Chapter 3
Solutions

P3.1: Express your weight in the units of pounds and newtons, and your mass in the units of slugs and kilograms.

Solution:

Let w and m represent weight and mass.

$$\boxed{w = 180 \text{ lb}}$$

Convert to SI using the factor from Table 3.6:

$$w = (180 \text{ lb})\left(4.448\ \frac{\text{N}}{\text{lb}}\right)$$

$$\boxed{w = 801 \text{ N}}$$

Calculate mass using gravitational acceleration in USCS:

$$m = \frac{w}{g} = \frac{180 \text{ lb}}{32.2 \ \text{ft}/\text{s}^2}$$

$$\boxed{m = 5.59 \text{ slugs}}$$

Convert to SI using the factor from Table 3.6:

$$m = (5.59 \,\text{slug})\left(14.59\ \frac{\text{kg}}{\text{slug}}\right)$$

$$\boxed{m = 81.6 \text{ kg}}$$

P3.2: Express your height in the units of inches, feet, and meters.

Solution:
Let h represent height.

$$\boxed{h = 6\text{ ft}}$$

$$h = (6\text{ ft})\left(12\ \frac{\text{in.}}{\text{ft}}\right)$$

$$\boxed{h = 72\text{ in.}}$$

Convert to SI using the factor from Table 3.6:

$$h = (6\text{ ft})\left(0.3048\ \frac{\text{m}}{\text{ft}}\right)$$

$$\boxed{h = 1.83\text{ m}}$$

P3.3: For a wind turbine that is used to produce electricity for a utility company, the power output per unit area swept by the blades is 2.4 kW/m^2. Convert this quantity to the dimensions of hp/ft^2.

Solution:
Convert to USCS using the factors from Table 3.6.

$$\left(2.4\frac{\text{kW}}{\text{m}^2}\right)\left(9.2903\times10^{-2}\,\frac{\text{m}^2}{\text{ft}^2}\right)\left(1.341\frac{\text{hp}}{\text{kW}}\right)=2.990\times10^{-1}\,\frac{\text{hp}}{\text{ft}^2}$$

$$\boxed{2.990\times10^{-1}\,\frac{\text{hp}}{\text{ft}^2}}$$

P3.4: A world-class runner can run half a mile in a time of 1 min and 45 s. What is the runner's average speed in m/s?

Solution:
Use the conversion factors listed in Tables 3.5 and 3.6:

1 mi = 5280 ft
1 ft = 0.3048 m
$1000\ \text{L} = 1\ \text{m}^3$

Convert mi to m using those factors:

$$\tfrac{1}{2}\ \text{mi} = \tfrac{1}{2}(5280\ \text{ft})\left(\frac{0.3048\ \text{m}}{1\ \text{ft}}\right) = 804.7\ \text{m}$$

Express the runner's speed in m/s:

$$\left(\frac{804.7\ \text{m}}{105\ \text{s}}\right) = 7.66\ \frac{\text{m}}{\text{s}}$$

$$7.66\ \frac{\text{m}}{\text{s}}$$

Alternatively, use the conversion factors:

1 mi = 1.609 km
1 km = 1000 m

Convert mi to m using those factors:

$$\tfrac{1}{2}\ \text{mi} = \tfrac{1}{2}(1.609\ \text{km})\left(\frac{1000\ \text{m}}{1\ \text{km}}\right) = 804.5\ \text{m}$$

Express the runner's speed in m/s:

$$\left(\frac{804.5\ \text{m}}{105\ \text{s}}\right) = 7.66\ \frac{\text{m}}{\text{s}}$$

$$\boxed{7.66\ \frac{\text{m}}{\text{s}}}$$

P3.5: One U.S. gallon is equivalent to 0.1337 ft^3, 1 ft is equivalent to 0.3048 m, and 1000 L are equivalent to 1 m^3. By using those definitions, determine the conversion factor between gallons and liters.

Solution:
Use the definitions of derived units and the conversion factors listed in Tables 3.2, 3.5, and 3.6:

$$1 \text{ gal} = 0.1337 \text{ ft}^3$$
$$1 \text{ ft} = 0.3048 \text{ m}$$
$$1000 \text{ L} = 1 \text{ m}^3$$

Convert gal to L using those factors:

$$1 \text{ gal} = \left(0.1337 \text{ ft}^3\right)\left(0.3048 \frac{\text{m}}{\text{ft}}\right)^3\left(1000 \frac{\text{L}}{\text{m}^3}\right) = 3.785 \text{ L}$$

$$\boxed{1 \text{ gal} = 3.785 \text{ L}}$$

P3.6: A passenger automobile is advertised as having a fuel economy rating of 29 mi/gal for highway driving. Express the rating in the units of km/L.

Solution:

Convert using factors from Table 3.6:

$$\left(29\,\frac{\text{mi}}{\text{gal}}\right)\left(0.2642\,\frac{\text{gal}}{\text{L}}\right)\left(1.609\,\frac{\text{km}}{\text{mi}}\right) = 12.33\ \frac{\text{km}}{\text{L}}$$

$$\boxed{12.33\ \frac{\text{km}}{\text{L}}}$$

P3.7: (a) How much horsepower does a 100 W household lightbulb consume? (b) How many kW does a 5 hp lawn mower engine produce?

Solution:

(a) Convert W to kW using the prefix definition in Table 3.3. Convert from kW to hp using the factor from Table 3.6:

$$(100\ \text{W})\left(0.001\,\frac{\text{kW}}{\text{W}}\right)\left(1.341\,\frac{\text{hp}}{\text{kW}}\right) = 0.1341\ \text{hp}$$

$\boxed{0.1341\ \text{hp}}$

(b) Convert from hp to kW using factor from Table 3.6:

$$(5\ \text{hp})\left(0.7457\,\frac{\text{kW}}{\text{hp}}\right) = 3.729\ \text{kW}$$

$\boxed{3.729\ \text{kW}}$

P3.8: The estimates for the amount of oil spilled into the Gulf of Mexico during the 2010 Deepwater Horizon disaster were 120-180 million gal. Express this range in L, m^3, and ft^3.

Solution:
Use the volume conversion factors listed in Tables 3.5 and 3.6:

1 gal = 3.7854 L
1 gal = 3.7854×10^{-3} m^3
1 gal = 0.1337 ft^3

Convert from gal to L:

$$(120{,}000{,}000 \text{ gal})\left(3.7854 \frac{\text{L}}{\text{gal}}\right) = 454.25 \text{ million L}$$

$$(180{,}000{,}000 \text{ gal})\left(3.7854 \frac{\text{L}}{\text{gal}}\right) = 681.37 \text{ million L}$$

$$\boxed{454.25 - 681.37 \text{ million L}}$$

Convert from gal to m^3:

$$(120{,}000{,}000 \text{ gal})\left(0.0037854 \frac{\text{m}^3}{\text{gal}}\right) = 454{,}250 \ \text{m}^3$$

$$(180{,}000{,}000 \text{ gal})\left(0.0037854 \frac{\text{m}^3}{\text{gal}}\right) = 681{,}370 \ \text{m}^3$$

$$\boxed{454{,}250 - 681{,}370 \text{ m}^3}$$

Convert from gal to ft^3:

$$(120{,}000{,}000 \text{ gal})\left(0.1337 \frac{\text{ft}^3}{\text{gal}}\right) = 16.04 \text{ million ft}^3$$

$$(180{,}000{,}000 \text{ gal})\left(3.7854 \frac{\text{ft}^3}{\text{gal}}\right) = 24.07 \text{ million ft}^3$$

$$\boxed{16.04 - 24.07 \text{ million ft}^3}$$

P3.9: In 1925, the Tri-State Tornado ripped a 219 mi path of destruction through Missouri, Illinois, and Indiana, killing a record 695 people. The maximum winds in the tornado were 318 mph. Express the wind speed in km/hr and in ft/s.

Solution:
Use the length conversion factors listed in Tables 3.5 and 3.6:

1 mi = 1.609 km
1 mi = 5280 ft

Convert from mph to km/hr:

$$\left(318\ \frac{\text{mi}}{\text{hr}}\right)\left(1.609\ \frac{\text{km}}{\text{mi}}\right) = 511.66\ \frac{\text{km}}{\text{hr}}$$

$$\boxed{511.66\ \frac{\text{km}}{\text{hr}}}$$

Convert from mph to ft/s:

$$\left(318\ \frac{\text{mi}}{\text{hr}}\right)\left(5280\ \frac{\text{ft}}{\text{mi}}\right)\left(\frac{\text{hr}}{3600\ \text{s}}\right) = 466.40\ \frac{\text{ft}}{\text{s}}$$

$$\boxed{466.40\ \frac{\text{ft}}{\text{s}}}$$

P3.10: Uphill water slides are becoming more popular at large water parks. Uphill speeds of riders can reach 19 ft/s. Express this speed in mph.

Solution:
Use the length conversion factors listed in Tables 3.5 and 3.6:

1 mi = 5280 ft

Convert from ft/s to mph:

$$\left(19\,\frac{\text{ft}}{\text{s}}\right)\left(\frac{\text{mi}}{5280\,\text{ft}}\right)\left(3600\,\frac{\text{s}}{\text{hr}}\right) = 12.95\,\text{mph}$$

$\boxed{12.95\text{ mph}}$

P3.11: A brand-new engineering hire is late for her first product development team meeting. She gets out of her car and starts running 8 mph. It is exactly 7:58 A.M., and the meeting starts at exactly 8:00 A.M. Her meeting is 500 yd away. Will she make it on time to the meeting? If so, with how much time to spare? If not, how late will she be?

Solution:
First find out how many feet she must run using 3 ft = 1 yd.

$$500\ \text{yd}\left(3\frac{\text{ft}}{\text{yd}}\right) = 1500\ \text{ft}$$

Next use the length conversion factor listed in Table 3.5 to find how fast she is running in ft/s.

1 mi = 5280 ft

$$8\frac{\text{mi}}{\text{hr}}\left(5280\frac{\text{ft}}{\text{mi}}\right)\left(\frac{\text{hr}}{3600\ \text{s}}\right) = 11.73\frac{\text{ft}}{\text{s}}$$

Next find out how long it will take her to run 1500 ft using the relationship (time x velocity = distance).

$$\text{time} = \frac{1500\ \text{ft}}{11.73\frac{\text{ft}}{\text{s}}} = 127.9\ \text{s}$$

Since it will take her 127.9 seconds to run the distance and she only has 120 seconds, she will not make the meeting on time and will be 7.9 seconds late.

P3.12: A robotic wheeled vehicle that contains science instruments is used to study the geology of Mars. The rover weighs 408 lb on Earth. (a) In the USCS dimensions of slugs and lbm, what is the rover's mass? (b) What is the weight of the rover as it rolls off the lander's platform (the lander is the protective shell that houses the rover during landing)? The gravitational acceleration on the surface of Mars is 12.3 ft/s^2.

Solution:

(a) The rover's mass is the same on Earth and Mars. On Earth, it weighs 408 lb, and the gravitational acceleration is 32.2 ft/s^2. By using $m = w/g$

$$m = \frac{408\,\text{lb}}{32.2\,\frac{\text{ft}}{\text{s}^2}} = 12.67\,\frac{\text{lb}\cdot\text{s}^2}{\text{ft}}$$

From Table 3.5, the dimension is equivalent to the derived unit of slug,

$\boxed{m = 12.67 \text{ slugs}}$

By definition, an object that weighs one pound has a mass of one pound–mass, so

$\boxed{m = 408 \text{ lbm}}$

We double check by using the definition in Table 3.5

$$m = (408\text{ lbm})\left(3.1081\times10^{-2}\,\frac{\text{slugs}}{\text{lbm}}\right) = 12.67\text{ slugs}$$

(b) Since the gravitational acceleration on Mars is only 12.3 ft/s^2, the weight becomes

$$w = (12.67\,\text{slugs})\left(12.3\,\frac{\text{ft}}{\text{s}^2}\right) = 155.9\,\frac{\text{slug}\cdot\text{ft}}{\text{s}^2}$$

This group of dimensions is dimensionally the same as lb.

$\boxed{w = 155.9 \text{ lb}}$

It would not be correct to calculate weight as the product of 408 lbm and 12.3 ft/s^2, since the units would not be dimensionally consistent.

P3.13: Calculate various fuel quantities for Flight 143. The plane already had 7682 L of fuel on board prior to the flight, and the tanks were to be filled so that a total of 22,300 kg were present at takeoff. (a) Using the incorrect conversion factor of 1.77 kg/L, calculate in units of kg the amount of fuel that was added to the plane. (b) Using the correct factor of 1.77 lb/L, calculate in units of kg the amount of fuel that should have been added. (c) By what percentage would the plane have been underfueled for its journey? Be sure to distinguish between weight and mass quantities in your calculations.

Solution:

(a) Amount of fuel that was added (kg):

$$22{,}300 \text{ kg} - (7{,}682 \text{ L})\left(1.77 \frac{\text{kg}}{\text{L}}\right) = 8{,}702.9 \text{ kg}$$

$\boxed{8{,}703 \text{ kg}}$

(b) Amount of fuel that should have been added (kg):

$$22{,}300 \text{ kg} - (7{,}682 \text{ L})\left(1.77 \frac{\text{lb}}{\text{L}}\right)\left(\frac{1}{32.2 \text{ ft/s}^2}\right)\left(14.59 \frac{\text{kg}}{\text{slug}}\right) = 16{,}139 \text{ kg}$$

$\boxed{16{,}139 \text{ kg}}$

(c) Percent that the plane was under–fueled:

$$\left(\frac{16{,}139 \text{ kg} - 8{,}703 \text{ kg}}{16{,}139 \text{ kg}}\right)(100\%) = 46.07\%$$

$\boxed{46.1\%}$

P3.14: Printed on the side of a tire on an all–wheel–drive sport utility wagon is the warning "Do not inflate above 44 psi," where psi is the abbreviation for the pressure unit pounds per square inch (lb/in^2). Express the tire's maximum pressure rating in (a) the USCS unit of lb/ft^2 (psf) and (b) the SI unit of kPa.

Solution:

(a) Convert the area measure from in. to ft:

$$\left(44\,\frac{\text{lb}}{\text{in}^2}\right)\left(12\,\frac{\text{in.}}{\text{ft}}\right)^2 = 6{,}336\,\frac{\text{lb}}{\text{ft}^2}$$

$\boxed{\text{6,336 psf where the abbreviation psf stands for pounds–per–square–foot.}}$

(b) Use a conversion factor from Table 3.6 and the SI prefix from Table 3.3:

$$\left(44\,\frac{\text{lb}}{\text{in}^2}\right)\left(6{,}895\,\frac{\text{Pa}}{\text{psi}}\right) = 3.034\times10^5\ \text{Pa} = 303.4\ \text{kPa}$$

$\boxed{\text{303.4 kPa}}$

P3.15: The amount of power transmitted by sunlight depends on latitude and the surface area of the solar collector. On a clear day at a certain northern latitude, 0.6 kW/m^2 of solar power strikes the ground. Express that value in the alternative USCS unit of (ft · lb/s)/ft^2.

<u>Solution</u>:
Use conversion factors from Table 3.6:

$$\left(0.6\,\frac{\text{kW}}{\text{m}^2}\right)\left(1{,}000\,\frac{\text{W}}{\text{kW}}\right)\left(0.7376\,\frac{\text{ft}\cdot\text{lb/s}}{\text{W}}\right)\left(0.3048\,\frac{\text{m}}{\text{ft}}\right)^2 = 41.1\ \frac{\text{ft}\cdot\text{lb/s}}{\text{ft}^2}$$

$$\boxed{41.1\ \frac{\text{ft}\cdot\text{lb/s}}{\text{ft}^2}}$$

P3.16: The property of a fluid called *viscosity* is related to its internal friction and resistance to being deformed. The viscosity of water, for instance, is less than that of molasses and honey, just as the viscosity of a light motor oil is less than that of grease. A unit used in mechanical engineering to describe viscosity is called the *poise*, named after the physiologist Jean Louis Poiseuille, who performed early experiments in fluid mechanics. The unit is defined by 1 poise = 0.1 $(\mathrm{N \cdot s})/\mathrm{m}^2$. Show that 1 poise is also equivalent to 1 $\mathrm{g/(cm \cdot s)}$.

<u>Solution</u>:

Expand the derived unit N in terms of the SI base units:

$$\left(0.1\ \frac{\mathrm{kg}}{\mathrm{m \cdot s}}\right)\left(1000\ \frac{\mathrm{g}}{\mathrm{kg}}\right)\left(0.01\ \frac{\mathrm{m}}{\mathrm{cm}}\right) = 1\frac{\mathrm{g}}{\mathrm{cm \cdot s}}$$

Apply SI prefixes from Table 3.3:

$$0.1\ \frac{\mathrm{N \cdot s}}{\mathrm{m}^2} = 0.1\ \frac{\mathrm{kg \cdot m \cdot s}}{\mathrm{s}^2 \cdot \mathrm{m}^2} = 0.1\frac{\mathrm{kg}}{\mathrm{m \cdot s}}$$

$$\boxed{1\frac{\mathrm{g}}{\mathrm{cm \cdot s}}}$$

P3.17: Referring to the description in P3.16, and given that the viscosity of a certain engine oil is 0.25 kg/(m · s), determine the value in the units (a) poise and (b) slug/(ft · s).

Solution:

(a) Express viscosity in terms of the derived unit (N · s)/m^2:

$$0.25\ \frac{\text{kg}}{\text{m}\cdot\text{s}} = 0.25\ \frac{\text{kg}\cdot\text{m}}{\text{m}^2\cdot\text{s}} = 0.25\frac{\left(\text{kg}\cdot\text{m/s}^2\right)\cdot\text{s}}{\text{m}^2} = 0.25\frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

Use the definition of poise P from P3.16:

$$\left(0.25\ \frac{\text{N}\cdot\text{s}}{\text{m}^2}\right)\left(10\ \frac{\text{P}}{(\text{N}\cdot\text{s})/\text{m}^2}\right) = 2.5\ \text{P}$$

$$\boxed{2.5\ \text{P}}$$

(b) Use conversion factors from Table 3.6:

$$\left(0.25\ \frac{\text{kg}}{\text{m}\cdot\text{s}}\right)\left(0.0685\ \frac{\text{slug}}{\text{kg}}\right)\left(0.3048\ \frac{\text{m}}{\text{ft}}\right) = 0.0052\frac{\text{slug}}{\text{ft}\cdot\text{s}}$$

$$\boxed{0.0052\frac{\text{slug}}{\text{ft}\cdot\text{s}}}$$

P3.18: Referring to the description in P3.16, if the viscosity of water is 0.01 poise, determine the value in terms of the units (a) slug/(ft · s) and (b) kg/(m · s).

Solution:

(a) Use conversion factors from Table 3.6:

$$\left(0.001\ \frac{\mathrm{kg}}{\mathrm{m\cdot s}}\right)\left(0.0685\ \frac{\mathrm{slug}}{\mathrm{kg}}\right)\left(0.3048\ \frac{\mathrm{m}}{\mathrm{ft}}\right)=2.088\times10^{-5}\ \frac{\mathrm{slug}}{\mathrm{ft\cdot s}}$$

$$\boxed{2.088\times10^{-5}\ \frac{\mathrm{slug}}{\mathrm{ft\cdot s}}}$$

(b) Express 0.01 P in terms of SI base units:

$$(0.01\,\mathrm{P})\left(0.1\ \frac{(\mathrm{N\cdot s})/\mathrm{m}^2}{\mathrm{P}}\right)=0.001\frac{\mathrm{N\cdot s}}{\mathrm{m}^2}=0.001\frac{\mathrm{kg}}{\mathrm{m\cdot s}}$$

$$\boxed{0.001\frac{\mathrm{kg}}{\mathrm{m\cdot s}}}$$

P3.19: The fuel efficiency of an aircraft's jet engines is described by the *thrust-specific fuel consumption* (TSFC). The TSFC measures the rate of fuel consumption (mass of fuel burned per unit time) relative to the thrust (force) that the engine produces. In that manner, even if an engine consumes more fuel per unit time than a second engine, it is not necessarily more inefficient if it also produces more thrust to power the plane. The TSFC for an early hydrogen-fueled jet engine was 0.082 (kg/h)/N. Express that value in the USCS units of (slug/s)/lb.

Solution:
Use SI to USCS conversion factors from Table 3.6:

$$\left(0.082\ \frac{\text{kg/hr}}{\text{N}}\right)\left(0.0685\ \frac{\text{slug}}{\text{kg}}\right)\left(2.778\times10^{-4}\ \frac{\text{hr}}{\text{s}}\right)\left(4.448\ \frac{\text{N}}{\text{lb}}\right)=6.94\times10^{-6}\ \frac{\text{slug/s}}{\text{lb}}$$

$$\boxed{6.94\times10^{-6}\ \frac{\text{slug/s}}{\text{lb}}}$$

P3.20: An automobile engine is advertised as producing a peak power of 118 hp (at an engine speed of 4000 rpm) and a peak torque of 186 ft · lb (at 2500 rpm). Express those performance ratings in the SI units of kW and N · m.

Solution:
For the power, apply the hp to kW conversion factor from Table 3.6:

$$(118\,\text{hp})\left(0.7457\ \frac{\text{kW}}{\text{hp}}\right) = 87.99\,\text{kW}$$

$$\boxed{87.99\text{ kW}}$$

For the torque, apply USCS to SI conversion factors from Table 3.6:

$$(186\,\text{ft}\cdot\text{lb})\left(4.448\ \frac{\text{N}}{\text{lb}}\right)\left(0.3048\ \frac{\text{m}}{\text{ft}}\right) = 252\,\text{N}\cdot\text{m}$$

$$\boxed{252\,\text{N}\cdot\text{m}}$$

P3.21: From Example 3.6, express the sideways deflection of the tip in the units of mils (defined in Table 3.5) when the various quantities are instead known in the USCS. Use the values F = 75 lb, L = 3 in., d = 3/16 in., and $E = 30 \times 10^6$ psi.

Solution:
Evaluate the deflection equation using numerical values that are dimensionally consistent:

$$\Delta x = \frac{64FL^3}{3\pi Ed^4} = \frac{64(75\text{ lb})(3\text{ in.})^3}{3\pi(30\times10^6\text{ lb/in}^2)(0.1875\text{ in.})^4} = 0.371\text{ in.}$$

Apply the definition of mil from Table 3.5:

1 mil= 0.001 m

$\boxed{\text{371 mils}}$

P3.22: Heat Q, which has the SI unit of joule (J), is the quantity in mechanical engineering that describes the transit of energy from one location to another. The equation for the flow of heat during the time interval Δt through an insulated wall is

$$Q = \frac{\kappa A \Delta t}{L}\left(T_{\mathrm{h}} - T_{\mathrm{l}}\right)$$

where κ is the thermal conductivity of the material from which the wall is made, A and L are the wall's area and thickness, and T_{h} - T_{l} is the difference (in degrees Celsius) between the high- and low-temperature sides of the wall. By using the principle of dimensional consistency, what is the correct dimension for thermal conductivity in the SI? The lowercase Greek character kappa (κ) is a conventional mathematical symbol used for thermal conductivity. Appendix A summarizes the names and symbols of Greek letters.

Solution:

Let [κ] denote the SI units for thermal conductivity. Apply the principle of dimensional consistency and the definition of watt in Table 3.2:

$$\mathrm{J} = \frac{[\kappa]\cdot \mathrm{m}^2 \cdot \mathrm{s} \cdot {}^\circ\mathrm{C}}{\mathrm{m}}$$

$$[\kappa] = \left(\frac{\mathrm{J}}{\mathrm{s}}\right)\frac{1}{\mathrm{m}\cdot{}^\circ\mathrm{C}} = \frac{\mathrm{W}}{\mathrm{m}\cdot{}^\circ\mathrm{C}}$$

$$\boxed{\frac{\mathrm{W}}{\mathrm{m}\cdot{}^\circ\mathrm{C}}}$$

P3.23: Convection is the process by which warm air rises and cooler air falls. The *Prandtl number* (*Pr*) is used when mechanical engineers analyze certain heat transfer and convection processes. It is defined by the equation

$$Pr = \frac{\mu c_{\mathrm{p}}}{\kappa}$$

where c_{p} is a property of the fluid called the specific heat having the SI unit kJ /(kg · °C); μ is the viscosity as discussed in Problem P3.16; and κ is the thermal conductivity as discussed in Problem P3.22. Show that *Pr* is a dimensionless number. The lowercase Greek characters mu (μ) and kappa (κ) are conventional mathematical symbols used for viscosity and thermal conductivity. Appendix A summarizes the names and symbols of Greek letters.

Solution:
Let [*Pr*] denote the units for Prandtl number. In the SI, a unit for viscosity is N · s/m^2, and from the solution to P3.16, the units for thermal conductivity are W/(m · °C). Apply the principle of dimensional consistency and the definition of watt from Table 3.2:

$$[Pr] = \frac{\left(\mathrm{kJ}/(\mathrm{kg}\cdot{}^\circ\mathrm{C})\right)\left(\mathrm{N}\cdot\mathrm{s}/\mathrm{m}^2\right)}{\left[\mathrm{W}/(\mathrm{m}\cdot{}^\circ\mathrm{C})\right]} = \frac{\mathrm{kJ}\cdot\mathrm{N}\cdot\mathrm{s}\cdot\mathrm{m}\cdot{}^\circ\mathrm{C}}{\mathrm{W}\cdot\mathrm{kg}\cdot{}^\circ\mathrm{C}\cdot\mathrm{m}^2} = \frac{\mathrm{kJ}\cdot\mathrm{N}\cdot\mathrm{s}^2}{\mathrm{W}\cdot\mathrm{kg}\cdot\mathrm{m}\cdot\mathrm{s}}$$

$$\boxed{= \left(\frac{\mathrm{kJ}}{\mathrm{s}}\right)\left(\frac{1}{\mathrm{W}}\right)(\mathrm{N})\left(\frac{1}{\mathrm{N}}\right) = \frac{\mathrm{kW}}{\mathrm{W}}}$$

which has no units but does contain a dimensionless factor of 1000 because of the "kilo" prefix.

P3.24: When fluid flows over a surface, the Reynolds number will output whether the flow is laminar (smooth), transitional, or turbulent. Verify that the Reynolds number is dimensionless using the SI. The Reynolds number is expressed as

$$R = \frac{\rho V D}{\mu}$$

where ρ is the density of the fluid, V is the free stream fluid velocity, D is the characteristic length of the surface, and μ is the fluid viscosity. The units of fluid viscosity are kg/(m·s).

<u>Solution</u>:
Let $[R]$ denote the units for Reynolds number. In the SI, a unit for density is kg/m^3, and a unit for velocity is m/s. Apply the principle of dimensional consistency:

$$[R] = \frac{(\mathrm{kg/m^3})(\mathrm{m/s})(\mathrm{m})}{(\mathrm{kg/m \cdot s})} = \frac{\mathrm{kg \cdot m \cdot m \cdot m \cdot s}}{\mathrm{kg \cdot m^3 \cdot s}} \boxed{= \frac{\mathrm{kg \cdot m^3 \cdot s}}{\mathrm{kg \cdot m^3 \cdot s}}}$$

which has no units.

P3.25: Determine which one of the following equations is dimensionally consistent.

$$F = \frac{1}{2} m \Delta x^2 , \quad F\Delta V = \frac{1}{2} m \Delta x^2 , \quad F\Delta x = \frac{1}{2} m \Delta V^2 , \quad F\Delta t = \Delta V , \quad F\Delta V = 2m\Delta t^2$$

where F is force, m is mass, x is distance, V is velocity, and t is time.

Solution:

Apply the principle of dimensional consistency using SI units from Table 3.2:

$$F = \frac{1}{2} m \Delta x^2$$

$$\frac{\text{kg} \cdot \text{m}}{\text{s}^2} = \text{kg} \cdot \text{m}^2$$ This is not dimensionally consistent.

$$F\Delta V = \frac{1}{2} m \Delta x^2$$

$$\left(\frac{\text{kg} \cdot \text{m}}{\text{s}^2}\right)\left(\frac{\text{m}}{\text{s}}\right) = \text{kg} \cdot \text{m}^2$$ This is not dimensionally consistent.

$$F\Delta x = \frac{1}{2} m \Delta V^2$$

$$\left(\frac{\text{kg} \cdot \text{m}}{\text{s}^2}\right)\text{m} = \text{kg} \cdot \left(\frac{\text{m}}{\text{s}}\right)^2$$

$$\boxed{\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} = \text{kg} \cdot \left(\frac{\text{m}}{\text{s}}\right)^2 \quad \textbf{This is dimensionally consistent.}}$$

$$F\Delta t = \Delta V$$

$$\left(\frac{\text{kg} \cdot \text{m}}{\text{s}^2}\right)\text{s} = \frac{\text{m}}{\text{s}}$$ This is not dimensionally consistent.

$$F\Delta V = 2m\Delta t^2$$

$$\left(\frac{\text{kg} \cdot \text{m}}{\text{s}^2}\right)\left(\frac{\text{m}}{\text{s}}\right) = \text{kg} \cdot \text{s}^2$$ This is not dimensionally consistent.

P3.26: Referring to Problem P3.23 and Table 3.5, if the units for c_p and μ are Btu/(slug·°F) and slug/(ft·h), respectively, what must be the USCS units of thermal conductivity in the definition of *Pr*?

Solution:
Solve for the thermal conductivity:

$$Pr = \frac{\mu c_p}{\kappa}$$

$$\kappa = \frac{\mu c_p}{Pr}$$

Let [κ] denote the units for the thermal conductivity.

$$[\kappa] = \frac{(\text{slug}/(\text{ft}\cdot\text{h}))(\text{Btu}/(\text{slug}\cdot{}^\circ\text{F}))}{-} = \frac{\text{slug}\cdot\text{Btu}}{\text{ft}\cdot\text{h}\cdot\text{slug}\cdot{}^\circ\text{F}} = \frac{\text{Btu}}{\text{ft}\cdot\text{h}\cdot{}^\circ\text{F}}$$

$$\boxed{\frac{\text{Btu}}{\text{ft}\cdot\text{h}\cdot{}^\circ\text{F}}}$$

P3.27: Some scientists believe that the collision of one or more large asteroids with the Earth was responsible for the extinction of the dinosaurs. The unit of kiloton is used to describe the energy released during large explosions. It was originally defined as the explosive capability of 1000 tons of trinitrotoluene (TNT) high explosive. Because that expression can be imprecise depending on the explosive's exact chemical composition, the kiloton subsequently has been redefined as the equivalent of 4.186×10^{12} J. In the units of kiloton, calculate the kinetic energy of an asteroid that has the size (box–shaped, 13 × 13 × 33 km) and composition (density, 2.4 g/cm^3) of our solar system's asteroid Eros. Kinetic energy is defined by

$$U_k = \frac{1}{2}mv^2$$

where m is the object's mass and v is its speed. Objects passing through the inner solar system generally have speeds in the range of 20 km/s.

Approach:
Calculate the volume of the asteroid and convert it to cm^3 using Table 3.3. Then calculate the mass of the asteroid using the volume and density. Convert the mass and velocity to appropriate units using Table 3.3. Then, calculate the kinetic energy.

Solution:
Volume:

$$(13 \text{ km})\,(13 \text{ km})\,(33\text{km}) = 5.577\times10^3 \text{ km}^3$$

$$= \left(5.577\times10^3 \text{ km}^3\right)\left(10^5 \frac{\text{cm}}{\text{km}}\right)^3$$

$$= 5.577 \text{ x } 10^{18} \text{ cm}^3$$

Mass:

$$\left(5.577\times10^{18} \text{ cm}^3\right)\left(2.4\frac{\text{g}}{\text{cm}^3}\right) = 1.338\times10^{19} \text{ g}$$

$$= 1.338\times10^{16} \text{ kg}$$

Speed:

$$\left(20\frac{\text{km}}{\text{s}}\right)\left(1000\frac{\text{m}}{\text{km}}\right) = 2\times10^4 \frac{\text{m}}{\text{s}}$$

Kinetic energy:

$$\frac{1}{2}\left(1.338\times10^{16} \text{ kg}\right)\left(2\times10^4 \frac{\text{m}}{\text{s}}\right)^2 = 2.68\times10^{24} \frac{\text{kg}\cdot\text{m}^2}{\text{s}^2}$$

$$= 2.68 \text{ x } 10^{24} \text{ N}\cdot\text{m}$$

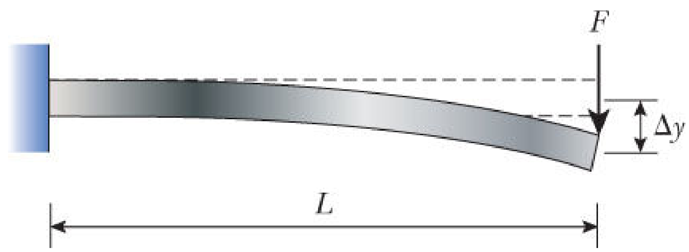
$$= 2.68 \text{ x } 10^{24} \text{ J}$$

$$= \left(2.68\times10^{24} \text{ J}\right)\left(\frac{1}{4.186\times10^{12}}\frac{\text{kiloton}}{\text{J}}\right)$$

$$= \boxed{6.4 \times 10^{11} \text{ kiloton}}$$

Discussion:
This kind of energy is larger than the most powerful nuclear weapons in the world, indicating just how destructive a collision with this size asteroid would be.

P3.28: A structure known as a cantilever beam is clamped at one end but free at the other, analogous to a diving board that supports a swimmer standing on it. Using the following procedure, conduct an experiment to measure how the cantilever beam bends. In your answer, report only the significant digits that you know reliably.



(a) Make a small tabletop test stand to measure the deflection of a plastic drinking straw (your cantilever beam) that bends as a force F is applied to the free end. Push one end of the straw over the end of a pencil, and then clamp the pencil to a desk or table. You can also use a ruler, chopstick, or a similar component as the cantilever beam itself. Sketch and describe your apparatus, and measure the length L. (b) Apply weights to the end of the cantilever beam, and measure the tip's deflection Δy using a ruler. Repeat the measurement with at least a half dozen different weights to fully describe the beam's force-deflection relationship. Penny coins can be used as weights; one penny weighs approximately 30 mN. Make a table to present your data. (c) Next draw a graph of the data. Show tip deflection on the abscissa and weight on the ordinate, and be sure to label the axes with the units for those variables. (d) Draw a best-fit line through the data points on your graph. In principle, the deflection of the tip should be proportional to the applied force. Do you find this to be the case? The slope of the line is called the stiffness. Express the stiffness of the cantilever beam either in the units lb/in. or N/m.

Solution:

A 1.6 mm diameter steel rod was used as the cantilever beam, and it was clamped in a vise as shown in Figure 1. Small weights were held in a plastic bag attached to the beam's free end. The distance between the beam's tip and the surface of the table was measured for each weight, and the data were recorded in Table 1. Beams of three different lengths were tested. Figure 2 shows a graph of force versus tip deflection, H–h, for the 20 cm beam length. The deflection is proportional to the force. The slope of the line is 22.3 mN/mm, or 22.3 N/m.

Figure 1: Test stand.

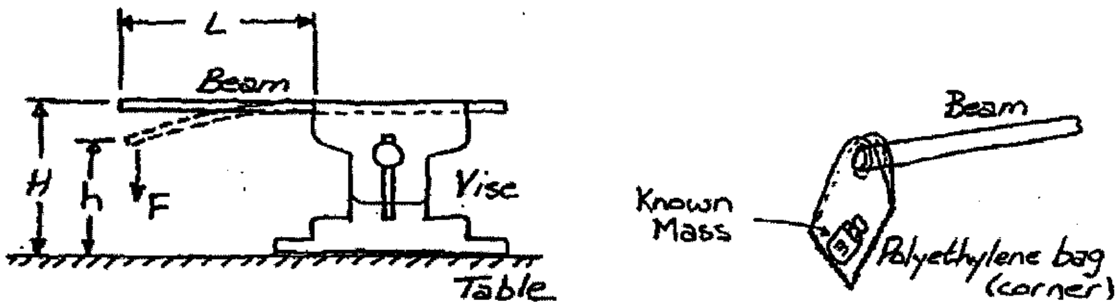
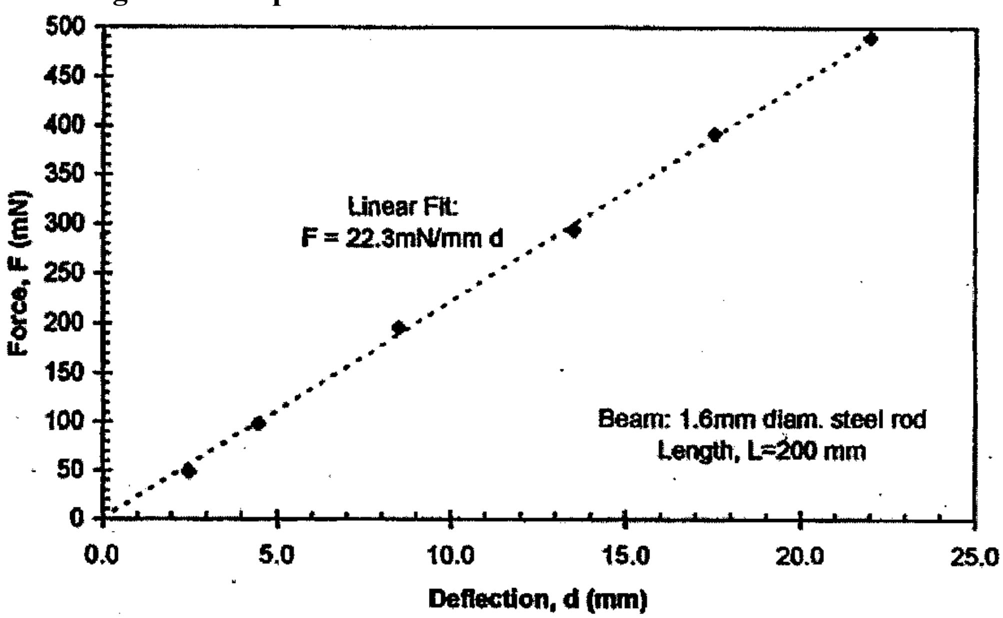


Table 1: Measured tip deflection.

Measured Data				Calculated Results	
Beam Length L (cm)	Mass m (g)	Undeflected Height H (cm)	Deflected Height h (cm)	Force F (mN)	Deflection d (mm)
10	20	13.95	13.80	196	1.5
10	40	13.95	13.65	392	3.0
20	5	13.95	13.70	49	2.5
20	10	13.95	13.50	98	4.5
20	20	13.95	13.10	196	8.5
20	30	13.95	12.60	294	13.5
20	40	13.95	12.20	392	17.5
20	50	13.95	11.75	491	22.0
30	20	13.95	10.90	196	30.5
30	40	13.95	8.10	392	58.5

Figure 2: Graph of force versus deflection for the 20 cm beam.



P3.29: Perform measurements as described in P3.28 for cantilever beams of several different lengths. Can you show experimentally that, for a given force F, the deflection of the cantilever's tip is proportional to the cube of its length? As in P3.28, present your results in a table and a graph, and report only those significant digits that you know reliably.

Solution:
A 1.6 mm-diameter steel rod was used as the cantilever beam, and it was clamped in a vise as shown in Figure 1. Small weights were held in a plastic bag attached to the beam's free end. The distance between the beam's tip and the surface of the table was measured for each weight, and the data were recorded in Table 1. Beams of three different lengths were tested. Figure 2 shows a graph of tip deflection, $H–h$, versus beam length for tip forces of 196 mN and 392 mN. The curve fit indicates that the deflection is proportional to the cube of the length in each case.

Figure 1: Test stand.

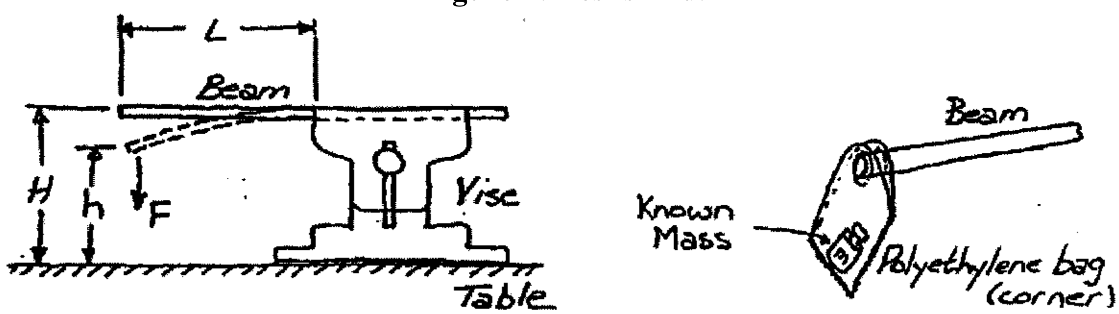
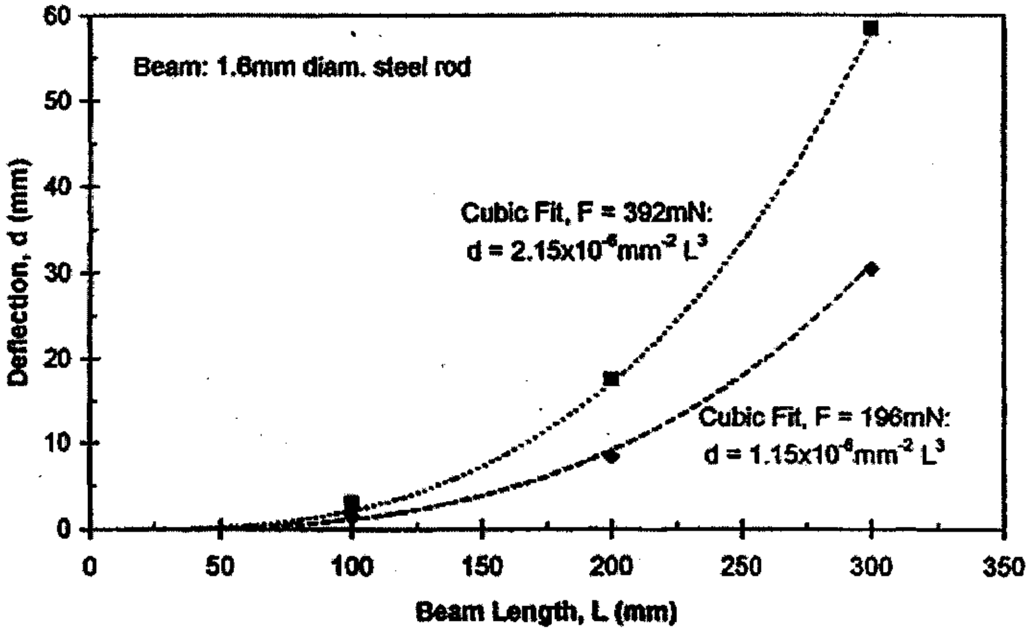


Table 1: Measured tip deflection.

Measured Data				Calculated Results	
Beam Length L (cm)	Mass m (g)	Undeflected Height H (cm)	Deflected Height h (cm)	Force F (mN)	Deflection d (mm)
10	20	13.95	13.80	196	1.5
10	40	13.95	13.65	392	3.0
20	5	13.95	13.70	49	2.5
20	10	13.95	13.50	98	4.5
20	20	13.95	13.10	196	8.5
20	30	13.95	12.60	294	13.5
20	40	13.95	12.20	392	17.5
20	50	13.95	11.75	491	22.0
30	20	13.95	10.90	196	30.5
30	40	13.95	8.10	392	58.5

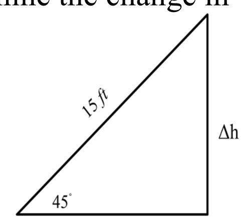
Figure 2: Graph of deflection versus beam length for two different applied forces.



P3.30: Using SI units, calculate the change in potential energy of a 150-lb person riding the 15 ft long uphill portion of a water slide (as described in P3.10). The change in potential energy is defined as $mg\Delta h$ where Δh is the change in vertical height. The uphill portion of the slide is set at an angle of 45˚.

Approach:
First determine the change in vertical height the rider experiences from the bottom to the top of the uphill portion of the slide. Assume a simple triangular representation of the uphill portion of the slide. Also, the mass of the rider is determined using gravitational acceleration. The height and mass are both converted to SI units using appropriate conversion factors, 1 ft = 0.3048 m and 1 slug = 14.5939 kg. Then, the change in potential energy can be calculated.

Solution:
Determine the change in vertical height the rider experiences.



$$\Delta h = \sin(45°) \cdot 15\,\text{ft} = 10.6\,\text{ft}$$

Convert the length to SI using the factor from Table 3.6:

1 ft = 0.3048 m

$$\Delta h = 10.6\,\text{ft}\left(0.3048\frac{\text{m}}{\text{ft}}\right) = 3.23\,\text{m}$$

Calculate the mass using gravitational acceleration in USCS:

$$m = \frac{w}{g} = \frac{150\,\text{lb}}{32.2\,{}^{\text{ft}}\!/_{\text{s}^2}}$$

m = 4.66 slugs

Convert to SI using the factor from Table 3.6:

1 slug = 14.5939 kg

$$m = (4.66\,\text{slug})\left(14.59\ \frac{\text{kg}}{\text{slug}}\right)$$

m = 68.0 kg

Calculate the change in potential energy

$$mg\,\Delta h = (68.0\text{ kg})\left(9.81\,\frac{\text{m}}{\text{s}^2}\right)(3.23\text{ m}) = 2154.7\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\cdot\text{m} = 2154.7\ \text{N}\cdot\text{m} = 2154.7\ \text{J}$$

$\boxed{2154.7\,\text{J}}$

Discussion:
This represents the amount of energy to propel the rider up the slide. The actual amount of energy needed would be higher as there would be energy losses in the system, including friction between the rider and the slide. To get a sense for the amount of energy this is, approximately one Joule of energy is required to lift an apple a vertical distance of one meter.

P3.31: Using the speed given in P3.10, calculate the power required to move the rider in P3.30 up the incline portion of the water slide, where power is the change in energy divided by the time required to traverse the uphill portion.

Approach:
Using the relationship, Power = ΔEnergy/ΔTime, calculate the power required. The change in energy is taken from P3.30 and the change in time is found using the rider's velocity and the distance they travel (ΔTime = Distance/Velocity). Assume the rider's velocity is constant throughout the uphill portion and that there are no friction losses.

Solution:

$$\Delta E = mg\Delta h = 2154.7\ \text{J}\ \ \text{(from P3.30)}$$

Convert the velocity to SI using the factor from Table 3.6:

$$1\cdot\text{ft} = 0.3048\ \text{m}$$

$$19\frac{\text{ft}}{\text{s}}\left(0.3048\frac{\text{m}}{\text{ft}}\right) = 5.79\frac{\text{m}}{\text{s}}$$

Convert the distance the rider travels using the factor from Table 3.6

$$1\cdot\text{ft} = 0.3048\ \text{m}$$

$$\text{d} = 15\ \text{ft}\left(0.3048\frac{\text{m}}{\text{ft}}\right) = 4.57\ \text{m}$$

Calculate the time it takes the rider to move up the hill:

$$\Delta t = \frac{d}{V} = \frac{4.57\ \text{m}}{5.79\ {}^{\text{m}}\!/\!_{\text{s}}} = 0.79\ \text{s}$$

Calculate the power required

$$\text{Power} = \frac{\Delta E}{\Delta t} = \frac{2154.7\ \text{J}}{0.79\ \text{s}} = 2727.5\ \text{W}$$

$$\boxed{2727.5\ \text{W}}$$

Discussion:
This represents the amount of power to propel the rider up the slide at the given speed. The actual amount of power needed would be higher as there would be energy losses in the system, including friction between the rider and the slide. If a higher speed is desired, more power would be required.

Problems P3.32-P3.40

For these estimation problems, students should set up the problems using the Approach-Solution-Discussion model as presented in the chapter. In the Approach phase, it will be very important to make appropriate assumptions concerning the problem and model. In the Solution phase, it will be critical to develop the correct set of equations to match the assumptions. In the Discussion phase, it is essential to consider the reasonableness of the solution, the relevance of the assumptions, and any conclusions one could draw from the solution.

P3.41: The modulus of elasticity, modulus of rigidity, Poisson's ratio, and the unit weight for various materials are shown below. The data is given as Material; Modulus of Elasticity, *E* (Mpsi & GPa); Modulus of Rigidity, *G* (Mpsi & GPa); Poisson's Ratio; and Unit Weight (lb/in^3, lb/ft^3, kN/m^3). Prepare a single table that captures this technical data in a professional and effective manner.

Aluminum alloys	10.3	71.0	3.8	26.2	0.334	0.098	169	26.6
Beryllium copper	18.0	124.0	7.0	48.3	0.285	0.297	513	80.6
Brass	15.4	106.0	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30.0	207.0	11.5	79.3	0.292	0.282	487	76.5
Cast iron, grey	14.5	100.0	6.0	41.4	0.211	0.260	450	70.6
Copper	17.2	119.0	6.49	44.7	0.326	0.322	556	87.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.350	0.065	112	17.6
Molybdenum	48.0	331.0	17.0	117.0	0.307	0.368	636	100.0
Nickel silver	18.5	127.0	7.0	48.3	0.322	0.316	546	85.8
Nickel steel	30.0	207.0	11.5	79.3	0.291	0.280	484	76.0
Phosphor bronze	16.1	111.0	6.0	41.4	0.349	0.295	510	80.1
Stainless steel	27.6	190.0	10.6	73.1	0.305	0.280	484	76.0

Solution:

A possible layout of the table is shown in Table 1. The columns should be clearly labeled with units and the data should be easy to read and understand.

Table 1. Data for Various Materials

Material	Modulus of Elasticity		Modulus of Rigidity		Poisson's	Unit Weight		
	(Mpsi)	(Gpa)	(Mpsi)	(Gpa)	Ratio	(lb/in^3)	(lb/ft^3)	(kN/m^3)
Aluminum alloys	10.3	71	3.8	26.2	0.334	0.098	169	26.6
Beryllium copper	18	124	7	48.3	0.285	0.297	513	80.6
Brass	15.4	106	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30	207	11.5	79.3	0.292	0.282	487	76.5
Cast Iron, gray	14.5	100	6	41.4	0.211	0.26	450	70.6
Copper	17.2	119	6.49	44.7	0.326	0.322	556	87.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.35	0.065	112	17.6
Molybdenum	48	331	17	117	0.307	0.368	636	100
Nickel silver	18.5	127	7	48.3	0.322	0.316	546	85.8
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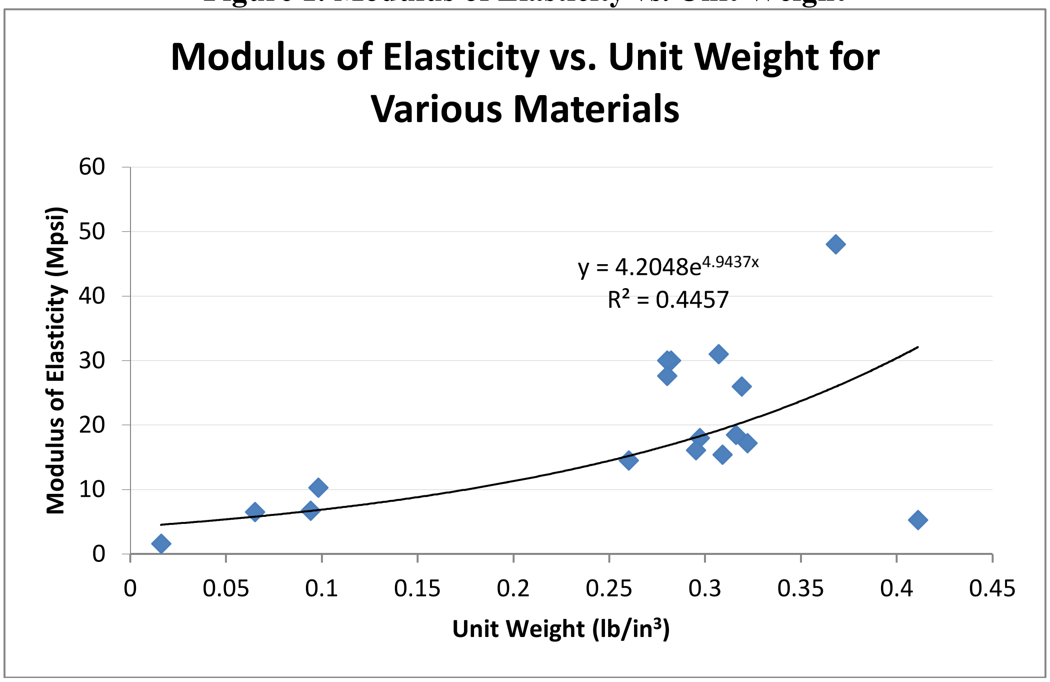
Phosphor bronze	16.1	111	6	41.4	0.349	0.295	510	80.1
Stainless steel	27.6	190	10.6	73.1	0.305	0.28	484	76

P3.42: For the data in P3.41, prepare a graph that charts the relationship between the modulus of elasticity (y-axis) and unit weight (x-axis) using the USCS unit system data. Explain the resulting trend, including a physical explanation of the trend, noting any deviations from the trend.

Solution:
A possible graph of the data is shown in Figure 1.

Figure 1. Modulus of Elasticity vs. Unit Weight



Trend observations could include:

- The general trend of an increasing Modulus of Elasticity as Unit Weight increases. They could explain this both from the data and a physical explanation of the materials in the data (e.g., in general, the denser the material, the harder it will be to deform). A trend line helps to visualize the trend. An exponential curve is shown in Figure 1.
- Two significant deviations exist on the plot:
  - The bottom point on the right is lead, which indicates that even though lead is extremely dense and therefore heavy, its Modulus of Elasticity is very low. Lead is a unique material in this way and as a result is used for applications that don't have a lot of force application. It is used for reliability, length of life, and thermal applications
  - The top point on the right is Molybdenum, which is known to be dense and very strong. It is used in high strength steels as a result, and is used in high temperature applications.
- The chart needs to look professional with clear axes labels, and USCS units.

P3.43*-P3.45*

These estimation problems are very open-ended and will be driven largely by the assumptions made by the students. The problems are all complex enough so that they could be assigned as group problems. The problems could also be administered in a flipped classroom environment as a way for the student groups to wrestle with the challenges of making technical estimates under the supervision of the instructor and teaching assistants.

Regardless of how the problems are administered, the students should set up the problem using the Approach-Solution-Discussion model as presented in the chapter. In the Approach phase, it will be critical for the students to make appropriate assumptions concerning the problem and model, especially for these open problems. In the Solution phase, it will be important to develop a valid set of equations to match the assumptions. In the Discussion phase, it is essential to consider the reasonableness of the solution, the relevance of the assumptions, and any conclusions one could draw from the solution.

For these types of problems, it is always interesting to track the maximum and minimum estimates for each problem from all the students/groups and report these to the class when the problems are returned or discussed. Discussing the sets of assumptions that led to the maximum and minimum answers typically facilitates an effective dialogue regarding better and worse sets of assumptions, especially when the answers differ by orders of magnitude. Reporting to the class the average and standard deviation of the estimated answers naturally reveals some interesting insights as well.