

Problem 1.4. "Twice as fast" on the Celsius (or Fahrenheit) scale would mean to move between the two points in half the time. There's no problem with this, because the interval in which 2°C is twice as fast as 1°C. But if we measure temperatures from absolute zero, then "twice as fast" 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 10 or 20 seconds; waiting three minutes is necessary only because we want a reading that is accurate to within a fraction of a degree. The numerical value of the "relaxation time" would therefore be anywhere from 10 to 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're both right next to each other all night long in a room that is pretty well insulated from the outside. In fact, the rug is just as cold as the tub, but it feels less cool to my feet much more slowly due to its relatively poor thermal contact and low heat capacity. (For another example, see the quote on page 48.)

Problem 1.7. (Thermal expansion of liquids.)

(a) The mercury thermometer tube has a circular cross-section with a roughly cylindrical bulb that measures 4 mm in diameter by 3 mm long; the volume is therefore about 47 mm^3 . Under a 1°C temperature increase, this small mercury column increases in volume by

$$\Delta V = \beta \cdot V \cdot \Delta T = (1.81 \times 10^{-4} \text{ K}^{-1})(47 \text{ mm}^3)(1 \text{ K}) = 8.513 \text{ mm}^3.$$

The expansion, however, takes place inside a narrow tube with a length of 8.5 mm (the length of a 1°C increase on the scale) and unknown cross-sectional area. Assuming that the tube is cylindrical, its radius would have to be

$$r = \sqrt{\frac{\Delta V}{\pi \Delta L}} = \sqrt{\frac{8.513 \text{ mm}^3}{\pi(8.5 \text{ mm})}} = 0.04 \text{ mm},$$

so the 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 denser 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 sink while the cooler water rises. The first water to freeze will therefore be at the top, and since ice is insulating from the bottom, the ice floats on the warmer. This ice then insulates the rest of the water from the cold weather, so even during a long, cold winter, only the shallow ponds freeze completely from 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. With the insulating layer of ice on top, the ice would spread down progressively, and any fish in the lake would be frozen along with it. (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 actual temperature increases 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 rail have different thermal expansion coefficients, so as the temperature increases, one expands more than the other, causing the rail to curl further and further.

(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 individual slices to the volume of the solid, neglecting the corner strips omitted from the diagram. Then the volume increases by

$$\Delta V = (\alpha_x L_x \Delta T) L_y L_z + (\alpha_y L_y \Delta T) L_x L_z + (\alpha_z L_z \Delta T) L_x L_y.$$

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

$$\Delta V = (\alpha_x L_x \Delta T) L_y L_z + (\alpha_y L_y \Delta T) L_x L_z + (\alpha_z L_z \Delta T) L_x L_y \\ = (\alpha_x + \alpha_y + \alpha_z) V \Delta T.$$

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 definition of α and β in terms of derivatives:

$$\alpha = \frac{1}{L} \frac{\Delta L}{\Delta T}, \quad \beta = \frac{1}{V} \frac{\Delta V}{\Delta T}.$$

(Technically, these should be partial derivatives, with pressure held fixed.) With the aid of the product rule, the derivative is now something less gratifying:

$$\beta = \frac{1}{V} \frac{\Delta V}{\Delta T} = \frac{1}{V} \frac{\Delta}{\Delta T} (L_x L_y L_z) = \frac{1}{V} \left[\frac{\Delta L_x}{\Delta T} L_y L_z + \frac{\Delta L_y}{\Delta T} L_x L_z + \frac{\Delta L_z}{\Delta T} L_x L_y \right] \\ = \frac{1}{V} [(\alpha_x L_x) L_y L_z + (\alpha_y L_y) L_x L_z + (\alpha_z L_z) L_x L_y] \\ = \frac{1}{V} (\alpha_x + \alpha_y + \alpha_z) L_x L_y L_z = \alpha_x + \alpha_y + \alpha_z.$$

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

$$V = \frac{nRT}{P} = \frac{(1 \text{ mol})(8.31 \text{ J/mol K})(300 \text{ K})}{(1.01 \times 10^5 \text{ Pa})} = 0.025 \text{ m}^3 = 25 \text{ liters}.$$

Problem 1.10. Consider an "average" room containing 4 meters square by 3 meters high. The number of air molecules (at room temperature and atmospheric pressure) is

$$N = \frac{PV}{kT} = \frac{(1.01 \times 10^5 \text{ Pa})(12 \text{ m}^3)}{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})} = 1.2 \times 10^{27} \approx 10^{27}.$$

(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 volume 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

$$\frac{V}{N} = \frac{kT}{P} = \frac{(1.38 \times 10^{-23} \text{ J/K})(300 \text{ K})}{(1.01 \times 10^5 \text{ Pa})} = 4.1 \times 10^{-28} \text{ m}^3 = 41 \text{ nm}^3.$$

If we imagine each molecule being in a cube of this volume, then the width of the cube would be the cube root of this number, 0.35 nm. This is then a good estimate of the average distance between neighboring molecules. The diameter of a molecule like N_2 or O_2 , on the other hand, is only a few Angstroms, about ten times smaller than this average distance.

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

- (a) Each nitrogen atom has 7 protons and 7 neutrons, so an N_2 molecule has 28 nucleons and a mass of 28 grams.
 (c) The atomic mass of lead is 207 (a weighted average over several common isotopes), so a mole of lead has a mass of 207 g.
 (d) A quartz "molecule" has 28 nucleons in the silicon atom and 32 in the two oxygen atoms, for a total of 88, so a mole of quartz has a mass of 88 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:

$$M = (0.78)(28 \text{ g}) + (0.21)(32 \text{ g}) + (0.01)(40 \text{ g}) = 29.04 \text{ g} = 29.0 \text{ g}.$$

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

$$\rho_a V g = \rho b V g + M g \quad \Rightarrow \quad \rho_a - \rho = M/V,$$

where ρ_a is the density of the surrounding air, V is the volume of the balloon, and M is the mass of the inflated 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

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

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

$$\frac{m_a P}{RT_a} - \frac{m_b P}{RT_b} = \frac{M}{V},$$

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

$$\frac{1}{T} = \frac{1}{T_a} - \frac{M}{m_b V}.$$

Let's assume an outside air temperature of 290 K, and atmospheric pressure. The volume of the balloon can be estimated from Figure 1.5. Comparing to the height of the people standing underneath, I estimate the balloon is the compressed to have a diameter of about 50 feet or 15 meters, and therefore a volume of $[4\pi/3]r^3 = 1770 \text{ m}^3$. The mass of the inflated balloon and payload is assumed to be 500 kg, so the previous equation reduces to

$$\frac{1}{T} = \frac{1}{290 \text{ K}} - \frac{500 \text{ kg}}{0.029 \text{ kg} [1770 \text{ m}^3] (290 \text{ K})} = \frac{1}{290 \text{ K}} - \frac{1}{1035 \text{ K}} = \frac{1}{179 \text{ K}}.$$

Thus the temperature inside the balloon must be about 179 K, or just over 100°C. (Thanks to Chuck MacArthur for informing me that this is indeed a typical operating temperature.)

Introduction To Thermal Physics Solution Manual

K Morrison



Introduction To Thermal Physics Solution Manual:

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Table of Contents Introduction To Thermal Physics Solution Manual

1. Understanding the eBook Introduction To Thermal Physics Solution Manual
 - The Rise of Digital Reading Introduction To Thermal Physics Solution Manual
 - Advantages of eBooks Over Traditional Books
2. Identifying Introduction To Thermal Physics Solution Manual
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Introduction To Thermal Physics Solution Manual
 - User-Friendly Interface
4. Exploring eBook Recommendations from Introduction To Thermal Physics Solution Manual
 - Personalized Recommendations
 - Introduction To Thermal Physics Solution Manual User Reviews and Ratings
 - Introduction To Thermal Physics Solution Manual and Bestseller Lists
5. Accessing Introduction To Thermal Physics Solution Manual Free and Paid eBooks
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 - Introduction To Thermal Physics Solution Manual Budget-Friendly Options
6. Navigating Introduction To Thermal Physics Solution Manual eBook Formats
 - ePub, PDF, MOBI, and More
 - Introduction To Thermal Physics Solution Manual Compatibility with Devices
 - Introduction To Thermal Physics Solution Manual Enhanced eBook Features
7. Enhancing Your Reading Experience

- Adjustable Fonts and Text Sizes of Introduction To Thermal Physics Solution Manual
 - Highlighting and Note-Taking Introduction To Thermal Physics Solution Manual
 - Interactive Elements Introduction To Thermal Physics Solution Manual
8. Staying Engaged with Introduction To Thermal Physics Solution Manual
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Introduction To Thermal Physics Solution Manual
 9. Balancing eBooks and Physical Books Introduction To Thermal Physics Solution Manual
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Introduction To Thermal Physics Solution Manual
 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
 11. Cultivating a Reading Routine Introduction To Thermal Physics Solution Manual
 - Setting Reading Goals Introduction To Thermal Physics Solution Manual
 - Carving Out Dedicated Reading Time
 12. Sourcing Reliable Information of Introduction To Thermal Physics Solution Manual
 - Fact-Checking eBook Content of Introduction To Thermal Physics Solution Manual
 - Distinguishing Credible Sources
 13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
 14. Embracing eBook Trends
 - Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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