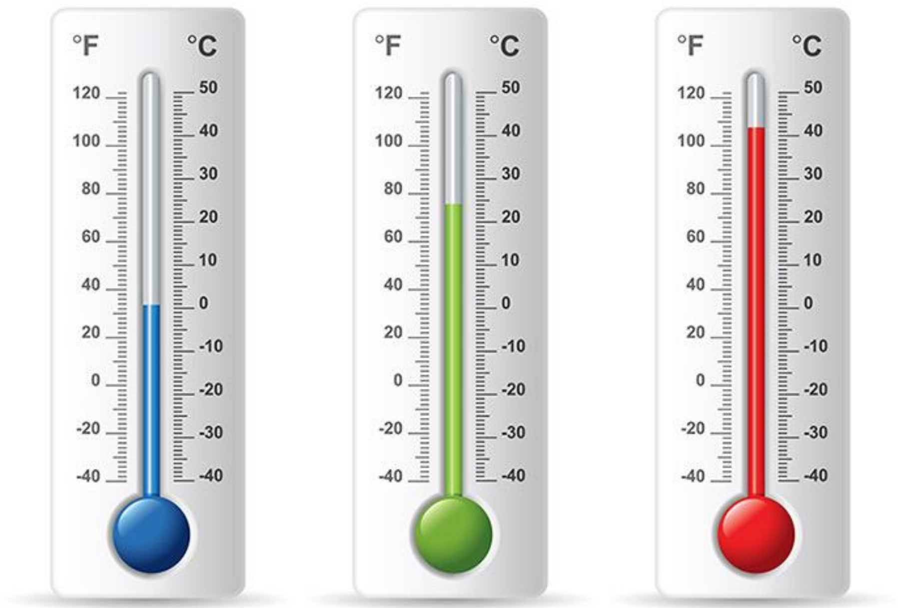
Chapter Three

Heat and properties of matter

Temperature:

- Basically temperature is <u>*a measure*</u> of ***hotness*** or ***coldness*** of an object
- Properly measured with instrumental ***thermometer***. (not by hand which is not sensitive enough nor precise)

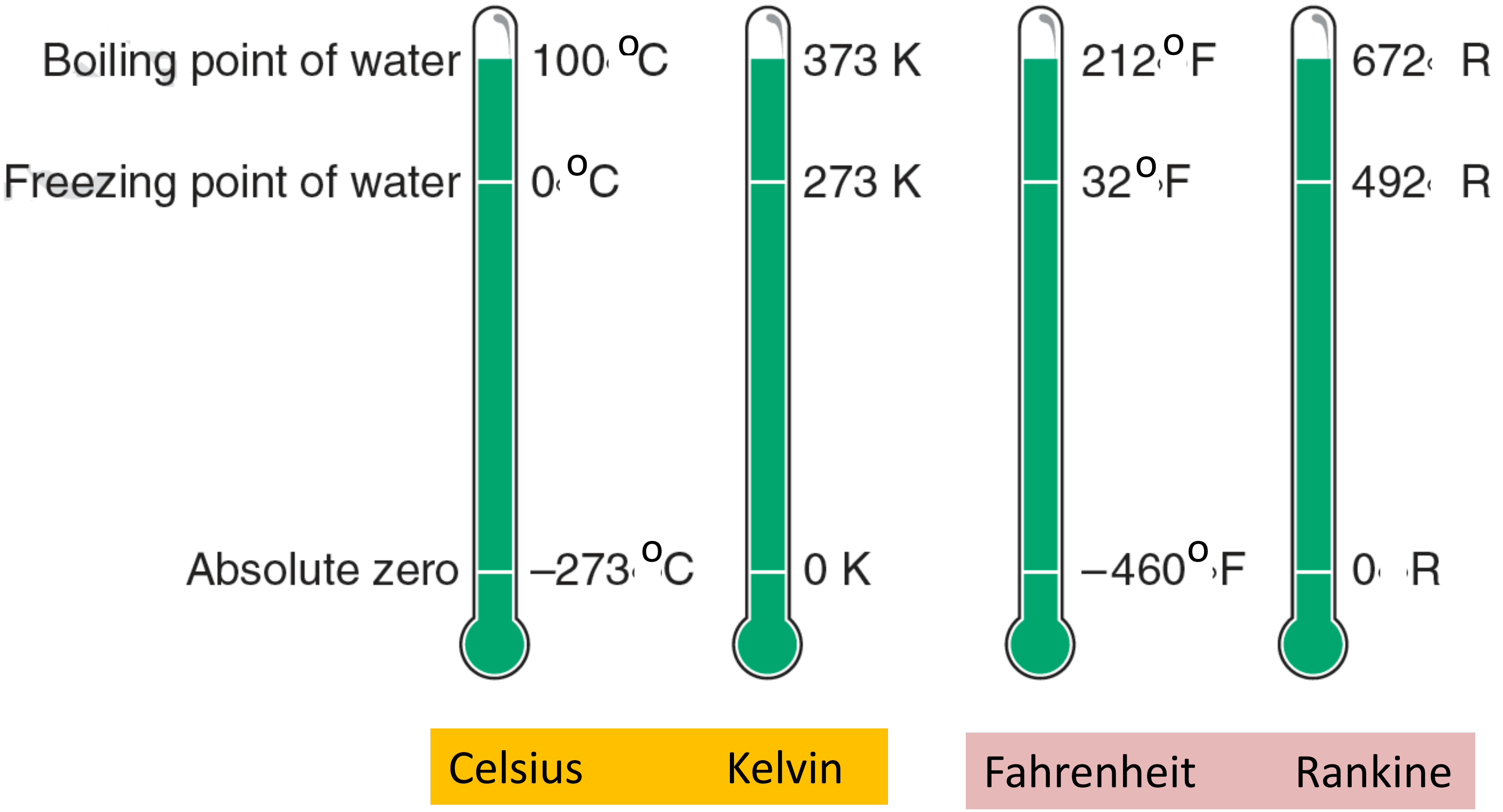
Thermometer example:



To measure temperature:
We use the change in volume as temperature changes

Common thermometer

Four basic temperature scales



Useful relationship

$$T_K = T_C + 273$$

$$T_R = T_F + 460$$

$$T_C = \frac{5}{9}(T_F - 32)$$

$$T_F = \frac{9}{5}T_F + 32$$

Conversions between different scales

EXAMPLE 3.1

The human body average temperature is 98.6°F. What is it in degrees Celsius?

Data:

$$T_F = 98.6°F$$
$$T_C = ?$$

Basic Equation:

$$T_C = \frac{5}{9}(T_F - 32°)$$

Working Equation: Same

Substitution:

$$T_C = \frac{5}{9}(98.6° - 32°)$$
$$= \frac{5}{9}(66.6°)$$
$$= 37.0°C$$

Change 18°C to Kelvin.

Data:

$$T_C = 18°C$$
$$T_K = ?$$

Basic Equation:

$$T_K = T_C + 273$$

Working Equation: Same

Substitution:

$$T_K = 18 + 273$$
$$= 291 \text{ K}$$

Change 535°R to degrees Fahrenheit.

Data:

$$T_R = 535°\text{R}$$
$$T_F = ?$$

Basic Equation:

$$T_R = T_F + 46\overline{0}°$$

Working Equation:

$$T_F = T_R - 46\overline{0}°$$

Substitution:

$$T_F = 535° - 46\overline{0}°$$
$$= 75°\text{F}$$

Heat

is a form of *internal kinetic* and *potential energy* contained in an object associated with the *motion of its atoms or molecules* and may be *transferred* from an object at a *higher temperature* to one at a *lower temperature*.

Heat cannot be stored. Heat is a transformed energy (example: work by friction force transforms into heat)

Units:

SI system → Joule (J)

U.S. system → ft lb

Other units:

Metric/SI system → kilocalorie (kcal)

British system → Btu (British thermal unit)

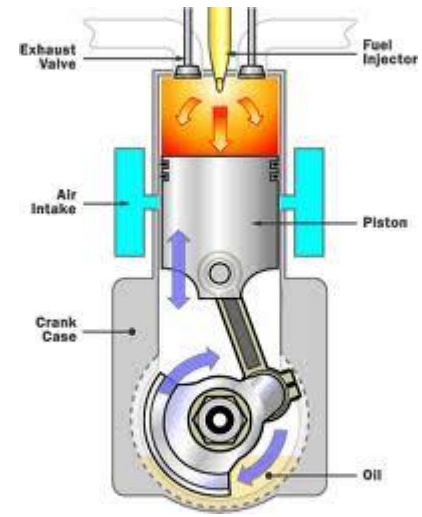
Conversation factors:

1 kcal = 4190 J ; 1 Btu = 778 ft lb

Friction causes a rise in temperature of the drill and plate.

Conversion of heat into useful work

EXAMPLES:



Internal combustion engine

In our bodies:

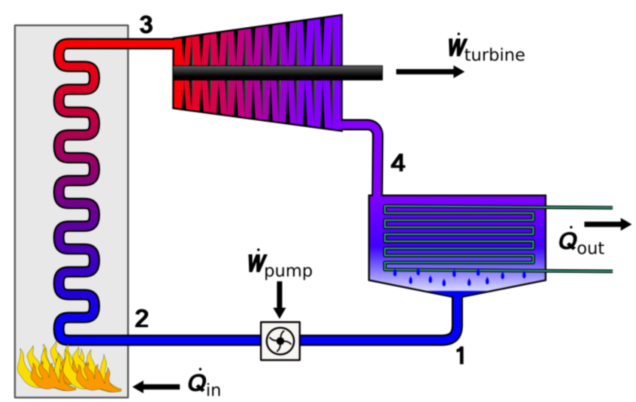
Food → Heat → muscular energy (~ 25 % of the heat) → work

By burning gases:

Heat → gas expansion → work (example: internal combustion engine in cars)

By steam.:

Heat → energetic steam → work (example: steam turbine)



Steam generator & turbine

EXAMPLES

1. Find the amount of work (in J) that is equivalent to 4850 cal of heat.

$$4850 \times 4.19 = 20{,}300\ J \quad = \quad 20.3\ kJ$$

2. How much work must a person do to offset eating a 775-calorie breakfast?

First, note that one food calorie equals one kilocalorie

$$775 \times 4190 = 3.25 \times 10^{6}\ J \quad = \quad 3.5\ MJ$$

3. A given coal gives off 7150 kcal/kg of heat when burned. How many joules of work result from burning one metric ton, assuming that 65.0% of the heat is lost?

First, note that one metric ton equals 1000 kg.

$$7150 \times 4190 \times 1000 \times 0.35 = 1.05 \times 10^{10}\ J \quad = 10.5\ GJ$$

Specific Heat

The **specific heat** of a substance is the amount of heat necessary to change the temperature of 1 kg of it 1°C (1 lb of it 1°F in the U.S. system). By formula,

$$c = \frac{Q}{m\Delta T} \text{ (metric system)}$$

$$Q = cm\Delta T$$

$$c = \frac{Q}{w\Delta T} \text{ (British system)}$$

$$Q = cw\Delta T$$

c = specific heat
Q = heat
m = mass
w = weight
ΔT = change in temperature

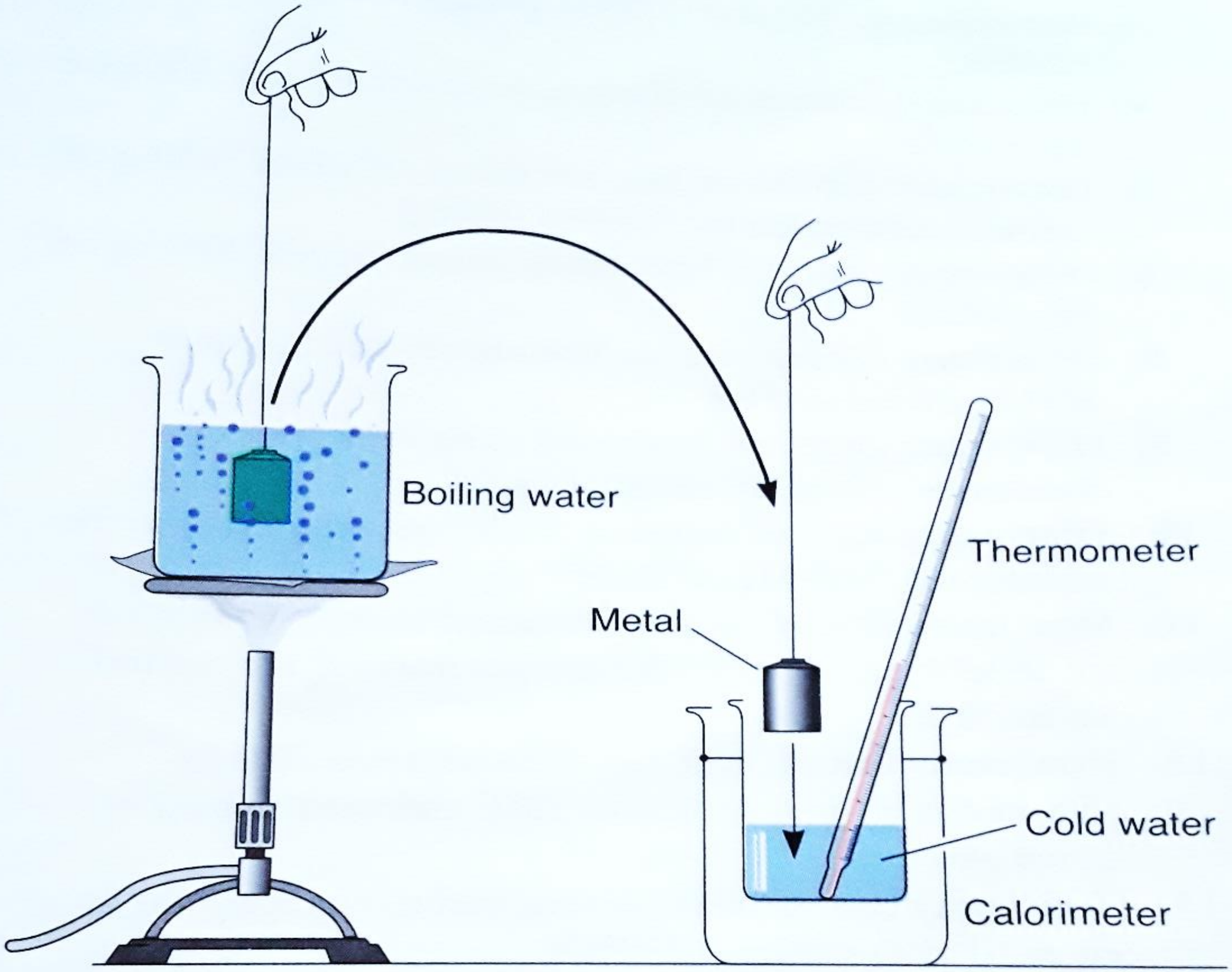


FIGURE 3.32

Apparatus for measuring the specific heat of a metal by the method of mixtures

EXAMPLE

How many kilocalories of heat must be added to 10.0 kg of steel to raise its temperature $15\bar{0}°C$?

Data:

$$m = 10.0 \text{ kg}$$
$$\Delta T = 15\bar{0}°\text{C}$$
$$c = 0.115 \text{ kcal/kg°C} \qquad \text{(from Table 15 of Appendix C)}$$
$$Q = ?$$

Basic Equation:

$$Q = cm\Delta T$$

Working Equation: Same

Substitution:

$$Q = \left(0.115 \frac{\text{kcal}}{\cancel{\text{kg}}\ \cancel{°\text{C}}}\right)(10.0\ \cancel{\text{kg}})(15\bar{0}\ \cancel{°\text{C}})$$
$$= 173 \text{ kcal}$$

EXAMPLE

How many joules of heat must be absorbed to cool 5.00 kg of water from 75.0°C to 10.0°C?

Data:

$$m = 5.00\ \text{kg}$$

$$\Delta T = 75.0°\text{C} - 10.0°\text{C} = 65.0°\text{C}$$

$$c = 4190\ \text{J/kg°C} \qquad \text{(from Table 15 of Appendix C)}$$

$$Q = ?$$

Basic Equation:

$$Q = cm\Delta T$$

Working Equation: Same

Substitution:

$$Q = \left(4190 \frac{\text{J}}{\cancel{\text{kg}}\,\cancel{°\text{C}}}\right)(5.00\ \cancel{\text{kg}})(65.0\cancel{°\text{C}})$$

$$= 1.36 \times 10^{6}\ \text{J} \qquad \text{or} \qquad 1.36\ \text{MJ}$$

Change of Phase

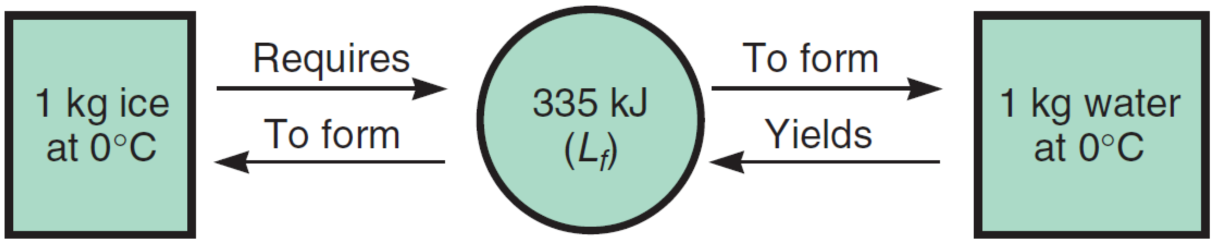
- Many industries concerned with a change of phase in the materials they use.
- Sometimes called change of state.
- Solid ⇨ liquid ⇨ gas

Molten iron at about 2900F is poured from a bucket into an open mold by a person in protective clothes and gloves.

FUSION

The change of phase from solid to liquid is called **melting or fusion.** The change from liquid to solid is called **freezing or solidification.**

EXAMPLE



The amount of heat required to melt 1 g or 1 kg or 1 lb of a liquid is called its **heat of fusion**, designated L_f.

$$L_f = \frac{Q}{m} \quad \text{(metric)} \qquad L_f = \frac{Q}{w} \quad \text{(U.S.)}$$

L_f = heat of fusion (see Table 15 in Appendix C)
Q = quantity of heat
m = mass of substance (metric system)
w = weight of substance (U.S. system)

No temperature change during change of phase

Notes

- Although there is no temperature change during change of phase, there is a transfer of heat.
- A melting solid absorbs heat and
- A solidifying liquid gives off heat.

EXAMPLE 3.9

If 1340 kJ of heat is required to melt 4.00 kg of ice at 0°C into water at 0°C, what is the heat of fusion of water?

Data:

$$Q = 1340 \text{ kJ}$$
$$m = 4.00 \text{ kg}$$
$$L_f = ?$$

Basic Equation:

$$L_f = \frac{Q}{m}$$

Working Equation: Same

Substitution:

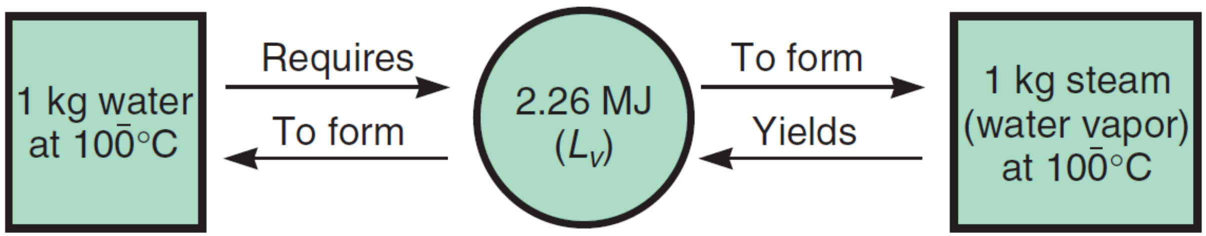
$$L_f = \frac{1340 \text{ kJ}}{4.00 \text{ kg}}$$
$$= 335 \text{ kJ/kg}$$

heat of fusion (water) $= 8\overline{0}$ cal/g, or $8\overline{0}$ kcal/kg, or 335 kJ/kg, or 144 Btu/lb

VAPORIZATION

The change of phase from liquid to a gas or vapor is called **vaporization.** The reverse process is called **condensation (liquid ← gas).**

EXAMPLE



The amount of heat required to vaporize 1 g or 1 kg or 1 lb of a liquid is called its **heat of vaporization**, designated L_v.

$$L_v = \frac{Q}{m} \quad \text{(metric)} \qquad L_v = \frac{Q}{w} \quad \text{(U.S.)}$$

L_v = heat of vaporization (see Table 15 in Appendix C)
Q = quantity of heat
m = mass of substance (metric system)
w = weight of substance (U.S. system)

No temperature change during change of phase

Notes:

- At the end of condensation, vapor becomes saturated.
- Example: relative humidity is the amount of vapor in atmosphere to that required to reach saturation (100%).
- At saturation, temperature called dew point.

EXAMPLE

If 135,000 cal of heat is required to vaporize $25\bar{0}$ g of water at $10\bar{0}$°C, what is the heat of vaporization of water?

Data:

$$Q = 135{,}000 \text{ cal}$$
$$m = 25\bar{0} \text{ g}$$
$$L_v = ?$$

Basic Equation:

$$L_v = \frac{Q}{m}$$

Working Equation: Same

Substitution:

$$L_v = \frac{135{,}000 \text{ cal}}{25\bar{0} \text{ g}}$$
$$= 54\bar{0} \text{ cal/g}$$

heat of vaporization (water) = $54\bar{0}$ cal/g, or $54\bar{0}$ kcal/kg, or 2.26 MJ/kg, or $97\bar{0}$ Btu/lb

EXAMPLE

If 15.8 MJ of heat is required to vaporize 18.5 kg of ethyl alcohol at 78.5°C (its boiling point), what is the heat of vaporization of ethyl alcohol?

Data:

$$Q = 15.8 \text{ MJ}$$
$$m = 18.5 \text{ kg}$$
$$L_v = ?$$

Basic Equation:

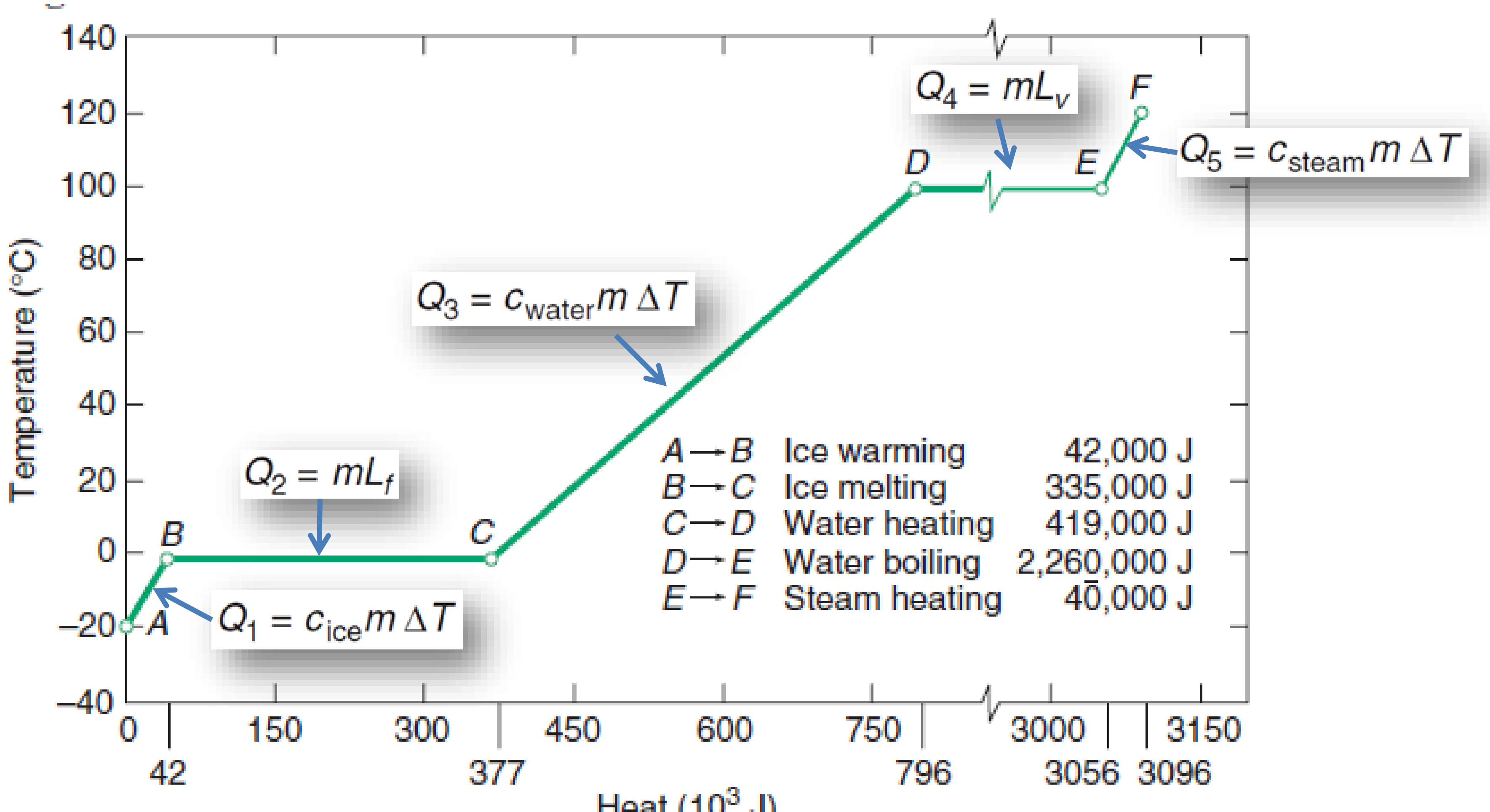
$$L_v = \frac{Q}{m}$$

Working Equation: Same

Substitution:

$$L_v = \frac{15.8 \text{ MJ}}{18.5 \text{ kg}}$$
$$= 0.854 \text{ MJ/kg or } 854 \text{ kJ/kg or } 8.54 \times 10^5 \text{ J/kg}$$

EXAMPLE



Heat gained by one kilogram of ice at –20°C as it is converted to steam at 120°C

EXAMPLE How many Btu of heat are released when 4.00 lb of steam at 222°F is cooled to water at 82°F?

To find the amount of heat released when steam at a temperature above its vaporization point is cooled to water below its boiling point, we need to consider three amounts (see Fig. **3.12**):

$Q_5 = c_{\text{steam}} w \Delta T$ (amount of heat released as the steam changes temperature from 222°F to 212°F)

$Q_4 = wL_v$ (amount of heat released as the steam changes to water)

$Q_3 = c_{\text{water}} w \Delta T$ (amount of heat released as the water changes temperature from 212°F to 82°F)

So the total amount of heat released is $Q = Q_5 + Q_4 + Q_3$

Data: $w = 4.00$ lb $\quad T_i$ of steam $= 222°\text{F}$ $\quad T_f$ of water $= 82°\text{F}$ $\quad Q = ?$

Basic Equation: $Q = Q_5 + Q_4 + Q_3$

Working Equation: $Q = c_{\text{steam}} w \Delta T + wL_v + c_{\text{water}} w \Delta T$

Substitution:

$$Q = \left(0.48 \frac{\text{Btu}}{\text{lb °F}}\right)(4.00\ \text{lb})(1\bar{0}\ \text{°F}) + (4.00\ \text{lb})\left(97\bar{0}\ \frac{\text{Btu}}{\text{lb}}\right) + \left(1.00 \frac{\text{Btu}}{\text{lb °F}}\right)(4.00\ \text{lb})(13\bar{0}\ \text{°F}) = 4420\ \text{Btu}$$

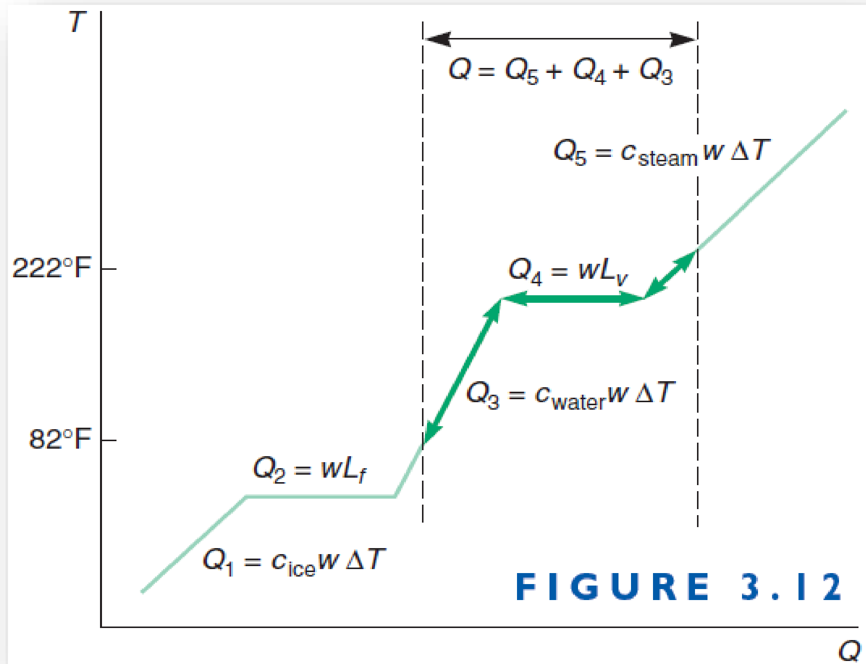
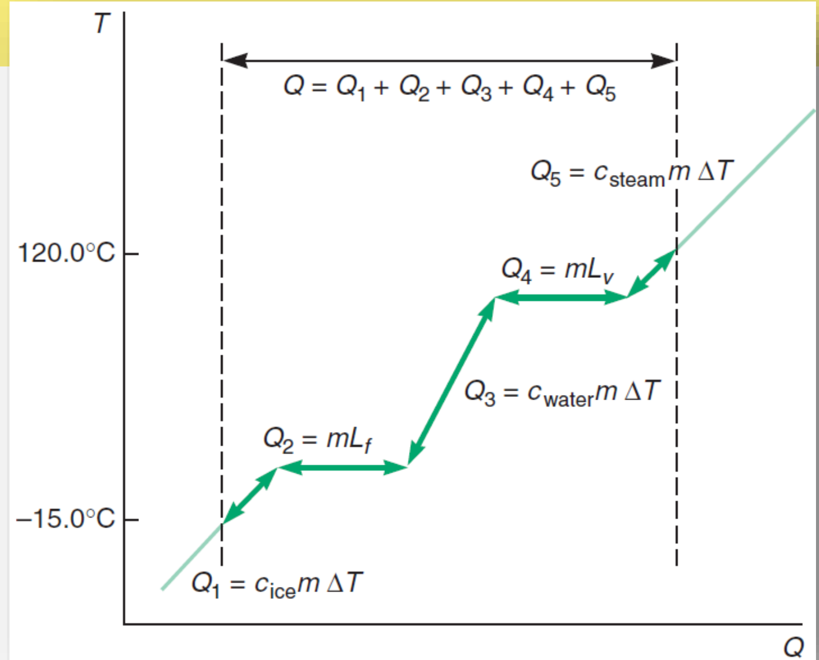


FIGURE 3.12

EXAMPLE

How many joules of heat are needed to change 3.50 kg of ice at −15.0°C to steam at 120.0°C?



Data: $m = 3.50 \text{ kg}$ $\quad T_i$ of ice $= -15.0°C$

T_f of steam $= 120.0°C$ $\quad Q = ?$

Basic Equation:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$

Working Equation:

$$Q = c_{ice} m \Delta T + m L_f + c_{water} m \Delta T + m L_v + c_{steam} m \Delta T$$

Substitution:

$$Q = \left(2100 \frac{\text{J}}{\text{kg °C}}\right)(3.50 \text{ kg})(15.0°\text{C}) + (3.50 \text{ kg})\left(335 \frac{\text{kJ}}{\text{kg}}\right) \times \frac{10^3 \text{ J}}{1 \text{ kJ}} \text{ (Change to joules.)}$$

$$+ \left(4190 \frac{\text{J}}{\text{kg °C}}\right)(3.50 \text{ kg})(100.0°\text{C}) + (3.50 \text{ kg})\left(2.26 \frac{\text{MJ}}{\text{kg}}\right) \times \frac{10^6 \text{ J}}{1 \text{ MJ}}$$

$$+ \left(2\bar{0}00 \frac{\text{J}}{\text{kg °C}}\right)(3.50 \text{ kg})(20.0°\text{C})$$

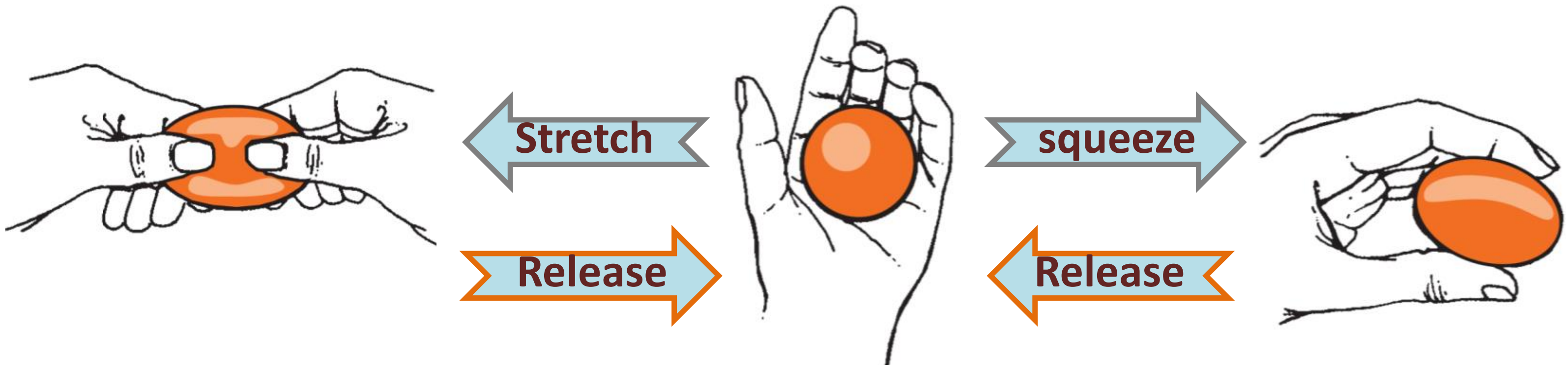
$$= 1.080 \times 10^7 \text{ J} \quad \text{or} \quad 10.80 \text{ MJ}$$

Properties of Matter

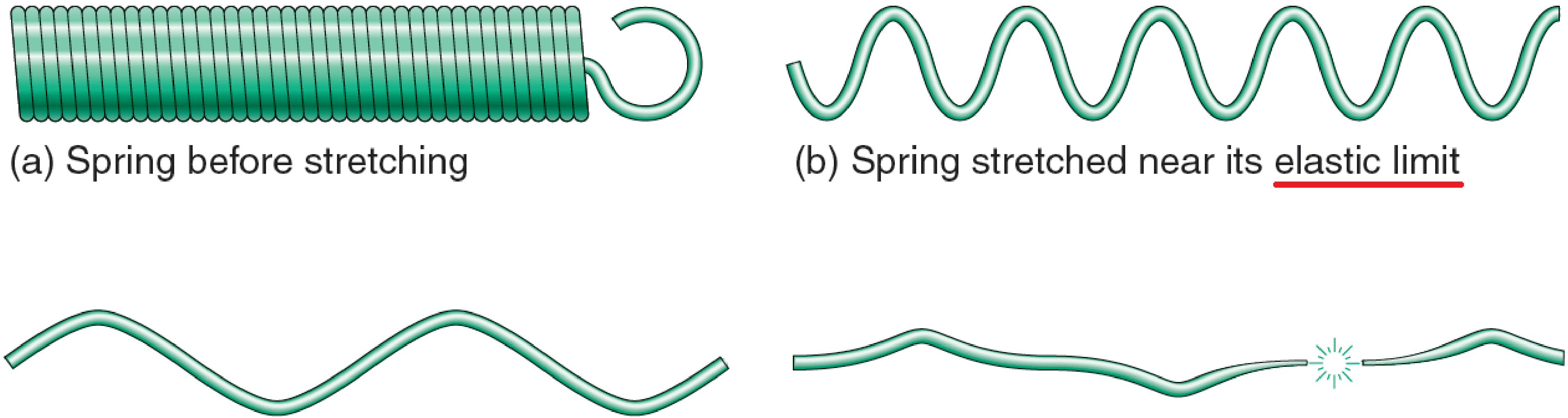
Elasticity

is a measure of a deformed object's ability to return to its original size and shape once the outside forces are removed.

EXAMPLE: Elasticity in a rubber ball



The elastic limit



(a) Spring before stretching

(b) Spring stretched near its elastic limit

(c) Spring stretched beyond its elastic limit

(d) Spring stretched much beyond its elastic limit … break occurs!

The elastic limit **of a solid is the point beyond which a deformed object *cannot* return to its original shape.**

Stress

Stress is the ratio of the outside applied force, which tends to cause a distortion, to the area over which the force acts. In other words,

$$\text{stress} = \frac{\text{applied force}}{\text{area over which the force acts}}$$

Or

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

S = stress, usually in N/m^2 (Pa) or lb/in^2 (psi)

$\Rightarrow$ **Pa ≡ Pascal (SI pressure unit)** $\Rightarrow$ **1 Pa = 1 N/m²**

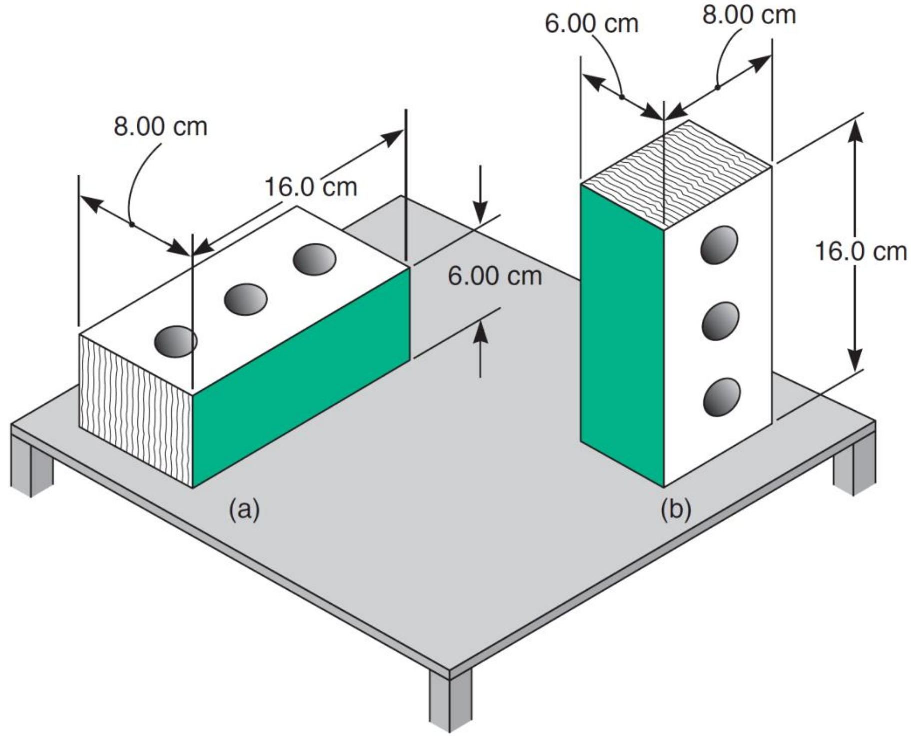
F = force applied, N or lb, perpendicular to the surface to which it is applied

A = area, m^2 or in^2

EXAMPLE:

Case 1
$F = 12.0\ \text{N}$
$A = 8.00\ \text{cm} \times 16.0\ \text{cm} = 128\ \text{cm}^2$
$S = \dfrac{F}{A} = \dfrac{12.0\ \text{N}}{128\ \text{cm}^2} \times \left(\dfrac{100\ \text{cm}}{1\ \text{m}}\right)^2$
$= 938\ \text{N/m}^2 = 938\ \text{Pa}$

Case 2
$F = 12.0\ \text{N}$
$A = 6.00\ \text{cm} \times 8.00\ \text{cm} = 48.0\ \text{cm}^2$
$S = \dfrac{F}{A} = \dfrac{12.0\ \text{N}}{48.0\ \text{cm}^2} \times \left(\dfrac{100\ \text{cm}}{1\ \text{m}}\right)^2$
$= 25\bar{0}0\ \text{N/m}^2 = 25\bar{0}0\ \text{Pa}$

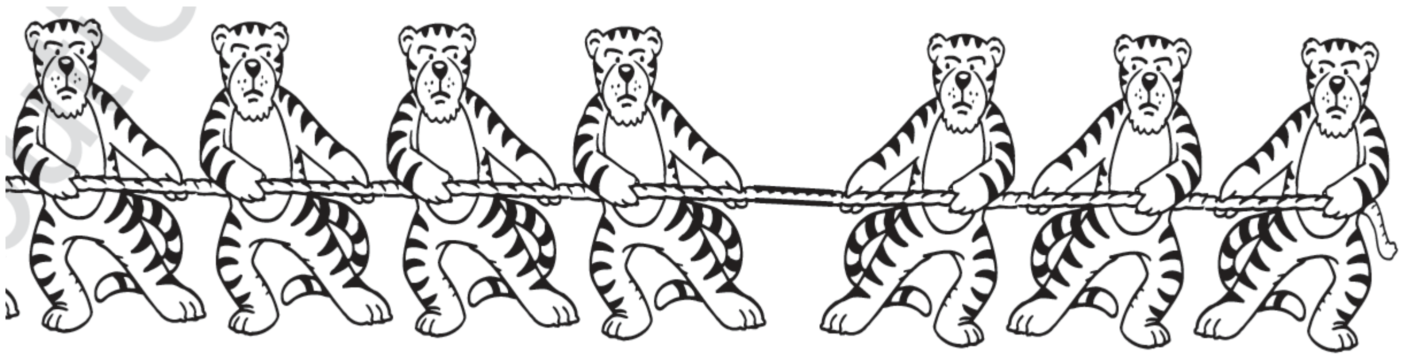


The weight of the brick is constant, but the stress on the table in part (b) is greater.

Stress, *basic types:*

1. *Tension*
2. *Compression*
3. *Shear*
4. *Torsion*
5. *bending*

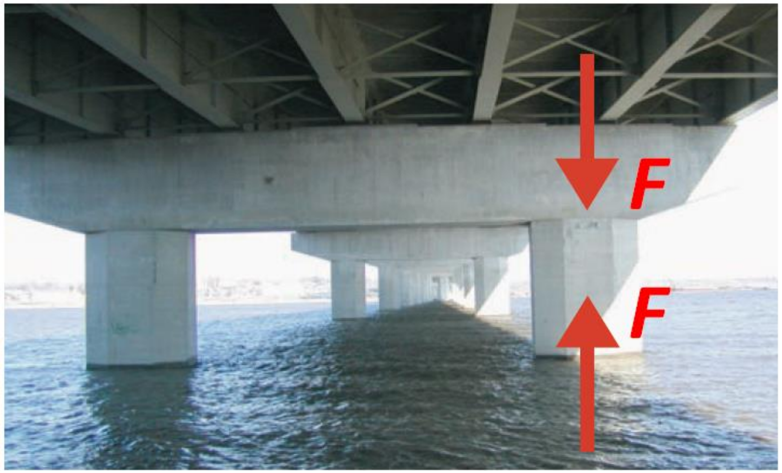
1. Tension



The rope in a tug-of-war competition is in constant tension.

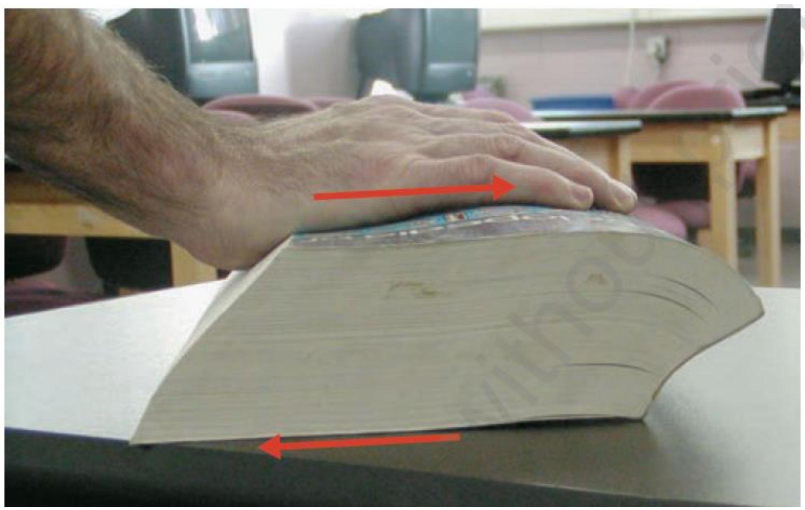
$$Tension = \frac{F}{A}$$

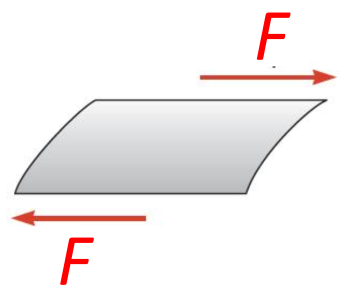
2. Compression



A column under the New Clark Bridge crossing the Mississippi River is in ***compression***.

3. Shear



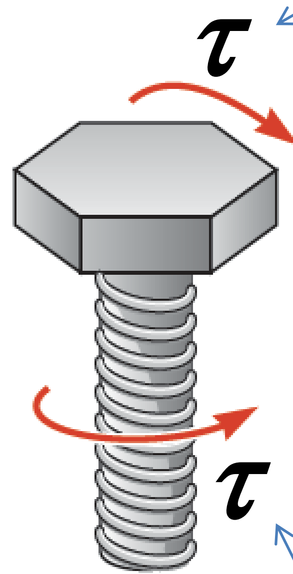


A book being pushed in this way is undergoing ***shear***.

4. Torsion

The twisting of the bolt in one direction is counteracted by the force of the wood resisting the turning motion.

Applied Torque (e.g. from hand)



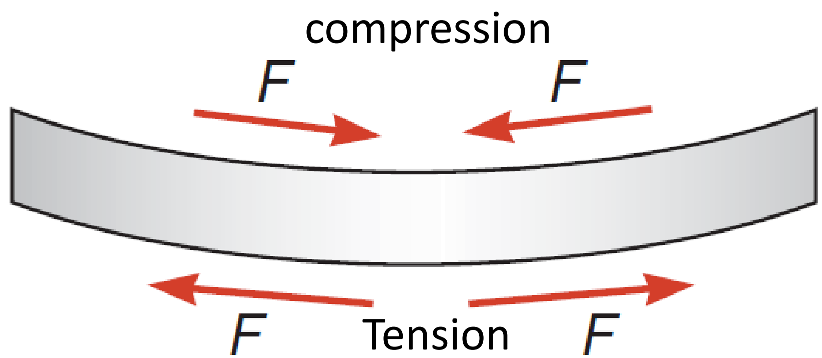
counteracting Torque (e.g. from wood)

$\tau = F \times d$ (Lever arm)

5. Bending

A beam that is bending

$$Bending \equiv Compression \oplus Tension$$



Important for thin & light but strong aircraft body. (See documentary by Richard Hammond, engineering connection, Airbus A380)

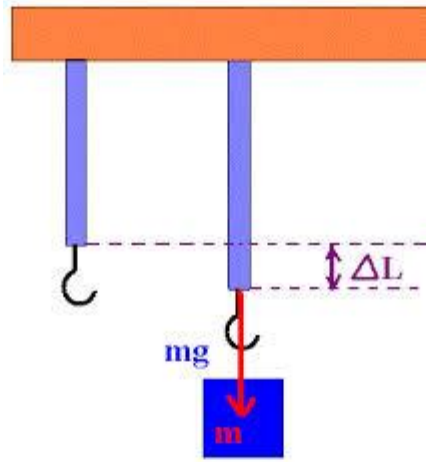
Stress causes *strain*

Strain:

is the deformation of an object due to an applied force.

$$\textit{Strain} \equiv \frac{\textit{change in length}}{\textit{Original length}}$$

(i.e., change in length per unit length)



Or

$$\textit{Strain} \equiv \frac{\textit{change in volume}}{\textit{Original volume}}$$

⋮

EXAMPLE:

A steel column in a building has a cross-sectional area of $25\overline{0}0 \text{ cm}^2$ and supports a weight of 1.50×10^5 N. Find the stress on the column.

Data:

$$A = 25\overline{0}0 \text{ cm}^2 \times \left(\frac{1 \text{ m}}{100 \text{ cm}}\right)^2 = 0.250 \text{ m}^2$$

$$F = 1.50 \times 10^5 \text{ N}$$

$$S = ?$$

Basic Equation:

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

Working Equation: Same

Substitution:

$$S = \frac{1.50 \times 10^5 \text{ N}}{0.250 \text{ m}^2}$$

$$= 6.00 \times 10^5 \text{ N/m}^2$$

$$= 6.00 \times 10^5 \text{ Pa} \quad \text{or} \quad 6\overline{0}0 \text{ kPa}$$

Hook's Law

Hooke's Law
The ratio of the force applied to an object to its change in length (resulting in its being stretched or compressed by the applied force) is constant as long as the elastic limit has not been exceeded.

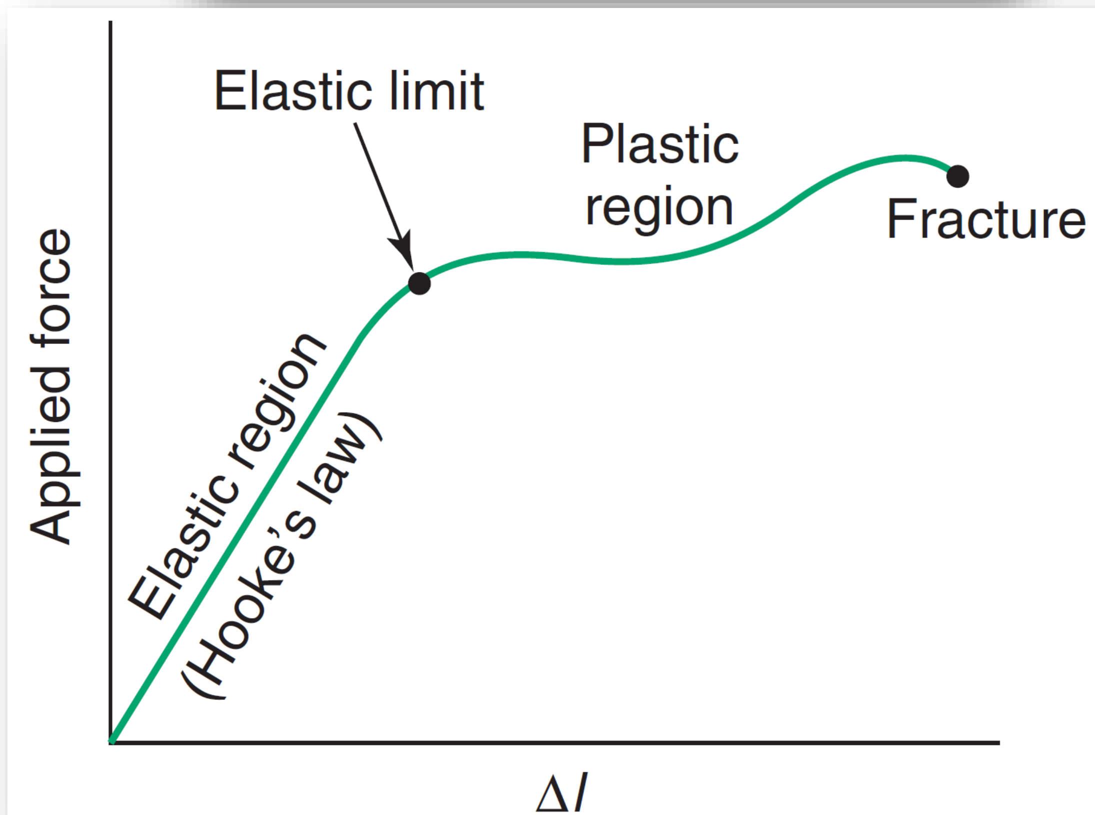
$$\frac{F}{\Delta l} = k$$

F = applied force

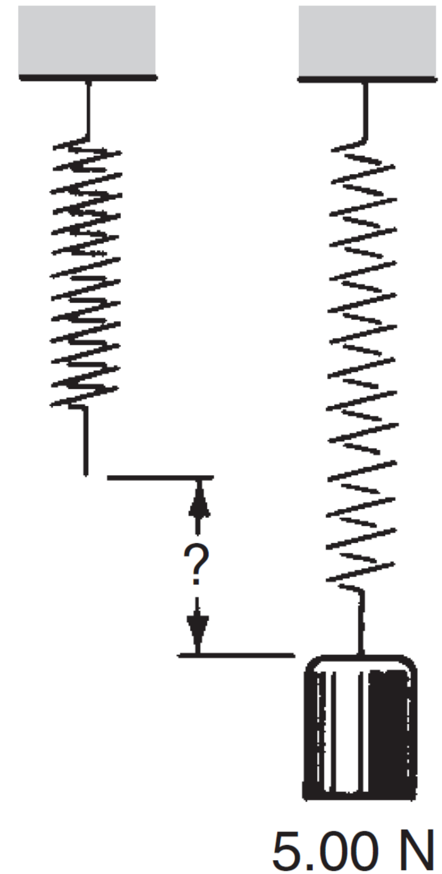
k = elastic constant

Δl = change in length

Δ (the Greek letter delta) = "change in."



A force of 5.00 N is applied to a spring whose elastic constant is 0.250 N/cm. Find its change in length.



Data: $F = 5.00\ \text{N}$

$k = 0.250\ \text{N/cm}$

$\Delta l = ?$

Basic Equation: $$\frac{F}{\Delta l} = k$$

Working Equation:

$$\Delta l = \frac{F}{k}$$

Substitution:

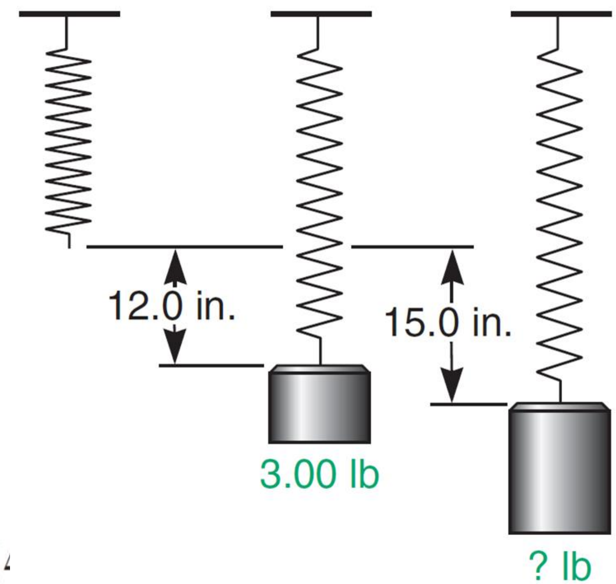
$$\Delta l = \frac{5.00\ \text{N}}{0.250\ \text{N/cm}} = 20.0\ \text{cm}$$

$$\frac{\text{N}}{\text{N/cm}} = \text{N} \div \frac{\text{N}}{\text{cm}} = \cancel{\text{N}} \cdot \frac{\text{cm}}{\cancel{\text{N}}} = \text{cm}$$

A force of 3.00 lb stretches a spring 12.0 in. What force is required to stretch the spring 15.0 in.?

Data:

$$F_1 = 3.00 \text{ lb}$$
$$l_1 = 12.0 \text{ in.}$$
$$l_2 = 15.0 \text{ in.}$$
$$F_2 = ?$$



Basic Equation:

$$\frac{F}{\Delta l} = k$$

Working Equations:

$$\frac{F}{\Delta l} = k \quad \text{and} \quad F = k($$

Substitution: There are two substitutions, one to find k and one to find the second force F_2:

$$\frac{3.00 \text{ lb}}{12.0 \text{ in.}} = k$$
$$0.250 \text{ lb/in.} = k$$

$$F_2 = (0.250 \text{ lb/}\cancel{\text{in.}})(15.0\ \cancel{\text{in.}})$$
$$= 3.75 \text{ lb}$$

EXAMPLE

A support column is compressed 3.46×10^{-4} m under a weight of 6.42×10^5 N. How much is the column compressed under a weight of 5.80×10^6 N?

First find *k:*

Data:

$F_2 = 6.42 \times 10^5 \text{ N}$ $\Delta l_2 = 3.46 \times 10^{-4} \text{ m}$ $k = ?$

Basic Equation:

$$\frac{F_2}{\Delta l_2} = k$$

Working Equation: Same

Substitution:

$$k = \frac{6.42 \times 10^5 \text{ N}}{3.46 \times 10^{-4} \text{ m}} = 1.86 \times 10^9 \text{ N/m}$$

Then:

Data:

$k = 1.86 \times 10^9 \text{ N/m}$ $F_1 = 5.80 \times 10^6 \text{ N}$ $\Delta l_1 = ?$

Basic Equation:

$$\frac{F_1}{\Delta l_1} = k$$

Working Equation:

$$\Delta l_1 = \frac{F_1}{k}$$

Substitution:

$$\Delta l_1 = \frac{5.80 \times 10^6 \text{ N}}{1.86 \times 10^9 \text{ N/m}} = 3.12 \times 10^{-3} \text{ m or } 3.12 \text{ mm}$$

Density

Density is a property of all three states of matter. **Mass density**, D_m, is defined as mass per unit volume. **Weight density**, D_w, is defined as weight per unit volume, or

$$D_m = \frac{m}{V} \qquad\qquad D_w = \frac{F_w}{V}$$

where D_m = mass density, m = mass, V = volume

D_w = weight density, F_w = weight, V = volume

Densities for Various Substances

Substance	Mass Density (kg/m^3)	Weight Density (lb/ft^3)
Solids		
Aluminum	2,700	169
Brass	8,700	540
Concrete	2,300	140
Liquids		
Oil	870	54.2
Seawater	1,025	64.0
Water	1,000	62.4
Gases*	At 0°C and 1 atm pressure	At 32°F and 1 atm pressure
Air	1.29	0.081
Helium	0.178	0.011
Hydrogen	0.0899	0.0056

(1 atm ~ 10^5 Pa)

Note:
Generally, density increases with decreasing temperature. Exception is water for which ice is less dense than liquid water)

EXAMPLE 3.18

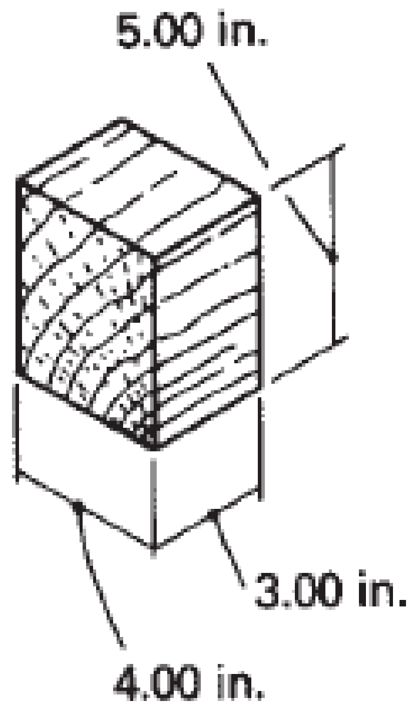
Find the weight density of a block of wood 3.00 in. × 4.00 in. × 5.00 in. with weight 0.700 lb.

Data:

$l = 4.00$ in. $\quad w = 3.00$ in. $\quad h = 5.00$ in. $\quad F_w = 0.700$ lb $\quad D_w = ?$

Basic Equations:

$$V = lwh \quad \text{and} \quad D_w = \frac{F_w}{V}$$



Working Equations: Same

Substitutions:

$$V = (4.00 \text{ in.})(3.00 \text{ in.})(5.00 \text{ in.})$$
$$= 60.0 \text{ in}^3$$

$$D_w = \frac{0.700 \text{ lb}}{60.0 \text{ in}^3}$$
$$= 0.0117 \frac{\text{lb}}{\text{in}^3} \times \left(\frac{12 \text{ in.}}{1 \text{ ft}}\right)^3$$
$$= 20.2 \text{ lb/ft}^3$$

EXAMPLE 3.19

Find the mass density of a ball bearing with mass 22.0 g and radius 0.875 cm.

Data:

$$r = 0.875 \text{ cm}$$
$$m = 22.0 \text{ g}$$
$$D_m = ?$$

Basic Equations:

$$V = \tfrac{4}{3}\pi r^3 \quad \text{and} \quad D_m = \frac{m}{V}$$

Working Equations: Same

Substitutions:

$$V = \tfrac{4}{3}\pi\,(0.875 \text{ cm})^3$$
$$= 2.81 \text{ cm}^3$$

$$D_m = \frac{22.0 \text{ g}}{2.81 \text{ cm}^3}$$
$$= 7.83 \text{ g/cm}^3$$
$$= 7.83 \frac{\cancel{\text{g}}}{\cancel{\text{cm}^3}} \times \left(\frac{100 \cancel{\text{cm}}}{1 \text{ m}}\right)^3 \times \frac{1 \text{ kg}}{10^3 \cancel{\text{g}}} = 7830 \text{ kg/m}^3$$

EXAMPLE 3.20

Find the weight density of a gallon of water weighing 8.34 lb.

Data:

$$F_w = 8.34 \text{ lb}$$
$$V = 1 \text{ gal} = 231 \text{ in}^3$$
$$D_w = ?$$

Basic Equation:

$$D_w = \frac{F_w}{V}$$

Working Equation: Same

Substitution:

$$D_w = \frac{8.34 \text{ lb}}{231 \text{ in}^3}$$
$$= 0.0361 \frac{\text{lb}}{\text{in}^3} \times \left(\frac{12 \text{ in.}}{1 \text{ ft}}\right)^3$$
$$= 62.4 \text{ lb/ft}^3$$