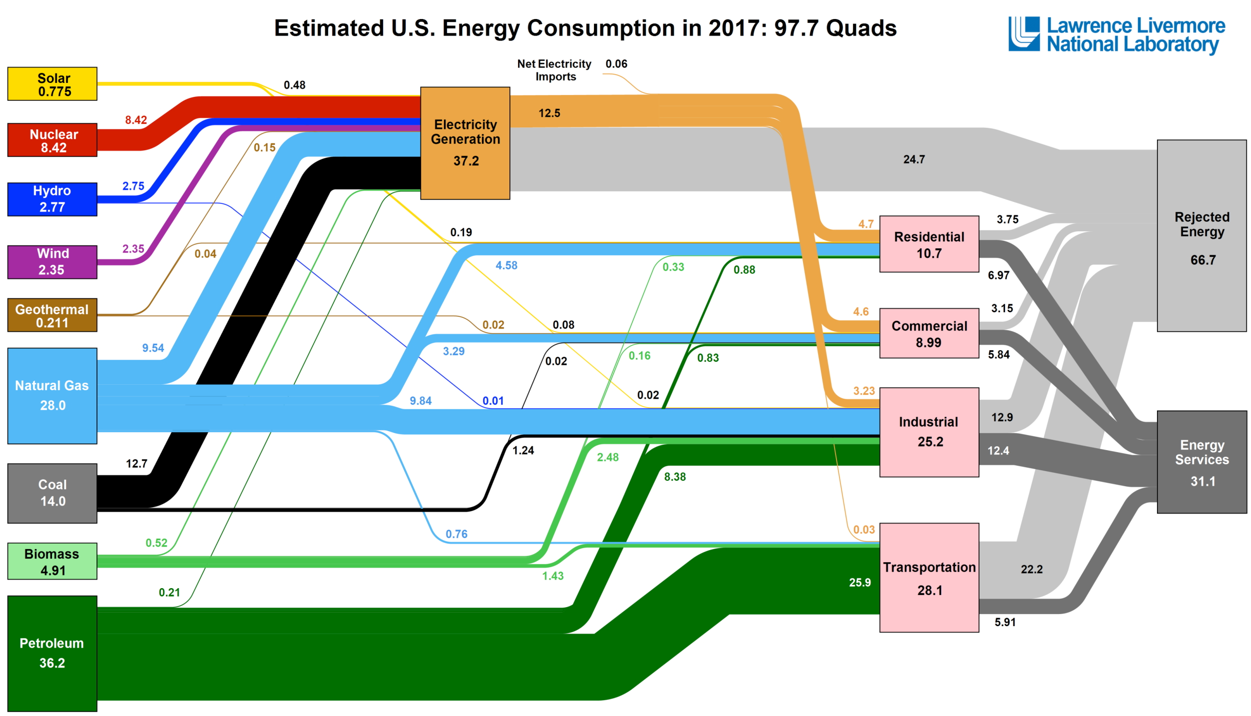
GEOS 24705 / ENST 24705 / ENSC 21100
Problem set #8
Due: Tues. Apr. 25

Problem 1: Efficiency of modern engines

In previous problem sets you looked at the efficiency of steam engines up to 1850. In this problem you'll estimate the efficiency for two parts of the modern energy system: the internal combustion engines that power our transportation, and the turbines that make most of our electricity. (A turbine is still technically a heat engine, but it's not an engine of the type we've discussed, with pistons and cylinders.) Below is the energy Sankey diagram for 2017. (In class you saw 2008, 2012, and 2016.) The left side of the Sankey diagram shows primary energy sources, using mostly the same convention for "primary" as we did in our problem using numbers from Braudel[1]; the right side shows final uses of energy. The thicknesses of the lines are proportional to the size of the energy flow. The dark grey is energy that we get out in forms that we want; the light grey is waste heat that we don't want and can't use. Note that while the definition of waste heat from heat engines is straightforward, deciding what (if anything) to call "waste heat" from buildings and industry is somewhat arbitrary, and it seems like the lab's practices on this have changed over time. Also, the diagram leaves out human and animal work, probably because these are negligible now relative to the rest of our energy system. The Quad is a unit of energy. As we saw in class, given the current U.S. population, one Quad of U.S. energy use in one year works out to about 100 W/person.



1 Defining what is meant by a "primary" energy flow involves somewhat arbitrary choices. You saw this already in the problem where you calculated European "primary" energy uses with numbers from Braudel. As in our problem, the Sankey diagram considers as "primary" the chemical energy from fossil fuels and biomass, which gets liberated as heat with 100% efficiency (same for the heat liberated by nuclear reactions in nuclear reactors). It's awkward however deciding how to book-keep energy derived from wind and hydro (and solar). In the Braudel problem we counted as primary the mechanical work done by windmills rather than the kinetic energy of the wind. Similarly, the Sankey diagram counts as the primary energy flow the electricity made by renewables (wind, hydro, and solar), not the kinetic energy of wind, the gravitational potential energy of falling water, or the radiation energy of the sun falling on solar panels.

Questions

A. **What fraction of U.S. energy usage goes through a heat engine?** That would be essentially all the energy used for transportation (electricity is negligible), and for electricity generation, those energy sources that use a heat engine to turn a generator: coal, gas, nuclear, and geothermal.

B. **What is the mean efficiency of the heat engines in the transportation sector in 2017?** The transportation sector is effectively 100% heat engines. The electricity input for transportation tiny, so you can ignore it.

C. **What is the mean efficiency of the heat engines in the electric sector in 2017?** Because electricity is made from many different energy sources, you have to be more careful at estimating the efficiency of only those heat-engine parts of the mixture. As discussed in footnote 1, you can assume that the solar, hydro, and wind inputs to the electricity generation box are the same as outputs for these source, and therefore subtract them from both sides.

D. **Compare your efficiencies for the heat engines used in transportation (B) and in making electricity via coal, gas, and nuclear (D, E, F) to the maximum efficiencies of steam engines in the Smil diagram. Also compare to the maximum efficiency for an advanced gas turbine/combined cycle system that you saw in PS7.**

   Problems E-H below are optional for the weekend; I will assign them as part of the short PS this week.

E. In the whole-U.S. Sankey diagram you can't disentangle efficiencies of the different kinds of heat-engines used for electricity generation. You can only figure out the average efficiency. But it turns out that U.S. states are fantastically diverse in their energy usage, so that by looking at individual states you can get a better idea of individual efficiencies. Lawrence Livermore didn't put out state-by-state figures for 2017 but there are figures from 2014 available on their website at https://flowcharts.llnl.gov/commodities/energy. Set the year to 2014 to best see.

   Find a state that whose electricity generation is overwhelmingly from coal and **estimate the efficiency of generating electricity from coal.** Note what state you used and why you picked it.

F. Find a state that whose electricity generation is overwhelmingly from gas and **estimate the efficiency of generating electricity from gas.** Note what state you used and why you picked it.

G. There is no state whose electricity generation is overwhelmingly nuclear, but several make significant use of nuclear. **Which state has the highest fraction of electricity nuclear energy in their electric sector?** Use this state to **estimate the efficiency of generating electricity from nuclear**. You will have to bookkeep carefully – use your estimates above to first subtract out both the inputs and outputs of coals and gas generation, which now are not equal.

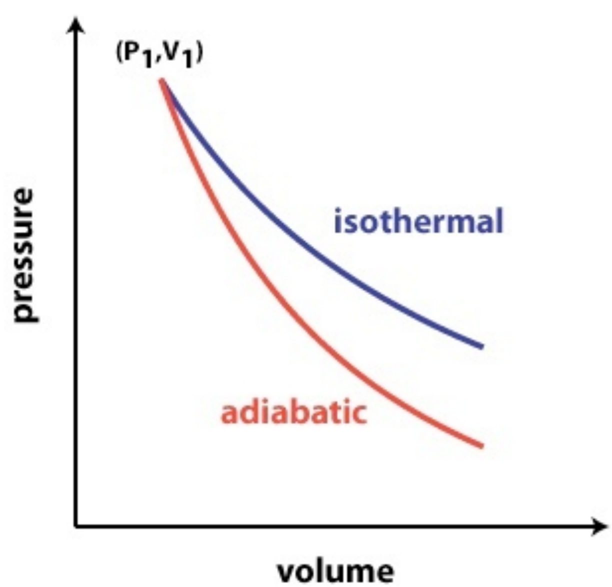
H. Pick at least 5 unusual states (that are unusual in different ways) and describe what is different and why conditions in that state led to a different pattern of energy usage. Good examples to use include (but are not limited to) Alaska, California, DC, Hawaii, Iowa, Louisiana, Maine, Washington, West Virginia. Extra credit for doing more than 5 states.

Problem 2: Limits to efficiency of heat engines - Carnot's theory

Background / review

In class we went through Carnot's arguments that allow deriving the limiting efficiency for heat engines. We discussed that any heat engine is a mechanism that transfers heat from a hot reservoir to a cool one, but extracts some of that heat flow as mechanical work. We also talked about Carnot's assumption that for the most efficient engine, you should add heat only at the hottest temperature and remove it only at the coldest temperature. That requirement immediately let us derive the four stages of the "Carnot cycle": there must be a stage at a constant temperature T_{hot} during which heat is added and one at a constant temperature T_{cold} where heat is removed, and those two stages must be connected by two additional stages during which NO heat is added or removed. Any process that does not involve adding or removing heat we call "adiabatic", so the Carnot cycle must consist of two "**isotherms**" and two "**adiabats**".

We also thought about the **shape** of isotherms and adiabats on a P-V diagram. From the ideal gas law PV = NkT, we realized that the isotherm (with T constant) is a curved line with $P \alpha 1/V$, as in the figure below.



We also realized that if you let compressed gas expand and push a piston (increasing volume and decreasing pressure in the cylinder), that piston does work on its environment.
If temperature stayed constant as the piston moves, then the internal energy of the gas would not have changed. But the work done by the piston must come from somewhere, so energy must have been added to the system. That is, gas can expand isothermally only if heat is added. This insight let us predict the evolution of the gas if we insulated the cylinder, preventing all heat exchange. In that case the work done by the piston could only have come out of the thermal energy in the gas, i.e. its temperature must fall. That is, "adiabatic expansion" lowers the gas temperature. (Similarly "adiabatic compression" raises it.) We then did the thought-experiment of letting two systems expand to the same final volume, one isothermally and one adiabatically. Since the final temperature of the adiabatic cylinder would be cooler than in the isothermal case, by the ideal gas law PV = NkT its pressure must be lower. On a P-V diagram, an adiabat must be *steeper* than an isotherm.

Carnot's cycle then looks like this (as a P-V diagram on the left and a T-S diagram on the right):

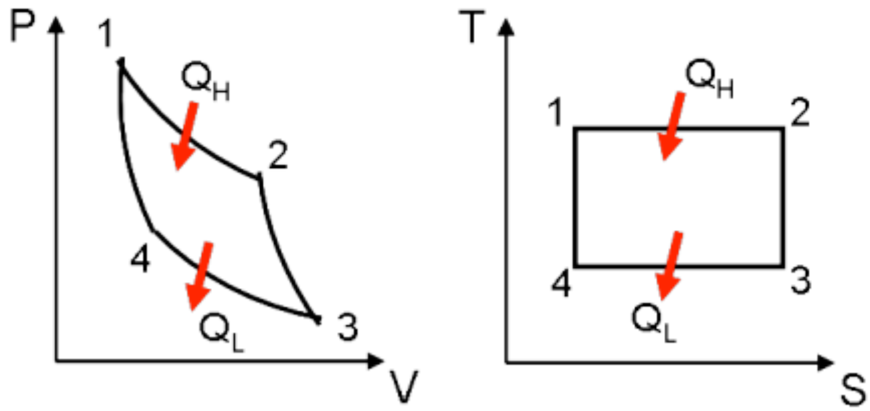


Fig.1. P-V and T-S diagrams of Carnot Cycle

Isotherms: During the isothermal leg from 1-2, the gas expands and would ordinarily cool – but heat is allowed to flow in to keep the temperature at T_{hot}. During the isothermal leg from 3-4, the gas is being compressed and would ordinarily warm – but heat flows out to keep the temperature at T_{cold}.

Adiabats: Consider 2→3. Here high-pressure gas is being allowed to expand into a larger volume doing work *on* its environment, and in the process it is cooling (temperature goes from T_{hot} to T_{cold}). The expanding gas is pushing on its environment, and that energy expended on that work is compensated for by a drop in temperature. It might seem a bit wrong that the gas is transforming thermal energy completely into work, but this isn't a violation of the 2nd Law, because in order to complete the engine cycle you have to do work on the gas again in leg 4→1 to re-compress the air and re-heat it. Think of the insulated cylinder that we considered in class, where the piston was pushed down and then allowed to pop back up again. In that case the work done on the piston exactly equaled the work done by the piston, so that over the course of one cycle there was zero net work. You should be able to convince yourself that the work done during the two adiabatic legs of the Carnot cycle exactly cancels.

The *net* work done by the engine over one cycle is the part of the original heat flow into the engine that DIDN'T flow back out again. In our terminology,

$$W = Q_{in} - Q_{out}.$$

The question that Carnot pondered was, how MUCH work can you get out of the whole cycle for a given heat flow in? What is the limiting efficiency: $e = W / Q_{in}$?

In the P-V diagram above, we know that the area enclosed by the engine cycle is the net work Q_{in}-Q_{out}., since work is the integral of P dV (pressure x change in volume). We derived the Carnot efficiency e easily by changing variables. Since the net work is the same as the net heat flow over the cycle (the integral of dQ), we can describe it more simply with a bit of sleight-of-hand, converting dQ to T (dQ/T). The expression dQ/T is in thermodynamics the change in entropy dS. In other words, dQ = T dS, and *the net work (the integral of dQ around the cycle) must also equal the area on a T-S diagram*. This reasoning made it simple to compute both the net work and the heat flows in and out of the engine.

The questions below are just review, to ensure that you really internalize these concepts.

Questions

Describe the four stages of the Carnot cycle. That is, for each stage:

A. Draw a cylinder and piston and explain what is happening during this stage of the cycle.

B. Draw the evolution of pressure and volume on a P-V diagram, and that of temperature and entropy on a T-S diagram.

C. State whether the piston is doing work or whether work is being done on the piston. Shade in the area under your P-V curve: this is the work done on or by the piston.

D. State whether heat is flowing into the gas, flowing out of it, or whether no heat flow occurs. Write an expression for the amount of heat transfer during the stage.

E. *(Optional)* **Derive the P-V relationship for the adiabatic segments of the cycle.** For an isothermal leg, the ideal gas law is all that you need, and the "rule" is just P*V = constant. If T is not constant then the ideal gas law isn't enough to tell you how P, V, and T all evolve together. You need another equation. But, you have a second equation here: you can write conservation of energy as $dQ = p\,dV + C_v\,dT$. Here Cv is the specific heat of the gas – the amount of energy required to raise the temperature by a given amount. The equation says that any added heat becomes either work or thermal energy. The equation is about changes (dV and dT); how do you use it in conjunction with the ideal gas law? Hint: try differentiating the ideal gas law, then substitute in to get a single equation in just P and V, then integrate.

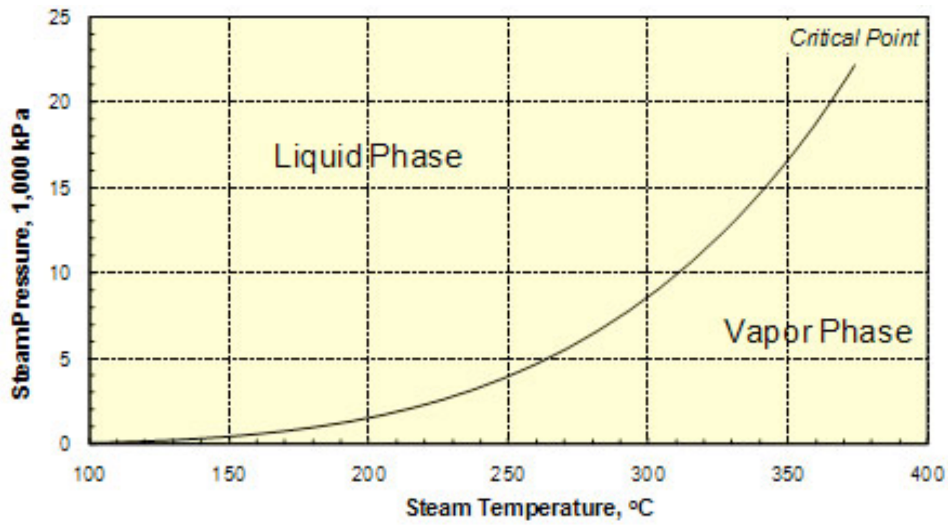
F. *(Optional)* **Integrate around the P-V diagram of the Carnot cycle to get total work.** You can integrate just the isothermal legs if you explain clearly why the work done by and on the engine on the adiabatic legs should cancel.

G. *(Optional)* **Show explicitly that the work done on the adiabatic legs will cancel.** If you didn't answer C for this, you can look up the relationship.

Problem 3: Implications of Carnot efficiency for steam engines

You saw that early engineers were striving to increase engine efficiencies. They could get some benefit by reducing wasteful frictional losses. They could (as you'll see later) try to make their engine cycles more like Carnot's. Most importantly, they could increase engine temperatures.

However, using steam imposes some particular difficulties here. To make steam, you have to heat water in a boiler, and while that steam is in contact with liquid water, its pressure is determined completely by the temperature of the water. (In physics we would say that "vapor pressure of water is a function only of temperature.") The rise of that vapor pressure with temperature is extremely steep. (See figure to right.)



Of course, higher pressure is good in one sense, because it means more engine power: pressure is force/area. This means that steam engine power *naturally* went up along with efficiency. The problem was, the connection between pressure and temperature for steam is SO steep that pressures became difficult to contain, and started to stretch the limits of what engineers could do. The quest for hotter engines and efficiency meant more powerful steam engines, but also dangerously high pressures in boilers, meaning that if a boiler failed the results were more and more catastrophic. As the 19^{th} century went on, boiler explosions became increasingly common and with greater fatalities.

Locomotive after a boiler explosion.

A. Toward the end of the steam era, in the quest for increased power and efficiency, high-pressure boilers were heated to ~275 Celsius. What would the Carnot efficiency be at this temperature? Compare to the actual efficiency of engines, from the Smil diagram.

B. Consider the steam pressure diagram above. The steam pressure looks very low at 100 C, but the units on the y axis are very large. Each tickmark is 1000 kPa, which is 1M Pa or 140 psi or, in the most intuitive units, 10 atmospheres. The steam pressure at 100 C is actually 0.1 tickmarks on this graph. What does that mean? Discuss.

C. For the last-generation steam engines at ~275 C, what was their steam pressure? You can read this off the diagram above, or for extra credit also compute it using the expression in the notes on steam. It is probably most intuitive to leave the answer in “atmospheres”.

D. If air is heated to 275 Celsius in an enclosed container, what is its pressure? You can answer this just with the ideal gas law PV=NkT. Since the container is enclosed, V is constant. Then pressure is proportional to temperature: $P_2/P_1 = T_2/T_1$. Remember though that when taking temperature ratios you must convert to Kelvin first. Compare to your answer in C.

E. *(Optional).* We saw that it is possible to make an engine whose working fluid is just air, as Carnot envisioned. The picture at left shows a hot air engine designed in 1875 and built in 1910, fired by coal and used to pump water. But, external combustion air engines never came into common use. If these engines avoided the terrible high pressures of steam engines, **why did people then continue use steam engines?** What was the drawback of the air engines? Think and discuss.

(Picture: rustyiron.com)

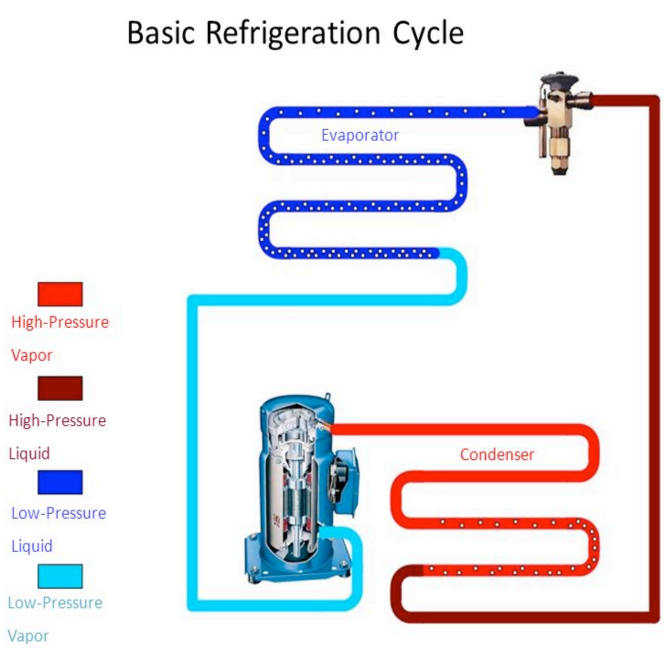
Problem 4: Heat engines and heat pumps

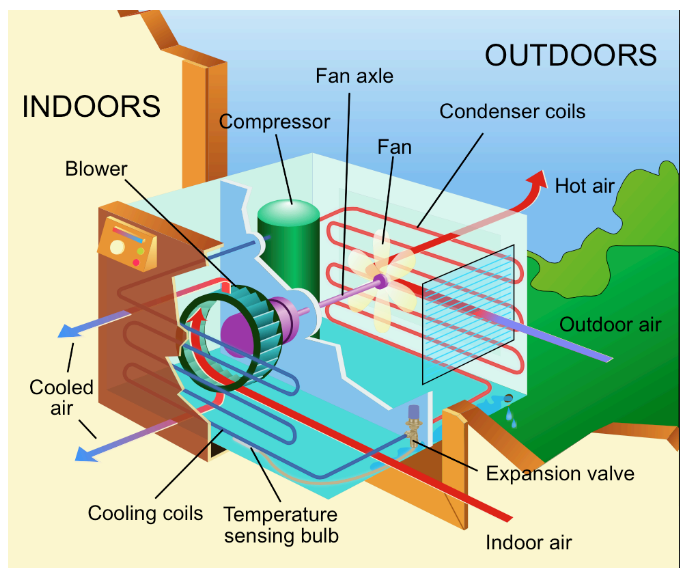
A heat engine is a device that moves heat down a temperature gradient (from hot to cold) and extracts some of that heat flow as mechanical work. A heat pump is a heat engine run in reverse: it takes mechanical work and uses it to push heat up a temperature gradient (from cold to hot). A refrigerator is a heat pump, using mechanical work to move heat from the interior of the refrigerator to the warmer exterior.

This problem focuses on heat pumps for two reasons. First, in class we saw that most people did not know how a refrigerator works, and since a refrigerator is part of everyday life we should understand their principles. Second, heat pumps may be more important in the future. Your home in Chicago is likely heated by natural gas (methane). There is likely a heater in your basement that burns natural gas, extracting its chemical energy into heat. Either that heat goes into heating air, and vents carry hot air through your building. Or, the heat may be used to boil water and make hot steam, which is circulated through the building in pipes and transfers its heat to room air through radiators. In either case, burning that natural gas releases CO2 to the atmosphere. If society were ever to move away from fossil fuels, we would likely heat our buildings is via electrical-driven heat pumps instead, which use electricity to do work to pump heat against a temperature gradient, i.e. to move heat from the cold outside into the warm inside.

Some heat pump systems are reversible, i.e. they can be run to bring heat into a building in the cold winter, or to push heat out of a building in the warm summer. A single system can then provide both heating and air-conditioning.

The best way to get an intuitive feel for a heat pump is to look at one: a refrigerator or air-conditioning unit. Just as a heat engine cycle involves compressing and then expanding a substance, your refrigerator or air conditioner must alternately compress and then expand its “working fluid”. Compress the fluid and it becomes hot, then move that hot fluid to somewhere colder and it loses heat. Then bring the now lower-energy fluid back to the cold part of the refrigerator and expand it, so that the fluid becomes cold and takes up more heat. Repeat the cycle so that heat is carried away and dumped outside. Every refrigerator therefore has tubing carrying its “working fluid”, a compressor, and an expander. Modern refrigerators have the extra complication that they use a fluid that actually condenses during part of the cycle, like a steam engine. Up until recently the fluid used in most refrigeration units was a “chlorofluorocarbon” or CFC, which had good properties for refrigeration, but when these were proven harmful to the ozone layer, newer units have been switched to “hydrofluorocarbons” or HCFCs instead.





In the first part of this problem you’ll look at an actual refrigeration unit to identify its elements. However, higher-end (more expensive) devices tend to have all their working parts concealed; only cheaper models have a lot visible. Conveniently there is a very cheap mini-fridge in the Hinds 4th floor coffee room, next to my office, that you can look at if your own fridge is not very educational.

A. **Look at the back of a refrigerator or the inside of an air conditioner and describe its parts.** Photograph it, label all the parts you can see, and explain what they do. Also look at the label and identify the refrigerant. (Bonus points for finding an older unit that still uses CFC’s). If you do not have a camera or phone that can take digital photos, you can do a hand sketch. For extra credit, do both a refrigerator and an air conditioner.

In the rest of this problem you'll think about the properties of heat pumps.

B. **Draw the diagram of the heat and work flows in an engine** (You've seen this often in class). Draw an equivalent diagram of a heat pump. (You also saw this in class). Then draw a heat pump connected to a heat engine, so that the work done by the engine drives the heat pump.

C. In an ideal reversible heat engine, the values of all the heat flows are identical no matter which direction the engine is run in. (They just switch direction). **What would happen if you could hook up a hypothetical better-than-Carnot-efficiency heat engine with a Carnot engine reversed as a heat pump?** (So that the engine drives the heat pump). Use your diagram to explain what would happen**. Is this possible?**

Interestingly, if you want to describe how good a heat pump is, efficiency isn't the right intuitive metric. The efficiency tells you the mechanical work you get out given a certain amount of heat transfer. With a heat pump, you want to do the LEAST mechanical work and transfer the MOST heat.

D. **Make up a metric** (call it "COP", for "coefficient of performance") **that describes how good a heat pump** is (i.e. how much heat you get transferred per work done) **and write down its definition.** Discuss.

E. Assume that your heat pump is ideal (that is, that it is a Carnot engine run in reverse, the best heat pump you can have). **Now rewrite your definition of COP in terms of T_{hot} and T_{cold} alone.**

F. **Does it take more work to pump heat across a large thermal gradient or a small one? Is that consistent with your intuition?**

G. **What is the physical meaning if COP > 1? Could you have COP < 1?**

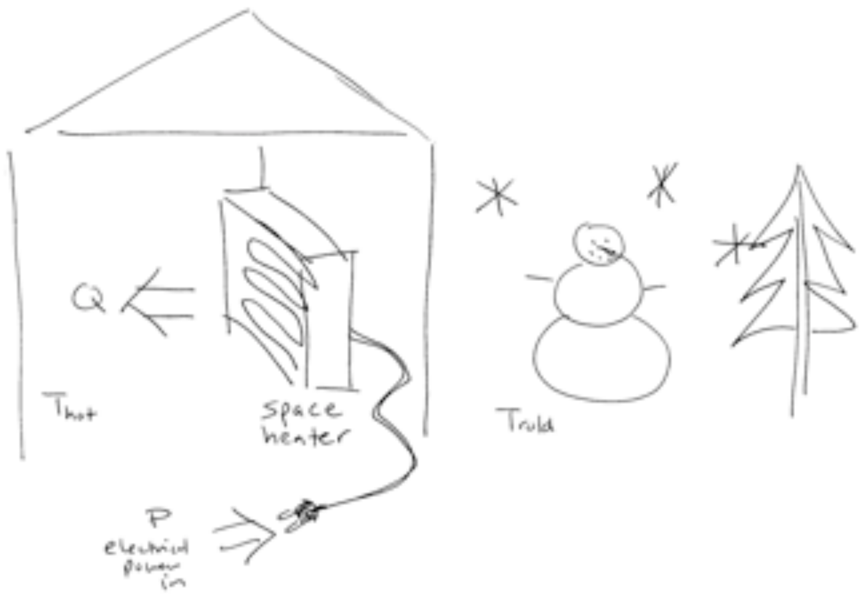
Consider the difference between heating your house with a heat pump, and with an electric space heater – see diagram next page. With a space heater, all the electrical energy is converted to heat. With a heat pump, you're using the using electricity to drive a motor (for the heat pump compressor) that produces a heat flow that may be bigger than your original electrical energy input.

For the problem, assume you're heating your room/apartment in a chilly Chicago winter (make reasonable assumptions). You can assume that in your heat pump system, the input electrical power gets perfectly converted to mechanical work without any losses.

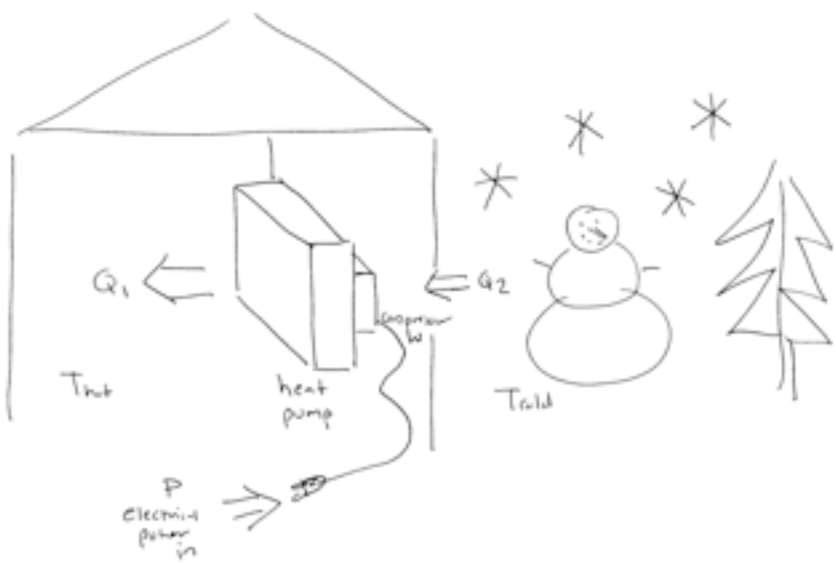
H. **What is the COP of an ideal heat pump in this situation? I**n practice, real heat pumps have COP is lower than the Carnot ideal by a factor of 2-4. **Estimate the COP of a realistic heat pump**.

I. **How much more electrical power would you need to heat your room with a space heater than with your assumed heat pump**? Is it better to convert electricity to heat directly, or to use it to drive the heat pump? Discuss.

Space heater:



And heat pump:



It turns out that comparing a heat pump to a space heater is not a fair comparison. Most people don't use space heaters, for good reason. A furnace is a much better choice than a space heater, because it burns fuel directly to make heat in your house; you can assume 100% efficiency of conversion. A space heater requires electricity that, in our current energy system, was largely produced in an inefficient heat engine. You estimated in problem 1 the efficiency of the heat engines used to produce electricity.

J. **How much more energy do you use heating with a space heater than a furnace?**

K. **Now compare a realistic heat pump to a furnace.** Whether a heat pump beats a furnace depends on the COP of the heat pump… you waste energy making electricity but then you gain again with the heat pump. For the heat pump system, draw the diagram of the energy flows starting from fuel burnt by the power plant engine for electricity production and ending with the flow of heat into your house. Write down an equation that relates those two heat flows. (This is obviously a function of both the generation efficiency e_g and the COP of your heat pump). Plug in values and discuss.

L. **Why don't more people use heat pumps?** Discuss, even if it's just speculation on your part.

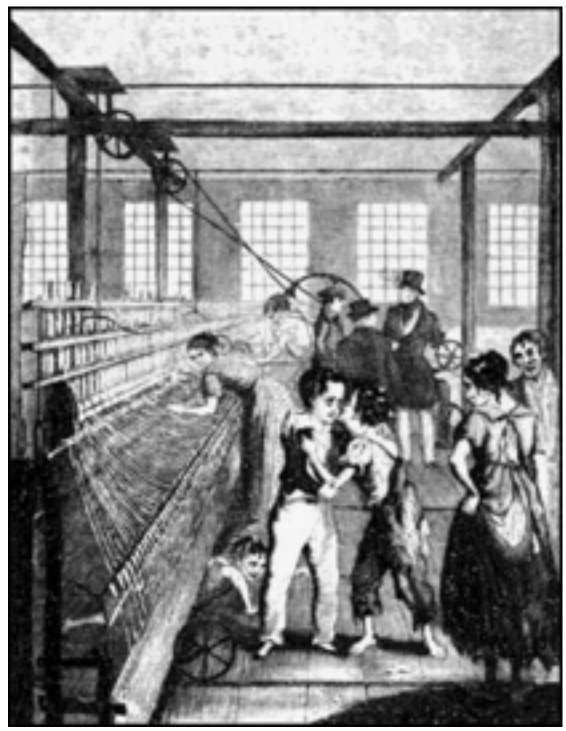
Problem 5: Social changes in the Industrial Revolution

Read about the social and economic effects of the Industrial Revolution on the site below and its linked primary sources. The point is to get a feel for the tremendous dislocations and society's reaction to them. You need not read everything carefully, but skim all and then **discuss and comment on at least two of the primary source documents**. Econ majors might focus on the two pieces on the labor supply, since this issue is still a major puzzle for economic historians. What caused the tremendous increase in child labor under brutal conditions? How did society get stuck in a situation where productivity increases went along with more hours, more people working, and lower wages?

http://geosci.uchicago.edu/~moyer/GEOS24705/HistoryReadings.html

Extra credit for discussion additional pieces from these readings, or for any of the readings on the Fordham Univ. primary source page for Industrial Revolution history:

https://sourcebooks.fordham.edu/mod/modsbook14.asp



Engraving from *"The Life and Adventures of Michael Armstrong, the Factory Boy"*, 1840 (Frances Trollope)

The most relevant selections are in "The Revolution in the Manufacture of Textiles", "Social and Political Effects", and "Literary Response"

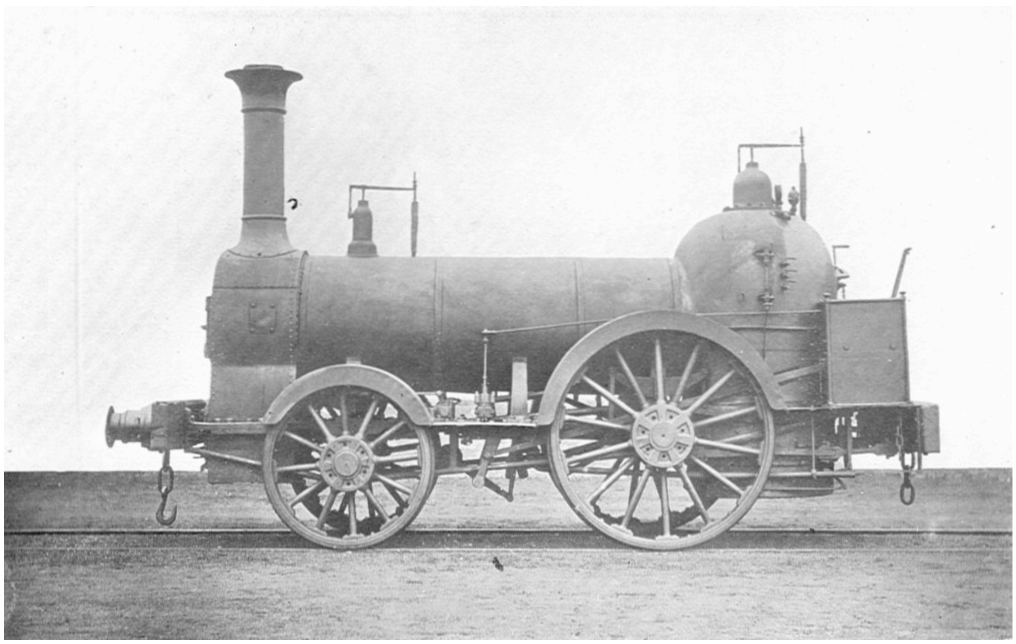
For more extra credit, read some of the chapter on railroads from Cronon's "Nature's Metropolis", about Chicago and its relationship to surrounding environment, and discuss. This is linked on the website. Cronon's book is one of the classic works of environmental studies.

Finally, you can get extra credit for identifying depictions of factories or social conditions in literature of these times (other than those sources already on the Fordham page).

Problem 6: Evolution of steam locomotives.

For each of the photographs below, guess what you can about the locomotive: when was it built, what region was it designed for and used in. Discuss what features of the design (pay attention to the wheel arrangement) led you to those conclusions. We won't grade harshly on accuracy; the point is to give you experience in looking closely at mechanical devices (and to prep you for Tuesday's lecture).

A



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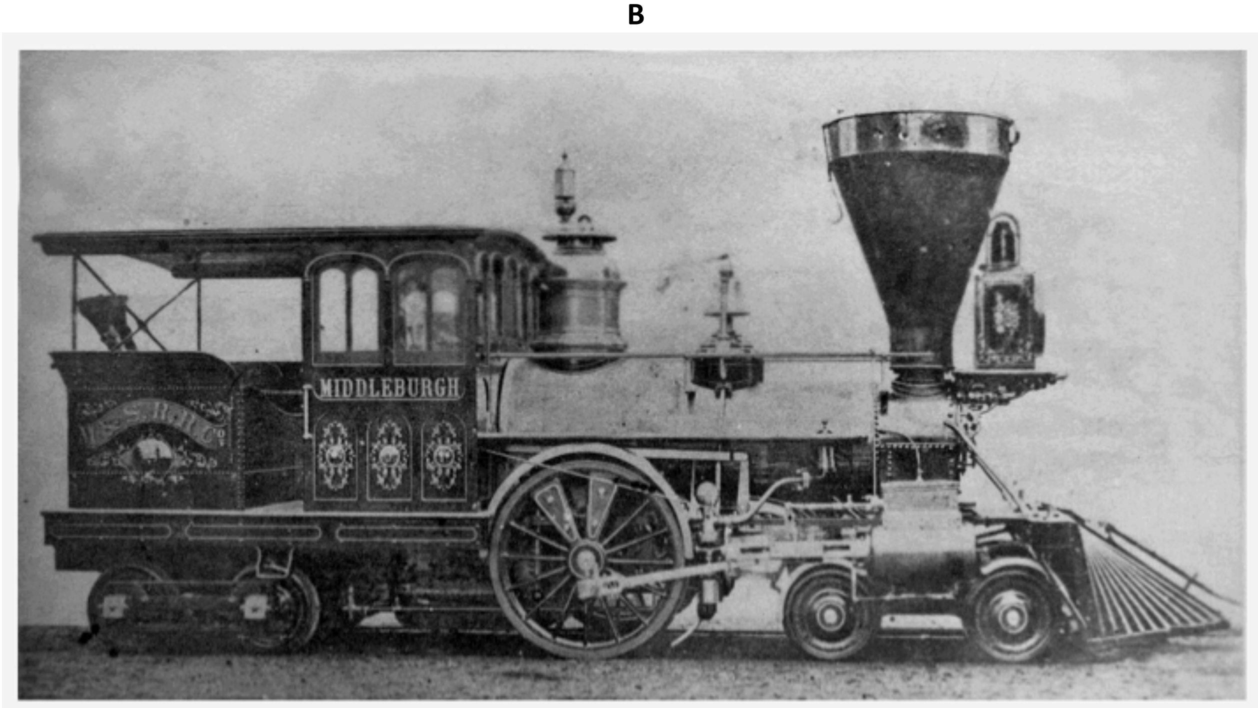

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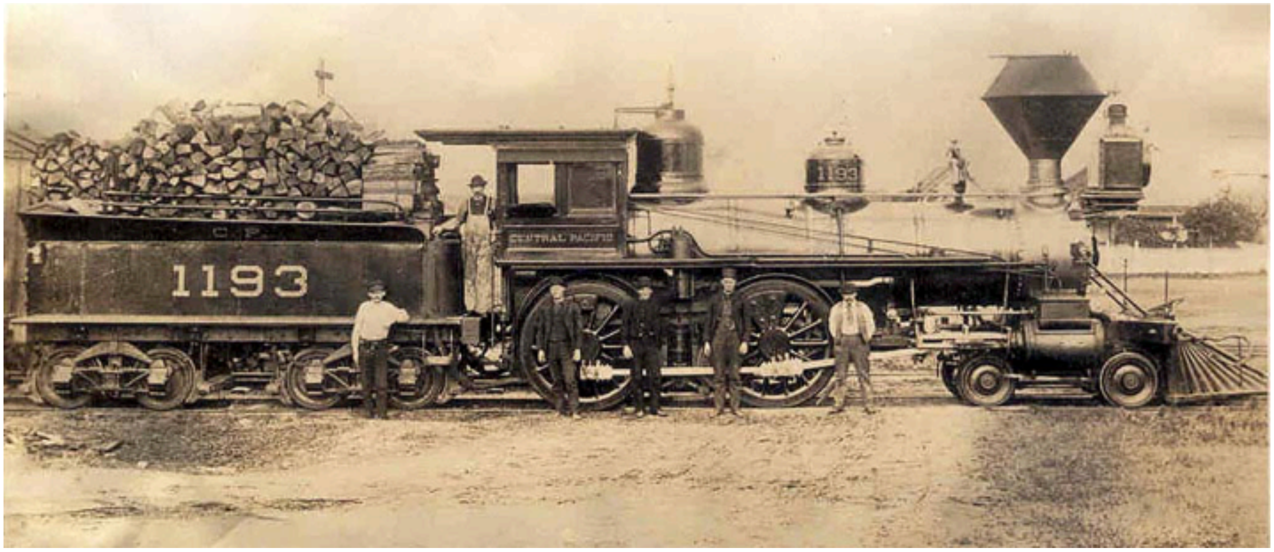

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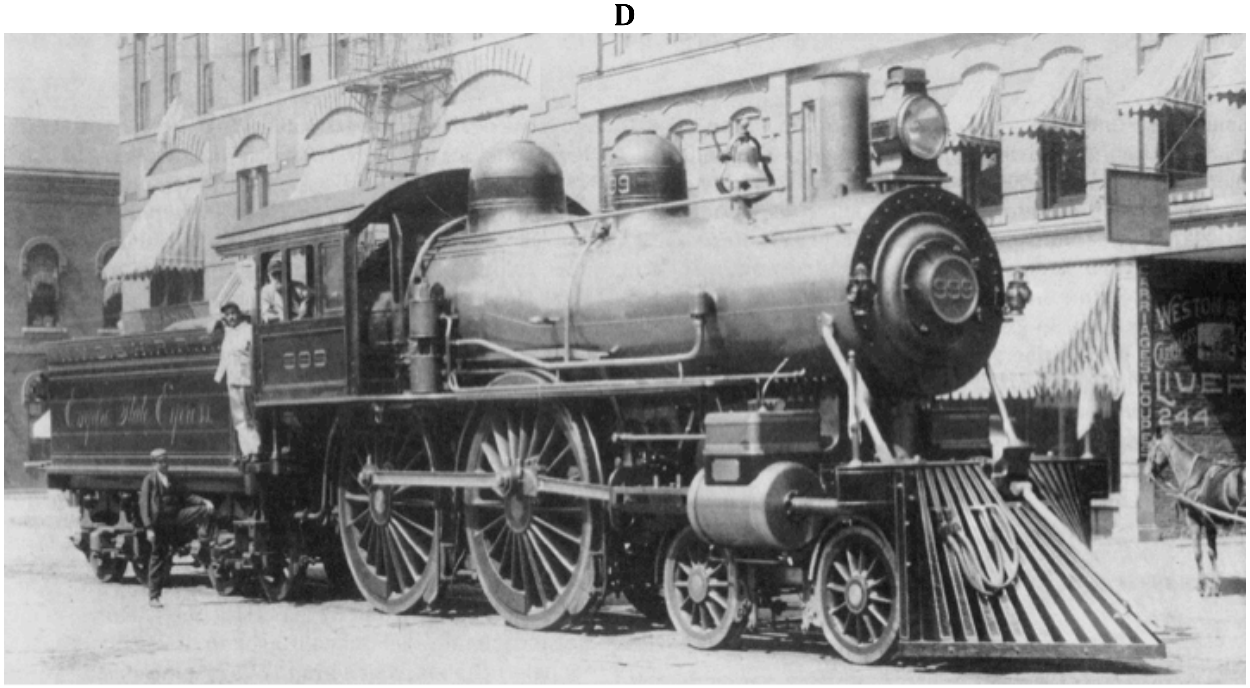
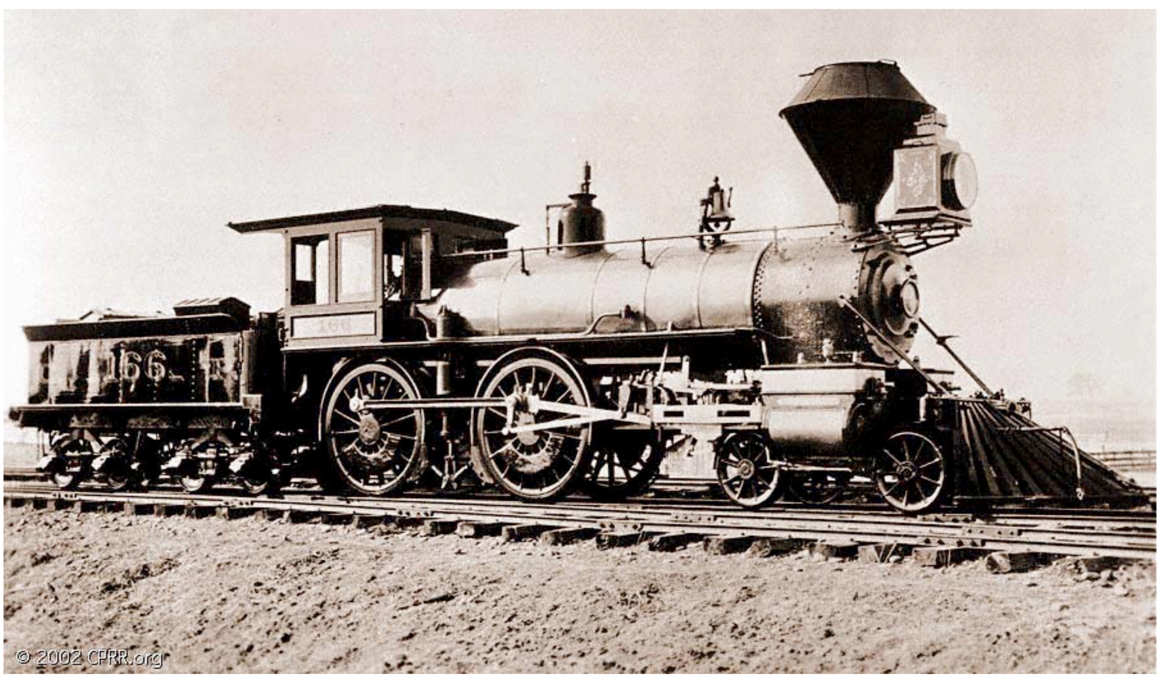


E

F



Extra credit for the engines below in G and H, which relate to children's literature. Why were these particular engine forms chosen? Think before Googling.

G (optional extra credit)

H (optional extra credit)