PROBLEMS

1.1 *Dorm-room dynamics*

a. An air conditioner cools down your room, removing thermal energy. Yet it *consumes* electrical energy. Is there a contradiction with the First Law?

b. Could you design a high-tech device that sits in your window, continuously converting the unwanted thermal energy in your room to electricity, which you then sell to the power company? Explain.

1.2 *Thompson's experiment*

Long ago, people did not use SI units.

a. Benjamin Thompson actually said that his cannon-boring apparatus could bring 25.5 pounds of cold water to the boiling point in 2.5 hours. Supposing that "cold" water is at 20 °C, find the power input into the system by his horses, in watts. [*Hint:* A kilogram of water weighs 2.2 pounds. That is, Earth's gravity pulls it with a force of $1\ \mathrm{kg} \times g = 2.2$ pound.]

b. James Joule actually found that 1 pound of water increases in temperature by one degree Fahrenheit (or 0.56 °C) after he input 770 foot pounds of work. How close was he to the modern value of the mechanical equivalent of heat?

1.3 *Metabolism*

Metabolism is a generic term for all of the chemical reactions that break down and "burn" food, thereby releasing energy. Here are some data for metabolism and gas exchange in humans.

food	kcal/g	liters O_2/g	liters CO_2/g
carbohydrate	4.1	0.81	0.81
fat	9.3	1.96	1.39
protein	4.0	0.94	0.75
alcohol	7.1	1.46	0.97

The table gives the energy released, the oxygen consumed, and the carbon dioxide released upon metabolizing the given food, per gram of food.

a. Calculate the energy yield per liter of oxygen consumed for each food type and note that it is roughly constant. Thus, we can determine a person's metabolic rate simply by measuring her rate of oxygen consumption. In contrast, the CO_2/O_2 ratios are different for the different food groups; this circumstance allows us to estimate what is actually being used as the energy source, by comparing oxygen intake to carbon dioxide output.

b. An average adult at rest uses about 16 liters of O_2 per hour. The corresponding heat release is called the "basal metabolic rate" (BMR). Find it, in kcal/hour and in kcal/day.

c. What power output does this correspond to in watts?

d. Typically, the CO_2 output rate might be 13.4 liters per hour. What, if anything, can you say about the type of food materials being consumed?

e. During exercise, the metabolic rate increases. Someone performing hard labor for 10 hours a day might need about 3500 kcal of food per day. Suppose the person does mechanical work at a steady rate of 50 W over 10 hours. We can define the body's efficiency as the ratio of mechanical work done to excess energy intake (beyond the BMR calculated in (b)). Find this efficiency.

1.4 *Earth's temperature*

The Sun emits energy at a rate of about $3.9 \cdot 10^{26}$ W. At Earth, this sunshine gives an incident energy flux I_e of about $1.4\,\mathrm{kW\,m^{-2}}$. In this problem, you'll investigate whether any other planets in our solar system could support the sort of water-based life we find on Earth.

Consider a planet orbiting at distance d from the Sun (and let d_e be Earth's distance). The Sun's energy flux at distance d is $I = I_e(d_e/d)^2$, because energy flux decreases as the inverse square of distance. Call the planet's radius R, and suppose that it absorbs a fraction α of the incident sunlight, reflecting the rest back into space. The planet intercepts a disk of sunlight of area πR^2, so it absorbs a total power of $\pi R^2 \alpha I$. Earth's radius is about 6400 km.

The Sun has been shining for a long time, but Earth's temperature is roughly stable: The planet is in a steady state. For this to happen, *the absorbed solar energy must get reradiated back to space as fast as it arrives* (see Figure 1.2). Because the rate at which a body radiates heat depends on its temperature, we can find the expected mean temperature of the planet, using the formula

$$\text{radiated heat flux} = \alpha\sigma T^4.$$

In this formula, σ denotes the number $5.7 \cdot 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$ (the "Stefan–Boltzmann constant"). The formula gives the rate of energy loss per unit area of the radiating body (here, the Earth). You needn't understand the derivation of this formula but make sure you do understand how the units work.

a. Using this formula, work out the average temperature at the Earth's surface and compare your answer to the actual value of 289 K.

b. Using the formula, work out how far from the Sun a planet the size of Earth may be, as a multiple of d_e, and still have a mean temperature greater than freezing.

c. Using the formula, work out how close to the Sun a planet the size of Earth may be, as a multiple of d_e, and still have a mean temperature below boiling.

d. *Optional:* If you know the planets' orbital radii, which ones are then candidates for water-based life, using this rather oversimplified criterion?

1.5 *Franklin's estimate*

The estimate of Avogadro's number in Section 1.5.1 came out too small partly because we used the molar mass of water, not of oil. We can look up the molar mass and mass density of some sort of oil available in the eighteenth century in the *Handbook of chemistry and physics* (Lide, 2006). The *Handbook* tells us that the principal component of olive oil is oleic acid and gives the molar mass of oleic acid (also known as 9-octadecenoic acid or $CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$) as $282\,\mathrm{g\,mole^{-1}}$. We'll

1.5. Use the modern Avogadro number, and the fact that 1 mole of water weighs 18g. Calculate the size of water molecule