1 Travel by car or bike

(*Remember to read the Homework-Write-Up Guide*)

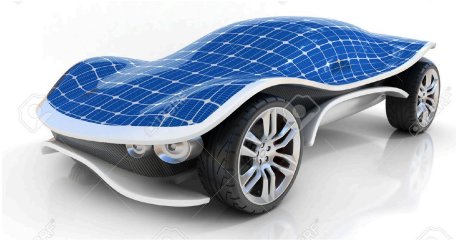
In this question you will compare the energy used by (i) an electric bicycle traveling 15 miles at 15 mph to (ii) the energy used by an electric car traveling the same distance at 60 miles per hour.

(a) Find the *ratio* of the energies used by the two options. I'm looking for a numerical value of the ratio. Use the simplest coarse-grained model for transport (kinetic energy of the wind tail) and clearly state your assumptions (for example, assume flat roads).

(b) Use a more refined model by including rolling resistance. The rolling resistance for cars and bicyles is equivalent to climbing an uphill grade of approximately 1%. (The exact value of the equivalent uphill grade depends on the tire pressure, and the viscoelasticity of the tire material).

2 Speed of a solar car

This self-driving solar car is travelling on a flat road on a windless day. The sun is directly overhead.



(a) Draw an energy flow diagram to describe the system. An arrow at the top of the flow diagram will represent incoming solar energy (landing on the solar panel). One circle will represent the solar panel, and one circle will represent the electric motor. Label each arrow with the correponding value of energy flow (a quantity measured in joules per second).

(b) Estimate how fast this self-driving solar car can travel on a flat road on a windless day when the sun is directly overhead. Give your answer in meters per second.

Use the following parameters for the system:

- The car is 1.8 m wide, 1 m tall and 3 m long. The top surface of the car is entirely covered with solar panels.
- The sun is directly overhead and the intensity of the sunlight is 1000 J/(s.m^2).
- The electric motors are powered directly by the solar panels (no battery power).
- The solar panels convert sunlight energy into electrical energy with 20% efficiency (the other 80% of sunlight energy is heating the solar panel).
- The electric motors convert electrical energy into mechanical work with efficiency 90% efficiency.
- The drag coefficient is 0.2.
- The energy dissipation associated with the tires rolling on the road can be neglicted.

3 Interstellar Rocket Travel

To travel to a nearby star, I want my rocket to accelerate to 10% the speed of light ($0.1c$, where c is the speed of light). I need to know approximately how much energy is required if I use a conventional rocket and conventional fuel. For this question, please neglect special relativity since corrections due to special relativity will be small.

(a) The rocket uses a combination of hydrocarbons and oxygen as fuel, estimate the energy density of the fuel in units of MJ/kg.

- The energy released when burning hydrocarbon fuel is ≈ 40 MJ per kilogram of hydrocarbon.
- 1 kg of hydrocarbons requires about 3 kg of oxygen (the rocket must carry its own oxygen).

(b) The rocket equation (below) allows us to calculate the change in speed of a rocket. The derivation of the rocket equation (see Wikipedia) uses conservation of momentum and assumes that the spent fuel is ejected, a little at a time, with an exhaust velocity v_e relative to the rocket. Assume $v_e = 6000$ m/s (generous estimate, since the current record is $v_e = 4600$ m/s). The change in speed is given by

$$\Delta v = v_e \ln \frac{m_{\text{wet}}}{m_{\text{dry}}}, \tag{1}$$

where m_{wet} is the initial mass of the rocket when it is loaded with fuel, and m_{dry} is the final mass of the rocket when the fuel tank is empty.

Find the ratio of $m_{\text{wet}}/m_{\text{dry}}$ that will give $\Delta v = 0.1c$. Express your answer using scientific notation (ten to the power of something).

(c) If $m_{\text{dry}} = 1{,}000$ kg (equivalent to a small car), how much energy is needed to accelerate to $0.1c$? Give your answer in units of MJ. Sensemaking: compare to the energy used by the population of humans on earth each year (approximately 10 billion people).

4 Heat loss from a single-family home in winter

Consider a family home that has a floor area of 50 feet $\times$ 50 feet, and a ceiling height of 10 feet. The house has typical the insulation for the Pacific Northwest: R-15 walls and an R-30 ceiling.

To help you with physics reasoning, I have converted the R-values into standard-international (SI) units for heat conductance per unit area:

$$\text{wall conductance per unit area} = 0.4 \ \frac{\text{W}}{\text{K.m}^2} \tag{2}$$

$$\text{ceiling conductance per unit area} = 0.2 \ \frac{\text{W}}{\text{K.m}^2} \tag{3}$$

Based on the units listed above, and the context (thermal insulation), you can visualize the meaning of these proportionality constants. For example, if there is a 1 kelvin temperature difference between inside/outside the house, every square meter of wall will leak energy at a rate of 0.4 J/s. Doubling the temperature difference, or doubling the wall area, will double the leak rate.

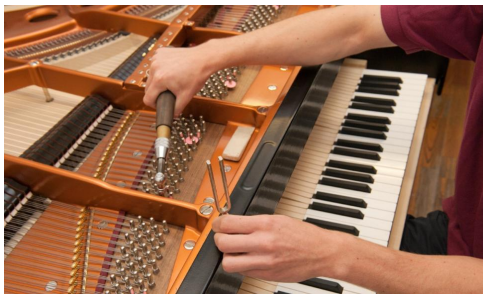
If the indoor temperature is 293 K (68°F), and the outdoor temperature is 273 K (32°F), how fast does heat energy leak out of the house (joules/second)? For this question, please assume the floor is

perfectly insulated so that no heat leaks out of the floor.

Sense making 1: Three of the most significant categories of human energy use in the United States are (1) the embodied energy of the stuff we buy $\approx$ 170 MJ/day per person, (2) the energy used driving cars $\approx$ 140 MJ/day per person, (3) the energy used by jet flights $\approx$ 100 MJ/day per person (all these energy rates are averaged over the course of a year). How does the heat loss from a family home compare to the other categories on this list?

Sense making 2: How many small, portable heaters are needed to heat this house? (assume 1 kW heaters). Does this seem like a realistic number of heaters?

5 Piano tuners in Chicago



In a fabled story about Enrico Fermi (famous physicist), Fermi was asked how many people work as piano tuners in Chicago. Fermi did some mental arithmetic and quickly answered the question with surprising accuracy. Your task is to recreate Fermi's calculation.

Fermi's approach to solving such problems has spread far beyond the physics community. Today, tech companies and business consulting companies expect their employees to do Fermi problems: https://www.youtube.com/watch?v=KAo6Vn5bDF0.

Background: Pianos were popular when Fermi was living in Chicago in the 1940s. The population of Chicago was about 2 million people. Approximately 1 in 10 households had a piano. Pianos got out of tune at regular intervals (about 2 or 3 years), so the piano owner would call a technician (the piano tuner) to tighten/loosen the 88 strings inside the piano. Each tuning job took at least an hour.

Fermi used his general knowledge to estimate proportionality constants: For example, the number of pianos in Chicago was proportional to the number of households (the proporitionality constant was 0.1.).

To recreate Fermi's calculation make your own quantitaive estimates of proportionality constants (practice using your reasoning skills; avoid using Google). Each proportionality constant will be approximate; that is the essence of this estimation technique. To organize your calculation in a logical, easy-to-follow fashion, set up each line of math with one proportionality constant. For example,

$$\text{“}(2 \times 10^6 \text{ people}) \div (3 \text{ people per household}) = 0.7 \times 10^6 \text{ households}\text{”} \tag{4}$$

Keep track of units as you go along: households, pianos, hours, etc. Use round numbers at each step of the calculation because a 5% calculational “error” will be smaller than the 10-30% uncertainty in the proportionality constants. How many piano tuners do you think were working in Chicago in the 1940s?