GEOS 24705
Problem set #4
Due: Tuesday Apr. 14

Readings:
Two readings for this week. Both are linked on the website, Braudel as a pdf and Galloway as both a pdf and an online book.

- Braudel, **“The Structures of Everyday Life”, “Energy”** chapter. Read for the ideas, not to memorize numbers. You may skim very lightly over the long section on animal power.

- Galloway, **“The History of Coal Mining in Great Britain”**, excerpts.
  - Chapter I: (p.1-10). **"Coal of Late Coming Into Common Use..."**. *Skimming OK. Note early environmental regulation on p. 9-10.*
  - Chapter II: (p. 11-18) **"Coal Comes Into Use for Domestic Purposes..."** *Skimming OK.*
  - Chapter III: (p. 19-27) **"The Increasing Scarcity of Wood Causes Coal to Come Into General Use For Domestic Purposes. First Difficulties in the Mines"**
  - in Chapter IV, which is mostly about taxes and regulation, only the paragraph on London's dependence on coal (p. 35)
  - Chapter VI: **"Increase in Mining Difficulties. Improvements in Mining Appliances. Invention of Railways”**. (p. 52-67). *Note when Galloway talks about "engines" to pump out the mines on p. 57 he is using the term very generally, heat engines have not been invented yet. He is talking first about hydropower (water wheels) and later "horse engines". The first "railways" are also horse-powered.*
  - Chapter VIII: (p. 76-82) **"Inadequacy of the Water-Raising Machinery, Invention of the Steam-Engine"**. *Note p. 77-78 covers problems with renewables as a source of power for pumping*.

Notes: prices are given in pounds (l), shillings (s, 20 to a pound) and pence (d, 12 to a shilling or 240 to a pound). A "fathom" is 6 feet, or about 1.8 meters. The "noxious gases" or "fire-damp" in the coal mines (p. 26) are methane; methane is often associated with coal seams.

Problem 1: Mechanization of agriculture

Mostly this is a video tour to give you a visceral sense of what the mechanization of agriculture means. Watch the following videos of different methods of wheat harvesting: all of the short ones and bits of the long ones.

Harvesting wheat with a hand sickle. Village practice today in Nepal.
http://www.youtube.com/watch?v=06edzfeznHM

Harvesting wheat with a scythe. An NGO brings "appropriate technology" from Middle Ages Europe to Nepal, and you can see what an improvement it is.
http://www.youtube.com/watch?v=fMxSCDp-f9I

The horse-drawn combine. An amazing actual film from 1938, near the end of the use of horse-drawn power for large-scale farm operations. At 1:52 there is film of a separate harvest operation using a steam engine. At 3:05 you get a more modern combine.
http://www.youtube.com/watch?v=PD2JITVuBAQ

The modern combine. Two options, both long and to be skipped around in. Both "brag" videos by operators. The first shows the 2013 harvest on a (very large) family farm. They have multiple crops but the first part of the video (starting 0:39) is wheat. The second shows two of the largest combines in the world, harvesting an incredible 168 acres in 7.5 hours.
http://www.youtube.com/watch?v=AwOXPMiM3AI
http://www.youtube.com/watch?v=Fl6RGoEqawQ

Questions

A. Estimate the rate of harvesting per area/person*hour for the four operations: sickle, scythe, horse-drawn combine, modern combine. Explain the basis for your estimates.

B. 1938 video: The "combine" combines two tasks necessary in turning the plant into food – what are they? What are people doing at 0:45? What are they doing at 1:52?

C. The combine in the 1938 film is purely a mechanical device, and has nothing to do with energy conversion. Why does the combine allow the main power source for harvesting to be a horse (or a diesel or steam engine) rather than a human?

D. The 1938 and modern videos let you compare wheat before and after the Green Revolution. Discuss the differences you can see and their cause. If it's hard to see the wheat in the 1938 video, look at 3:55-4:30 in this clearer promotional film from the same year: http://www.youtube.com/watch?v=-2Vlgj1IbX0

E. ***(Optional):*** on the Jonsson family farm video, at 11:50 a "chopper operator" is introduced, who then proceeds to harvest several fields. The taller is corn (maize). What is he doing; what will these crops be used for?

Problem 2: Energy density

Energy density is a concept that is deeply important to many applications, especially those involving transportation.

Consider a few possible substances from which we typically extract energy, and determine their “mass energy density” (in energy per mass, in units of J/kg or MJ/kg, i.e. million Joules per kg). *(For extra credit, also do the volume energy density in MJ/liter & discuss).*

The lower the mass energy density, the heavier the fuel you have to carry. The lower your volume density, the bigger your fuel tank (or battery pack) needs to be.

For these problems, don’t Google unless instructed to do so – it’s not educational. State the source of your information in your answers.

A. **Dry sugars/carbohydrates,** from the nutrition label of some package in your kitchen: flour, cornstarch, sugar, etc. Bonus for doing two and comparing.

B. A **carbohydrate diluted** in water: **orange (or other fruit) juice**.

C. A **pure fat**: an easy option is **cooking oil** of some kind. From the food label. Bonus for doing several.

D. How does the energy density of fats compare to that of carbohydrates? Give a ratio.

E. **Gasoline** (a hydrocarbon). OK to get info from web, and convert units as necessary.

F. How does your answer for E compare to that in part C? Diesel cars can be converted to run on biodiesel made from waste cooking oil. Discuss. Would their mileage be compromised (or enhanced)?

G. Electrochemical energy storage in **batteries**.

The power (energy/time) put out by a battery, if connected in an electrical circuit is

$P = I \cdot V$

where P is power, I is electrical current, and V is the battery voltage (which stays constant over the lifetime of the battery. (We’ll discuss all this in more detail later). If current is expressed in the standard unit of Amperes (or “Amps”) and V in volts then the units of power become the standard Watts (J/s). All batteries will state their voltage, but not all bother to tell you anything about the total energy stored in the battery. (Very strange: with batteries we buy a product without demanding to know how much is in the package). If the battery energy content is stated, it’s given as the total current the battery can produce over its lifetime, in “Amp · hours”. The battery’s total energy content (in units of Joules * 3600) is then “Amp · hours” x voltage.

Laptop or industrial batteries do typically list Amp-hours (abbreviated “Ah”), so if you can access a laptop battery the information you need should be written on it.

You then need to weigh the battery. Other options that typically list Ah: rechargeable batteries in cordless drills or other power tools, cellphone batteries, car batteries. (A field trip to Ace Hardware on 55th or Radio Shack on 53rd would definitely get you something.) If you can find the Amp-hours of a battery that has no weight listed and cannot be removed to weigh, it's OK to Google the weight of that particular battery, but it's more educational to do this problem on objects that you can hold in your hand.

If you can't find a single actual physical battery that states its amp-hours, Andrew will have a battery (and a scale) at office hours. Whichever option you take, state your information source and the type of battery. NiCad, lead-acid, and Li-ion batteries all have different energy densities.

H. You frequently hear people discussing electric cars. Why do you never read of any proposals for electric airplanes?

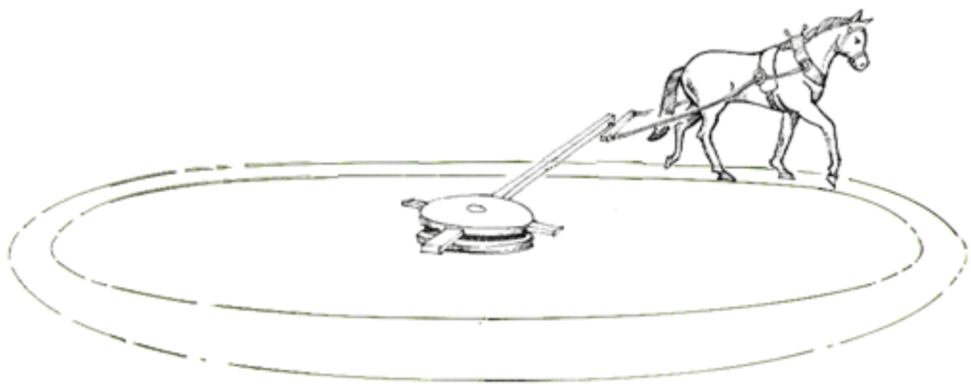
Problem 3: Defining and measuring mechanical work and efficiency

Background

After James Watt invented the first really practical steam engine (patented in 1769, first functional production model in 1774), he was faced with the difficulty of marketing it to skeptical potential consumers who needed convincing why they should buy his product. Watt initially tried advertising his engines as improvements over older and less efficient Newcomen steam engines: he offered to sell an engine for 1/3 the savings in coal that the purchaser would realize over a Newcomen engine. Watt realized eventually though that the majority of his potential customers had never previously purchased any sort of steam engine. To reach these buyers he needed to compare his product with what they were currently using: the horse-engine.

Watt decided he needed a metric relating the mechanical work done by his new engine with that done by a horse. After some careful observations of horses in action turning gristmills and lifting coal up out of a mine, he codified a unit of "horsepower" in 1783. That definition allowed him to demonstrate to potential buyers how many horses his engine could replace. For example, the first rotative steam engine he made, sold to a brewer in 1785 as a replacement for a horse wheel, was billed as "10 horsepower".

In class we estimated a horsepower by assuming 100 W output for a person and scaling up by the assumed mass of a horse vs. a person. That gave us an estimate of 600 W, not too far off from the definition of a horsepower (760 W). (Interestingly, some people have argued that Watt was overoptimistic about the capacity of a horse, and that the average horse can only put out about 0.7 horsepower of work, a bit under the class guess. Watt couldn't have been deliberately fudging his numbers, though – it would have been in his economic interest to undersell the capability of a horse, not oversell it.)



In this problem you'll think about the inputs and outputs of person- and horse-engines.

Questions

A. Other people's estimates of output power: look at Braudel p. 337, at the quote from Forest de Belidor about the relative power output of man and horse. State Belidor's assumption. Is that estimate consistent with the class estimate?

B. Use a thought-estimate about food to estimate your mechanical efficiency, i.e. the ratio of output power to input power. Estimate the additional food you'd need eat per day if you were physically active during whole workday, as opposed to being sedentary, and get your efficiency from remembering that the definition of efficiency is "energy output in the form that you want / total energy input". Don't forget to correct for the fact that a "workday" is not 24 hours.

C. Use a thought-estimate about water to estimate your mechanical efficiency: think about the extra water that you'd need to drink while exercising. That water serves to replace water that you sweated out. Think: why do you sweat? You sweat when you're hot to cool off. The evaporation of sweat provides cooling because as you know, it takes energy for liquid water to become vapor. Think: why do you feel hot when exercising? Because your body is not 100% mechanically efficient, so you must consume more energy (from food) than your 100 W of output power, and the excess energy becomes heat that must be carried away. Your drinking water therefore provides an estimate of total heat production. Estimate your rate of heat loss & your mechanical efficiency. State your assumptions. Compare to your answer in B and discuss.

D. ***(Optional)***. It might be hard to really feel the evaporative cooling of water, but you can definitely feel evaporative cooling by splashing yourself with rubbing alcohol that then evaporates. (Try it! Even if you don't answer this question.) But the latent heat of vaporization of rubbing alcohol (isopropyl alcohol) is actually only about 1/3 that of water. Why does it feel colder?

E. ***(Optional):*** Use Watt's actual data to calculate horsepower. Watt estimated that a horse could pull with a force of 180 pounds while turning a mill wheel. The horse walked on a circle of 12 feet in radius and turned the wheel 144 times in an hour. You will have to convert out of English units.

Problem 4: Defining and measuring thermal energies

Background

How do you measure an amount of thermal energy? A thermometer won't do it - temperature is not the same as energy, and in fact different substances require different amounts of energy for the same change in temperature. In the very early days of thermodynamics, there was no clear agreement on how to measure thermal energy. The French chemist Lavoisier advocated for a unit defined in terms of "latent heat", the energy needed to change the phase of a substance. When considering evaporative energy fluxes on Earth we estimated the energy required to change from a liquid to a gas (the "latent heat of vaporization"). Energy is also required to change from a solid to a liquid, i.e. to melt (the "latent heat of fusion"). The latent heat of fusion for water is much smaller but not insignificant than the latent heat of vaporization: ~0.3 MJ/kg as opposed to 2.3 MJ/kg. The units of latent heat are the same as the units of energy density: J/kg, because it represents a kind of energy "carried" with the substance. Lavoisier argued that the best way to measure thermal energy was to determine how much heat was required to melt a certain mass of ice. To determine the thermal energy released in burning, Lavoisier burned different substances and measured the ratio of fuel consumed to ice melted.

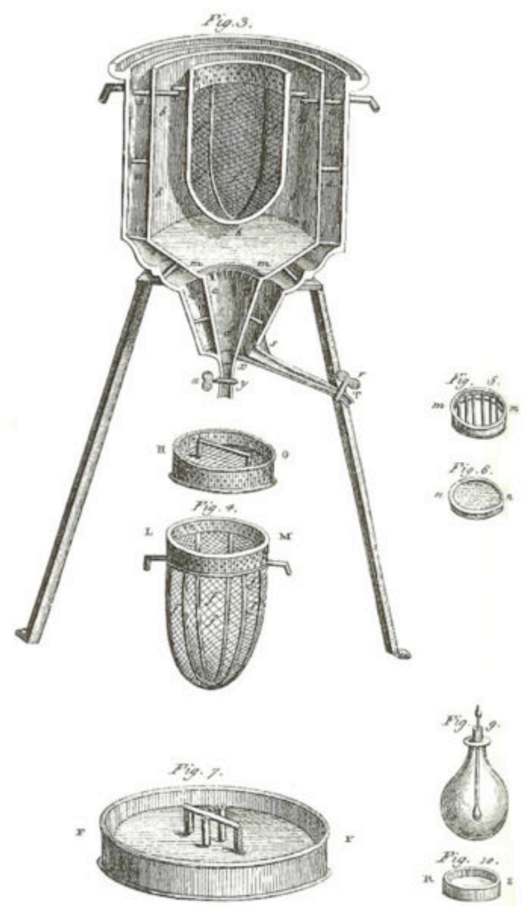


Figure: Lavoisier's "ice calorimeter". The fuel to be burnt goes in the dome-shaped chamber at the center, and ice is placed in the inner and outer jackets that surround it. When the fuel is burnt, heat is transferred to the ice in the inner jacket and melts it. Water from that melting ice drips out of the device and is collected below and weighed at the end of the experiment. The outer jacket serves just to insulate the inner jacket from the warm surrounding environment.

Lavoisier used his chamber to measure not only heat of combustion but also metabolic heat, by putting a small animal (e.g. a rabbit) in the chamber and letting it sit normally for some time. The rate of ice melting then provided a measure of body heat production, i.e. the animal's basal metabolism.

Some version of this calorimeter – either one that melts ice or one that heats liquid water – remains the way that calorie contents of foods are determined.

Questions

A. What ratio would Lavoisier measure if he burned wood to melt ice? I.e. what is the ratio (kg wood / kg ice) in his experiment? You can assume that dry wood is essentially a sugar, whose energy density you estimated in problem 2.

Lavoisier lost out in the argument over quantifying heat to other French scientists. Thermal energy was first officially described in terms of not latent heat but of "specific heat" – the amount of energy required to raise a substance's temperature. The calorie is defined as the amount of energy required to raise 1 gram of liquid water by 1 degree C. (Technically, from 14.5-15.5 degrees, since the specific heat of water is very slightly temperature-dependent).

B. Convert units to compare values – what is the specific heat of water in energy per mass of water per degree of temperature rise, or J/kg/degree?

Now consider how very much thermal energy there is in everyday substances. Let's consider how wonderful the world would be if the 2nd law of thermodynamics didn't hold and we could meet our energy needs by sucking the heat out of some ordinary substance, say seawater.

A. What is the thermal energy in seawater, in MJ/kg, the normal units of energy density, for each 10 degrees Celsius temperature change?

B. ***Optional:*** What is the *total* thermal energy in water? That is, the amount of energy you could extract if you took the water down to absolute zero. For this problem you need to assume a temperature for your water in Kelvin (1 degree K = 1 degree C + 273.15, so a degree temperature *change* is the same in Kelvin as in Celsius, but 0 Kelvin is absolute zero – you can't get any colder than that.) You need to take the liquid water down to zero, then freeze the water (releasing the latent heat of fusion), then take the resulting ice down to absolute zero. The specific heat of ice is about half that of liquid water. *(Physics students: why is the specific heat of solid water less than that of liquid?)*

C. How does this thermal energy density compare to the chemical energy in gasoline?

D. Would this energy be useful, if we could extract it? Consider the volume of ocean water that you "own" as an average world citizen. Since the ocean is 2/3 of the land surface, you "own" twice as much ocean area as you do land area. The average depth of the ocean is about 4 kilometers. How much thermal energy do you "own", in MJ, assuming that you have the power to reduce the temperature of your ocean by 10 degrees? At your current power usage rate (10,000 W), how many years would that ocean power last?

E. Why can't we power the world by extracting thermal energy from seawater? Think hard on this, it's fundamental to physics and to energy technology…

Now consider the latent heat of vaporization:

F. How does the latent heat of vaporization compare to the thermal energy you just calculated?

G. Guess what volume of gasoline would it take to boil away a liter of hot water. State your guess. Then properly estimate by comparing the chemical energy density of gasoline to the latent heat of vaporization of water. (Note that these have the same units – explain why).

H. How does your answer in G relate to the fact that burning yourself on steam in the kitchen is very painful?

Problem 5: Pre-industrial energy usage

In this problem you'll use Braudel's numbers to estimate the per capita power use in pre-industrial-revolution Europe, to understand how far we had come in the progression from 100 W → 10,000 W.

Before you can make this estimation, you need to check one calculation that Braudel worried over. On p. 367, he relates work in horsepower to the chemical energy in wood (that is released as heat on burning), but he worries that his calculation may not be very accurate. Note that Braudel is counting not primary energy inputs but mechanical work outputs (not the the power in animal feed, but instead the mechanical work those animals do). That's presumably why Braudel's wood number on p. 371 is weirdly scaled down (30% of total chemical energy content). He is presumably thinking of the mechanical efficiency engines driven by burning wood. But in pre-modern times, people were just burning wood for heat, so this approach is wrong.

A. First, state Braudel's assertion: how many horsepower correspond to how many tons of wood? Convert this to MJ/kg in wood. How wrong is Braudel's number?

B. With that in mind estimate the per capita power use in Europe before the steam engine.

   Use the figures that Braudel states in his concluding pages for Europe's power use. Braudel's estimates cover most economic activities. He excludes food, wind, and coal, which was still small. If you want to include windpower, you can use Braudel's estimate of its size relative to hydropower. You'll bookkeep up all Braudel's horsepower and tons of wood values and convert each to W and then to W/person. You can assume that the workers who provide the human-power in Braudel's inventory make up 1/3 of the total population (the rest being the elderly and children).

C. List all the various energy conversions that people are doing in Braudel's chapter, and describe the energy conversion chain. For example: *"use of animal power for ploughing, milling, etc.= chemical energy (feed) → mechanical work"*. If this list brings something to mind, discuss. (We will discuss in class).