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.

	3/28	Th	Properties of Solids, Liquids & Gases	Ch. 10.1-3	E 10.1-8	G 10.2-3	
13	4/2	T	Buoyancy & Fluid Properties	Ch. 10.4-6	E 10.9-13	G 10.5	
	4/4	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	4/9	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	**Set 8**
	4/11	Th	**Midterm Exam 3**	Ch. 1-13 (no 7,11)			
15	4/16	T	2nd Law of Thermodynamics, Entropy	Ch. 14.3-5	E14.7-13	G 14.3-4	**Set 9**
	4/18	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	4/23	T	Sound, Doppler Effect	Ch. 11.3-5	E 11.6-13	G 11.3-4	**Sets 10&11**
	4/25	Th	Review				
17	5/1	W	**Final Exam 8:00-10:00 pm, Rm TBD**	Ch. 1-14			

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^3

Mass Densities[a] of Common Substances

Substance	Mass Density ρ (kg/m^3)
Solids	
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
Liquids	
Blood (whole, 37 °C)	1060
Ethyl alcohol	806
Mercury	13 600
Oil (hydraulic)	800
Water (4 °C)	1.000×10^3
Gases	
Air	1.29
Carbon dioxide	1.98
Helium	0.179
Hydrogen	0.0899
Nitrogen	1.25
Oxygen	1.43

[a] Unless otherwise noted, densities are given at 0 °C and 1 atm pressure.

Example: Blood as a Fraction of Body Weight

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

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

$$m = \rho V$$

$$\text{(a) } W = mg$$

$$= \rho V g$$

$$= \left(1060\,\text{kg/m}^3\right)\left(5.2\times10^{-3}\,\text{m}^3\right)\left(9.80\,\text{m/s}^2\right) = 54\text{ N}$$

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

Table 11.1 Mass Densities[a] of Common Substances

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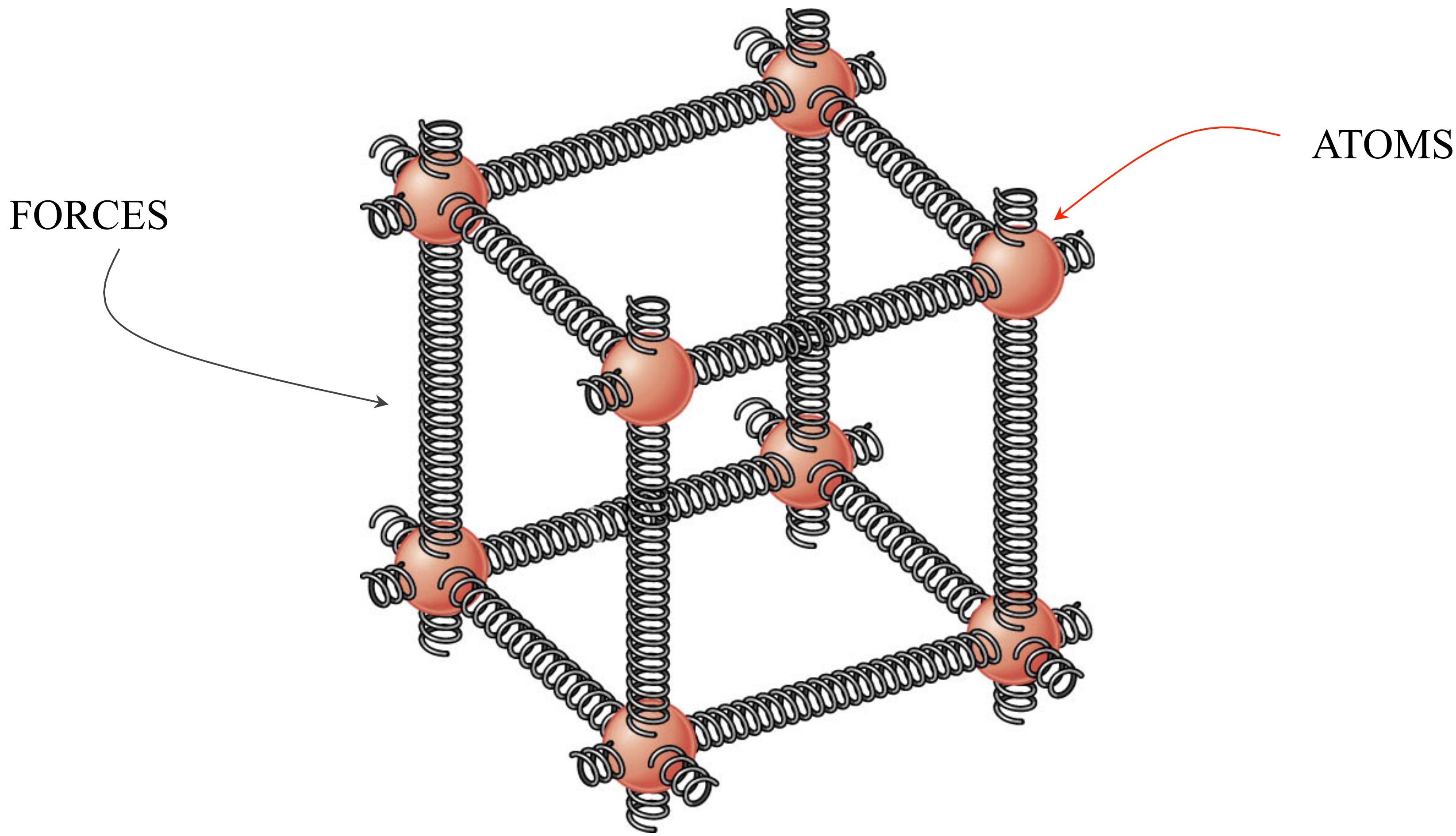
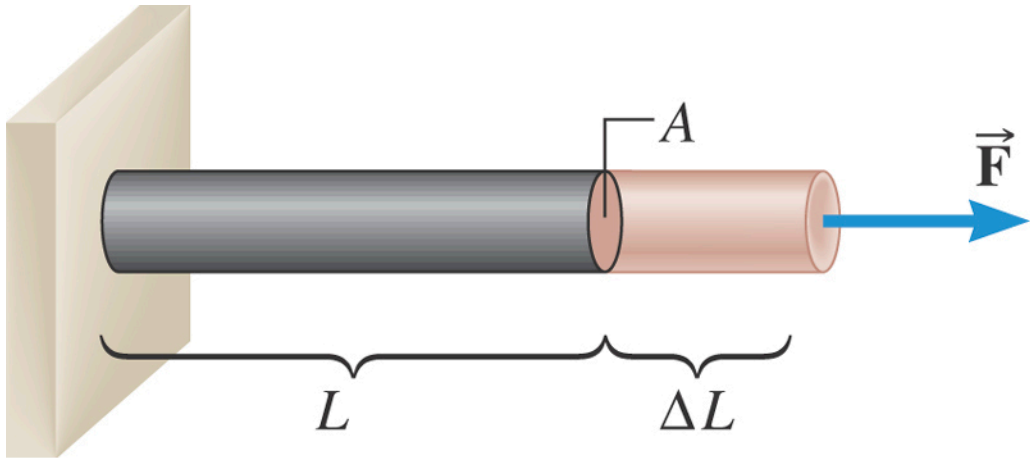
Ice	917
Iron (steel)	7860
Lead	11 300
Quartz	2660
Silver	10 500
Wood (yellow pine)	550
Liquids	
Blood (whole, 37 °C)	1060
Ethyl alcohol	806
Mercury	13 600
Oil (hydraulic)	800
Water (4 °C)	1.000×10^3
Gases	
Air	1.29
Carbon dioxide	1.98
Helium	0.179
Hydrogen	0.0899
Nitrogen	1.25
Oxygen	1.43

[a] Unless otherwise noted, densities are given at 0 °C and 1 atm pressure.

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



STRETCHING, COMPRESSION, AND YOUNG'S MODULUS



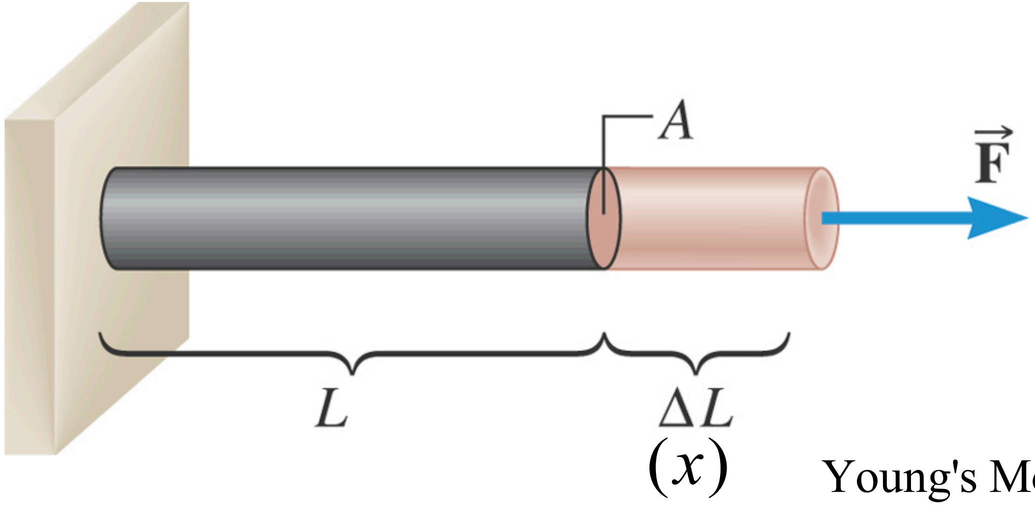
$$F = Y\left(\frac{\Delta L}{L}\right)A$$

Young's modulus has the units of pressure: N/m^2

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

$$Y_{\text{Steel}} = 2.0\times10^{11}\ \text{N/m}^2$$

Spring Constants and Young's Modulus



Y: Young's Modulus

A, L: Area and length of rod

ΔL: Change in rod length (x)

Young's Modulus & Spring Constants

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

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

THEN

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

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

10.2 Solids and Elastic Deformation

Table 10.1 Values for the Young's Modulus of Solid Materials

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

Note: 1 Pascal (Pa) = 1 N/m^2

$$1 \text{ GPa} = 1\times10^{9} \text{ N/m}^2$$

10.2 Solids and Elastic Deformation

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

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

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

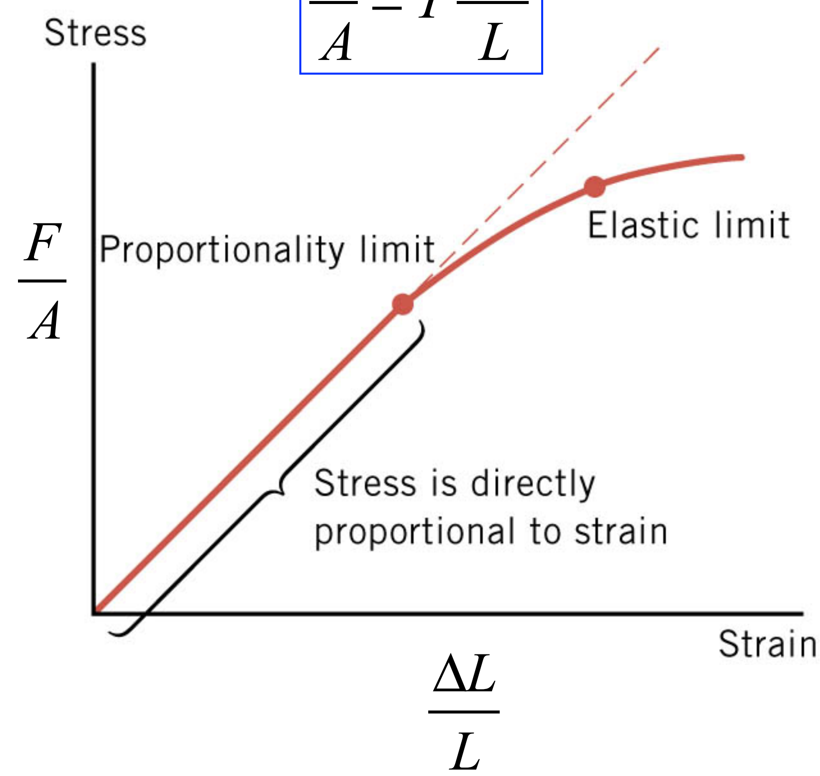
$$\boxed{\frac{F}{A} = Y\frac{\Delta L}{L}}$$

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: N/m^2



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 7.7×10^{-4} m^2. Determine the amount that each thighbone compresses under the extra weight.

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

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

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

$$= \frac{(540\ \text{N})(0.55\ \text{m})}{\left(9.4\times10^{9}\ \text{N/m}^2\right)\left(7.7\times10^{-4}\ \text{m}^2\right)}$$

$$= 4.1\times10^{-5}\,\text{m} = 0.041\text{mm}$$

Clicker Question 10.1

A cylindrical, 0.500-m rod 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?

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

a) $1.5\times10^{8}\ \mathrm{N/m^2}$

b) $1.2\times10^{9}\ \mathrm{N/m^2}$

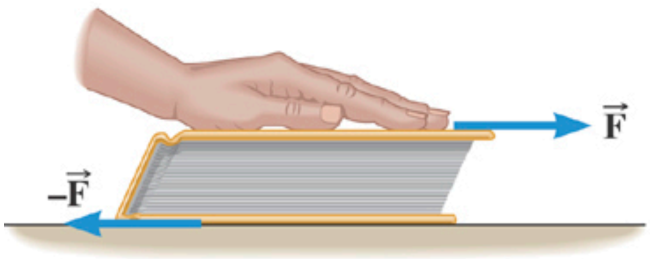
c) $7.5\times10^{7}\ \mathrm{N/m^2}$

d) $4.8\times10^{9}\ \mathrm{N/m^2}$

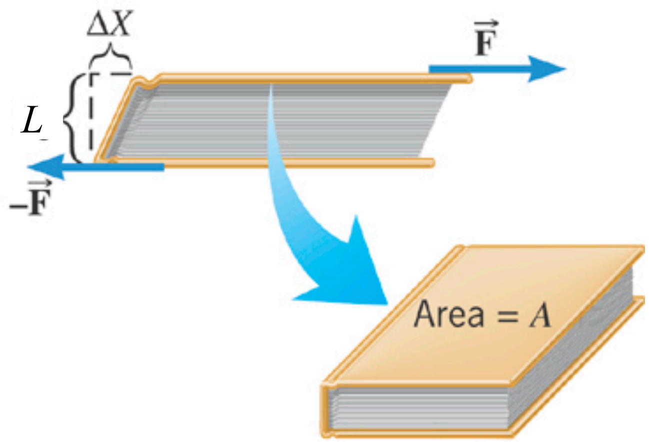
e) $1.5\times10^{7}\ \mathrm{N/m^2}$

10.2 Elastic Deformation

SHEAR DEFORMATION AND THE SHEAR MODULUS



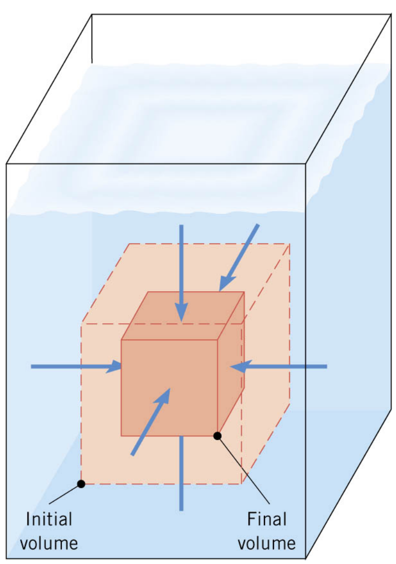
(a)



(b)

$$\boxed{F = S\left(\frac{\Delta x}{L}\right)A}$$

VOLUME DEFORMATION AND THE BULK MODULUS



Pressure Change

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

B: Bulk modulus
Table 10.2

Clicker Question 10.2

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

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

a) 0.413%

b) 0.297%

c) 0.187%

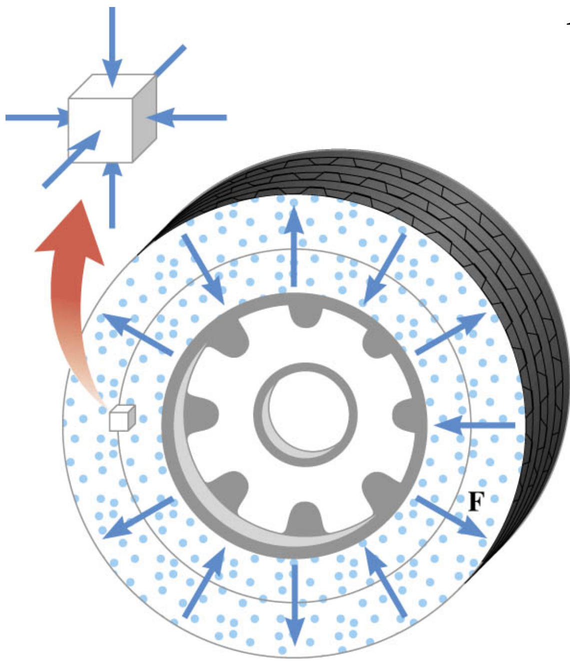
d) 0.114%

e) Need to know the initial size of the cube

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: $1\ \mathrm{N/m^2} = 1\mathrm{Pa}$

Pascal

10.3 Pressure

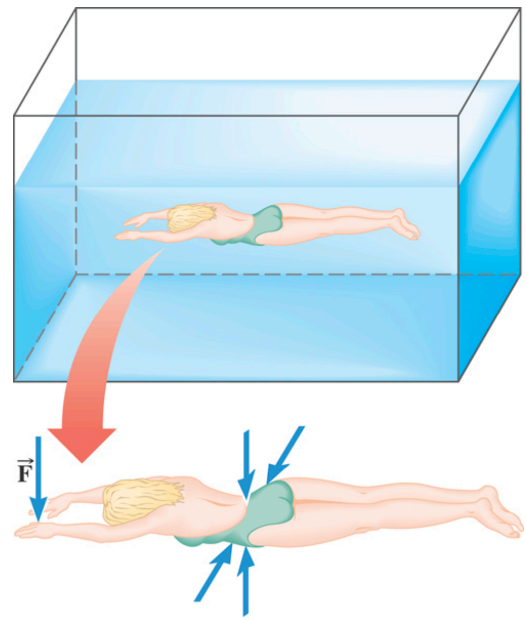
Pressure is the amount of force acting on an area:

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

SI unit: N/m^2

(1 Pa = 1 N/m^2)

Example 2 The Force on a Swimmer



Suppose the pressure acting on the back of a swimmer's hand is 1.2x10^5 Pa. The surface area of the back of the hand is 8.4x10^{-3}m^2.

(a) Determine the magnitude of the force that acts on it.
(b) Discuss the direction of the force.

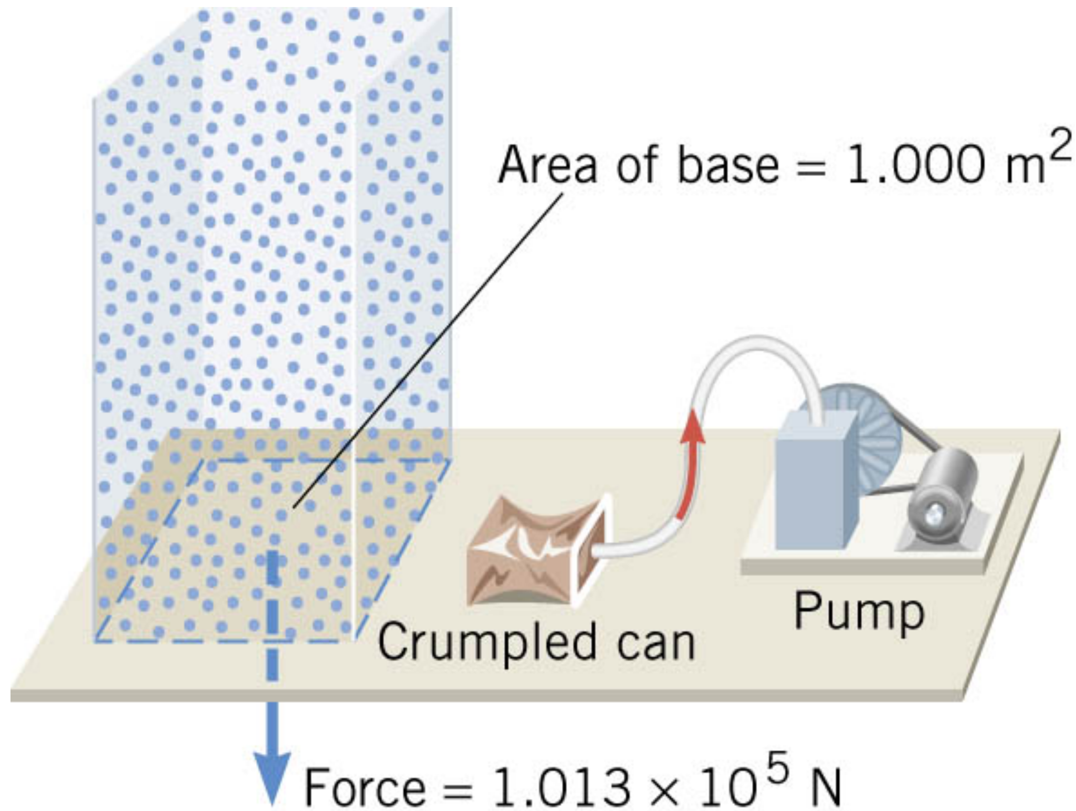
$$F = PA = \left(1.2\times10^5\,\mathrm{N/m^2}\right)\left(8.4\times10^{-3}\,\mathrm{m^2}\right)$$
$$= 1.0\times10^3\ \mathrm{N}$$

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

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

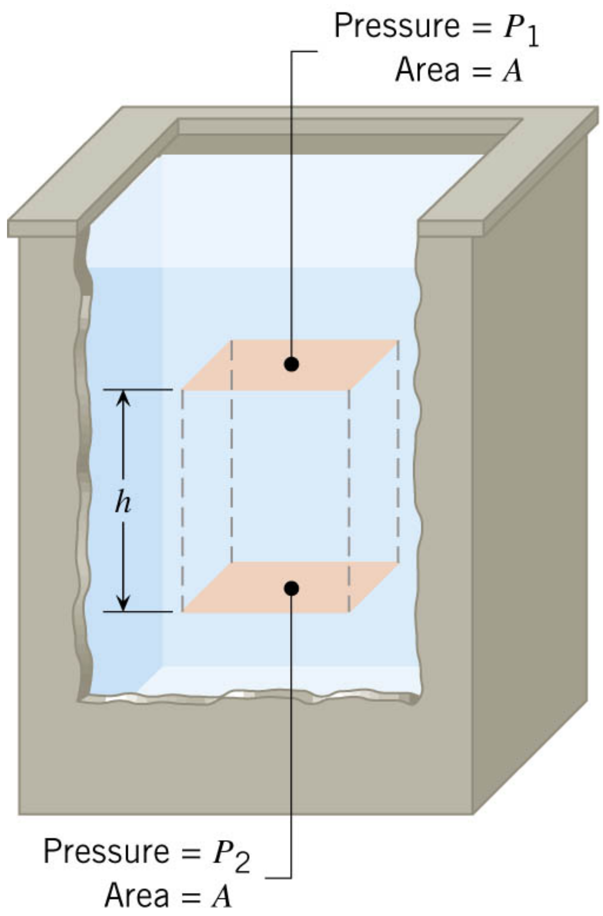
10.3 Pressure

Atmospheric Pressure at Sea Level: 1.013×10^5 Pa = 1 atmosphere

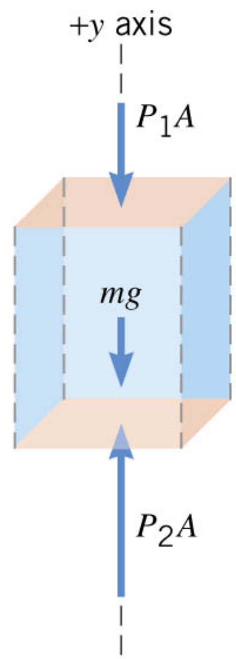


Fluid density is ρ

Equilibrium of a volume of fluid



(*a*)



(*b*) Free-body diagram of the column

$$F_2 = F_1 + mg$$

with $F = PA,\ m = \rho V$

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

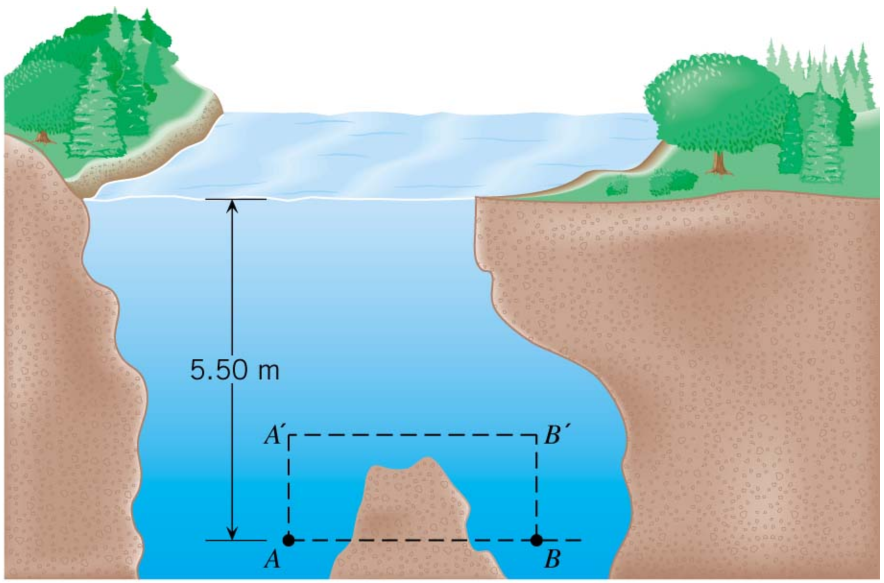
with $V = Ah$

$$\boxed{P_2 = P_1 + \rho g h}$$

Pressure grows linearly with depth (h)

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

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

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

$$\begin{aligned} P_2 &= P_1 + \rho g h \\ &= \left(1.01\times 10^5\ \text{Pa}\right) + \left(1.00\times 10^3\,\text{kg/m}^3\right)\left(9.80\,\text{m/s}^2\right)\left(5.50\ \text{m}\right) \\ &= 1.55\times 10^5\ \text{Pa} \end{aligned}$$

Clicker Question 10.3

The density of mercury is 13.6 x 10^3 kg/m^3. The pressure 100 cm below the surface of a pool of mercury is how much higher than at the surface?

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

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

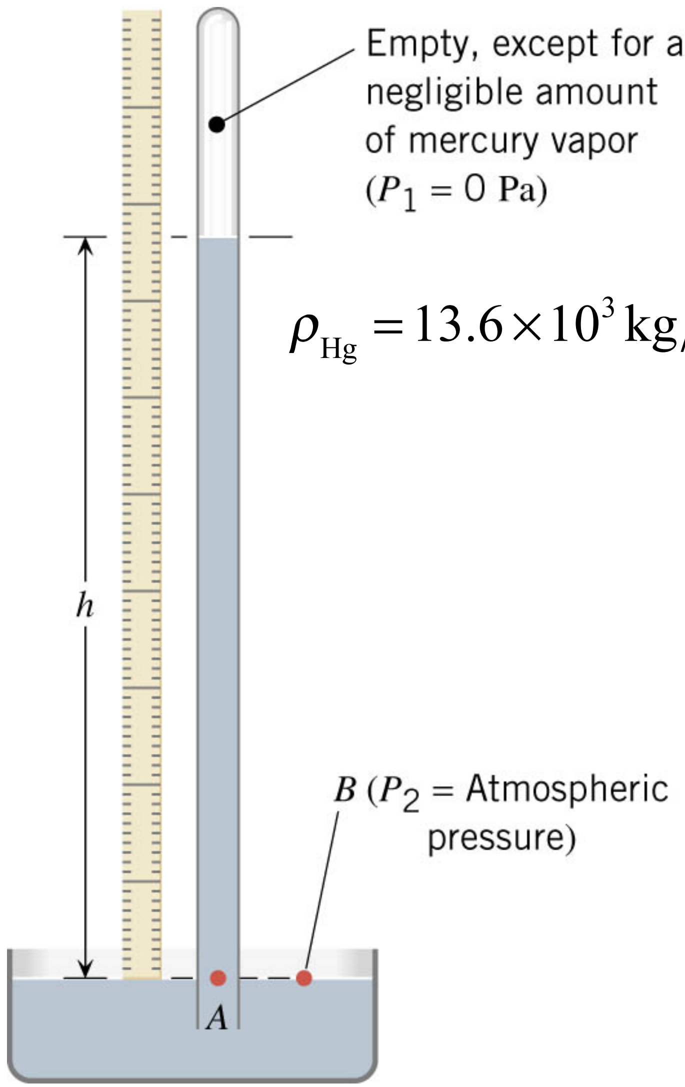
b) $130\ \mathrm{Pa}$

c) $1.3\times10^3\ \mathrm{N/m^2}$

d) $1.3\times10^4\ \mathrm{Pa}$

e) $1.3\times10^5\ \mathrm{N/m^2}$

10.3 Pressure Gauges



$$\rho_{Hg} = 13.6\times10^3\,\mathrm{kg/m^3}$$

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

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

$$P_2 = \rho g h$$

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

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

$$= \frac{\left(1.01\times10^5 \text{ Pa}\right)}{\left(13.6\times10^3\,\mathrm{kg/m^3}\right)\left(9.80\,\mathrm{m/s^2}\right)}$$

$$= 0.760 \text{ m} = 760 \text{ mm of Mercury}$$

Clicker Question 10.4

What is the force that causes a liquid to move upward in a drinking straw a 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

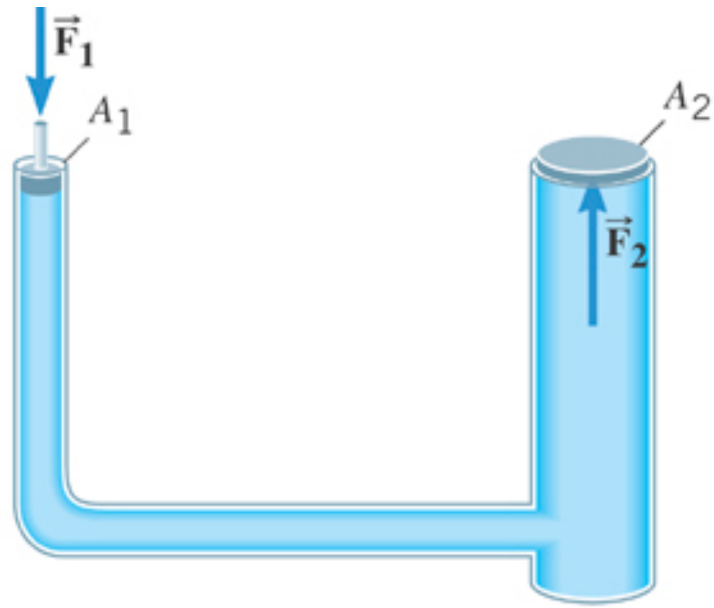
e) the force due to friction on the surface of the straw

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.

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

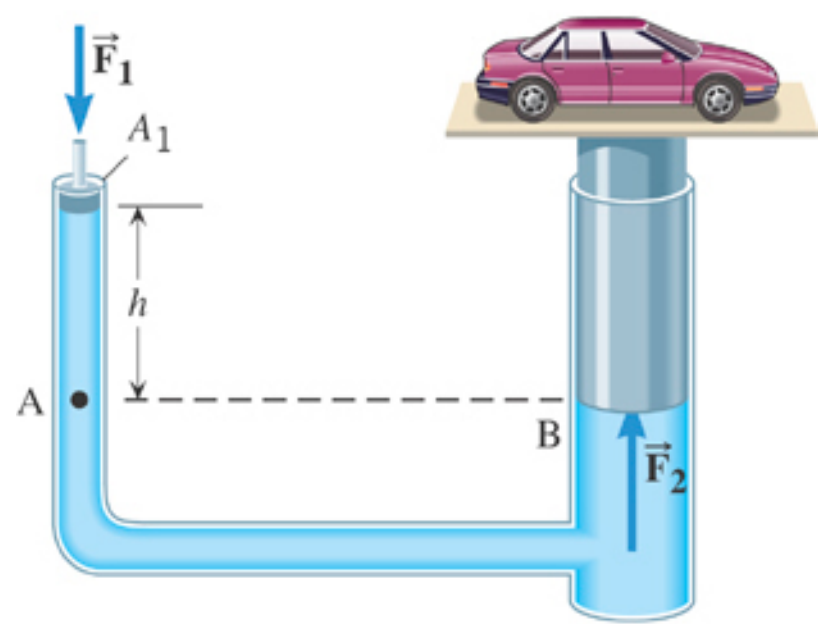


(a)

Assume weight of fluid in the tube is negligible

$$P_2 = P_1 + \rho g h \qquad \boxed{\rho g h << P}$$

$$P_2 = P_1$$



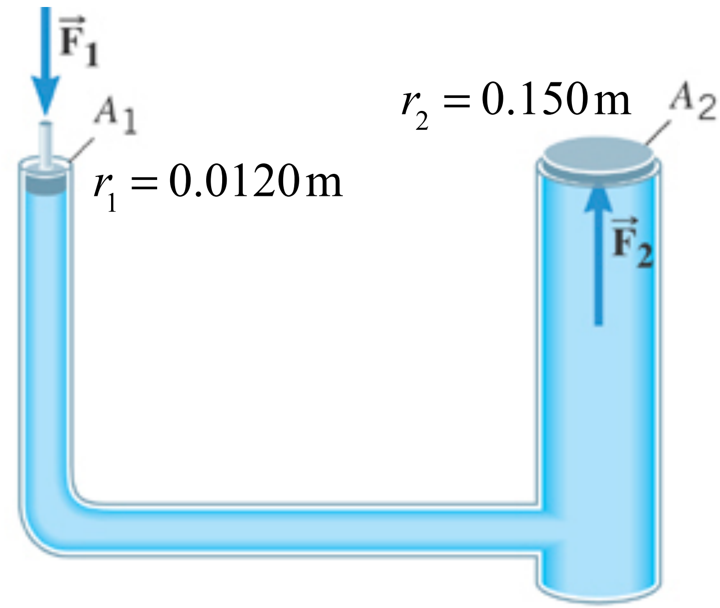
Small ratio

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

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.

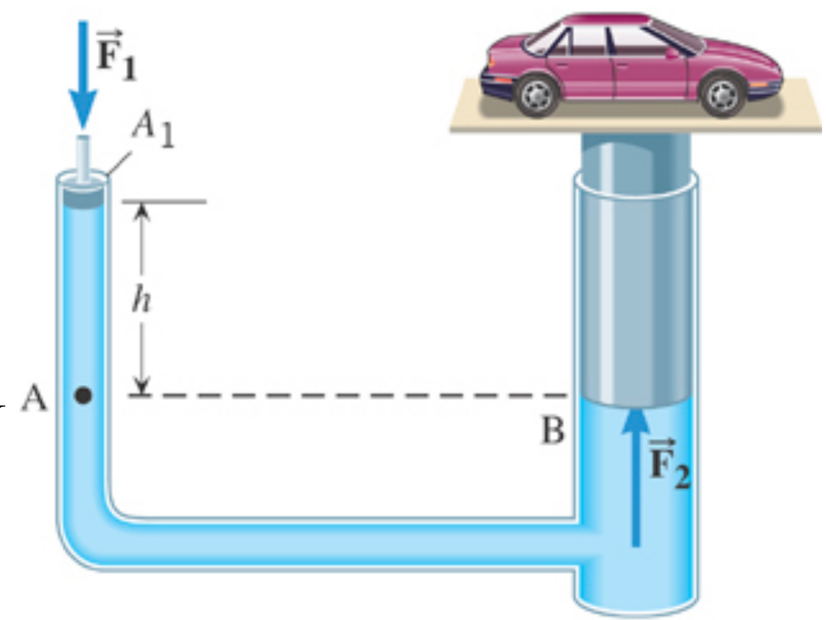
The combined weight of the car and the plunger is 20500 N. Suppose that the input piston has a negligible weight and the bottom surfaces of the piston and plunger are at the same level. What is the required input force?

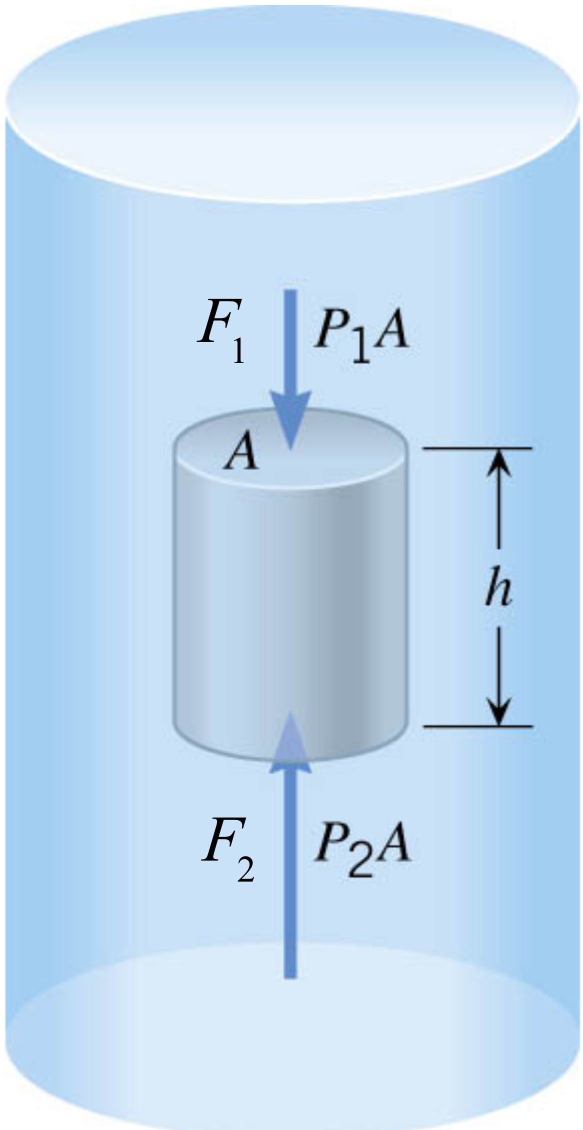


(a)

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

$$= (20500\ \mathrm{N})\frac{\pi(0.0120\ \mathrm{m})^2}{\pi(0.150\ \mathrm{m})^2} = 131\ \mathrm{N}$$





Buoyant Force

$$
\begin{aligned}
F_B &= F_2 + (-F_1) \\
&= P_2 A - P_1 A = \left(P_2 - P_1\right) A \\
&= \rho g h A \qquad \text{since } P_2 = P_1 + \rho g h \\
&= \underbrace{\rho V}_{\text{mass of displaced fluid}} g \qquad \text{and } V = hA
\end{aligned}
$$

Buoyant force = Weight of displaced fluid

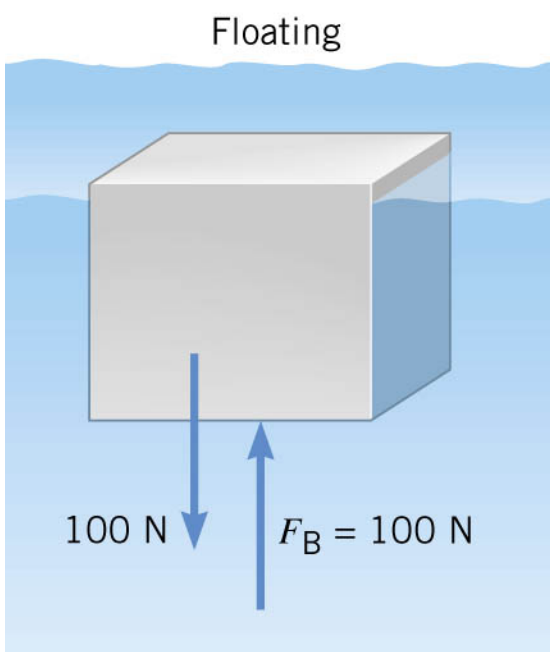
ARCHIMEDES' PRINCIPLE

Any fluid applies a buoyant force to an object that is partially or completely immersed in it; the magnitude of the buoyant force equals the weight of the fluid that the object displaces:

$$\boxed{\underbrace{F_B}_{\substack{\text{Magnitude of} \\ \text{buoyant force}}} = \underbrace{W_{\text{fluid}}}_{\substack{\text{Weight of} \\ \text{displaced fluid}}}}$$

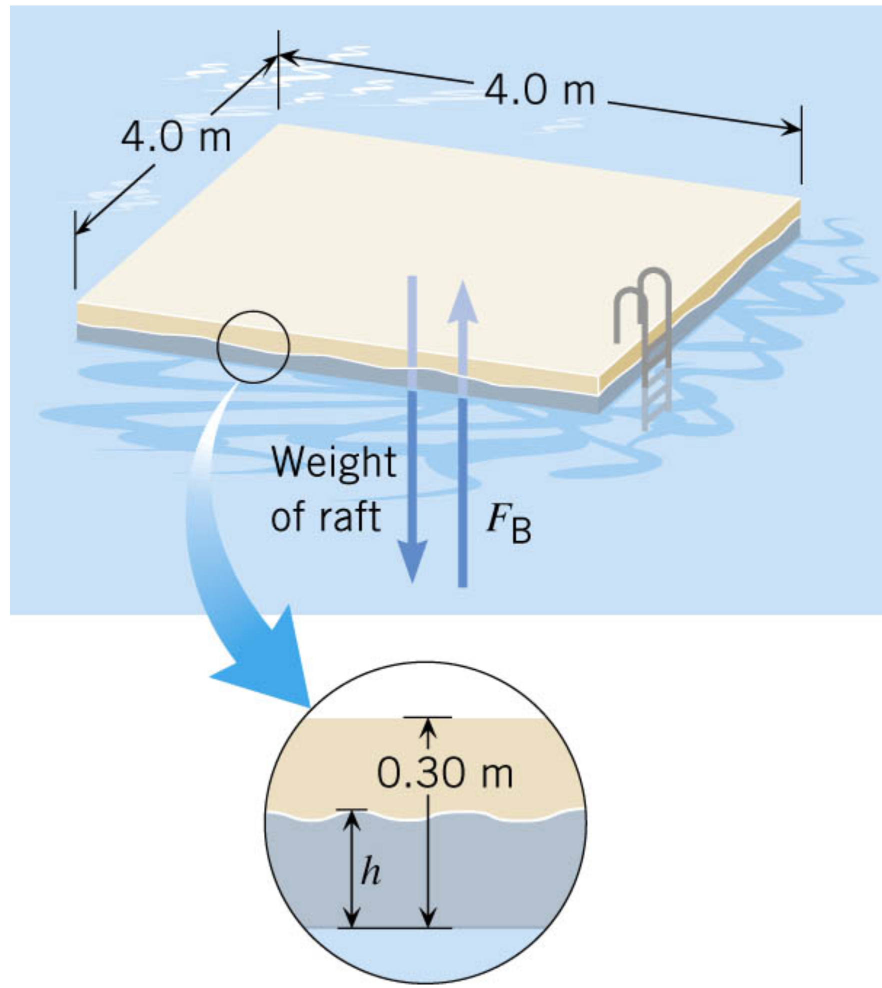
CORROLARY

If an object is floating then the magnitude of the buoyant force is equal to the magnitude of its weight.



Example: A Swimming Raft

The raft is made of solid square pinewood. Determine whether the raft floats in water and if so, how much of the raft is beneath the surface.



$$W_{raft} = m_{raft} g = \rho_{pine} V_{raft} g$$
$$= \left(550\,\text{kg/m}^3\right)\left(4.8\,\text{m}^3\right)\left(9.80\,\text{m/s}^2\right)$$
$$= 26000\ \text{N}$$

If $W_{\text{raft}} < F_{\text{B}}^{\text{max}}$, raft floats

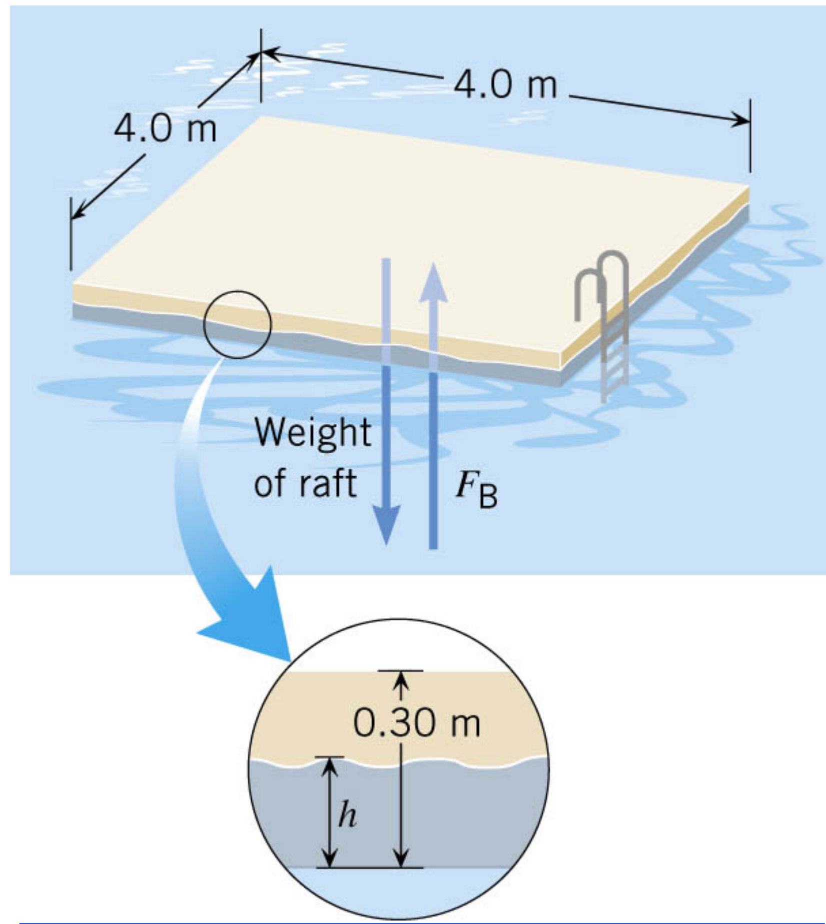
$$F_{\text{B}}^{\text{max}} = W_{\text{fluid}} \quad \text{(full volume)}$$

$$F_B^{\text{max}} = \rho V g = \rho_{water} V_{water} g$$
$$= \left(1000\,\text{kg/m}^3\right)\left(4.8\,\text{m}^3\right)\left(9.80\,\text{m/s}^2\right)$$
$$= 47000\ \text{N}$$

$W_{raft} < F_B^{\text{max}}$ Raft floats

Raft properties

$$V_{raft} = (4.0)(4.0)(0.30)\,\text{m}^3 = 4.8\ \text{m}^3$$
$$\rho_{pine} = 550\ \text{kg/m}^3$$



Part of the raft is above water

How much of raft below water?

Floating object

$$\boxed{F_B = W_{raft}}$$

$$\boxed{\begin{aligned} F_B &= \rho_{water} g V_{water} \\ &= \rho_{water} g (A_{water} h) \end{aligned}}$$

$$h = \frac{W_{raft}}{\rho_{water} g A_{water}} \qquad \boxed{W_{raft} = 26000 \text{ N}}$$

$$= \frac{26000\text{N}}{\left(1000\,\text{kg/m}^3\right)\left(9.80\,\text{m/s}^2\right)\left(16.0 \text{ m}^2\right)}$$

$$= 0.17 \text{ m}$$