1. Using a simplified model of a solar cell, we can (with some effort) calculate the optimal bandgap for an ideal single-threshold solar energy conversion device (an ISTD). Assume the following:
   1) All carriers thermalize before charge transfer takes place; we'll assume no "hot carriers."
   2) The device absorbs no light below its threshold, and all light above it. In other words, the absorption coefficient is:
   $$\alpha = \begin{Bmatrix} 0 \ \text{ for } E_{photon} < E_{gap} \\ \infty \ \text{ for } E_{photon} \geq E_{gap} \end{Bmatrix}$$
   3) The internal quantum yield and internal efficiency of the device are independent of the bandgap of the device and the wavelength of the radiation, and are 100%. Thus, the energy collected per photon absorbed depends only on the device bandgap.
   Note: This is generally not a very good assumption! In real life one must give up some potential in order to actually drive a significant number of electrons through a load.
   4) The incident solar radiation is that of a perfect blackbody at temperature T, whose spectral photon flux distribution (photons per unit area per unit time per unit wavelength) is given by:
   $$J_{photon,blackbody}(\lambda) = \frac{2\pi c}{\lambda^4}\left(\frac{1}{e^{hc/\lambda kT}-1}\right) [=] \frac{\text{photons}}{\left(\text{m}^2 \text{ of area}\right)\left(\text{sec of time}\right)\left(\text{m of wavelength}\right)}$$
   Please note that this is a distribution function, which means that in actual usage it goes into an integral. Specifically, the number of photons within a wavelength window $d\lambda$ is given by
   $$dJ_{photon,blackbody}(\lambda) = \frac{2\pi c}{\lambda^4}\left(\frac{1}{e^{hc/\lambda kT}-1}\right) d\lambda \ [=] \ \frac{\text{photons}}{\text{m}^2 \ \text{sec}}$$
   If you wish to change this to $dJ(E_{photon})$, a distribution function in energy, you will have to be careful to write $d\lambda$ in terms of dE_{photon} and E_{photon} (and some physical constants).

   There are two ways in which you may do this problem:
   a. Your first option is to clearly describe the mathematical steps (integrals, derivatives, and the like) you would have to go through in order to determine:
      i. the optimal bandgap for an ISTD as a function of the blackbody temperature of the solar source available in the local area.
      ii. the maximum efficiency attainable by an ISTD as a function of the blackbody temperature of the solar source in the area.

      You should also do a little concrete thinking:

      iii. How would the optimal bandgap for such a device change (if at all) as the blackbody temperature of the local source was increased? Clearly explain your logic.
      iv. The maximum efficiency of an ISTD turns out to be independent of the temperature of the local blackbody source. Rationalize this fact in light of your answer to (iii).
   b. The second way in which you may do this problem is more concrete. The math involved is (as best I can tell) not vulnerable to analytic methods. However, numerical integration allows the answers to the questions above to be calculated. If you choose this option, you do not need to explain in detail the methodology you used. Rather, the numeric validity of your answers will be of prime importance. Submit an electronic copy of your spreadsheet and/or Mathematica worksheet, however.
      i. Determine the optimal bandgap for ISTDs exposed to local blackbody solar sources at 4000. K, 7000. K, and 12000. K. Rationally estimate and clearly indicate the uncertainty in your result.
      ii. Determine the maximum efficiency obtainable by ISTDs exposed to local blackbody solar sources at 4000. K, 7000. K, and 12000. K. Again, be sure to consider and indicate uncertainty.

   Hint: You may wish to consult a paper in which a similar analysis was performed, albeit with a somewhat more realistic model: C. H. Henry, *J. Appl. Phys.*, **51,** 4494-500 (1980), which appears in your reading packet starting on p. 57.

2. How thick would a wafer of Si have to be to absorb 99% of the 800. nm (red) photons hitting it perpendicular to its surface, assuming no reflection losses at the front surface and complete reflection at the back surface? What thickness of GaAs would be required to accomplish the same feat?
   Hint: (You can find absorption coefficients in Figure 3.8 on page 62 of "Chapter 3;" that's page 27 of the reading packet.)

3. I used to dream of driving a solar-powered car some day. Sadly, I've since learned that any realizable dream along those lines requires modifying a lot more than just the power source of the vehicle: certainly driving habits, acceleration expectations, and the materials of which the vehicle are constructed would have to change markedly. Let's get a rough idea of the magnitude of the problem, shall we?
   a. The exposed upward-facing surface area of a typical passenger vehicle is about 4 m^2 (feel free to pick a different realistic number if you don't like this one or are going to consider a particularly small or large vehicle). Based on the maximum 31% external efficiency reported by Henry (his article starts on p. 58 of your reading packet) for an ideal single-gap device exposed to AM1.5 conditions on a cloudless day, what is the maximum power that could be extracted from a solar array covering the upward-facing surfaces of an ideal single-gap device? The total solar power density under AM1.5 conditions is 844 W/m^2.
   b. Convert your answer to part (a) into horsepower. Realize that this is an upper limit that assumes no reflection losses from the surface of the device, that the sun is directly overhead, and that there are no clouds. How about them apples. Damn, and I spent my whole graduate career chasing this dream. Is there any hope? Well, if you use a multi-gap device, you can do better, but they make the expensive single-crystal single-gap devices we've considered here appear downright cheap. You can also do better by concentrating the sun onto a smaller area and cooling the resulting device; that saves on fabrication costs for a multi-gap device, too. But this is a pretty good indication of the problem.
   c. Calculate what speed a vehicle of your choice from the list on the site below (or another vehicle you find a coefficient of drag and frontal surface area for, if you have one you are particularly interested in) would be able to maintain on solar power, assuming only aerodynamic drag is holding it back, and that the drivetrain is 100% efficient. You'll get information very helpful to doing this here:
      http://www.nmt.edu/~weinkauf/es111/ES 111 car drag problem.htm
      Hint: You can check that your answer to part (c) is in about the right ballpark by reading through this website: http://rpm2.8k.com/humpwr.htm
      Note that this says nothing about acceleration; the reason U.S. car engines are often designed to put out 100's of HP is that people want to be able to accelerate quickly, not because they need it to maintain a reasonable highway cruising speed.

4. Based on what you learned to do in 3(c), above, imagine the same vehicle is powered by an ideal (100% efficient) hydrogen fuel cell and electric motor. How many grams of hydrogen would you have to consume per hour to maintain a cruising speed of 70. MPH, again assuming you need to only overcome aerodynamic drag? What volume of water would come out of your tailpipe every hour under those conditions?
   (Don't be too careful with this, feel free to make simplifying assumptions: you are just after a ballpark figure. But *state* your assumptions clearly! It's is important to know what you are brushing under the rug.)