

Preface to the Instructor

With the exception of some “open-ended” problems, this *Instructor’s Solutions Manual* contains a solution to each of the numerical problems in the textbook *An Introduction to Mechanical Engineering* (second edition). The description and style of these solutions (writing a brief approach, keeping track of units, making sketches, staying organized and so forth) are intended to guide students with respect to the formatting and presentation of their own work.

In addition, the compact disk accompanying this manual includes electronic versions of all photographs and figures in the textbook, and an electronic version of this manual. My intention is that these resources will be useful to instructors in two ways. First, instructors are able to easily import photographs, drawings, and other art from the textbook into their own handouts and lectures without the burden of having to photocopy or scan from the textbook itself. Second, since many courses today have companion web sites, instructors can use the compact disk to post electronic versions of solutions to their own problem sets.

I hope that you will find this *Instructor’s Solutions Manual* to be a useful resource for your own teaching of mechanical engineering courses at the freshman and sophomore levels. As always, if you should have any comments on the textbook or manual, I would certainly appreciate hearing from you.

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Problem 2.1: Express your weight in the units *lb* and *N*, and your mass in the units *slug* and *kg*.

Solution:

Let w and m represent weight and mass.

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

Convert to SI using the factor from Table 2.6:

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

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

Calculate mass using gravitational acceleration in USCS:

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

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

Convert to SI using the factor from Table 2.6:

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

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

Problem 2.2: Express your height in the units *in*, *ft*, and *m*.

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 2.6:

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

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

Problem 2.3: The solar power transmitted to the ground is 0.6 kW/m^2 . Convert this quantity to the dimensions of hp/ft^2 .

Solution:

Convert to USCS using the factors from Table 2.6.

$$\left(0.6 \frac{\text{kW}}{\text{m}^2}\right) \left(9.2903 \times 10^{-2} \frac{\text{m}^2}{\text{ft}^2}\right) \left(1.341 \frac{\text{hp}}{\text{kW}}\right) = 7.475 \times 10^{-2} \frac{\text{hp}}{\text{ft}^2}$$

$$\boxed{7.475 \times 10^{-2} \frac{\text{hp}}{\text{ft}^2}}$$

Problem 2.4: One U.S. gallon is equivalent to 0.1337 ft^3 , one foot is equivalent to 0.3048 m , and 1000 liters is 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 2.2, 2.5, and 2.6:

$$1 \text{ gal} = 0.1337 \text{ ft}^3$$

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

$$1000 \text{ L} = 1 \text{ m}^3$$

Convert gal to L using those factors:

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

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

Problem 2.5: 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 2.6:

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

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

Problem 2.6: (a) How many horsepower does a 100 W household light bulb 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 2.3. Convert from kW to hp using the factor from Table 2.6:

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

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

b) Convert from hp to kW using factor from Table 2.6:

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

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

Problem 2.7: 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/s²*.

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/s²*. By using $m = w/g$

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

From Table 2.5, the dimension is equivalent to the derived unit of slug.

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

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

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

We double check by using the definition in Table 2.5

$$m = (408 \text{ lbm}) \left(3.1081 \times 10^{-2} \frac{\text{slugs}}{\text{lbm}} \right) = 12.67 \text{ slugs}$$

b) Since the gravitational acceleration on Mars is only 12.3 *ft/s²*, the weight becomes

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

The dimension is the dimensionally consistent group that is the same as *lb*.

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

It would not be correct to calculate weight as the product of 408 *lbm* and 12.3 *ft/s²*, since the units would not be dimensionally consistent.

Problem 2.8: Calculate various fuel quantities for Flight 143. The plane already had 7,682 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 take-off. (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 percent would the plane have been under-fueled 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:

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

$$\boxed{46.1\%}$$

Problem 2.9: 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 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*:

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

$$\boxed{6,336 \text{ psf}}$$

where the abbreviation *psf* stands for pounds-per-square-foot.

b) Use a conversion factor from Table 2.6 and the SI prefix from Table 2.3:

$$\left(44 \frac{lb}{in^2}\right) \left(6,895 \frac{Pa}{psi}\right) = 3.034 \times 10^5 Pa = 303.4 kPa$$

$$\boxed{303.4 kPa}$$

Problem 2.10: 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 $(\text{ft} \cdot \text{lb/s})/\text{ft}^2$.

Solution:

Use conversion factors from Table 2.6:

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

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

Problem 2.11: 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 a 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 $1 \text{ poise} = 0.1 \text{ (N} \cdot \text{s)/m}^2$. Show that 1 poise is also equivalent to $1 \text{ g/(cm} \cdot \text{s)}$.

Solution:

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

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

Apply SI prefixes from Table 2.3:

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

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

Problem 2.12: Referring to the description in Problem 2.11, and given that the viscosity of a certain engine oil is $0.25 \text{ kg}/(\text{m} \cdot \text{s})$, determine the value in the units (a) *poise*, and (b) *slug/ft · s*.

Solution:

a) Express viscosity in terms of the derived unit $(\text{N} \cdot \text{s})/\text{m}^2$:

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

Use the definition of poise P from Problem 2.11:

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

$$\boxed{2.5 P}$$

b) Use conversion factors from Table 2.6:

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

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

Problem 2.13: Referring to the description in Problem 2.11, 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:

Express 0.01 *P* in terms of SI base units:

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

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

Use conversion factors from Table 2.6:

$$\left(0.001 \frac{kg}{m \cdot s} \right) \left(0.0685 \frac{slug}{kg} \right) \left(0.3048 \frac{m}{ft} \right) = 2.088 \times 10^{-5} \frac{slug}{ft \cdot s}$$

$$\boxed{2.088 \times 10^{-5} \frac{slug}{ft \cdot s}}$$

Problem 2.14: The fuel efficiency of an aircraft's jet engines is described by the thrust-specific fuel consumption, or 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, just because an engine might consume more fuel per unit time than a second engine, it would not necessarily be more inefficient if it also produced 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 $(\text{slug/s})/\text{lb}$.

Solution:

Use SI to USCS conversion factors from Table 2.6:

$$\left(0.082 \frac{\text{kg/hr}}{\text{N}}\right) \left(0.0685 \frac{\text{slug}}{\text{kg}}\right) \left(2.778 \times 10^{-4} \frac{\text{hr}}{\text{s}}\right) \left(4.448 \frac{\text{N}}{\text{lb}}\right) = 6.94 \times 10^{-6} \frac{\text{slug/s}}{\text{lb}}$$

$$\boxed{6.94 \times 10^{-6} \frac{\text{slug/s}}{\text{lb}}}$$

Problem 2.15: 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 2.6:

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

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

For the torque, apply USCS to SI conversion factors from Table 2.6:

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

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

Problem 2.16: For the exercise of Example 2.6, express the sideways deflection of the tip in the units of mils (defined in Table 2.5) when the various quantities are instead known in the USCS. Use the values $F = 75 \text{ lb}$, $L = 3 \text{ in}$, $d = 3/16 \text{ in}$, and $E = 30 \times 10^6 \text{ psi}$.

Solution:

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

$$\Delta x = \frac{64FL^3}{3\pi Ed^4} = \frac{64(75 \text{ lb})(3 \text{ in.})^3}{3\pi (30 \times 10^6 \text{ lb/in.}^2)(0.1875 \text{ in.})^4} = 0.371 \text{ in.}$$

Apply the definition of *mil* from Table 2.5:

$$1 \text{ mil} = 0.001 \text{ in.}$$

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

Problem 2.17: 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

$$Q = \frac{\kappa A \Delta t}{L} (T_h - T_l)$$

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 $[\kappa]$ denote the SI units for thermal conductivity. Apply the principle of dimensional consistency and the definition of *watt* in Table 2.2:

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

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

W
$m \cdot {}^\circ C$

Problem 2.18: 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

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

where c_p is a property of the fluid called the specific heat having the SI unit $\text{kJ}/(\text{kg} \cdot ^\circ\text{C})$; μ is the viscosity as discussed in Problem 2.11; and κ is the thermal conductivity as discussed in Problem 2.17. 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 $[\text{Pr}]$ denote the units for Prandtl number. In the SI, a unit for viscosity is $\text{N} \cdot \text{s}/\text{m}^2$, and from the solution to Problem 2.11, the units for thermal conductivity are $\text{W}/(\text{m} \cdot ^\circ\text{C})$. Apply the principle of dimensional consistency and the definition of *watt* from Table 2.2:

$$\begin{aligned} [\text{Pr}] &= \frac{(\text{kJ}/(\text{kg} \cdot ^\circ\text{C}))(\text{N} \cdot \text{s}/\text{m}^2)}{[\text{W}/(\text{m} \cdot ^\circ\text{C})]} = \frac{\text{kJ} \cdot \text{N} \cdot \text{s} \cdot \text{m} \cdot ^\circ\text{C}}{\text{W} \cdot \text{kg} \cdot ^\circ\text{C} \cdot \text{m}^2} = \frac{\text{kJ} \cdot \text{N} \cdot \text{s}^2}{\text{kg} \cdot \text{m} \cdot \text{s}} \\ &= \left(\frac{\text{kJ}}{\text{s}}\right) \left(\frac{1}{\text{W}}\right) (\text{N}) \left(\frac{1}{\text{N}}\right) = \frac{\text{kW}}{\text{W}} \end{aligned}$$

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

Problem 2.19: Referring to Problem 2.18 and Table 2.5, if the units for c_p and μ are $Btu/(slug \cdot ^\circ F)$ and $slug/(ft \cdot h)$, respectively, what must be the USCS units of thermal conductivity in the definition of Pr ?

Solution:

Apply the principle of dimensional consistency and determine the units for thermal conductivity so that the Prandtl number is dimensionless. Let $[\kappa]$ denote the USCS units for thermal conductivity:

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

$$[\kappa] = \left(\frac{Btu}{slug \cdot ^\circ F} \right) \left(\frac{slug}{ft \cdot hr} \right) = \frac{Btu / hr}{ft \cdot ^\circ F}$$

$$\boxed{\frac{Btu / hr}{ft \cdot ^\circ F}}$$

Problem 2.20: 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 has been subsequently redefined as the equivalent of $4.186 \times 10^{12} J$. In the units of kiloton, calculate the kinetic energy of an asteroid that has the size (box-shaped, $13 \times 13 \times 33 \text{ km}$) and composition (density, 2.4 g/cm^3) of our solar system's asteroid Eros. Kinetic energy is defined by

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

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 .

Solution:

Volume:

$$\begin{aligned} (13 \text{ km})(13 \text{ km})(33 \text{ km}) &= 5.577 \times 10^3 \text{ km}^3 \\ &= \left(5.577 \times 10^3 \text{ km}^3\right) \left(10^5 \frac{\text{cm}}{\text{km}}\right)^3 \\ &= 5.577 \times 10^{18} \text{ cm}^3 \end{aligned}$$

Mass:

$$\begin{aligned} \left(5.577 \times 10^{18} \text{ cm}^3\right) \left(2.4 \frac{\text{g}}{\text{cm}^3}\right) &= 1.338 \times 10^{19} \text{ g} \\ &= 1.338 \times 10^{16} \text{ kg} \end{aligned}$$

Speed:

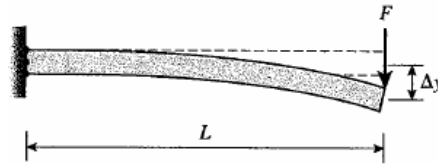
$$\left(20 \frac{\text{km}}{\text{s}}\right) \left(1000 \frac{\text{m}}{\text{km}}\right) = 2 \times 10^4 \frac{\text{m}}{\text{s}}$$

Kinetic energy:

$$\begin{aligned} \frac{1}{2} \left(1.338 \times 10^{16} \text{ kg}\right) \left(2 \times 10^4 \frac{\text{m}}{\text{s}}\right)^2 &= 2.68 \times 10^{24} \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} \\ &= 2.68 \times 10^{24} \text{ N} \cdot \text{m} \\ &= 2.68 \times 10^{24} \text{ J} \\ &= \left(2.68 \times 10^{24} \text{ J}\right) \left(\frac{1}{4.186 \times 10^{12}} \frac{\text{kiloton}}{\text{J}}\right) \\ &= 6.4 \times 10^{11} \text{ kiloton} \end{aligned}$$

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

Problem 2.21: 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 those significant digits that you know reliably.

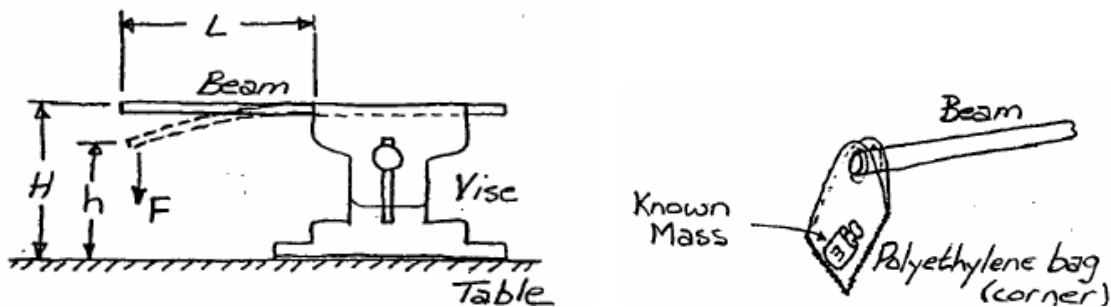


(a) Make a small table top test stand to measure the deflection of a plastic drinking straw (your cantilever beam) that bends as a force F is applied to the free end. Push one end of the straw over the end of a pencil, and then clamp the pencil to a desk or table. You can also use a ruler, chopstick, 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.

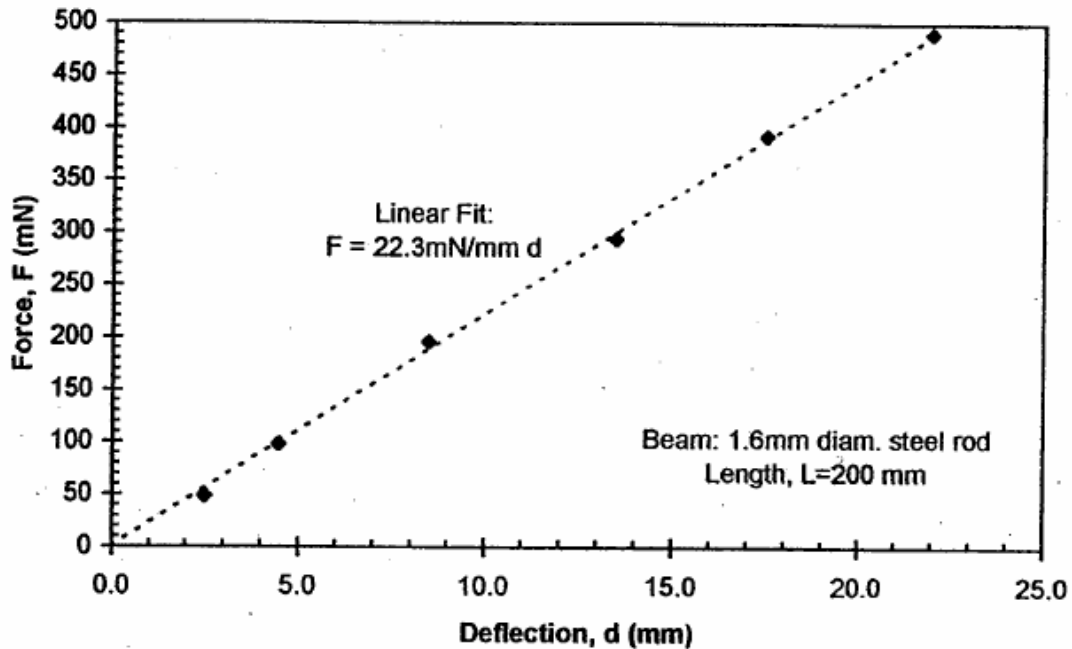


Problem 2.21, continued

Table 1: Measured tip deflection.

Beam Length L (cm)	Measured Data			Calculated Results	
	Mass m (g)	Undeformed Height H (cm)	Deformed 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.



Problem 2.22: Perform measurements as described in Problem 2.21 for cantilever beams of several different lengths. Can you show experimentally that for a give force F , the deflection of the cantilever's tip is proportional to the cube of its length? As in Problem 2.21, 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.

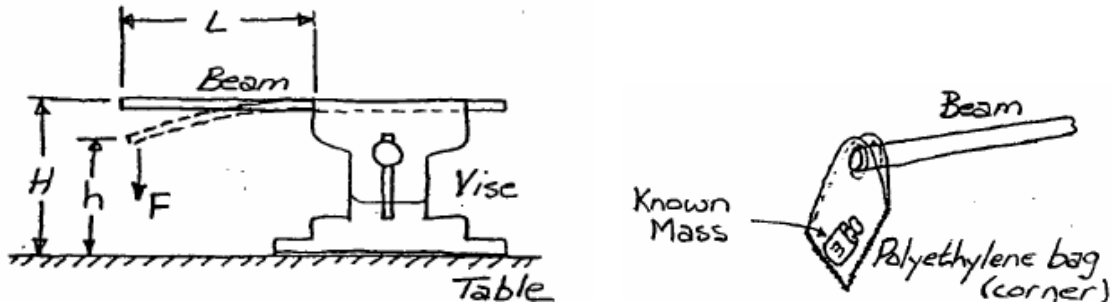


Table 1: Measured tip deflection.

Measured Data				Calculated Results	
Beam Length	Mass	Undeformed Height	Deformed Height	Force	Deflection
L (cm)	m (g)	H (cm)	h (cm)	F (mN)	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

Problem 2.22, continued

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

