

# *Chapter 10*

## ***Solids & Liquids***

Next 6 chapters use all the concepts developed in the first 9 chapters, recasting them into a form ready to apply to specific physical systems.

	3/27	Th	Properties of Solids, Liquids & Gases	Ch. 10.1-3	E 10.1-8	G 10.2-3	
13	4/1	T	Buoyancy & Fluid Properties	Ch. 10.4-6	E 10.9-13	G 10.5	<b>Set 9</b>
	4/3	Th	Temperature, Heat, Kinetic Theory	Ch. 12.1-4; 13.1-2	E 12.1-13, E 13.1-4	G 12.1-4, G 13.2	
14	4/8	T	Phase Changes, Intro. Thermodynamics	Ch. 13.2-4; 14.1-2	E 13.5-14, E 14.1-6	G 13.3-4, G 14.1-2	<b>Set 10</b>
	4/10	Th	<b>Midterm Exam 3</b>	Ch. 1-13 (no 7,11)			
15	4/15	T	2nd Law of Thermodynamics, Entropy	Ch. 14.3-5	E 14.7-13	G 14.3-4	
	4/17	Th	Oscillations, Waves & Interference	Ch. 7.1-6; 11.1-2	E 7.1-9, E 11.1-5	G 7.1-4, G 11.1-2	
16	4/22	T	Sound, Doppler Effect	Ch. 11.3-5	E 11.6-13	G 11.3-4	<b>Set 11</b>
	4/24	Th	Review				
17	4/28	M	<b>Final Exam 8:00-10:00 pm, Rm TBD</b>	Ch. 1-14			

## 10.1 Phases of Matter , Mass Density

### THREE PHASES OF MATTER

Solids, Liquids, Gases

Combination of Temperature and Pressure determine the phase.

### DEFINITION OF MASS DENSITY

The mass density of a substance is the mass of a substance divided by its volume:

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

***SI Unit of Mass Density:*** kg/m<sup>3</sup>

**Mass Densities<sup>a</sup>  
of Common Substances**

Substance	Mass Density $\rho$ (kg/m <sup>3</sup> )
<b>Solids</b>	
Aluminum	2700
Brass	8470
Concrete	2200
Copper	8890
Diamond	3520
Gold	19 300
Ice	917
Iron (steel)	7860
Lead	11 300
Quartz	2660
Silver	10 500
Wood (yellow pine)	550
<b>Liquids</b>	
Blood (whole, 37 °C)	1060
Ethyl alcohol	806
Mercury	13 600
Oil (hydraulic)	800
Water (4 °C)	$1.000 \times 10^3$
<b>Gases</b>	
Air	1.29
Carbon dioxide	1.98
Helium	0.179
Hydrogen	0.0899
Nitrogen	1.25
Oxygen	1.43

### 10.3 Fluids

#### **Example: Blood as a Fraction of Body Weight**

The body of a man whose weight is 690 N contains about  $5.2 \times 10^{-3} \text{ m}^3$  of blood.

(a) Find the blood's weight and (b) express it as a percentage of the body weight.

$$m = \rho V$$

$$(a) W = mg$$

$$= \rho V g$$

$$= (1060 \text{ kg/m}^3) (5.2 \times 10^{-3} \text{ m}^3) (9.80 \text{ m/s}^2) = 54 \text{ N}$$

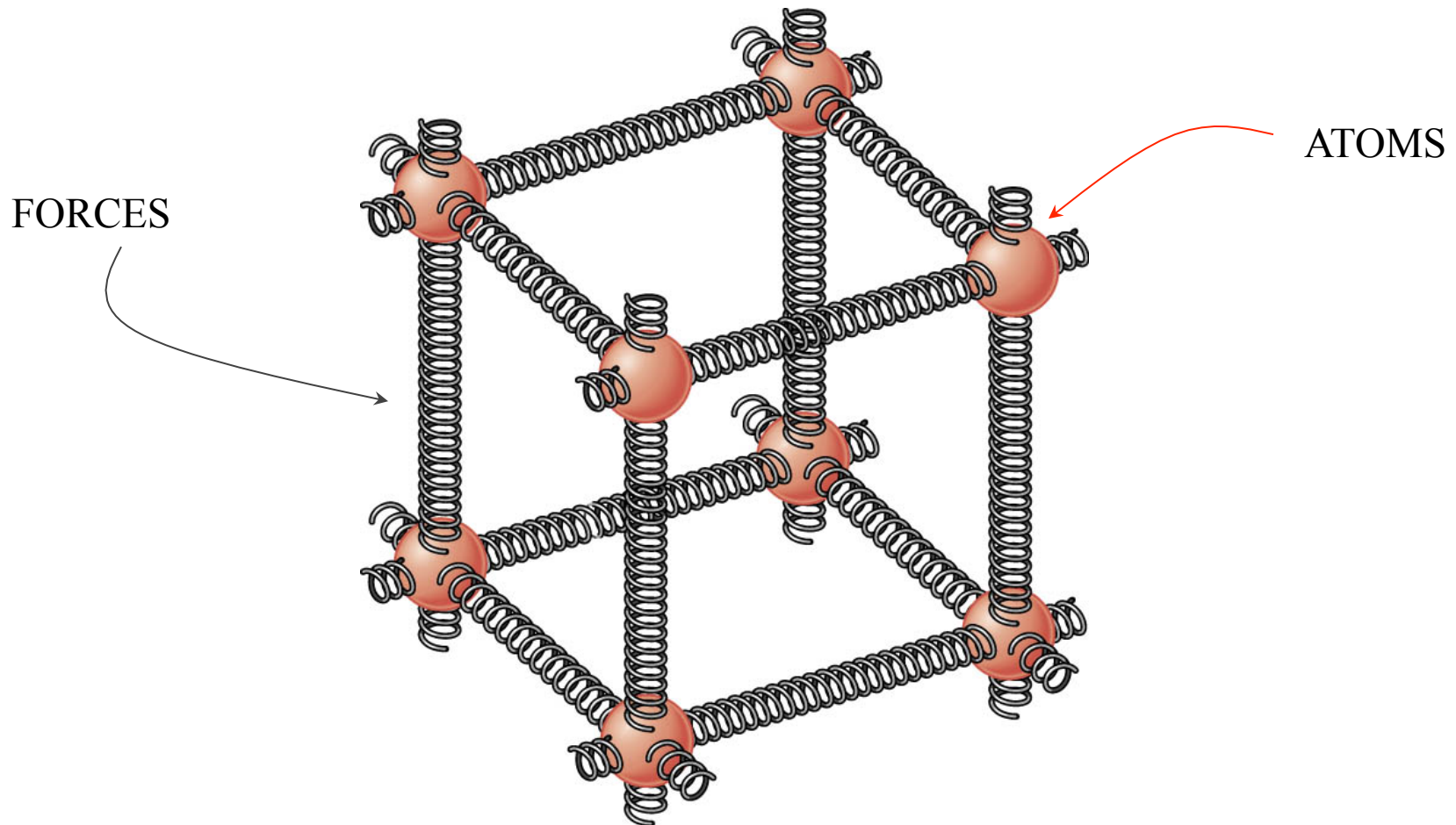
$$(b) \% = \frac{54 \text{ N}}{690 \text{ N}} \times 100\% = 7.8\%$$

Mass Densities <sup>a</sup> of Common Substances	
Substance	Mass Density $\rho$ (kg/m <sup>3</sup> )
<b>Solids</b>	
Aluminum	2700
Brass	8470
Concrete	2200
Copper	8890
Diamond	3520
Gold	19 300
Ice	917
Iron (steel)	7860
Lead	11 300
Quartz	2660
Silver	10 500
Wood (yellow pine)	550
<b>Liquids</b>	
Blood (whole, 37 °C)	1060
Ethyl alcohol	806
Mercury	13 600
Oil (hydraulic)	800
Water (4 °C)	$1.000 \times 10^3$
<b>Gases</b>	
Air	1.29
Carbon dioxide	1.98
Helium	0.179
Hydrogen	0.0899
Nitrogen	1.25
Oxygen	1.43

<sup>a</sup> Unless otherwise noted, densities are given at 0 °C and 1 atm pressure.

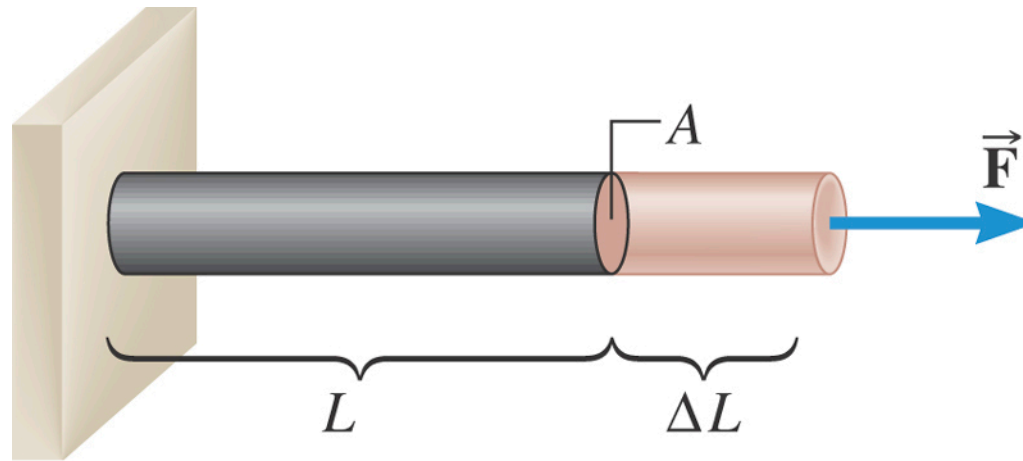
## 10.2 Solids and Elastic Deformation

Because of these atomic-level “springs”, a material tends to return to its initial shape once forces have been removed.



## 10.2 Solids and Elastic Deformation

### STRETCHING, COMPRESSION, AND YOUNG'S MODULUS



$$F = Y \left( \frac{\Delta L}{L} \right) A$$

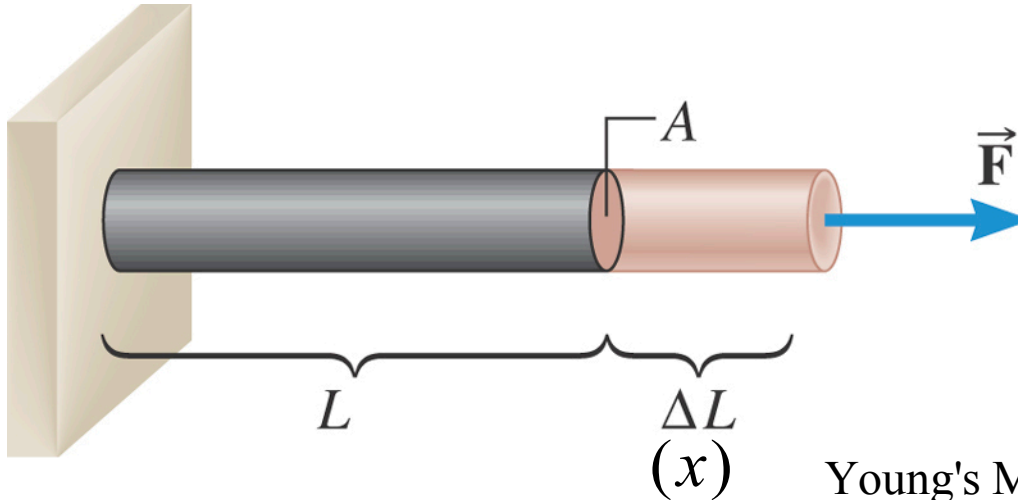
Young's modulus has the units of pressure:  $\text{N/m}^2$

Young's modulus is a characteristic of the material (see table 10.2)

$$Y_{\text{Steel}} = 2.0 \times 10^{11} \text{ N/m}^2$$

## 10.2 Solids and Elastic Deformation

### Spring Constants and Young's Modulus



Young's Modulus & Spring Constants

$Y$ : Young's Modulus

$A, L$ : Area and length of rod

$\Delta L$ : Change in rod length ( $x$ )

$$F = Y \left( \frac{\Delta L}{L} \right) A$$

$$= \left( \frac{YA}{L} \right) \Delta L; \quad \text{let } \Delta L = x$$

**THEN**

$$F = kx \text{ (Hooke's law)}$$

$$\text{with } k = \left( \frac{YA}{L} \right) \text{ (spring constant)}$$

## 10.2 Solids and Elastic Deformation

### Values for the Young's Modulus of Solid Materials

Material	Young's Modulus $Y$ (N/m <sup>2</sup> )
Aluminum	$6.9 \times 10^{10}$
Bone	
Compression	$9.4 \times 10^9$
Tension	$1.6 \times 10^{10}$
Brass	$9.0 \times 10^{10}$
Brick	$1.4 \times 10^{10}$
Copper	$1.1 \times 10^{11}$
Mohair	$2.9 \times 10^9$
Nylon	$3.7 \times 10^9$
Pyrex glass	$6.2 \times 10^{10}$
Steel	$2.0 \times 10^{11}$
Teflon	$3.7 \times 10^8$
Titanium	$1.2 \times 10^{11}$
Tungsten	$3.6 \times 10^{11}$

Note: 1 Pascal (Pa) = 1 N/m<sup>2</sup>

$$1 \text{ GPa} = 1 \times 10^9 \text{ N/m}^2$$



## 10.2 Solids and Elastic Deformation

In general the quantity  $\frac{F}{A}$  is called the **Stress**.

The change in the quantity divided by that quantity is called the **Strain**:

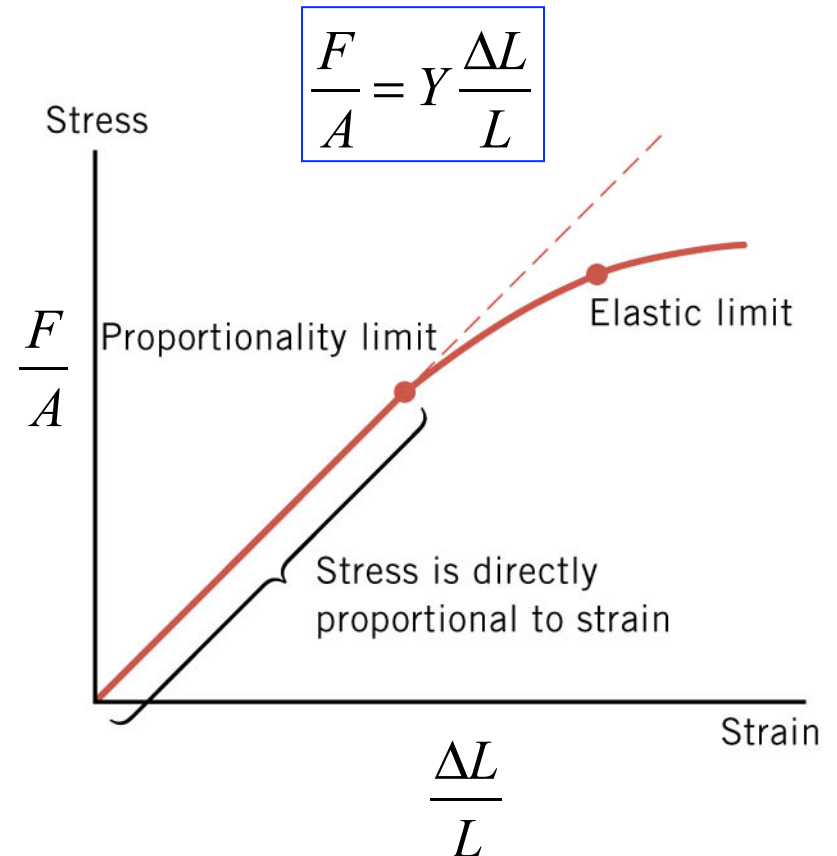
$$\frac{\Delta V}{V} \quad \frac{\Delta L}{L} \quad \frac{\Delta x}{L}$$

### HOOKE'S LAW FOR STRESS AND STRAIN

Stress is directly proportional to strain.  
Slope is Young's modulus  $Y$ .

**Strain is a unitless quantity, and**

**SI Unit of Stress:**  $\text{N/m}^2$



## 10.2 Elastic Deformation

### **Example: Bone Compression**

In a circus act, a performer supports the combined weight (1080 N) of a number of colleagues. Each thighbone of this performer has a length of 0.55 m and an effective cross sectional area of  $7.7 \times 10^{-4} \text{ m}^2$ . Determine the amount that each thighbone compresses under the extra weight.



$$F = Y \left( \frac{\Delta L}{L} \right) A$$

$$\text{each leg} = \frac{1080 \text{ N}}{2}$$

$$\Delta L = \frac{FL}{YA}$$

$$\begin{aligned} &= \frac{(540 \text{ N})(0.55 \text{ m})}{(9.4 \times 10^9 \text{ N/m}^2)(7.7 \times 10^{-4} \text{ m}^2)} \\ &= 4.1 \times 10^{-5} \text{ m} = 0.041 \text{ mm} \end{aligned}$$

*Clicker Question 10.1*

A cylindrical rod, 0.500 m long has a diameter of 0.02 m. The rod is stretched to a length of 0.501 m by a force of 3000 N.

What is the Young's modulus of the material?

$$F = Y \left( \frac{\Delta L}{L} \right) A$$

$$A = \pi r^2$$

- a)  $1.5 \times 10^8 \text{ N/m}^2$
- b)  $1.2 \times 10^9 \text{ N/m}^2$
- c)  $7.5 \times 10^7 \text{ N/m}^2$
- d)  $4.8 \times 10^9 \text{ N/m}^2$
- e)  $1.5 \times 10^7 \text{ N/m}^2$

### Clicker Question 10.1

A cylindrical rod, 0.500 m long has a diameter of 0.02 m. The rod is stretched to a length of 0.501 m by a force of 3000 N.

What is the Young's modulus of the material?

$$F = Y \left( \frac{\Delta L}{L} \right) A$$

$$A = \pi r^2$$

a)  $1.5 \times 10^8 \text{ N/m}^2$

b)  $1.2 \times 10^9 \text{ N/m}^2$

c)  $7.5 \times 10^7 \text{ N/m}^2$

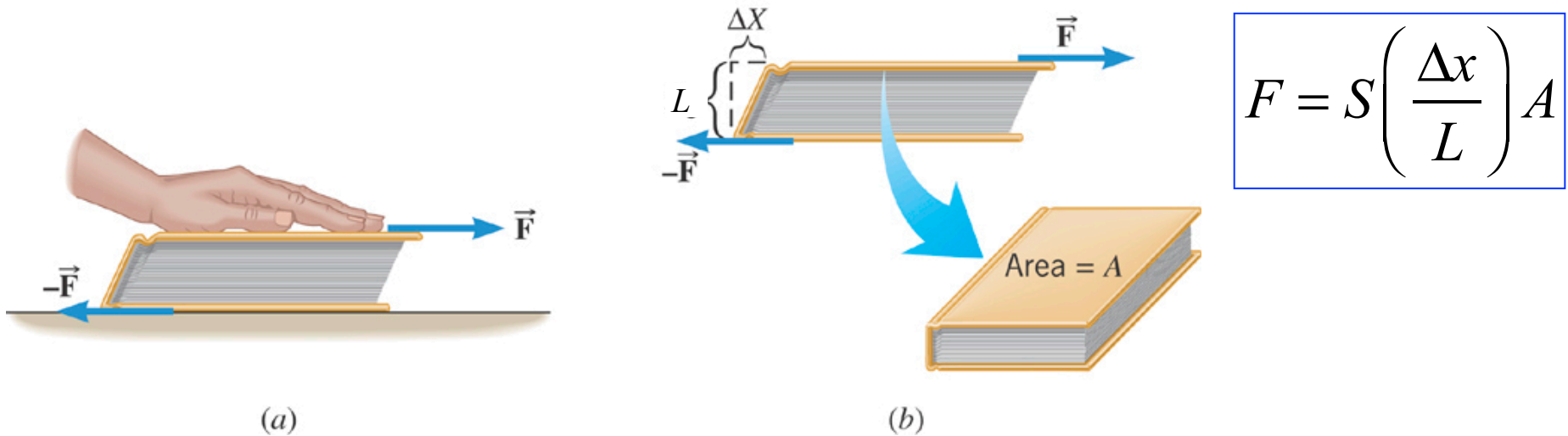
d)  $4.8 \times 10^9 \text{ N/m}^2$

e)  $1.5 \times 10^7 \text{ N/m}^2$

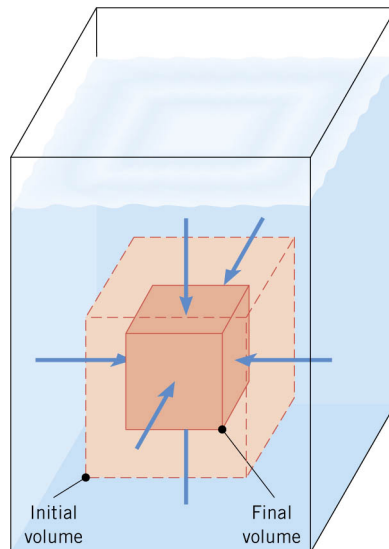
$$\begin{aligned} Y &= \frac{L}{\Delta L} \frac{F}{A} = \frac{0.500}{1 \times 10^{-3}} \frac{3 \times 10^3 \text{ N}}{\pi (.01)^2 \text{ m}^2} \\ &= \frac{1.5 \times 10^3 \text{ N}}{3.14 \times 10^{-7} \text{ m}^2} = 4.8 \times 10^9 \text{ N/m}^2 \end{aligned}$$

## 10.2 Elastic Deformation

### SHEAR DEFORMATION AND THE SHEAR MODULUS



### VOLUME DEFORMATION AND THE BULK MODULUS



Pressure  
Change

$$\Delta P = -B \left( \frac{\Delta V}{V} \right)$$

$B$ : Bulk modulus  
Table 10.2

### Clicker Question 10.2

A cube made of brass ( $B = 6.70 \times 10^{10} \text{ N/m}^2$ ) is taken by submarine from the surface where the pressure is  $1.01 \times 10^5 \text{ N/m}^2$  to the deepest part of the ocean at a depth of  $1.10 \times 10^4 \text{ m}$  where it is exposed to a pressure is  $1.25 \times 10^8 \text{ N/m}^2$ . What is the percent change in volume as a result of this movement?

$$\Delta P = -B \left( \frac{\Delta V}{V} \right)$$

- a) 0.413%
- b) 0.297%
- c) 0.187%
- d) 0.114%
- e) Need to know the initial size of the cube

### Clicker Question 10.2

A cube made of brass ( $B = 6.70 \times 10^{10} \text{ N/m}^2$ ) is taken by submarine from the surface where the pressure is  $1.01 \times 10^5 \text{ N/m}^2$  to the deepest part of the ocean at a depth of  $1.10 \times 10^4 \text{ m}$  where it is exposed to a pressure is  $1.25 \times 10^8 \text{ N/m}^2$ . What is the percent change in volume as a result of this movement?

$$\Delta P = 1.25 \times 10^8 - .00101 \times 10^8 \text{ N/m}^2$$

$$\Delta P = -B \left( \frac{\Delta V}{V} \right)$$

$$\begin{aligned} \frac{\Delta V}{V} &= -\frac{\Delta P}{B} \\ &= -\frac{1.25 \times 10^8}{6.70 \times 10^{10}} = 0.187 \times 10^{-2} \\ \% &= \frac{\Delta V}{V} (100\%) = 0.187\% \end{aligned}$$

a) 0.413%

b) 0.297%

c) 0.187%

d) 0.114%

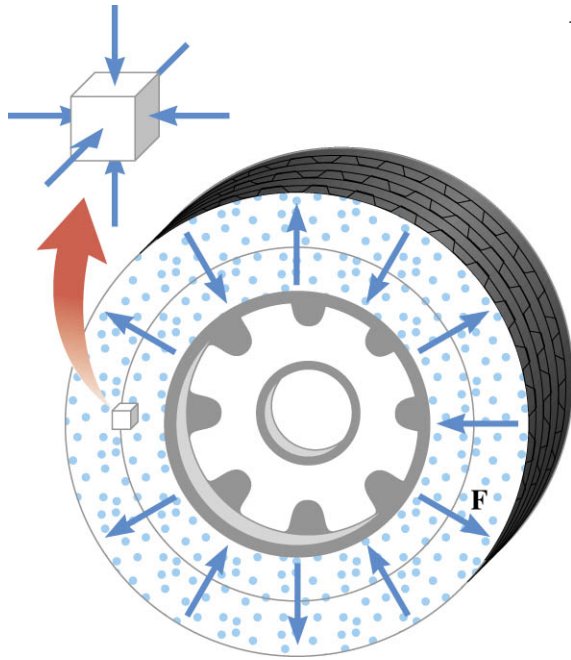
e) Need to know the initial size of the cube

### 10.3 Pressure

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

Pressure = Force per unit Area

The same pressure acts inward in every direction on a small volume.



**SI Unit of Pressure:**  $1 \text{ N/m}^2 = 1 \text{ Pa}$

Pascal



### 10.3 Pressure

Pressure is the amount of force acting on an area:

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

SI unit:  $\text{N/m}^2$   
(1 Pa = 1  $\text{N/m}^2$ )

#### **Example: The Force on a Swimmer**

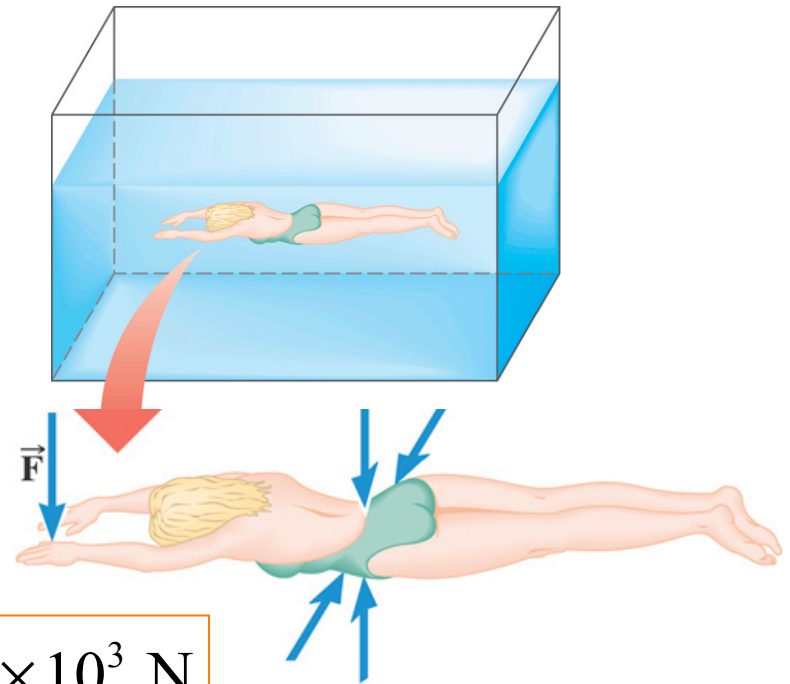
Suppose the pressure acting on the back of a swimmer's hand is  $1.2 \times 10^5$  Pa. The surface area of the back of the hand is  $8.4 \times 10^{-3} \text{m}^2$ .

- (a) Determine the magnitude of the force that acts on back of the hand.
- (b) Discuss the direction of the force.

$$\text{a) } F = PA = (1.2 \times 10^5)(8.4 \times 10^{-3}) \text{ N} = 1.0 \times 10^3 \text{ N}$$

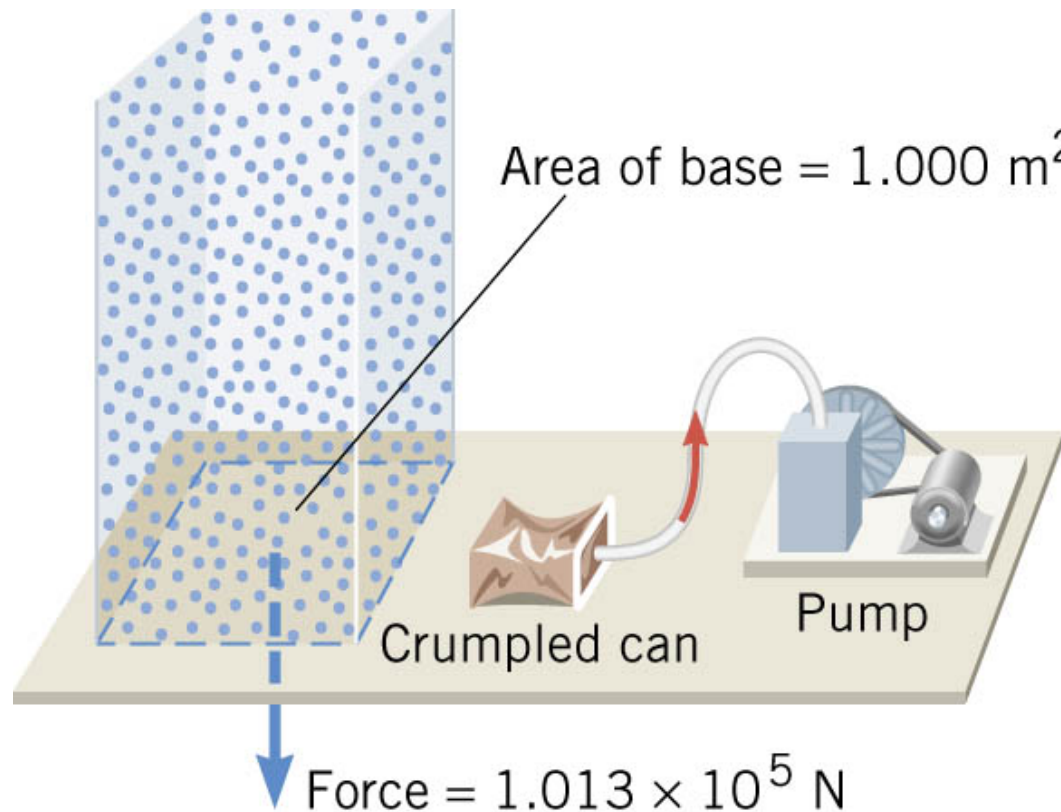
Since the water pushes perpendicularly against the back of the hand, the force is **directed downward**.

Pressure on the underside of the hand is somewhat greater (greater depth). So force upward is somewhat greater - buoyancy

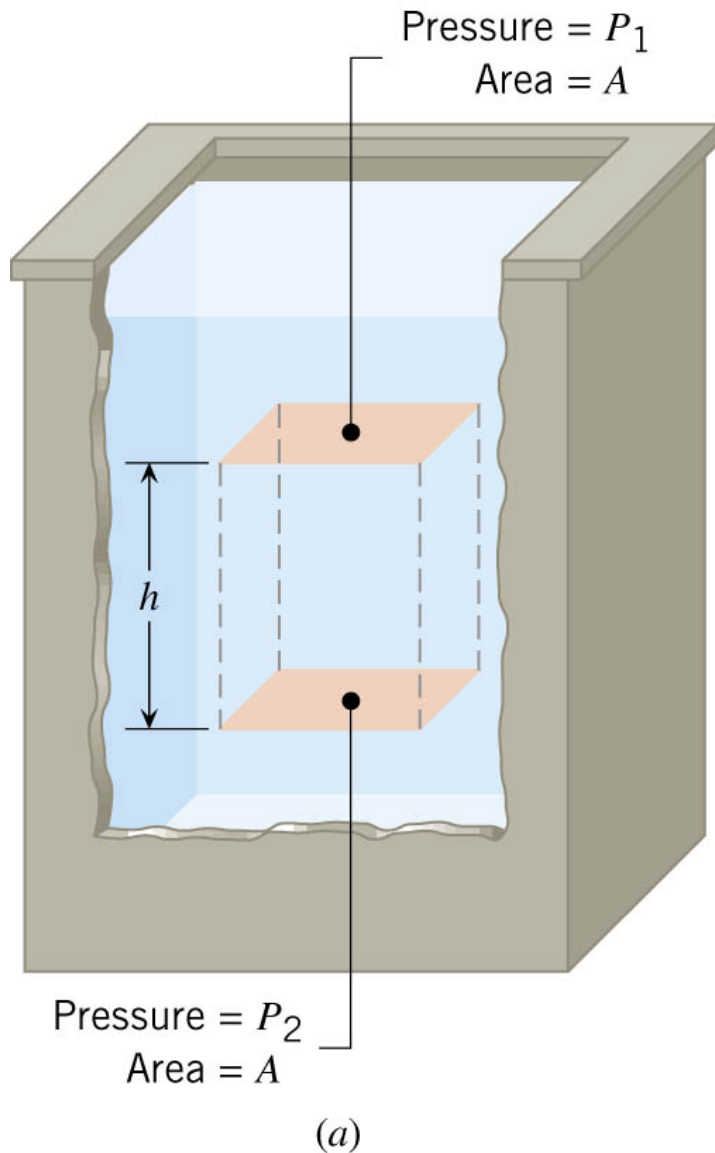


### 10.3 Pressure

***Atmospheric Pressure at Sea Level:***  $1.013 \times 10^5 \text{ Pa} = 1 \text{ atmosphere}$



### 10.3 Pressure and Depth in a Static Fluid



Fluid density is  $\rho$

Equilibrium of a volume of fluid

$$F_2 = F_1 + mg$$

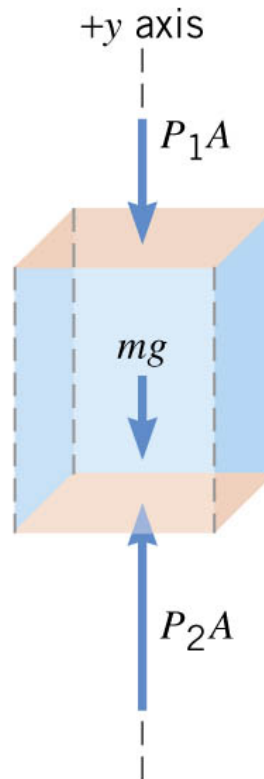
$$\text{with } F = PA, m = \rho V$$

$$P_2 A = P_1 A + \rho V g$$

$$\text{with } V = Ah$$

$$P_2 = P_1 + \rho gh$$

Pressure grows linearly  
with depth ( $h$ )

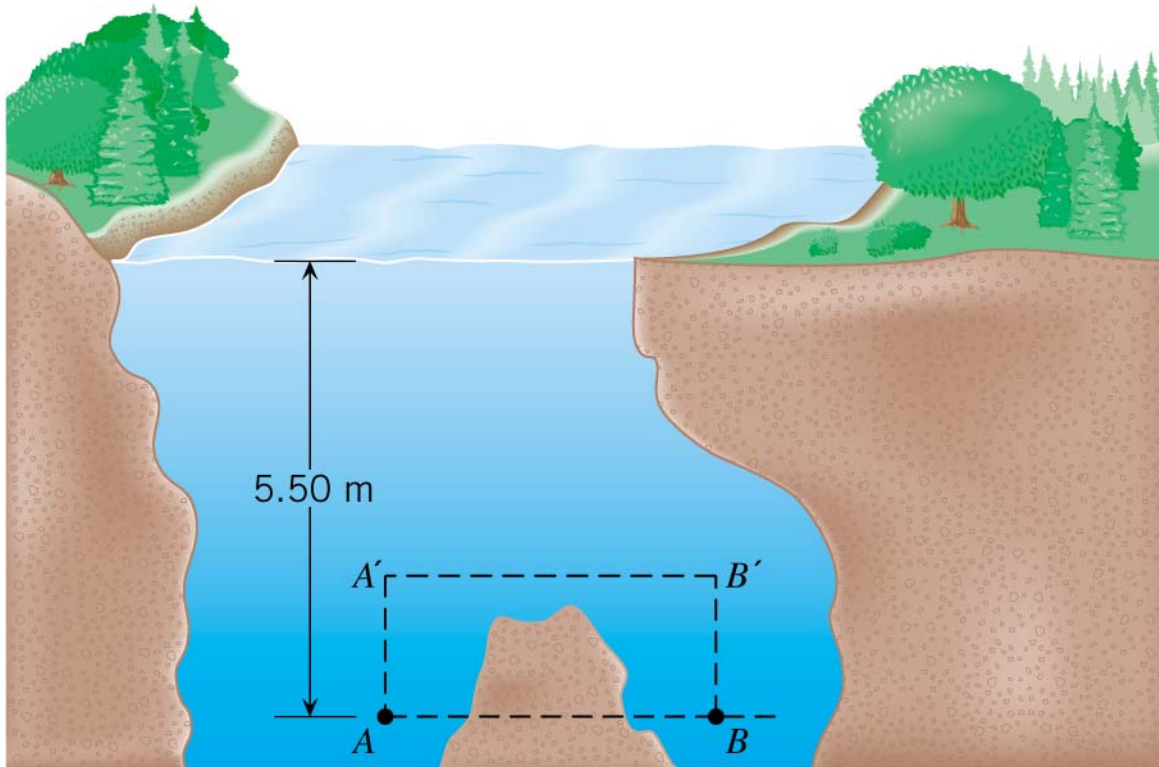


(b) Free-body diagram  
of the column

### 10.3 Pressure and Depth in a Static Fluid

#### **Example: The Swimming Hole**

Points A and B are located a distance of 5.50 m beneath the surface of the water. Find the pressure at each of these two locations.



Atmospheric pressure

$$P_1 = 1.01 \times 10^5 \text{ N/m}^2$$

$$P_2 = P_1 + \rho gh$$

$$P_2 = P_1 + \rho gh$$

$$= (1.01 \times 10^5 \text{ Pa}) + (1.00 \times 10^3 \text{ kg/m}^3)(9.80 \text{ m/s}^2)(5.50 \text{ m})$$

$$= 1.55 \times 10^5 \text{ Pa}$$

### Clicker Question 10.3

The density of mercury is  $13.6 \times 10^3 \text{ kg/m}^3$ . The pressure 100 cm below the surface of a pool of mercury is how much higher than at the surface?

$$P_2 = P_1 + \rho gh$$

- a)  $13 \text{ N/m}^2$
- b)  $130 \text{ Pa}$
- c)  $1.3 \times 10^3 \text{ N/m}^2$
- d)  $1.3 \times 10^4 \text{ Pa}$
- e)  $1.3 \times 10^5 \text{ N/m}^2$

### Clicker Question 10.3

The density of mercury is  $13.6 \times 10^3 \text{ kg/m}^3$ . The pressure 100 cm below the surface of a pool of mercury is how much higher than at the surface?

$$P_2 = P_1 + \rho gh$$

a)  $13 \text{ N/m}^2$

b)  $130 \text{ Pa}$

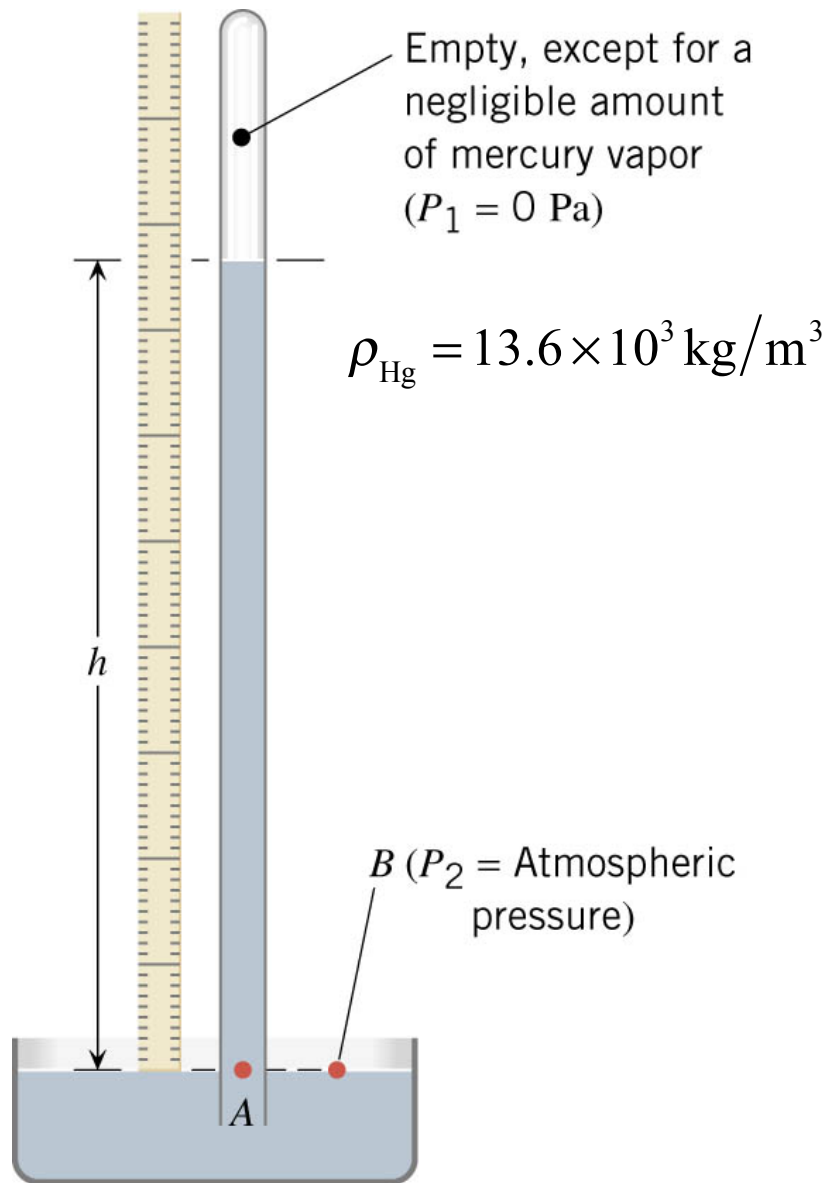
c)  $1.3 \times 10^3 \text{ N/m}^2$

d)  $1.3 \times 10^4 \text{ Pa}$

e)  $1.3 \times 10^5 \text{ N/m}^2$

$$\begin{aligned} P_2 - P_1 &= \rho gh \\ &= (13.6 \times 10^3 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(1.0 \text{ m}) \\ &= 1.3 \times 10^5 \text{ N/m}^2 \end{aligned}$$

### 10.3 Pressure Gauges



$$P_2 = P_1 + \rho g h$$

$$P_1 = 0 \text{ (vacuum)}$$

$$P_2 = \rho g h$$

$$P_{\text{atm}} = \rho g h$$

$$h = \frac{P_{\text{atm}}}{\rho g}$$

$$\begin{aligned} &= \frac{(1.01 \times 10^5 \text{ Pa})}{(13.6 \times 10^3 \text{ kg/m}^3)(9.80 \text{ m/s}^2)} \\ &= 0.760 \text{ m} = 760 \text{ mm of Mercury} \end{aligned}$$

*Clicker Question 10.4*

What is the force that causes a liquid to move upward in a drinking straw as a person takes a drink?

- a) the force due to a low pressure generated by sucking
- b) the force due to the pressure within the liquid
- c) the force due to the atmospheric pressure
- d) the force due to the low pressure in the lungs
- e) the force due to friction on the surface of the straw



*Clicker Question 10.4*

What is the force that causes a liquid to move upward in a drinking straw as a person takes a drink?

- a) the force due to a low pressure generated by sucking
- b) the force due to the pressure within the liquid
- c) the force due to the atmospheric pressure
- d) the force due to the low pressure in the lungs
- e) the force due to friction on the surface of the straw

### 10.3 Pascal's Principle

#### PASCAL'S PRINCIPLE

Any change in the pressure applied to a completely enclosed fluid is transmitted undiminished to all parts of the fluid and enclosing walls.

$$P_2 = \frac{F_2}{A_2}; \quad P_1 = \frac{F_1}{A_1}$$

Assume weight of fluid in the tube is negligible

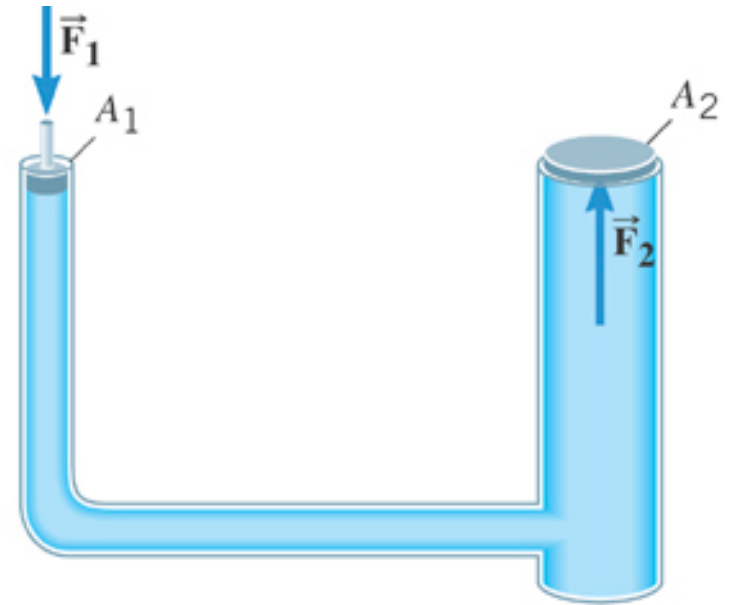
$$\rho gh \ll P$$

$$P_2 = P_1 + \rho gh$$

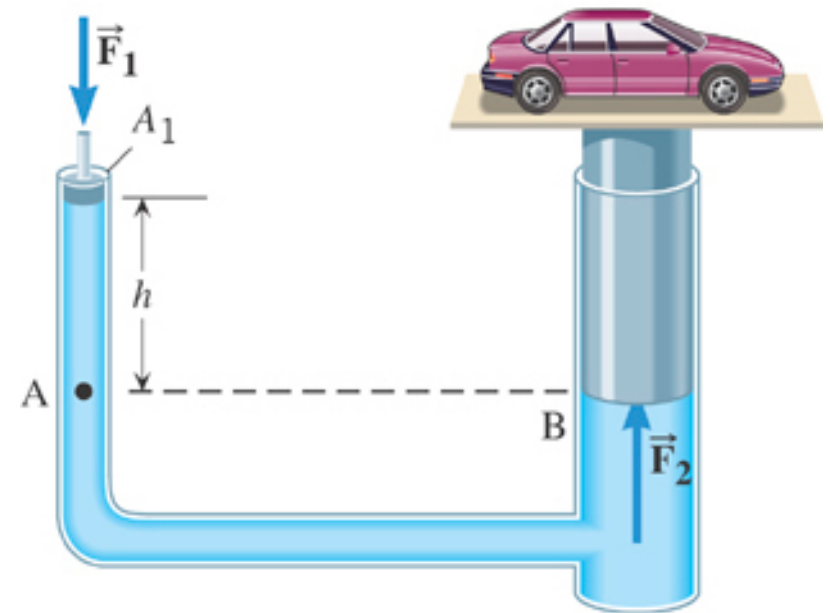
$$P_2 = P_1$$

Small ratio

$$\frac{F_2}{A_2} = \frac{F_1}{A_1} \Rightarrow F_1 = F_2 \left( \frac{A_1}{A_2} \right)$$



(a)



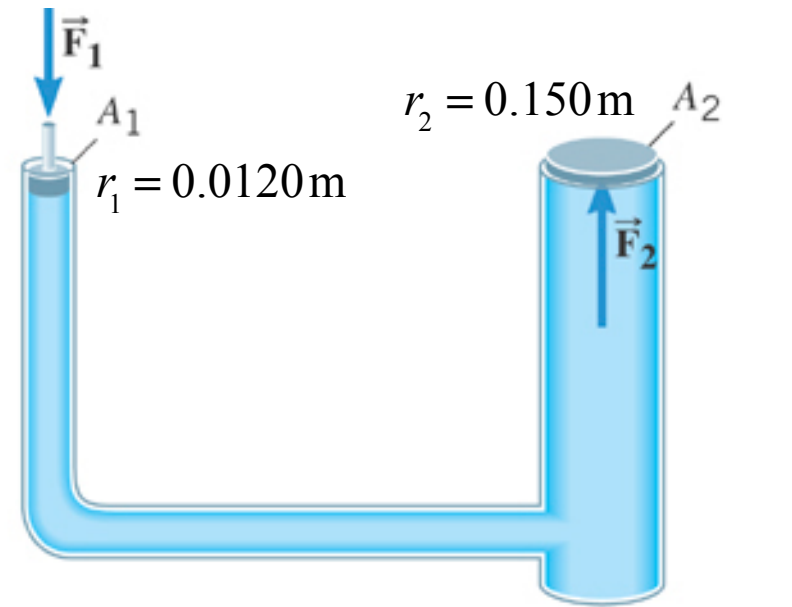
### 10.3 Pascal's Principle

#### Example: A Car Lift

The input piston has a radius of 0.0120 m and the output plunger has a radius of 0.150 m.

The combined weight of the car and the plunger is 20500 N. Suppose that the input piston has a negligible weight and the bottom surfaces of the piston and plunger are at the same level. What is the required input force?

$$F_1 = F_2 \left( \frac{A_1}{A_2} \right)$$
$$= (20500 \text{ N}) \frac{\pi (0.0120 \text{ m})^2}{\pi (0.150 \text{ m})^2} = 131 \text{ N}$$



(a)

