Problem 1.4. "Twice as hot" on the Celsius [or Fahrenheit] scale would make no sense, because the zero point is chosen arbitrarily. There's no fundamental reason, for instance, to which 2°C is twice as hot as 1°C. But if we measure temperature from absolute zero, then "twice as hot" makes perfect sense: the melting point of lead is twice room temperature; the sun's surface is 20 times room temperature; and so on. This is another good reason to use kelvin temperatures.

Problem 1.5. I was taught to leave the thermometer in my mouth for at least three minutes. However, the bulb of the thermometer must come most of the way up to body temperature within 30 or 20 seconds; waiting three minutes is unnecessary only because one must a reading that is accurate to within a fraction of a degree. The numerical value of the "relaxation time" could therefore be anywhere from 10 or 20 seconds to three minutes, depending on exactly how we define it.

Problem 1.6. On a cold morning, when I step from the bathroom rug into the tub for my shower, the tub feels a lot colder to my feet than the rug. Yet they must be at essentially the same temperature, since they've been right next to each other all night long in a room that is pretty well insulated from the weather. In fact the rug is just as cold as the tub, but it sucks heat out of my feet much more slowly due to its relatively poor thermal contact and low heat capacity. For another example, see the quote on page 68.

Problem 1.7. (Thermal expansion of liquids.)

(a) The mercury thermometer from my medicine cabinet has a roughly cylindrical bulb that measures 4 mm in diameter by 5 mm long. Its volume is therefore about 60 mm³. Under a 1°C temperature increase, this much mercury should increase its volume by

$$\Delta V = \beta \cdot V \cdot \Delta T = (1.82 \times 10^{-4}\ \text{K}^{-1})(60\ \text{mm}^3)(1\ \text{K}) = 0.011\ \text{mm}^3.$$

The expansion, however, takes place inside a narrow tube with a length of 5.5 cm. (The length of a 1°C increment on the scale) and unknown cross-sectional area. Assuming that the tube is cylindrical, its radius would have to be

$$r = \sqrt{\frac{\Delta V}{\pi \ell}} = \sqrt{\frac{0.011\ \text{mm}^3}{\pi(5.5\ \text{mm})}} = 0.02\ \text{mm},$$

so its diameter would be only 0.04 mm. No wonder it's so hard to see the column of mercury, even with the optical magnification of the glass!

(b) As the water in a lake cools, the densest water will sink to the bottom and the less dense water will rise to the top. Below 4°C, this means that the warmer water will stick within the cooler water mass. The first water to freeze will therefore be at the top, and since ice is even less dense, the ice floats on the surface. The ice then insulates the rest of the water from the cold weather, so even during a long, cold winter, only the smallest people have completely frozen top to bottom.

If the thermal expansion coefficient of water were always positive, then the coldest water in a lake would always be at the bottom, so ice would form first at the bottom.

If ice were also more dense than liquid water, the lake would freeze from the bottom up. Without the insulating layer of ice on its top, many lakes would freeze completely, and any fish in those lakes would be frozen along with them. (If ice were still less dense than water, I suppose bits of ice would form at the bottom and then float to the surface.)

Problem 1.8. (Thermal expansion of solids.)

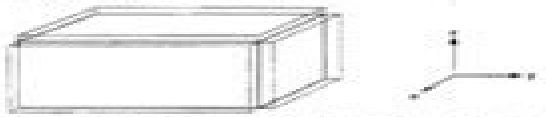
(a) Let's say the seasonal temperature extremes are −30 and +40 Celsius, for a total variation of 70 K. Under this variation, the change in length of a 1-km steel bridge would be

$$\Delta L = \alpha L \Delta T = (1.1 \times 10^{-5}\ \text{K}^{-1})(1000\ \text{m})(70\ \text{K}) = 0.77\ \text{m} = 77\ \text{cm}.$$

To be safe, I'd design the bridge to accommodate at least a meter of thermal expansion.

(b) The two metals in the coil have different thermal expansion coefficients, so as the temperature increases, one expands more than the other, causing the coil to coil further and turn.

(c) Imagine a rectangular solid with dimensions L_x, L_y, and L_z. When the temperature increases, the solid expands in all three dimensions:



Assuming that the expansion is infinitesimal, we consider it to be equivalent to adding the three shaded slabs to the volume of the solid, neglecting the corner strips omitted from the diagram. Then the volume increase is

$$\Delta V = (\Delta L_x)L_yL_z + (\Delta L_y)L_xL_z + (\Delta L_z)L_xL_y.$$

Writing each ΔL in terms of the appropriate linear expansion coefficient, this becomes

$$\begin{aligned}\Delta V &= (\alpha_x L_x \Delta T)L_yL_z + (\alpha_y L_y \Delta T)L_xL_z + (\alpha_z L_z \Delta T)L_xL_y \\ &= (\alpha_x + \alpha_y + \alpha_z)V\,\Delta T.\end{aligned}$$

Comparing to the definition of the volume expansion coefficient β, we see that this result has the same form, with $\beta = \alpha_x + \alpha_y + \alpha_z$.

Alternatively, we can rewrite the definitions of α and β in terms of derivatives:

$$\alpha = \frac{1}{L}\frac{dL}{dT}, \qquad \beta = \frac{1}{V}\frac{dV}{dT}.$$

(Technically, these should be partial derivatives, with pressure held fixed.) With the aid of the product rule, the derivative in now working from symbol-pushing:

$$\begin{aligned}\beta &= \frac{1}{V}\frac{dV}{dT} = \frac{1}{V}\frac{d}{dT}(L_xL_yL_z) = \frac{1}{V}\left[\frac{dL_x}{dT}L_yL_z + \frac{dL_y}{dT}L_xL_z + \frac{dL_z}{dT}L_xL_y\right] \\ &= \frac{1}{V}\left[(\alpha_xL_x)L_yL_z + (\alpha_yL_y)L_xL_z + (\alpha_zL_z)L_xL_y\right] \\ &= \frac{1}{V}\left[\alpha_x + \alpha_y + \alpha_z\right]L_xL_yL_z = \alpha_x + \alpha_y + \alpha_z.\end{aligned}$$

Problem 1.9. For a mole of air at room temperature and atmospheric pressure,

$$V = \frac{nRT}{P} = \frac{(1\ \text{mol})(8.31\ \text{J/mol·K})(300\ \text{K})}{10^5\ \text{N/m}^2} = 0.025\ \text{m}^3 = 25\ \text{liters}.$$

Problem 1.10. Consider an "average" room measuring 4 meters square by 3 meters high. The number of air molecules [at room temperature and atmospheric pressure] in

$$N = \frac{PV}{kT} = \frac{(10^5\ \text{N/m}^2)(4\ \text{m})(4\ \text{m})(3\ \text{m})}{(1.38 \times 10^{-23}\ \text{J/K})(300\ \text{K})} = 1.2 \times 10^{27} \approx 10^{27}.$$

(That's about 2000 moles.)

Problem 1.11. Since the rooms are connected by an open door, the pressure must be the same in each room; if it weren't, air would rush from one room into the other. Also, we're told that the volumes of each room is the same. Now look at the ideal gas law: $PV = NkT$. The left-hand-side is the same for both rooms, so Room B, which has a smaller T, must have a larger N, hence a larger mass of air.

Problem 1.12. The volume per molecule for an ideal gas at room temperature and atmospheric pressure is

$$\frac{V}{N} = \frac{kT}{P} = \frac{(1.38 \times 10^{-23}\ \text{J/K})(300\ \text{K})}{10^5\ \text{N/m}^2} = 4.1 \times 10^{-26}\ \text{m}^3 = 41\ \text{nm}^3.$$

If we imagine each molecule living in a cube of this volume, then the width of the cube would be the cube root of this number, 3.5 nm. This is then a good estimate of the average distance between neighboring molecules. The diameter of a molecule like N_2 or H_2O, on the other hand, is only a few Ångstroms, about ten times smaller than this average distance.

Problem 1.13. In each case we merely need to determine the total number of protons

(b) Each nitrogen atom has 7 protons and 7 neutrons, so an N_2 molecule has 28 nucleons and a mole of them therefore has a mass of 28 grams.

(c) The atomic mass of lead is 207 [a weighted average over several isotopes (setopes)], so a mole of lead has a mass of 207 g.

(d) A generic "molecule" has 28 nucleons in the silicon atom and 32 in the two oxygen atoms, for a total of 60, so a mole of quartz has a mass of 60 g.

Problem 1.14. For a mole of pure N_2, the mass would be 28 g; for O_2, the mass would be 32 g; and for Ar, the mass would be 40 g. For the mixture found in dry air, therefore, the mass would be the weighted average

$$M = (0.78)(28\ \text{g}) + (0.21)(32\ \text{g}) + (0.01)(40\ \text{g}) = 28.96\ \text{g} \approx 29.0\ \text{g}.$$

Problem 1.15. The upward buoyant force on the balloon is equal to the weight of the air displaced. Assuming that this force is approximately in balance with gravity, we can write

$$\rho_a V g = (M + \rho V)g \qquad \Longrightarrow \qquad \rho_a - \rho = M/V,$$

where ρ_a is the density of the surrounding air, V is the volume of the balloon, and M is the mass of the stuffed balloon and payload, and ρ is the density of the air inside the balloon. According to the ideal gas law, the density of air is

$$\rho = \frac{m}{V} = \frac{mP}{NkT},$$

where m is the mass of one mole of air (29 g, as shown in the previous problem). This formula applies either inside or outside the balloon, with the same pressure in both places but different temperatures. Therefore the balance of forces implies

$$\frac{mP}{RT_a} - \frac{mP}{RT} = \frac{M}{V},$$

where T is the temperature inside the balloon and T_a is the temperature outside. A bit of algebra then yields

$$\frac{1}{T} = \frac{1}{T_a} - \frac{M}{mv}\frac{R}{P}.$$

Let's assume an outside air temperature of 290 K, and atmospheric pressure. The volume of the balloon was (an estimated) 5 m. Figure 0.1. Comparing to the heights of the people standing underneath, I estimate the balloon in the foreground to have a diameter of about 30 feet or 10 meters, and therefore a volume of $\frac{4}{3}\pi r^3 = 1770\ \text{m}^3$. The mass of the stuffed balloon and payload is assumed to be 500 kg, so the previous expressions evaluates to

$$\frac{1}{T} = \frac{1}{290\ \text{K}} - \frac{500\ \text{kg}}{0.029\ \text{kg}}\frac{8.31\ \text{J/K}}{(10^5\ \text{N/m}^2)(1770\ \text{m}^3)} = \frac{1}{290\ \text{K}} - \frac{1}{1205\ \text{K}} = \frac{1}{379\ \text{K}}.$$

Thus the temperature inside the balloon must be about 379 K (or just over 100°C. (Thanks to Chuck Mellenthin for informing me that this is indeed a typical operating temperature.)

Introduction To Thermal Physics Solution Manual

Mark Steyvers

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