Solutions Manual

for

Intermediate Physics for Medicine and Biology, 4th Edition

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CHAPTER 1

1.1 Approximate the dimensions of a red blood cell as 8 μm × 8 μm × 2 μm. Approximate the dimensions of a hemoglobin molecule as 6 nm × 6 nm × 6 nm. The number N of hemoglobin molecules is equal to the volume of a red blood cell divided by the volume of a hemoglobin molecule:
$N = \frac{\left(8\times10^{-6}\,\mathrm{m}\right)^2\left(2\times10^{-6}\,\mathrm{m}\right)}{\left(6\times10^{-9}\,\mathrm{m}\right)^3} = 0.6\times10^9 = 600\,\mathrm{million}$. We do not expect a "back-of-the-envelope" calculation such as this one to be accurate to, say, a factor of 2 or π. But it should give a quick order of magnitude estimate.

1.2 The length of the DNA in one cell is
$\left(3\times10^9\,\mathrm{base\,pairs}\right)\left(1/3\times10^{-9}\,\mathrm{m/base\,pair}\right)\left(2\right) = 2\,\mathrm{m}$. Approximate the cross section of a DNA molecule as 2.5 nm × 2.5 nm. The volume of the DNA in one cell is then $\left(2\,\mathrm{m}\right)\left(2.5\times10^{-9}\,\mathrm{m}\right)^2 = 13\times10^{-18}\,\mathrm{m}^3$. The volume of a sphere is $4\pi r^3/3$, implying a radius of 1.4 μm, or a diameter of about 2.8 μm. Cell nuclei typically have a diameter of about 5 μm, so all our DNA will fit inside the nucleus, with some room left over.

1.3 The volume of 1 mole of gas at standard temperature and pressure is 22.4 liters. The volume/molecule is then $\left(\frac{22.4\,\mathrm{liters}}{\mathrm{mole}}\right)\left(\frac{\mathrm{m}^3}{1000\,\mathrm{liters}}\right)\left(\frac{\mathrm{mole}}{6\times10^{23}\,\mathrm{molecules}}\right) = 37\times10^{-27}\,\mathrm{m}^3$. This volume corresponds to a cube with each side 3.3 nm long. The size of an air molecule is about 0.1 nm. So air is mostly empty space.

1.4 A water molecule contains 18 protons and neutrons, each having a mass of 1.6×10^{-27} kg. Atoms have radii of about 0.1 nm, and the O-H bond length is about 0.1 nm. The water molecule has the two hydrogen atoms asymmetrically placed, so you can't pack the molecules as tightly as you can pack spheres. Also, the hydrogen bonds linking two water molecules are rather weak, so the hydrogen bond length is about 0.2 nm. Based on this data, a reasonable estimate is that each water molecule occupies a space of about 0.3 nm × 0.3 nm × 0.3 nm. The density is then about
$\frac{18\left(1.6\times10^{-27}\,\mathrm{kg}\right)}{\left(0.3\times10^{-9}\,\mathrm{m}\right)^3} = 1100\,\mathrm{kg\,m^{-3}}$.

1.5 Take torques around the point of contact of the toes with the floor; then the toe force can be ignored in the torque equation.

$\Sigma F_y = 0$:

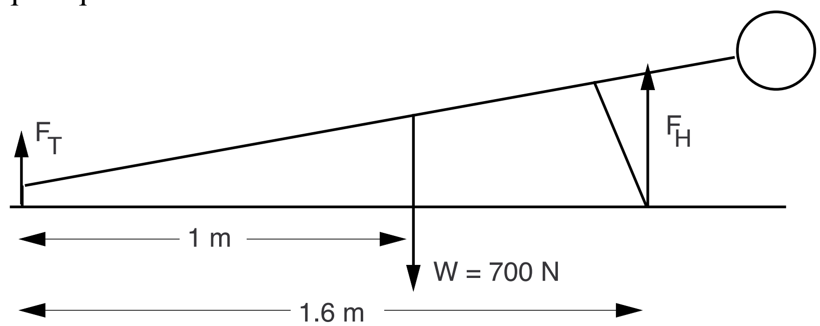
$F_T + F_H - 700 = 0$

$\Sigma \tau = 0$:

$1.6 F_H - (1)(700) = 0$,

so $F_H = 700/1.6 = 438$ N

$F_T = 700 - 438 = 262$ N.



Each hand experiences 219 N, and each foot 131 N.

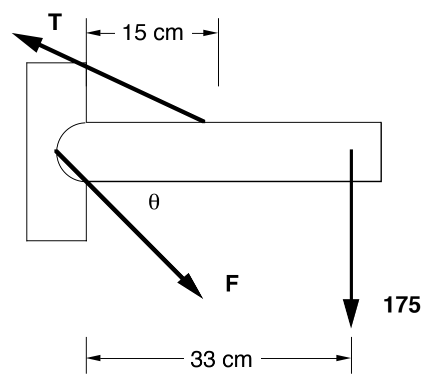
1.6 Take torques about the elbow: $5T - (15)(15) - (38)(40) = 0$; $T = 349$ N

$\Sigma F_y = 0$ so $-F + T - 15 - 40 = 0$

$F = 349 - 15 - 40 = 294$ N

Note that T is nearly 10 times the weight the person is holding.

1.7 $\Sigma F_x = 0$: $F_x - T\cos 17^\circ = 0$



$\Sigma F_y = 0$: $T\sin 17^\circ - F_y - 175 = 0$

$\Sigma\tau = 0$ around the shoulder: $(15)(T\sin 17^\circ) - (33)(175) = 0$

$T = (33)(175)/(15\sin 17^\circ)$

$= 1317$ N

Then from y: $F_y = -175 + (1317)(\sin 17^\circ) = 210$ N

from x: $F_x = (1317)(\cos 17^\circ) = 1259$ N

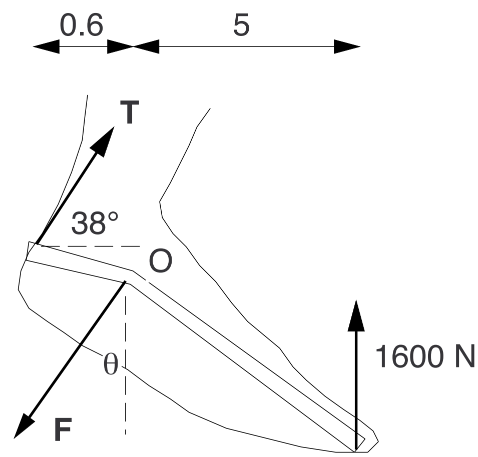
$F = (F_x^2 + F_y^2)^{1/2} = 1276$ N (about 286 pounds) The angle with the x axis is $\tan^{-1}(210/1259) = 9.5^\circ$

1.8 If torques are taken about O, the slight vertical displacement of the point of application of T can be neglected.

Σx: $\quad T\cos 38^\circ - F\sin\theta = 0$

Σy: $\quad T\sin 38^\circ + 1600 - F\cos\theta = 0$

$\Sigma\tau$: $\quad (5)(1600) - (0.6)T\sin 38^\circ = 0$

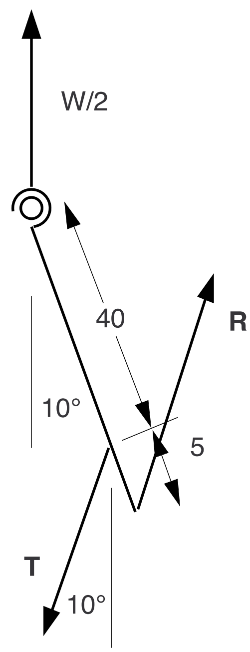


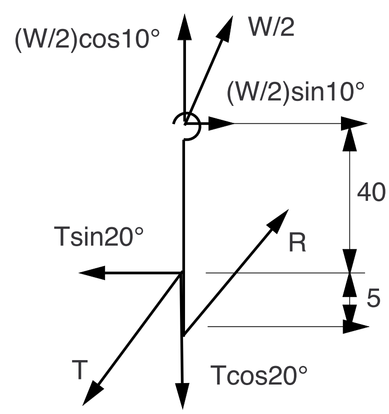
$$T\sin 38^\circ = (5)(1600)/0.6$$
$$= 1.33\times 10^4$$
$$T = 2.2\times 10^4\,N$$
$$F\cos\theta = 1.33\times 10^4 + 1600$$
$$= 1.5\times 10^4$$

$$F\sin\theta = T\cos 38^\circ = 1.71\times 10^4$$
$$F = [(1.5\times 10^4)^2 + (1.71\times 10^4)^2]^{1/2} = 2.3\times 10^4\,\mathrm{N}$$
$$\theta = \tan^{-1}(1.71\times 10^4/1.5\times 10^4) = 49^\circ$$

1.9 (**a**) Consider the whole body as the object. F_x would be the only horizontal force. By $\Sigma F_x = 0$, it must be zero. F_y is $W/2$ if both hands carry equal shares of the weight.

(**b**) T makes an angle of 20° with the forearm, which means it makes an angle of 10° with the vertical. Take torques about the elbow so that **R** does not contribute. It is easiest to redraw the x and y axes so that y is along the forearm (shown in the drawing on the right).





$$-45(W/2)\sin 10^\circ + (5)T\sin 20^\circ = 0 \qquad T = \frac{W(45)\sin 10^\circ}{(2)(5)\sin 20^\circ} = 2.28W$$

Then go back to y being vertical and x horizontal (the drawing on the left).

$R_h = T\sin 10° = 0.40W \qquad R_v = T\cos 10° - W/2 = 1.75W$

$R = \sqrt{R_h^2 + R_v^2} = 1.8W$

1.10 **(a)** Let the *x* direction be along the spine, and the *y* direction be perpendicular to *x*.

$$\Sigma F_x = 0 \quad \text{gives} \quad R_x - F\cos(12) - W\sin\theta = 0$$

$$\Sigma F_y = 0 \quad \text{gives} \quad R_y - F\sin(12) - W\cos\theta = 0$$

Take the torque about the point where the pelvis attaches to the spine.

$$\Sigma\tau = 0 \quad \text{gives} \quad \frac{2}{3}LF\sin(12) - LW\cos\theta = 0$$

Solve the torque equation for F: $F = 7.21W\cos\theta$.

Then the force equations are solved for the two components of **R**:

$$R_x = W\left[7.21\cos\theta + \sin\theta\right] \quad \text{and} \quad R_y = 0.5W\cos\theta\ .$$

(b)

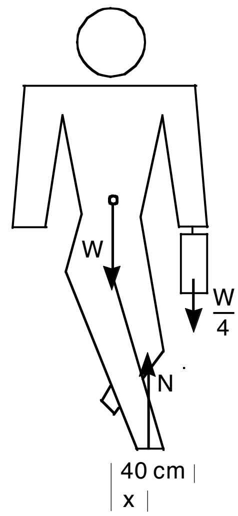
θ	0°	90°
R_x	$7.2W$	W
R_y	$0.5W$	0
R	$7.2W$	W

The force on the spine by the pelvis is over seven times larger if the spine is horizontal than if it is vertical. You really should "lift with your legs (θ = 90°), not with your back (θ = 0°)"!

(c) $$\phi = \tan^{-1}\left(\frac{R_y}{R_x}\right) = \tan^{-1}\left(\frac{0.5\cos\theta}{7.21\cos\theta + \sin\theta}\right).$$

ϕ = 0° for θ = 90°, and ϕ = 4° for θ = 0°.

1.11 We must first find how far the foot is from the midline of the body. Ignore the mass of the arm and shifts in posture, leg movement, etc. Compute the torque about the point where the foot meets the floor:



$$xW = (40 - x)W/4$$

$$xW = 10W - xW/4$$

so

$$x = 8 \text{ cm}.$$

Next, redraw Fig. 1.13 with the foot 8 cm across the midline. The normal force is now $(5/4)W = 1.25W$. The weight of the leg ($W/7$) still acts 10/18 of the way along the leg or 10/18 of the horizontal distance from greater trochanter to the foot. $(10/18)(18 + 8) = 14.4$ cm. Assume **F** has not changed direction and that the horizontal component still exerts negligible torque around the point in the head of the femur.

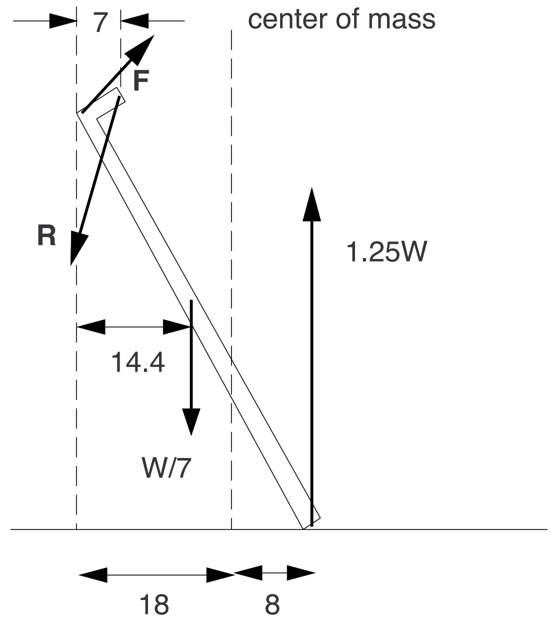
$\Sigma\tau$:

$-7F\sin 70^\circ - (14.4 - 7)W/7 + (26-7)(1.25W) = 0$

$-6.58F - 1.06W + 23.75W = 0$

$F = 3.45W$

This is much greater than the $1.6W$ without the suitcase.



R_x and R_y are found from $\Sigma F_x = 0$ and $\Sigma F_y = 0$:

$F \sin 70^\circ + 1.25W - W/7 - R_y = 0$

so $R_y = 4.35W$

$F \cos 70^\circ = R_x$

so $R_x = 1.18W$

$R = \sqrt{4.35^2 + 1.18^2}\ W = 4.5\ W$

$\theta = \tan^{-1}(4.35/1.18) = 75^\circ$ from the horizontal

1.12 **(a)** $\text{tensile strength} = E\varepsilon = \left(0.2\times 10^{10}\right)0.5 = 100\times 10^{7}\,\text{Pa}$

From Table 1.3, the tensile strength of steel is $50\times 10^{7}\,\text{Pa}$. So, the spider's thread has twice the tensile strength as steel.

(b) $\varepsilon = \dfrac{50\times 10^{7}}{20\times 10^{10}} = 2.5\times 10^{-3} = 0.25\%$. This is MUCH less than the spider's thread.

1.13 The change in volume is $\Delta V = (V + \Delta V) - V = (l_x + \Delta x)(l_y + \Delta y)(l_z + \Delta z) - l_x l_y l_z$,
$\Delta V = l_y l_z \Delta x + l_z l_x \Delta y + l_x l_y \Delta z$. So, after dividing by V, we get
$\dfrac{\Delta V}{V} = \dfrac{\Delta x}{l_x} + \dfrac{\Delta y}{l_y} + \dfrac{\Delta z}{l_z}$ or $\dfrac{\Delta V}{V} = \varepsilon_x + \varepsilon_y + \varepsilon_z$.

1.14 $\tan\theta = \dfrac{\delta}{h} = \varepsilon_s$. If $\varepsilon_s << 1$, then $\tan\theta \approx \theta$, so $\varepsilon_s = \theta$.

1.15 Let p_0 = atmospheric pressure
p = water pressure
p_L = pressure in the lungs

Then

$$p - p_L \le 86 \text{ torr}$$
$$p_L \ge p - 86$$

For inspiration, $p_0 > p_L \ge p - 86$

$$p_0 > p - 86 = p_0 + \rho_w gh - 86$$
$$\rho_w gh < 86 \text{ Torr or } \rho_{Hg} g(86)$$
$$h < (\rho_{Hg} 86/\rho_w) = (13.6/1)(8.6) \text{ cm} = 117 \text{ cm for the lungs}$$

or 87 cm for the mouth

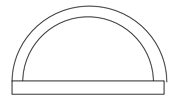
1.16 **(a)** Take a typical height to be 1.6 m.
$\Delta p = \rho gh = (1000\,\text{kg/m}^3)(9.8\,\text{m/s}^2)(1.6\,\text{m}) = 15700\,\text{Pa} = 118$ torr .

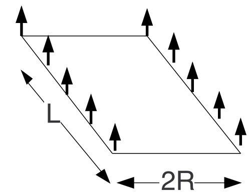
(b) If blood pressure were not measured at the height of the heart, then there would be a pressure difference due to the height difference. For instance, if the pressure were measured 10 cm below the heart, it would be about 7.5 torr too large. Since a typical blood pressure is "100/60" (meaning 100 torr when the heart is contracting, and 60 torr between contractions), this would represent about a 10% error.

(c) The blood vessels in our head are built to withstand relatively small pressures, but those in our feet must withstand larger pressures. When you stand on your head, the vessels in your head must now contend with about 100 torr extra pressure, which is uncomfortable. However, try standing on your head underwater! The increase in water pressure with depth balances the higher blood pressure, and you feel OK.

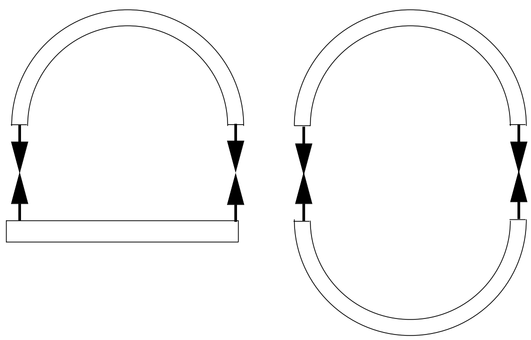
1.17 5 torr = 665 Pa. $h = \dfrac{665\text{ Pa}}{(9.8\,\text{m/s}^2)(1000\,\text{kg/m}^3)} = 0.068\,\text{m} = 6.8\,\text{cm}$.

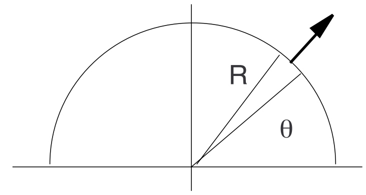
1.18 The total downward force on the flat plate is $F = pL2R$. If the plate is not accelerated, this must be balanced by a force exerted by the walls of the semi-circular segment. If the force per unit length is f,
$2Lf = pL2R$, so
$f = pR$.





By the third law, the reaction to this is the force on the hemi-cylinder. This force is the same whether it is exerted by a flat plate or by another hemi-cylinder.





We can get the same answer by direct integration of the force exerted on the hemi-cylinder by the gas inside. Consider the strip of length L and width $Rd\theta$. The force is pressure times area: $d\mathbf{F} = pdS = pRL\,d\theta$.
The components are $dF_x = dF\cos\theta$ and $dF_y = dF\sin\theta$. The total force is obtained by integrating from $\theta = 0$ to $\theta = \pi$.

$$F_x = \int_0^\pi dF_x = pRL\int_0^\pi \cos\theta\, d\theta = pRL\left[\sin\theta\right]_0^\pi = pRL(0-0) = 0$$

$$F_y = \int_0^\pi dF_y = pRL\int_0^\pi \sin\theta\, d\theta = pRL\left[-\cos\theta\right]_0^\pi = pRL[-(-1)+(1)] = 2pRL$$

The force per unit length at the edge is $f = F_y/2L = pR$.

As the wall of an aortic aneurysm balloons out, R increases and the force per unit length also increases. Since the wall is already weakened to cause the original ballooning, the prognosis is not good.

1.19 In analogy with the previous problem, imagine a hemisphere of the soap bubble attached to a spherical flat plate. The force on the flat disk is $\Delta p \pi R^2$ and must be equal to the circumference times the tension per unit length, T: $\Delta p \pi R^2 = 2\pi RT \quad \Delta p = 2T/R$.

1.20 The total mass of the fish plus air bladder is $1030V + 1.2U$.

The total volume is V+U. The "effective density" is thus (1030V+1.2U)/(V+U). To be neutrally buoyant, the effective density must equal the density of the surrounding water $1000 = \frac{1030V + 1.2U}{V + U}$. Solving for U gives $U = 0.03V$.

$$\text{The volume fraction} = \frac{U}{V+U} = \frac{0.03V}{V + 0.03V} = 0.029 = 2.9\%$$

1.21 Consider the force on an element of fluid between r and $r + dr$. The cross sectional area is A. $[p(r + dr) - p(r)]A = ma = \rho dr A r\omega^2$, so $[p(r + dr) - p(r)]/dr = \rho r\omega^2$. Therefore

$$dp/dr = \rho\omega^2 r \qquad \int dp = \rho\omega^2 \int r dr \qquad p - p_0 = \rho(\omega^2/2)r^2.$$

1.22 **(a)** $F = ma$,
$$\frac{\rho_{fluid}\omega^2 r^2}{2}\Delta x\Delta y - \frac{\rho_{fluid}\omega^2 (r+\Delta r)^2}{2}\Delta x \Delta y = -\rho\omega^2 r \Delta x\Delta y\Delta r$$
$$\frac{\rho_{fluid}\omega^2 V}{2}\left(\frac{r^2 - (r+\Delta r)^2}{\Delta r}\right) = -\rho\omega^2 rV.$$

Take the limit as Δr goes to zero
$$-\rho_{fluid}\omega^2 rV = -\rho\omega^2 rV,$$
so the "effective weight", F_{eff}, is
$$F_{eff} = (\rho - \rho_{fluid})\omega^2 rV.$$

(b) $ratio = \dfrac{\omega^2 r}{g}$

(c) 40,000 rev min^{-1} = 4189 rad s^{-1}. $\qquad ratio = \dfrac{(4189\,\mathrm{rad\,s^{-1}})^2(0.1\,\mathrm{m})}{9.8\,\mathrm{m s^{-2}}} = 179{,}000.$

(d) Particles will move until they reach a point r where $\rho_{fluid}(r)$ is equal to ρ. If the two particles have different densities, they will migrate to different locations.

1.23 **(a)** $F_{eff} = (\rho - \rho_{fluid})\omega^2 rV = ku$, where k is the constant of proportionality.

so, $\quad u = \dfrac{(\rho - \rho_{fluid})\omega^2 rV}{k}$.

(b) $\quad S = \dfrac{u}{\omega^2 r} = \dfrac{(\rho - \rho_{fluid})V}{k}$.