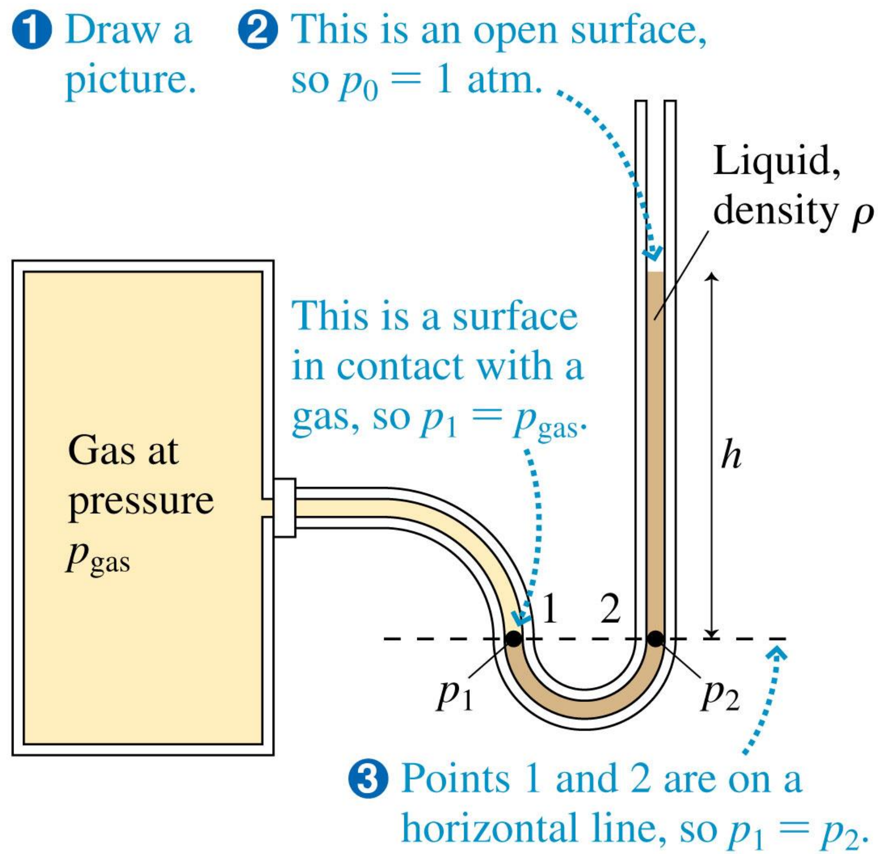
Hydrostatics

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:** $p = p_0 + \rho g d$.

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

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

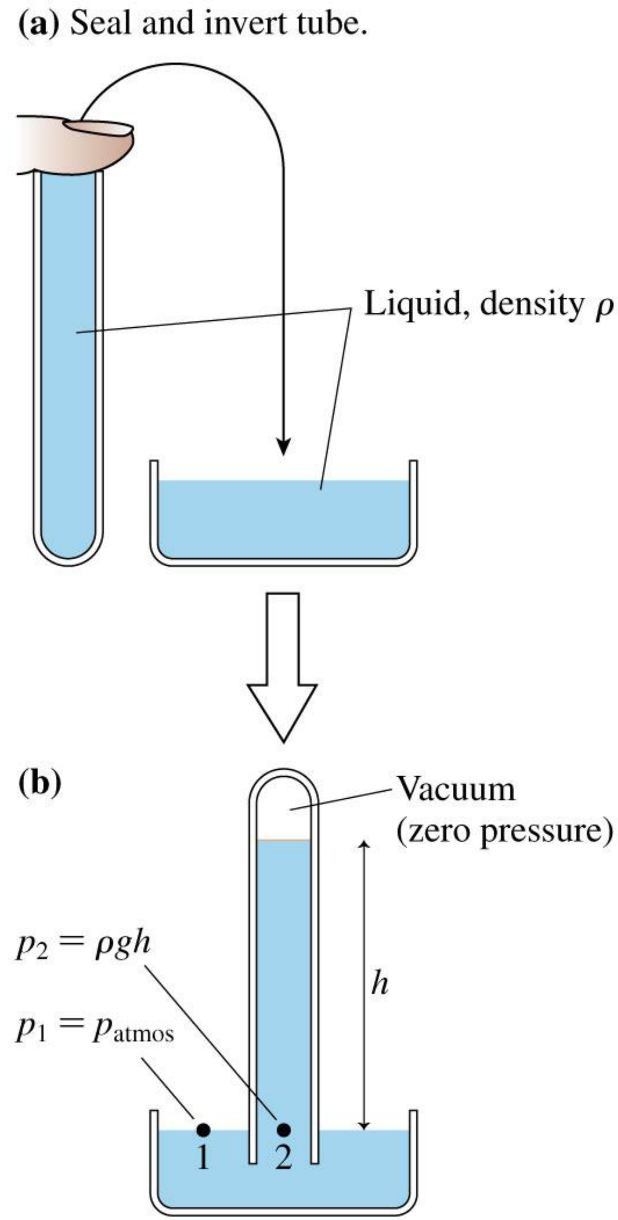


Manometers and Barometers

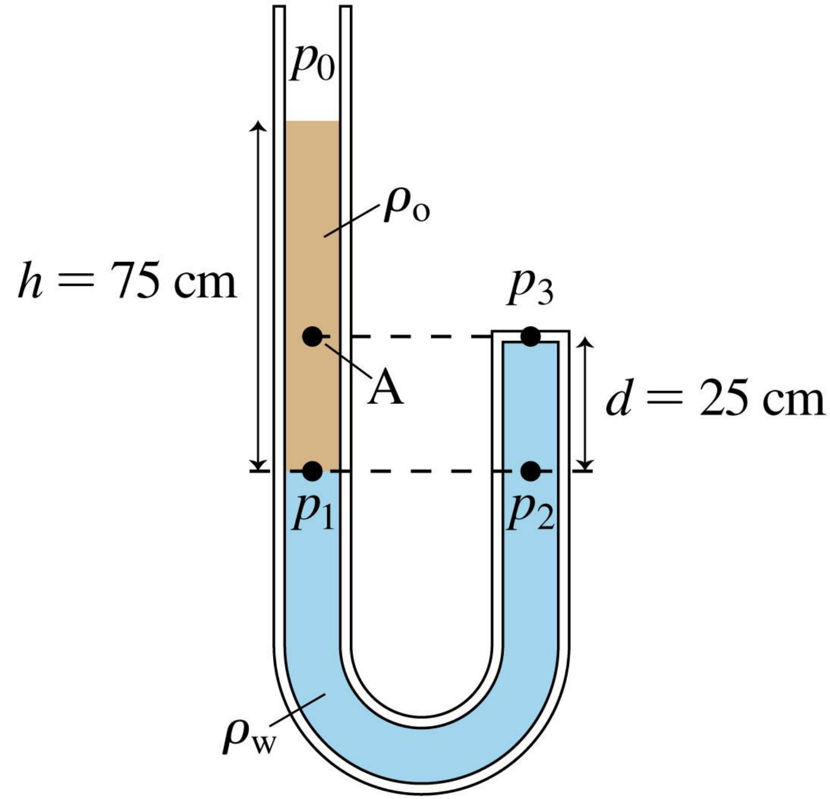
- A *barometer* measures the atmospheric pressure p_{atmos}.
- A glass tube is placed in a beaker of the same liquid. Some, but not all liquid leaves the tube.
- p_2 is the pressure due to the weight of the liquid in the tube and

  $p_1 = p_{\text{atmos}}$.
- Equating the two pressures gives

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

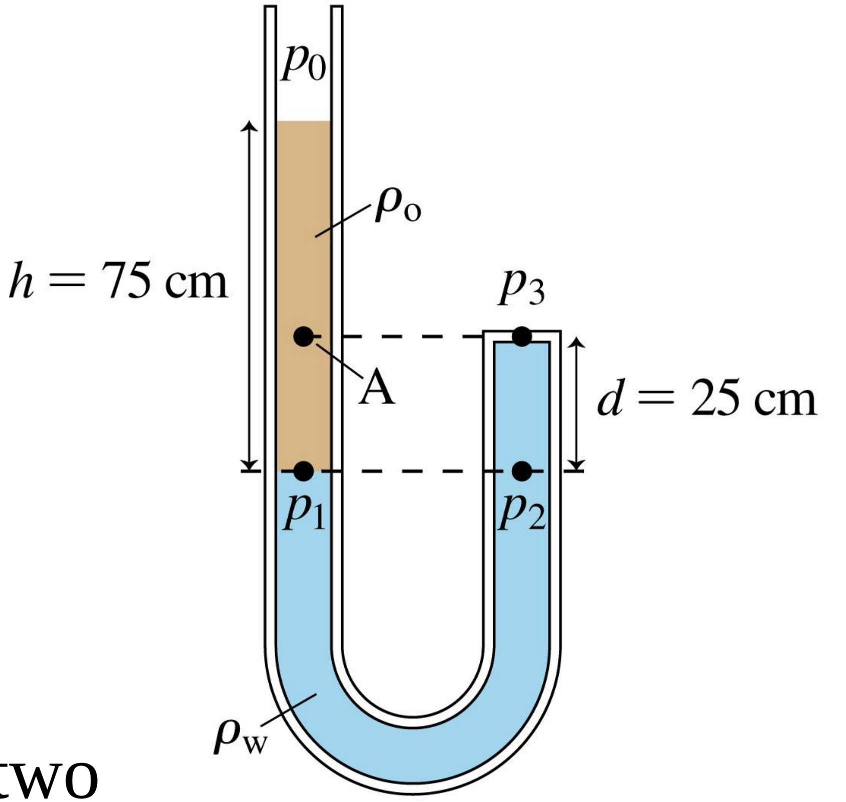


Example 13.4 Pressure in a tube with two liquids



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?

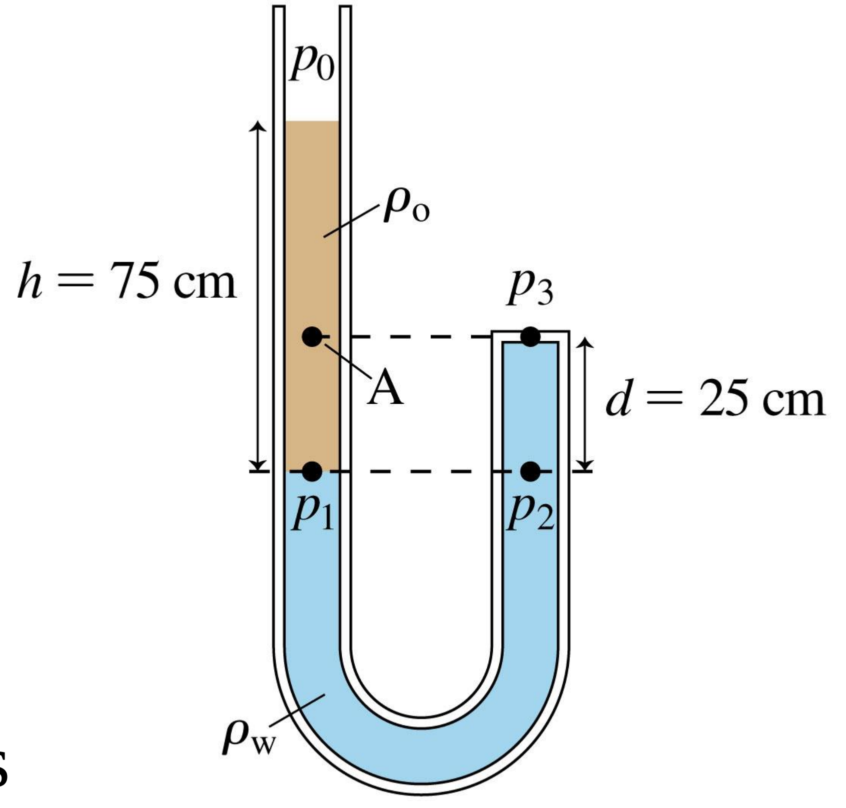
Example 13.4 Pressure in a tube with two liquids (cont.)



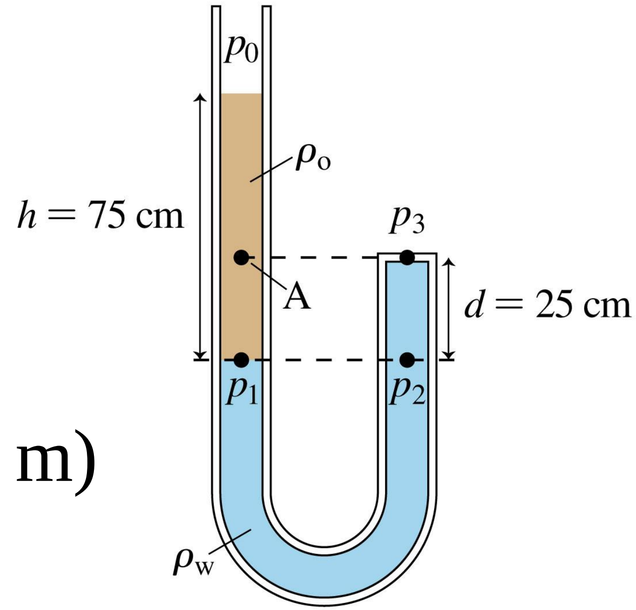
PREPARE We start by drawing the picture shown in the figure. We know that the pressure at the open surface of the oil is $p_0 = 1$ atm. Pressures p_1 and p_2 are the same because they are on a horizontal line that connects two points in the *same* fluid. (The pressure at point A is *not* equal to p_3, 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 $\rho_w = 1000\ \text{kg/m}^3$ and $\rho_o = 900\ \text{kg/m}^3$.



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



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

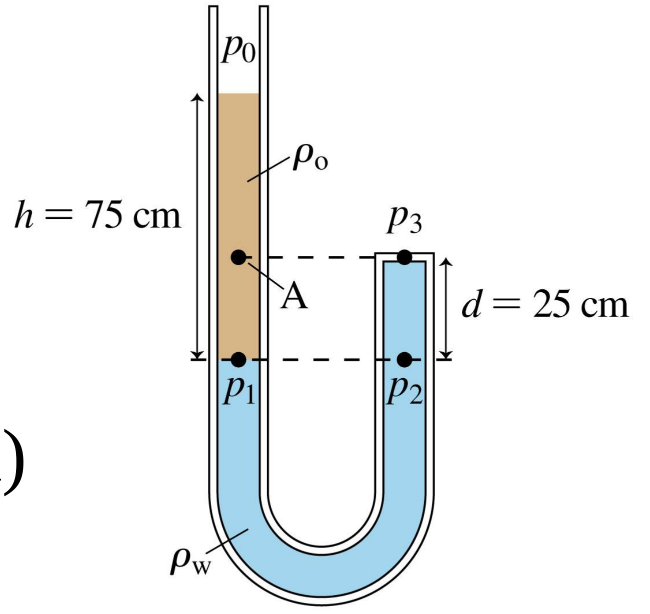
$$p_1 = p_0 + \rho_o g h$$
$$= 1 \text{ atm} + (900 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(0.75 \text{ m})$$
$$= 1 \text{ atm} + 6620 \text{ Pa}$$

(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

$$p_2 = p_3 + \rho_w g\, d$$
$$= p_3 + (1000\ \text{kg/m}^3)(9.8\ \text{m/s}^2)(0.25\ \text{m})$$
$$= p_3 + 2450\ \text{Pa}$$



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

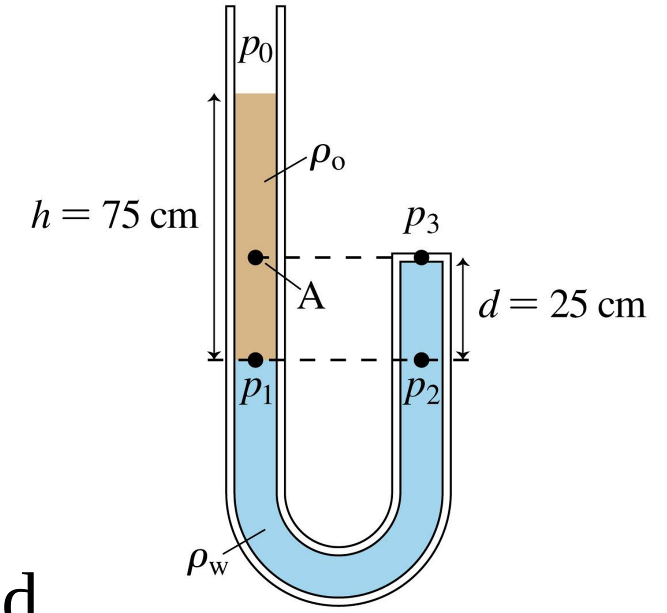
But we know that $p_2 = p_1$, so

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

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

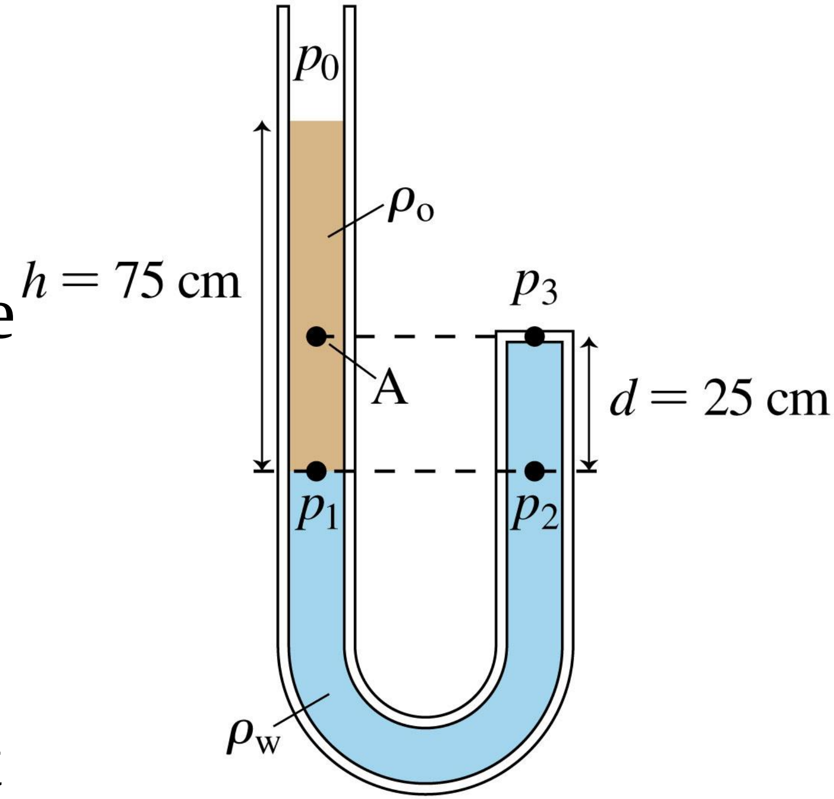
$= 1\text{ atm} + 4200\text{ Pa}$

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 $\rho g(0.50\text{ m}) = 5000\text{ Pa} = 5\text{ kPa}$. This is not too far from our answer, giving us confidence that it's correct.



Section 13.5 Fluids in Motion

Fluids in Motion

For fluid *dynamics* we use a simplified *model* of an <u>ideal fluid</u>. We assume

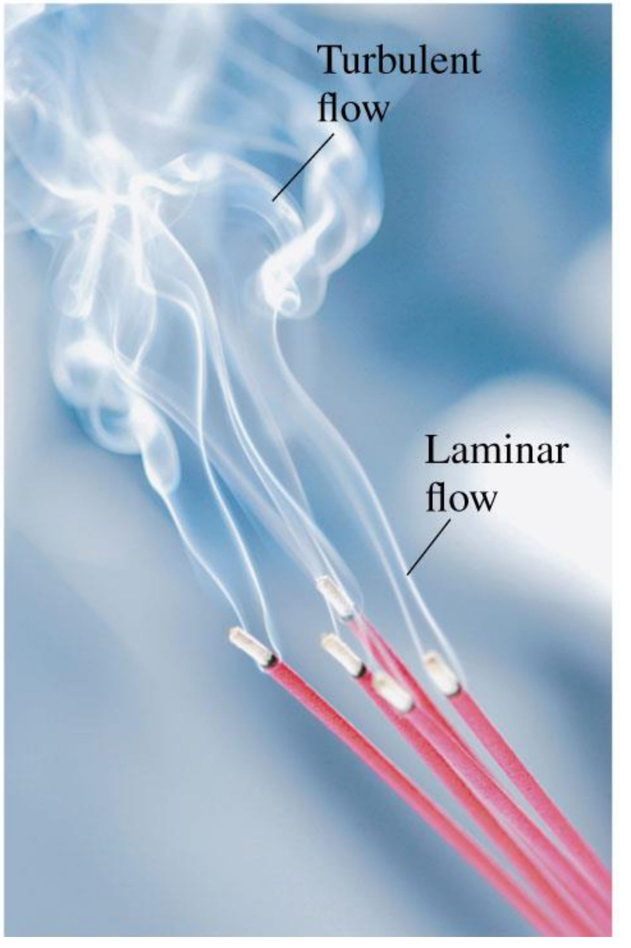
1. The fluid is *incompressible*.

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*. Viscosity is resistance to flow, and assuming a fluid is nonviscous is analogous to assuming the motion of a particle is frictionless.

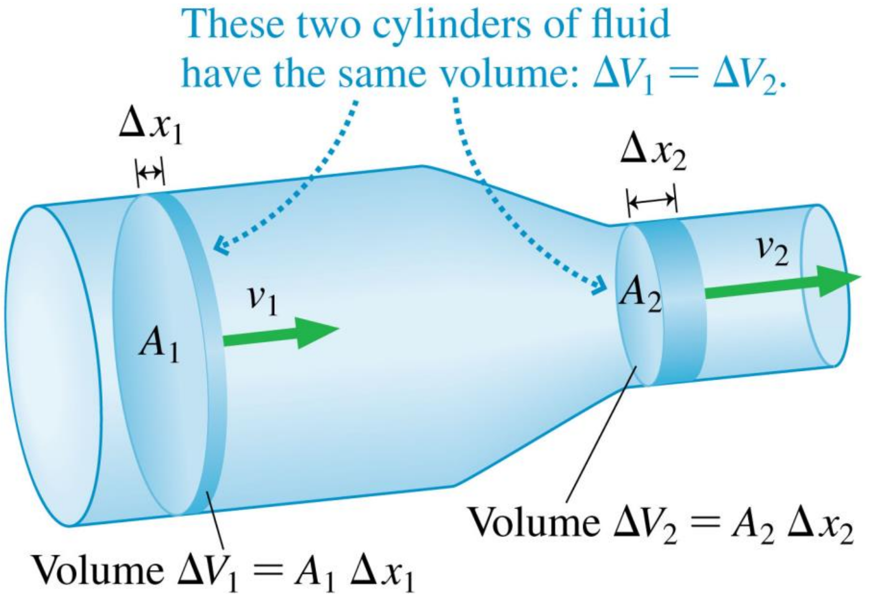
Fluids in Motion

- 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.**

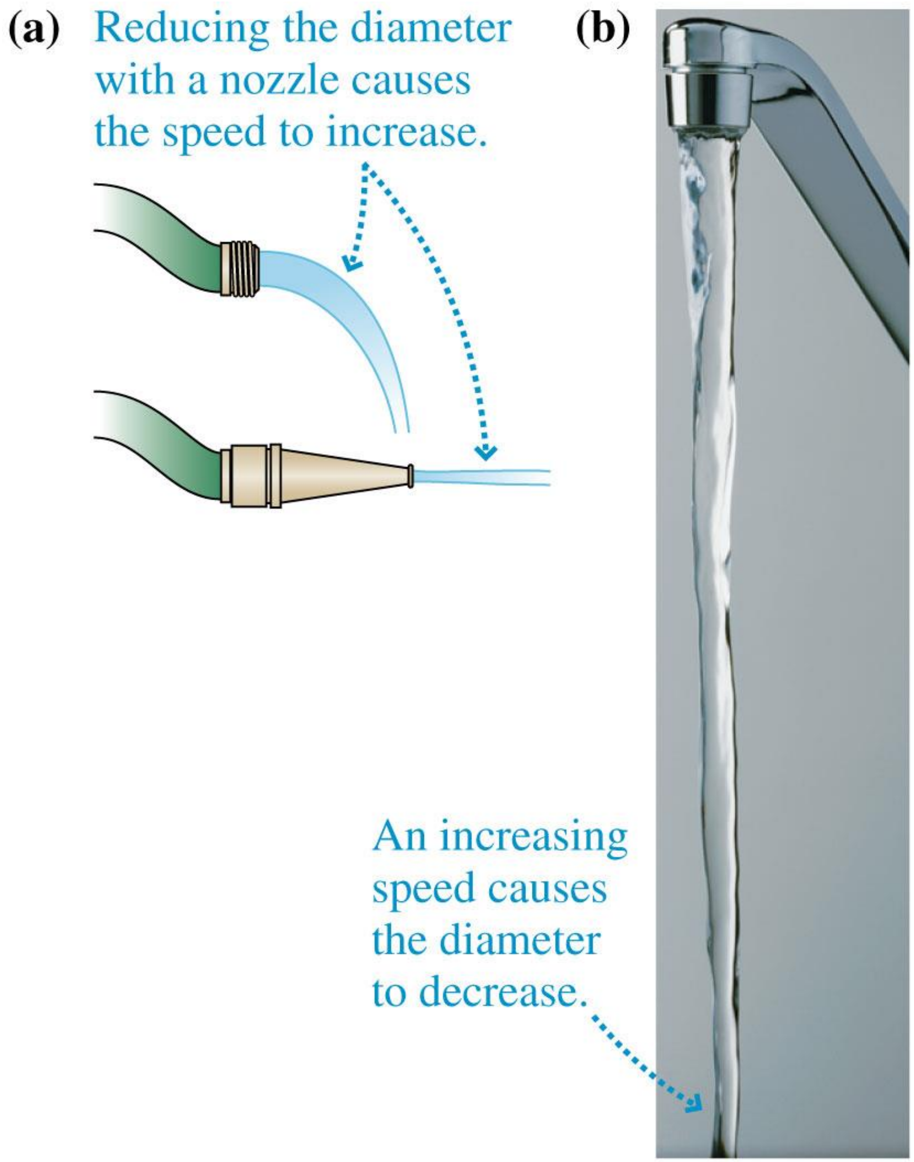
The Equation of Continuity

- The *rate* at which fluid flows through a tube (volume per second) is called the **volume flow rate** $Q = vA$.

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 all points in the tube.**

$$Q_1 = v_1 A_1 = Q_2 = v_2 A_2$$



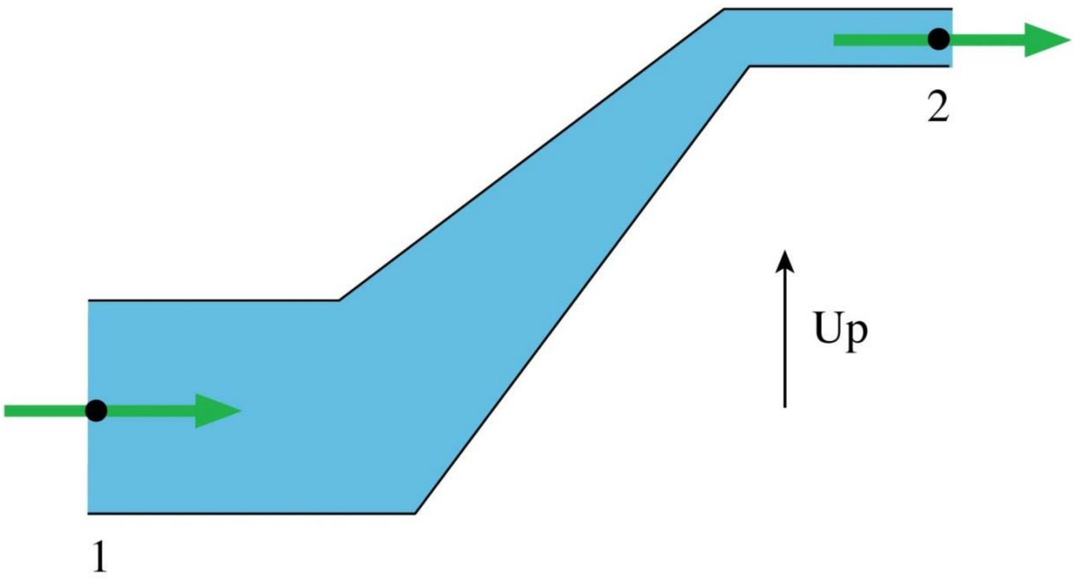
QuickCheck 13.10

- 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. $v_1 < v_2$



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

The volume flow rate is:

$Q = \Delta V/\Delta t = (10\text{ L})/(20\text{ s}) = 0.50\text{ L/s}.$

To convert this to SI units, recall that:

$1\text{ L} = 1000\text{ mL} = 10^3\text{ cm}^3 = 10^{-3}\text{ m}^3.$

Thus $Q = 5.0 \times 10^{-4}\text{ m}^3\text{/s}$. We can find the speed of the water from Equation 13.13:

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

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

SOLVE

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.

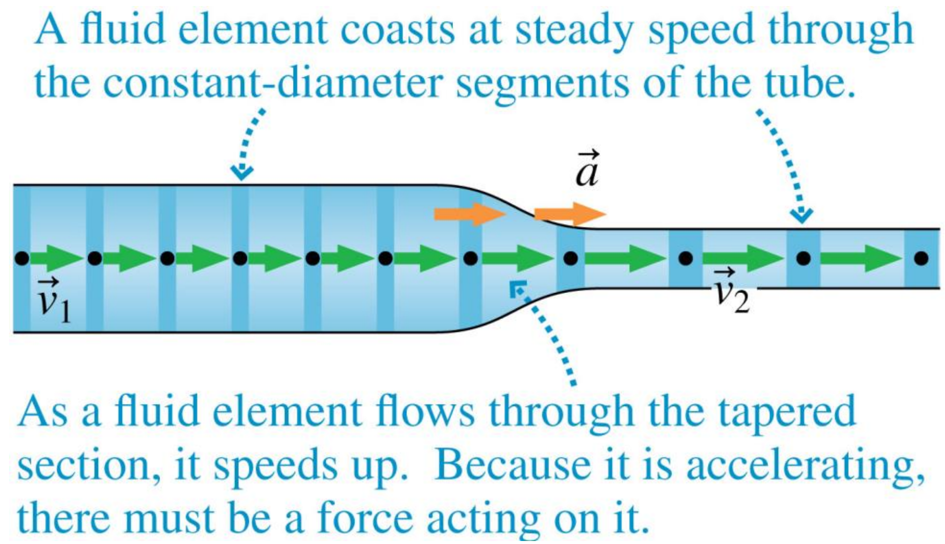
$$v_1 A_1 = v_2 A_2$$

$$v_1 \pi r_1^2 = v_2 \pi r_2^2 \quad \boxed{v_1 r_1^2 = v_2 r_2^2}$$

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*.

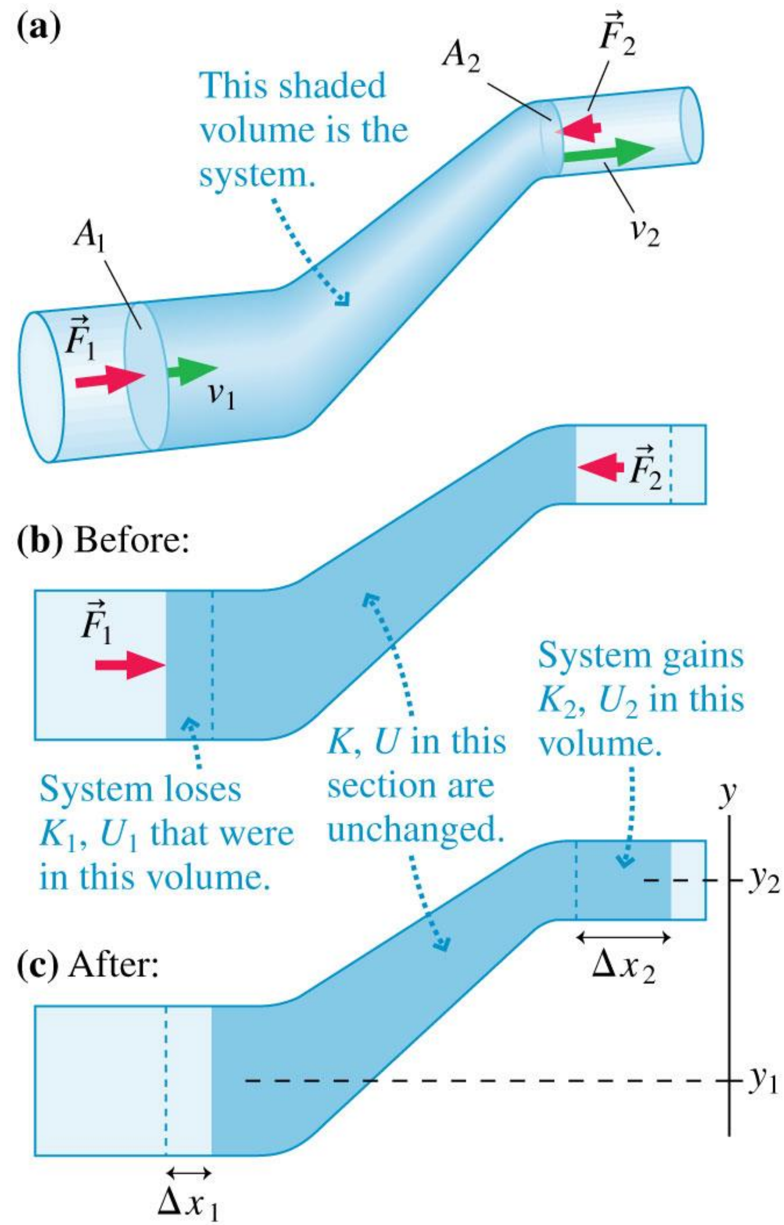
Bernoulli's Equation

- 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

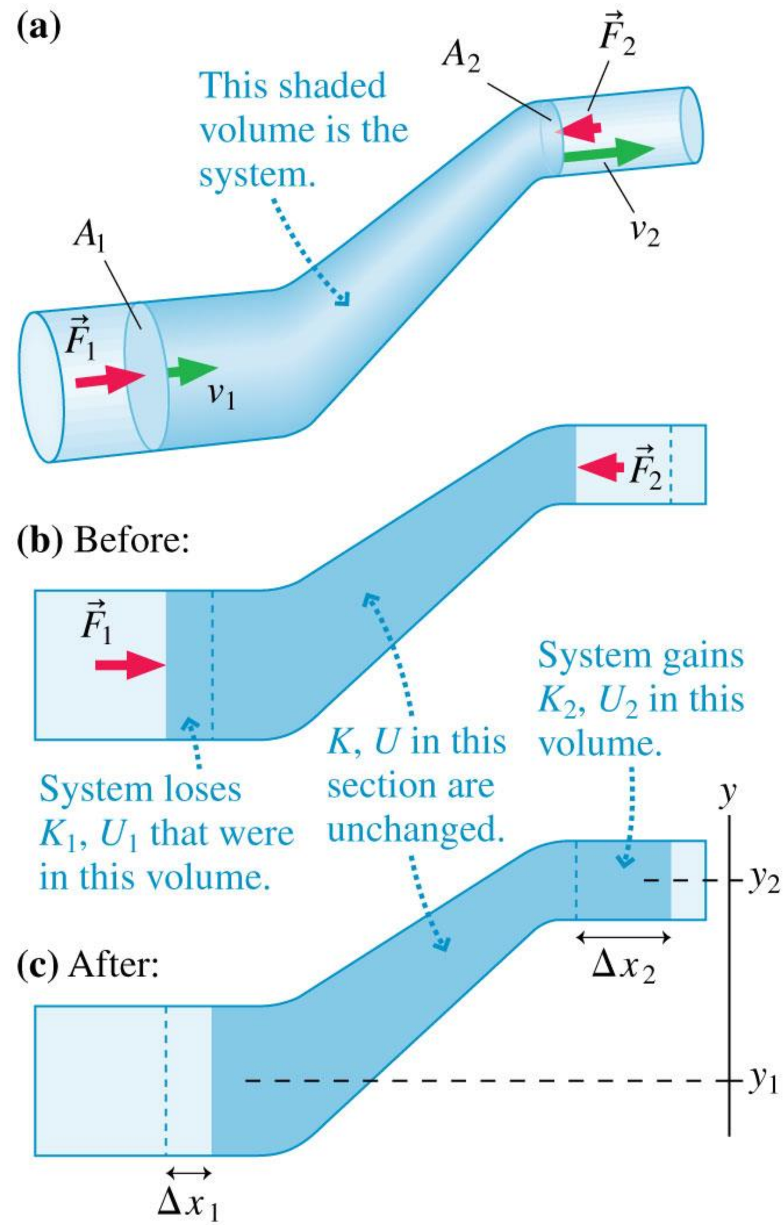
- The net change in gravitational potential energy is

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

- 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

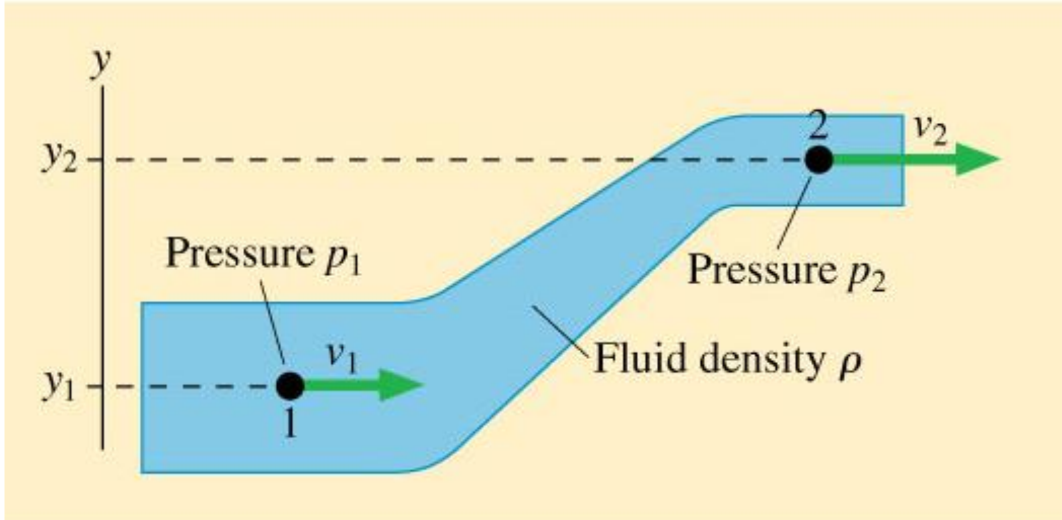
- The *net* work done on the system is:

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

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

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

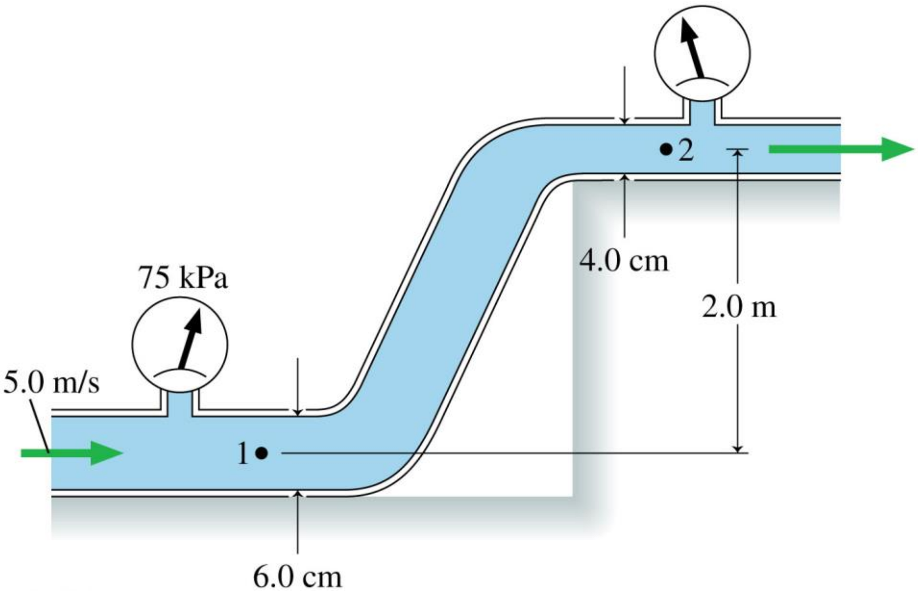
- Rearranged, this equation is **Bernoulli's equation**, which relates ideal-fluid quantities at two points along a streamline:



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

Example 13.12 Pressure in an irrigation system

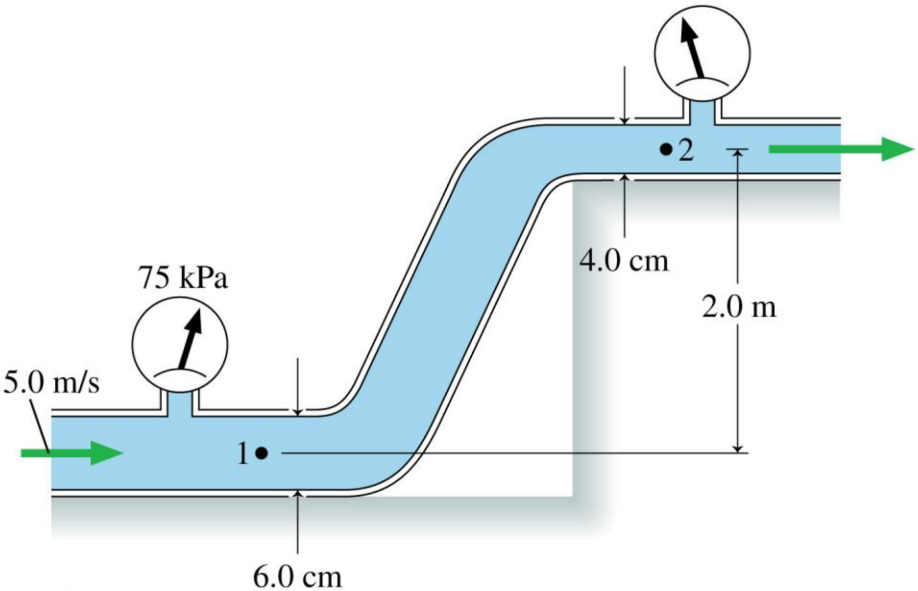
Water flows through the pipes shown in the figure. The water's speed through the lower pipe is 5.0 m/s, and a pressure gauge reads 75 kPa. What is the reading of the pressure gauge on the upper pipe?



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, relates the pressures, fluid speeds, and heights at points 1 and 2. It is easily solved for the pressure p_2 at point 2:

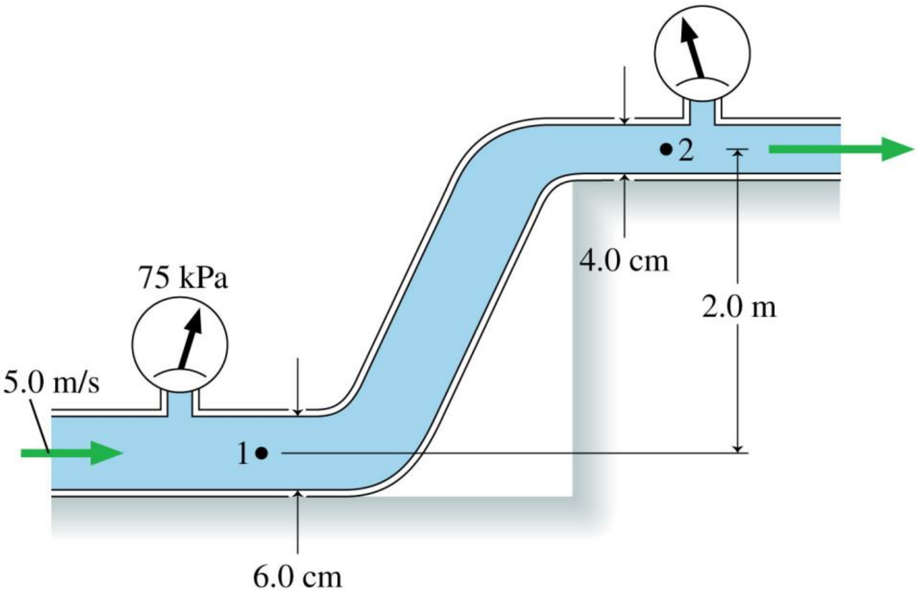


$$p_2 = p_1 + \frac{1}{2}\rho v_1^2 - \frac{1}{2}\rho v_2^2 + \rho g y_1 - \rho g y_2$$

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

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



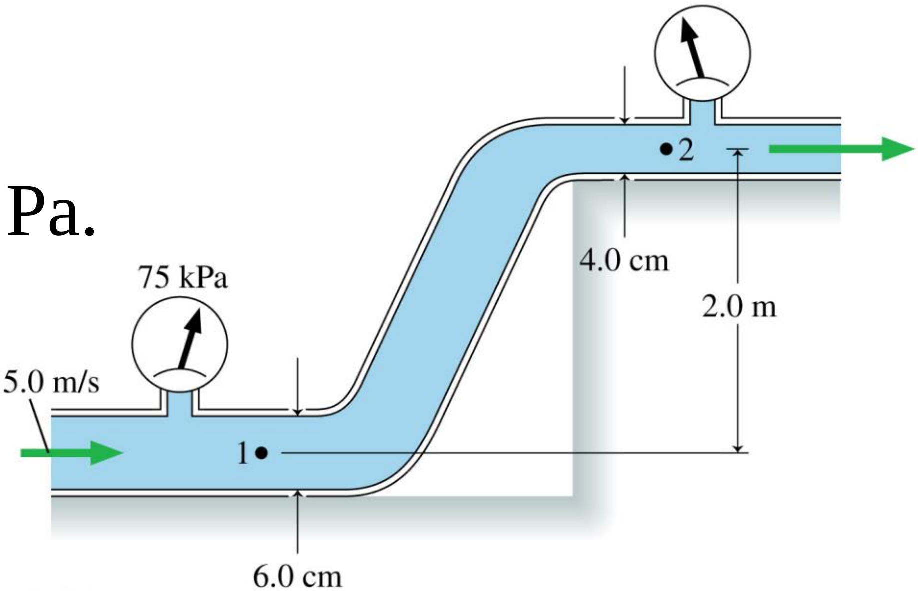
$$v_1 A_1 = v_2 A_2$$

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.

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 13.4

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.

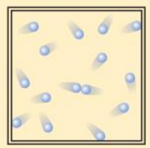
Summary

GENERAL PRINCIPLES

Fluid Statics

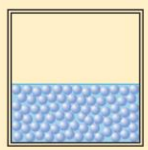
Gases

- 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

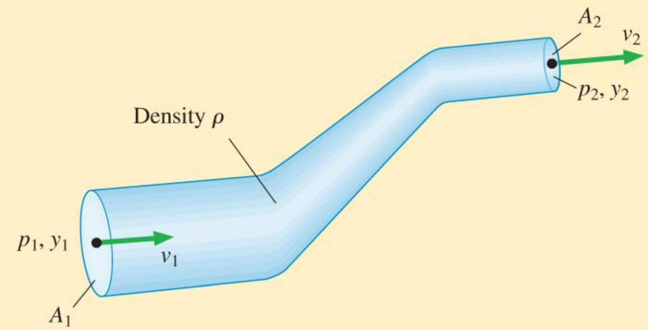


- Hydrostatic pressure at depth d is $p = p_0 + \rho g d$
- The pressure is the same at all points on a horizontal line through a liquid (of one kind) in hydrostatic equilibrium

Fluid Dynamics

Ideal-fluid model

- Incompressible
- Smooth, laminar flow
- Nonviscous



Equation of continuity

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

Bernoulli's equation is a statement of energy conservation:

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