GEOS 24705 / ENST 24705 / ENSC 21100
Problem set #4
Due: Tuesday April 10

Problem 1: Mechanization of agriculture
This problem is intended to give you a visceral sense of what modern agriculture is and what producing food requires. One big change that has occurred in ag is the increase in crop yields of the Green Revolution. Another is the reduction in labor that has come with mechanization.

Watch the following videos of different methods of wheat harvesting -- all of the short ones and bits of the long ones – and observe how agriculture has gone from the primary occupation of mankind to a sector that, in the U.S. and wealthy W. Europe, employs 1-2% of the population, even while producing excess food for export. (Even robust farm subsidies in France only push up farm employment to 3% of the population.) Each farmer singlehandedly feeds over a hundred others. Farming is not what you think of from books or old movies.

Watch the following videos. Then answer the questions below. The first sequence concerns different ways of harvesting wheat
…with a hand sickle. Village practice today in Nepal.
http://www.youtube.com/watch?v=06edzfeznHM
Note that despite the primitive harvest technology the wheat looks like some short, stubby post-Green Revolution varieity

….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

…..with a 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

..wait a 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 in Montana (note all the Scandinavian names, common in far north U.S. rural areas). The farm has multiple crops but the first part of the video (starting 0:39) is wheat. The second video shows two of the largest combines at the time, harvesting 168 acres in 7.5 hours. The last video is a 2014 Guiness World Record of wheat harvesting, with record given as tons/hour.
http://www.youtube.com/watch?v=AwOXPMiM3AI
http://www.youtube.com/watch?v=Fl6RGoEqawQ
https://www.youtube.com/watch?v=Y5I04EObZNo

Corn harvests. (2015 also offers the innovation of drone shots):
https://www.youtube.com/watch?v=G1LnJQLi4e4 (type 1)
https://www.youtube.com/watch?v=zoev7ltHLoI (type 2)
https://www.youtube.com/watch?v=njI9SrPcoKM&nohtml5=False (type 3)
or https://www.youtube.com/watch?v=yJBk-m5MS7c

Questions

A. Estimate the rate of harvesting as area/person*time for the four operations: sickle, scythe, horse-drawn combine, modern combine. Explain the basis for your estimates. The last two wheat videos give estimates of the harvest rate, the first in units of acres/time and the second in terms of tons/time. You can assume a present-day U.S. wheat yield of 43 bushels per acre with one bushel of dry wheat (ag uses old-fashioned units!) weighing 60 pounds. (Again, the whole energy field uses awful units so it is good to practice unit conversion).

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. Why are so many horses pulling the combine in the 1938 film?

D. The combine itself in the 1938 film is purely a mechanical device, and has nothing to do with energy conversion. And yet it somehow provides the tremendous advantage of allowing the main power source for harvesting to be a horse (or later a diesel or steam engine) rather than a human. Explain this.

E. 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 3:37-4:13 in this promotional film from the same year: https://www.youtube.com/watch?v=OUwAaVL1trg (Note: at 4:16 you can see a farmer cranking a telephone generator of the type that you used in lab.)

F. Describe the 3 types of corn harvesters. Why do they differ? What are the crops used for in each case? You can see a smaller version of type 3 also on the Jonsson family farm video, at 11:50, starting with where they introduce the "chopper operator".

G. *(Optional)* For extra credit, find another harvest video that is even better than this one, for use for next year's class. The GoPro camera means that there are now many of these.

Problem 2: Energy densities of food and other substances

Energy density is a concept that is deeply important to many applications, especially those involving transportation. The "mass energy density" is the energy that can be extracted per mass of substance. We'll always use units of MJ/kg, i.e. million Joules per kg. The "volume energy density" is the energy per volume, typically given in units of MJ/liter. 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. We're not covering transportation in class yet, but we need to start thinking of energy densities when we consider energy derived from burning wood or food (as in the next problems).

Food energy density is often stated in units of Calories/gram. (Remember one Calorie is 1000 Physics calories.) Carbohydrates and proteins are both around 4 Cal/g. Fat, whose entire purpose is to store energy, is as you'd expect more energy dense, at about 9 Cal/g. In these problems, you'll estimate the mass energy density of various substances in more standard units of MJ/kg. (The M means "mega" or million). We want you to examine actual substances, so don't Google unless instructed to do so – it's not educational. For all problems state the source of your information. Extra credit for also calculating the volume energy density.

A. **Dry sugars/carbohydrates.** Get this from the nutrition label of some package in your kitchen: flour, cornstarch, sugar, etc. Do at least two and compare. Given values also in Cal/g to check – do carbohydrates seem to match the rule of thumb of 4 Cal/g?

B. *(Optional)*: 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. Check also to see if the fat meets the rule of thumb of 9 Cal/g.

D. **Gasoline** (a hydrocarbon). Here it's OK to get info from the web; convert units as necessary.

E. 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)?

F. Electrochemical energy storage in **batteries**. You can weigh a battery to get its mass, but how do you know its energy content? It's a strange fact that most batteries don't actually state their energy content (what other product do we buy without demanding to know how much is in the package?) but some do list it. 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). In this equation, 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, and some will give the total current the battery can produce over its lifetime, in "Amp · hours" or Ah. The battery's total energy content (in units of Joules * 3600) is then Ah x V. Laptop or industrial batteries do typically list Ah, sometimes also rechargeable batteries in cordless drills or other power tools, cellphone batteries, or car batteries. (A field trip to Ace Hardware on 55th would definitely get you something.) 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.

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

Problem 3: Agricultural yield and land use

In class we saw that we currently use about 1/3 of the Earth's surface area for food production, with about 13% (2600 m^2) farmed for crops and a slightly larger portion used for pasturing animals. That cropland is for our current mix of foods, and includes crops grown for animals and low-calorie vegetables that take up substantial land but don't provide a lot of energy. We saw from slides that people in Bangladesh seemed to feed themselves on approximately 500 m^2 per person. (Slides also give photosynthetic efficiencies.) In this problem you'll consider the minimum land you could support yourself on, given a monotonous grain diet and high-yield farming, and then consider the extra resources required for meat production. Getting the same number of calories from an animal as opposed to a plant is necessarily more land-intensive: it still involves plants converting solar energy into chemical energy in sugars, with low photosynthetic efficiency, but then there's another inefficient step: an animal must eat the plant and converts the chemical energy in plant material to chemical energy in meat.

A. What is the minimum land you could feed yourself from? Maize (which Americans call "corn") is the crop that produces the most calories per acre of any grain, and so is the food of choice if you're just trying to grow cheap calories. How much land would you need to feed yourself a minimal (corn-only) diet with best-yielding modern agricultural methods? Compare that to the arable land per person in Bangladesh. What is the inferred efficiency of converting sunlight to food in Bangladesh, and is that reasonable?

B. Consider a cow raised on grass. We want ultimately to calculate the efficiency of converting sunlight to chemical energy in beef. Start by estimating the total energy input of sunlight hat went to 'build' that cow, in Joules. First, how much sunlight was used? The standard rule of thumb for raising grass-fed beef is that you'd need about 1 acre of good pastureland per cow. A cow is typically slaughtered at about 18 months of age.

C. The cow doesn't of course use sunlight directly but eats grass. How much "grass energy" went to build the cow? From today's lecture, you know that good pastureland is about 1% efficient at capturing sunlight and converting it to chemical energy. You can assume the cow eats all the new grass production during its lifetime.

D. Now estimate the energy you get out of eating the cow. First you need the mass of the cow. (You can guess this or look it up if you fear your intuition about cows is lacking). Then you need to estimate the fraction of the cow that can be eaten. You have some sense of this if you've ever bought a whole chicken or turkey to cook – anyone who has cooked a Thanksgiving dinner knows they have to buy a turkey whose weight is substantially more than the amount of meat your guests can eat. Finally, you need an energy density for meat. Since fats and proteins have different energy density, the calorie content of meat depends on its fat content. Beef is often about 15% fat, i.e. its energy density is ~0.85*4 + 0.15*9 ~ 5 Cal/g.

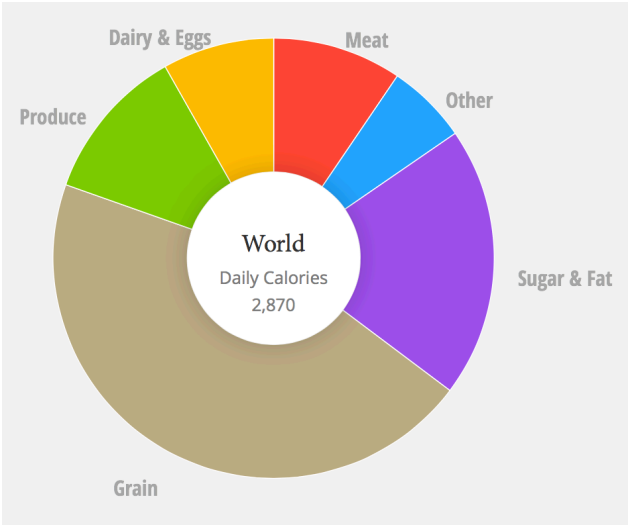
E. Compute the overall efficiency of the cow at producing edible food from sunlight, and discuss.

F. Divide C by D to get a factor that describes the additional land you'd need if you ate grass-fed beef rather than grass. This is just the inverse of the efficiency of the cow at converting food to meat, and so it's independent of the food source. You'd get the same value if you calculated the additional land you'd need to eat maize-fed beef rather than maize. But, for optional extra credit, adjust your result to compute the factor that describes the additional land you'd need to eat grass-fed beef rather than maize.

G. ***(Optional)*** Consider the chicken. Do you think a chicken would be more or less efficient at converting its food to meat than a cow is? Explain what evidence you use to make this inference. Then check by estimating this efficiency. Data: a regular-size "broiler" chicken raised for eating consumes about ¼ pound of food a day and is slaughtered at about 6 weeks age. If you don't know the mass of a chicken, you can do a field trip to the meat section at Treasure Island or another grocery store to investigate.

H. ***(Optional)*** If you made the trek to a meat counter, compare the prices of chicken and beef. Do these relate to the efficiencies you just calculated? Discuss.

I. ***(Optional)*** Visit the excellent website put together by National Geographic that gives an interactive tool for visualizing food consumption across the world. https://www.nationalgeographic.com/what-the-world-eats/. Below is the graphic that shows world food in 2011, but you can get sub-category breakdowns by clicking, or get any other year since 1960 (or a movie of changes over time) by clicking at the bottom. Poke around on this site and discuss interesting things you that see. (You don't need numbers, just discuss. We may do numerical questions with this site later.)



Problem 4: Estimating the power and efficiency of the human engine

In the previous problems you considered the efficiency of transforming sunlight to chemical energy in food, or one form of chemical energy to another (grass → meat). In this problem you'll consider the efficiency of converting the chemical energy in food to mechanical work. You can tell that the human body is not perfectly efficient at turning the chemical energy in food into work, because whenever you do significant work you become warm – you convert some chemical energy into heat rather than the work.

A. First, estimate your output power over several hours of sustained effort. You can do this in many ways, just explain your estimate clearly. You could remember the rowing machine lab. Or do a thought experiment: imagine walking up a hill of known vertical height h, imagine the time t to walk up it, assume the energy output is the gravitational potential energy that you gain (E = m*g*h), and estimate your output energy E and your power E/t. Or you can do an experiment: walk up a staircase, keeping your pace to one sustainable for several hours.

If you estimate your power output from a walking experiment (either a thought-experiment or a real one), you should nudge your estimate upwards somewhat to account for mechanical inefficiencies: walking requires that you do unnecessary work lifting and lowering your legs that doesn't contribute to increasing your mean gravitational potential energy. This is why walking even on flat ground takes effort.

Then you'll estimate your efficiency at turning food into work in two ways

B. Estimate your efficiency by directly considering the additional food intake that results from your effort. If you walk for several hours, you're going to be snacking while walking, or eating a really large dinner at the end of the day. A typical energy bar is about 200 Calories. (Remember that a nutritional Calorie is really 1000 calories). How many would you eat during your several-hour hike? This is your additional intake energy. Divide the work that you did during your exercise by your additional intake to get your efficiency of converting food to work.

C. Estimate your efficiency by considering the extra water that you drink. You drink when you exercise because you lose water by sweating. But why do you sweat in the first place? Because your body puts out extra heat, and it removes that heat by evaporative cooling. So, estimate how much water you drink during your period of exercise. (A standard water bottle is about a liter). Use the latent heat of vaporization (the true value) to get the energy/time carried away by evaporative cooling, in W. Since your total energy input goes to both work + heat, your efficiency is

e = (power out as work)/(power out as work + power shed by evaporative cooling).

D. ***(Optional)***. It might be hard to feel the evaporative cooling of water, but you can definitely feel evaporative cooling if you splash 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 alcohol feel colder?

E. ***(Optional*)**: Note that the rowing machines in the gym have a reading of calories burned as well as one of output power. How do they get that? By measuring your output power and *assuming* an efficiency. Go to the gym, take both readings off the machine, and derive what efficiency the rowing machine manufacturer assumed. Get the factor at a few different levels of effort. Is the assumed efficiency constant regardless of the work you're putting out?

F. ***(Optional)*** The era of greatest interest in human-powered vehicles was the 1980s to early 1990s. That period saw the setting of the distance record for human-powered flight that still stands: in 1988 the plane Daedalus 88, built by the MIT Aeronautics and Astronautics Dept. and powered by the Greek Olympic cyclist Kanellos Kanellopoulos, flew 119 km from the Greek island of Crete to crash-land just meters from the beach on the island of Santorini. (A Japanese team was trying to beat this in 2012 but seems not to have succeeded.) In developing Daedalus the MIT team worked out a lot of the framework for thinking about human power that now is used in athletic training. Read the article posted under "Readings" that summarizes the MIT engineering team's analysis, and compare their findings on efficiency to your estimates above.

Also for those who completed the Humanities core, why was "Daedalus" an appropriate name for this vehicle?

Problem 5. Sustained power from the human engine

Background: Some of the greatest power outputs of any humans are put out by professional cyclists. Many top cyclists are capable of doing 400 W of mechanical work steadily for the course of a bike race (even without doping, it seems). Interestingly, it's not wear and tear on the body that limits the practical length of bike races. The length of bike races is limited not by the legs' tolerance for the exercise but by the stomach's ability to take in fuel: people can't digest more than ~ 10,000 Calories / day. In this problem you'll be a race director and design a bike race like the Tour de France around that constraint. For the sake of this problem, assume the mechanical efficiency of each bike rider is ~ 20%. That is, the power that riders put out as work is only 20% of the total power they must take in as food.

Problems:

A A Tour de France race averages around 5 hours (note that this is 5 hours hurtling along at 40 km/hour; you would take far, far longer). During that time their average power may be close to the peak power many of you found you could put out (~ 400 W). So assume that your rider – we'll call him Lance – puts out 400 W that whole time. What are his energy requirements for a race day (in J, or Calories)?

Don't forget to add the amount a sedentary person would eat/day – he needs to keep his basal metabolism going too. And be precise with this calculation – don't do an order-of-magnitude estimate. Note: the fact that you need to be precise to get the "right" answer means that I fiddled with the inputs a bit to make your answer match reality – in this problem you'll be calculating a small difference of two large numbers, and that's a hard estimation to make.

B If Lance can eat only 10,000 Calories per day, how much weight would he lose (kg of fat) each race day? From Problem 1 you should have gotten that fat is ~ 9 Cal/g. Convert to pounds as well if you don't have a good sense for what a kg is.

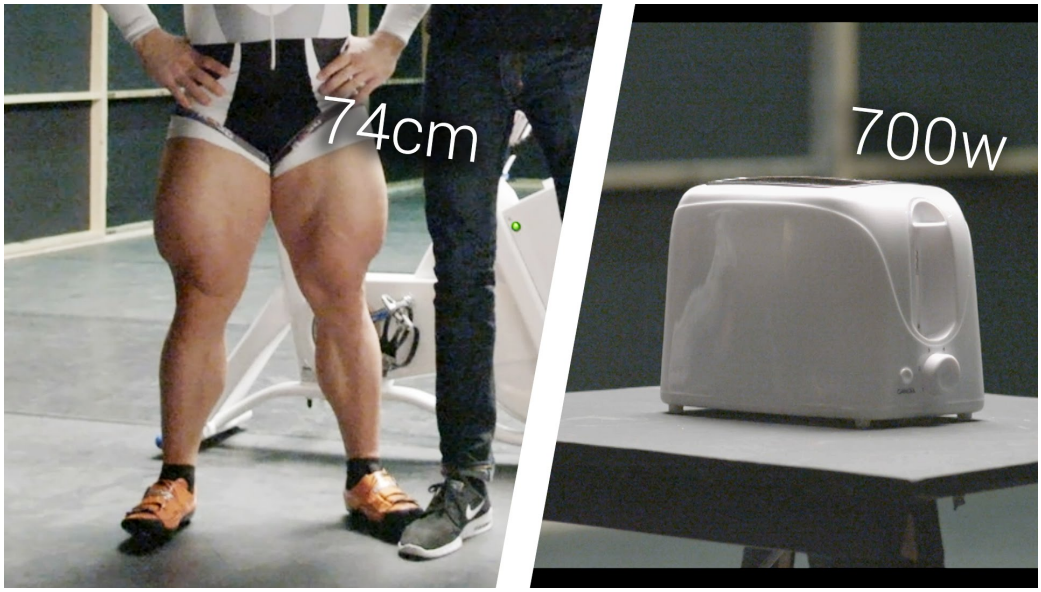
C If there were no rest days during an ~20-day Tour de France, how much mass of fat would Lance lose (in kg or pounds)?

D If Lance is 165 pounds to begin with, and has 3% body fat, is this a safe amount of fat to lose?

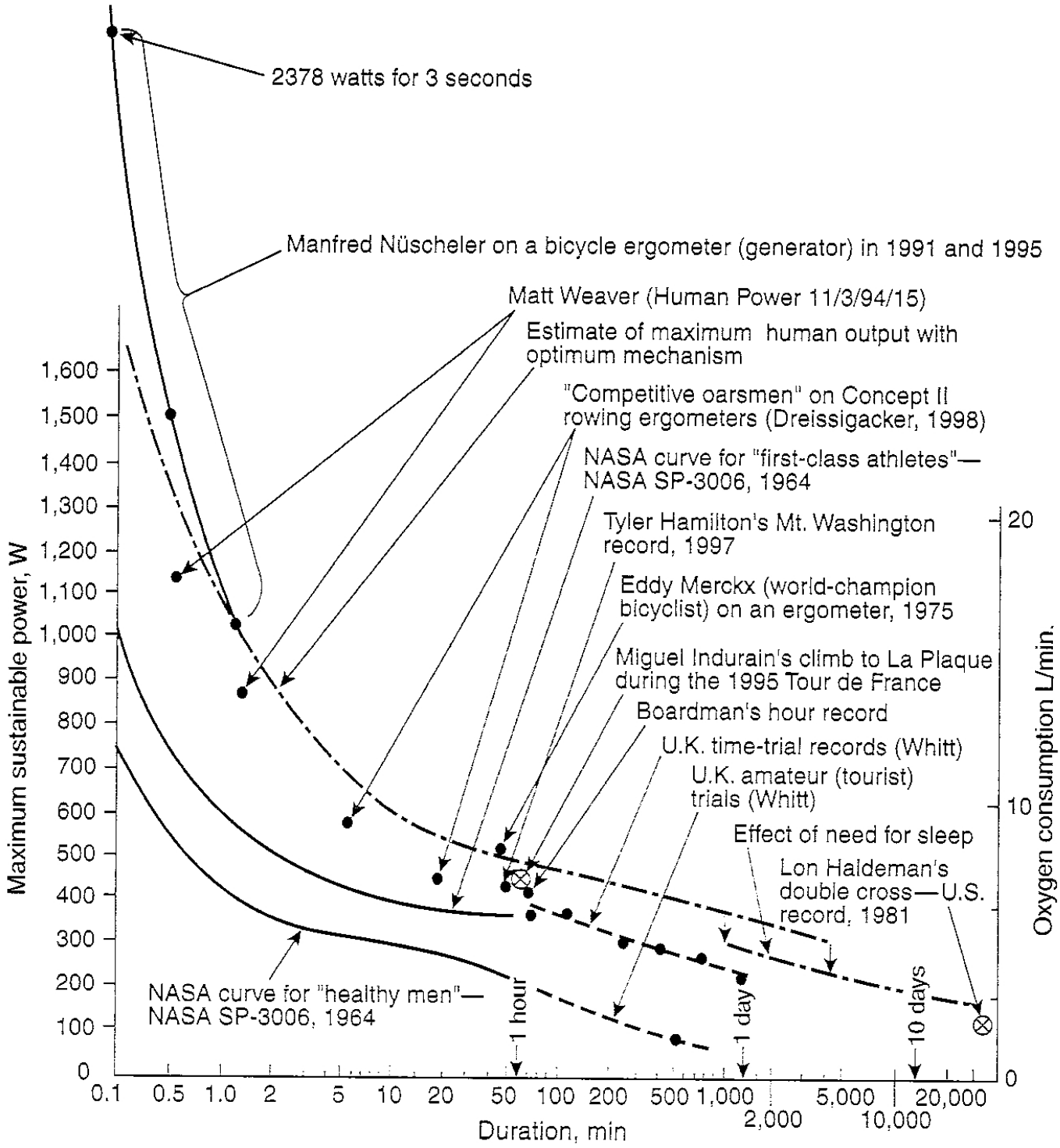
E As race director you might conclude this is not safe. If so you need to assign some rest days. Assume that on rest days the riders can still eat 10,000 Calories/day and that they sit still or ride gently and recuperate. How many rest days must you schedule to ensure that everyone maintains a safe weight during the Tour?

F Google – how many rest days are there on the Tour? Did you make the right choice?

G ***(Optional)*** The greater the power output, the shorter time one can sustain it. Watch this video https://www.youtube.com/watch?v=S4O5voOCqAQ of the German Olympic sprint cyclist Robert Forstemann trying to drive a 700 W toaster for long enough to toast a piece of bread. *(Caution: he swears in this video, In English.)*



Then compare to the chart on the next page, which uses data up through the 1990s. Plot Forstemann's effort on the chart.



(Note that two of the cyclists on this chart, Indurain and Hamilton, were proven dopers. The far right data point is from ultramarathon cycling and represents average power while cycling across the U.S. and back, calculated for the whole trip inclusive of sleeping time.)

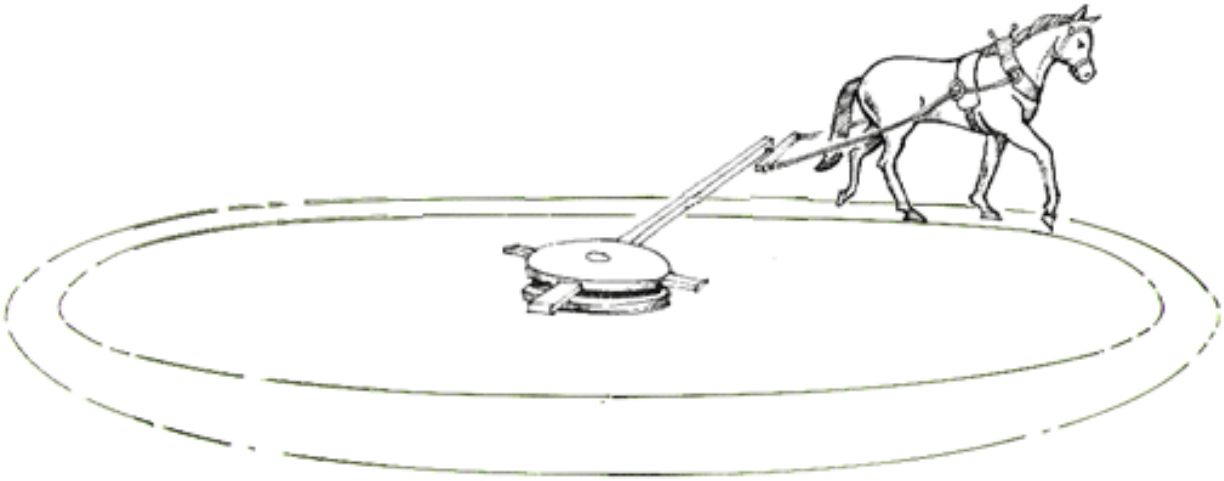
Problem 6: The horse-engine

Background

People have been using horse-engines for thousands of years. The first domesticated horses may have been used for meat, but people quickly discovered their utility for doing work -- pulling and carrying – and for many purposes they replaced the person-engine. Evidence of horse riding dates to over 5000 years ago.

The work output by a horse was not quantified, however, til far later, after the invention of the first real competition for the horse-engine. James Watt, who invented the first commercially practical steam engine (patented in 1769, first functional production model in 1774), now has his name on the current standard unit of power, but he himself actually defined a different unit of power. Watt encountered difficulty at first marketing his engines to skeptical potential consumers. He initially tried advertising his engines as improvements over older and less efficient Newcomen steam engines, offering to sell an engine for 1/3 the operating cost savings in coal that the purchaser would realize. However, he soon realized that this sales pitch was unconvincing because 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 actually using: the horse-engine.

Watt decided he really needed a metric that could compare the mechanical work done by his new engine with that done by a horse. After some careful observations in 1783 of horses in action (turning gristmills and lifting coal out of mines), he codified a unit of “horsepower”. This quantitative metric allowed him to demonstrate to potential buyers how many horses his engine could replace. The first rotative steam engine he made, sold to a brewer in 1785 to replace a horse wheel, was billed as “10 horsepower”.



In this problem you’ll come up with your own estimate of the “horsepower” in units of Watts, and then compare to Watt’s estimate. This class doesn’t have a horse to observe, but you can start with estimating your own capabilities. Don’t look up what a horsepower is til you’ve finished parts A-D.

Questions

A. As in problem 4, estimate the mechanical work you could put out steadily during a workday, in Watts. (Don't average over 24 hours; just consider the time you're working). You can just use your prior answer, but do a check on it by realizing that no matter how much you train you cannot match the output of Lance Armstrong, so your value should be < 400 W.

B. A horse is obviously more powerful than you are. But since you're mechanically not so different from a horse, you could reasonably guess that your power output *per mass of muscle* might be equal to that of a horse. That is, you could assume that both you and the horse have equal power relative to mass. You know your own mass and you just estimated your power above. Now estimate the mass of a horse, and use all this information to estimate the horses' power output in W. This is your guess at the value of 1 horsepower.

C. *(Optional)* Use Watt's actual data (unfortunately in English units that you will have to convert) to calculate a horsepower. Watt observed a horse walking in a circle turning a mill wheel. The horse walked a circle of 24 feet in diameter and turned the wheel 2.5 times per minute, and Watt estimated that it pulled with a force of 180 pounds. (Note that in this context, the word "pound" really means the unit of "pounds-force", i.e. the force m*g you would have to exert to move a 1-pound mass m against the acceleration of gravity g).

D. Look up the current standard definition of horsepower (in W) and compare to your estimates above, and discuss.

E. ***(Optional)***. Use info in the article by Smil (posted on the website) to calculate the *input* power of the horse, in W, from food. Is your result reasonable given your answers above?

Note: Of course, if bigger horses produce more power, there's a natural incentive to breed for size: hence Clydesdales, Percherons, Belgians, Friesians, Shires, and other draft horse breeds that are over twice the weight of typical riding horses (just as a tractor weighs much more than a passenger car.) These horses can stand over 6' tall at the shoulder.

World champion Percheron show horse.

You can see him in action here:
https://www.youtube.com/watch?v=b9cMHfjocDc

For real pulling contests, see:

https://www.youtube.com/watch?v=H_xB4sE_AVY
https://www.youtube.com/watch?v=gWRscujkPxU