GEOS 24705 / ENST 24705
Problem Set #11
Due: Thurs. May 3rd

Problem 1: The beginnings of the electrical system

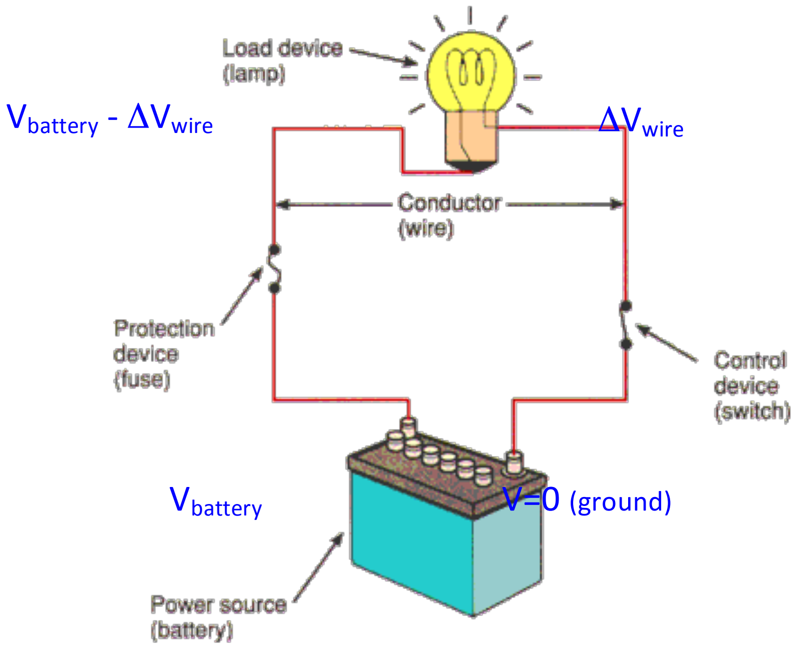
Read the posted readings on the beginnings of the electrical system, and the dueling technologies of Edison vs. Tesla. Even if this is difficult to comprehend it will be good background before Thursday's lecture.

Edison, one of the founders of the electricity industry, had a vision of the electrical system that was easy to understand: his generating station would generate a constant voltage (as a battery would), and electrical current would flow from that station down wires to houses and businesses. The system would be analogous to a hydropower system: think of Edison's generators as pumping electric charge up to some "height" from which it flows down to "ground" at the customer. This is "DC" – direct current. He would deliver a direct flow of current to his customers whenever they wanted power. Edison established his electricity company in the U.S. based on this DC technology. His first customers used his electricity only for lighting (using his lightbulb) but factories were another potential customer base for him, since DC electric motors had also been invented by this time.

Given all those advantages, it is informative that Edison did not succeed in having his technology become the standard. All modern electricity systems are built on the "alternating current" or "AC" standard propounded by Tesla. Edison had one enormous drawback to his system: he had no easy way of transforming voltages.

Your household electricity is necessarily at a relatively low voltage, because high voltages are dangerous. In the U.S., household electricity is 110 V; in Europe it's 220 V, but any higher than that is not safe. Remember that the power that flows, if you stick your finger in an electrical socket, goes as the square of the voltage: $P = V^2/R$, where R is the resistance of your body and V is the total voltage difference between the socket and the ground that you stand on. At 110 V, getting a shock is jarring but not fatal. At 220 V, 4x more power will flow, and some fatalities may occur (mostly heart attacks). That's about as dangerous as anyone is willing to get. Because Edison couldn't transform voltages, he had to generate and distribute his electrical power at a safe consumer voltage. And that constraint limited how he could operate his business.

Why did the ability to transform voltages matter to Edison? The answer is related to losses in the wires. Edison was sending power to lightbulbs in his customers' homes, where it would be consumed as resistance heating, producing light. (The filament of a lightbulb is basically just a large resistor). But the wires leading to customers' houses are also themselves slightly resistive, and so some power "burns off' in the wires, heating them up. Anytime there is resistance, there will be some resistive heating. To understand how much is lost, we need to think a system like the one below: a generator making power at some voltage (here a battery at $V_{battery}$), wires (with small resistance R_{wire}) connecting the power source to a load, and the load itself, a lightbulb with resistance R_{bulb})



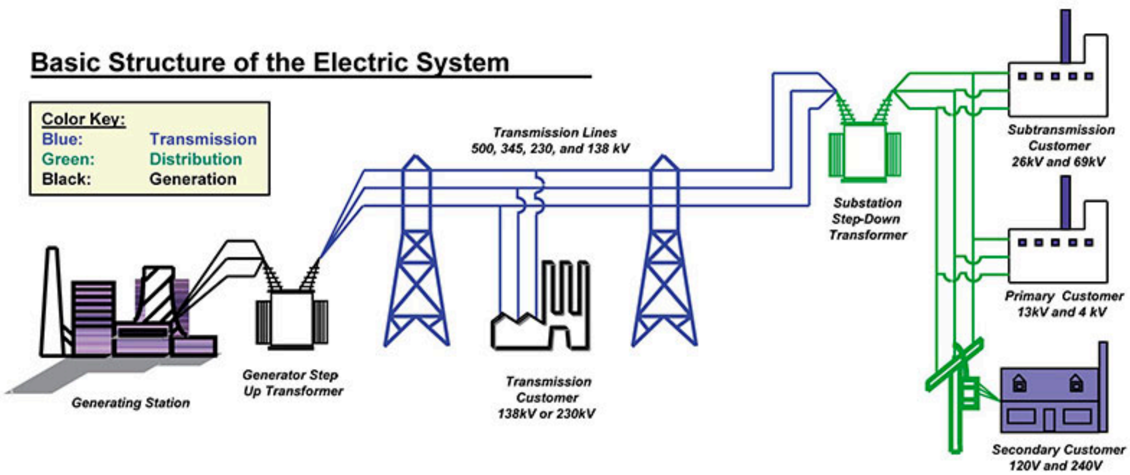
Example of voltage drops in a simple electrical system. Blue labels show the voltage at different locations. This diagram assumes that the outgoing and return wires have the resistance R_{wire} and so each experience a voltage drop ΔV_{wire}.

Because charge is conserved, the current flowing in the wire must be the same everywhere – there's nowhere for charges to go. So I is identical in the wires and in the lightbulb. The voltage on the other hand drops in stages from $V_{battery}$ at one battery terminal to zero (ground) at the other terminal. Remember Ohm's law, V = IR, or more properly $\Delta V = IR$, where the Δ sign means a change. The voltage will drop slightly as current passes through a wire with weak resistance, then strongly when it passes through a load with high resistance. The analogy with a river (a current of water) is a good one. Imagine that a current of water is flowing from some high place to the ground. The voltage drops a little bit along the wire, and then makes a large drop at the lightbulb (imagine a waterfall that accounts for most of the loss in altitude), then a last small drop in the return wire til reaching ground. The combination of all those change (drops across wire, lightbulb, wire) is the total drop $V_{battery}$.

How to compute the resulting power loss? If you use the formula $P = V^2/R$ to calculate losses in a wire, the voltage drop V you'd use is only the small drop in the wire itself, ΔV_{wire}. It is therefore easier to use the other form of the power equation, $P = I^2 R_{wire}$. From this equation you can easily see that the lost power goes as the square of the current, and is proportional to the resistance in the wires. To minimize your losses, you obviously want to use low-resistance material, but even more importantly, you want currents to be low.

How can you transmit power at all if current is low? You're sending less charge to the customer! To compensate, you have to then jack up the voltage, so that each charge that is delivered carries more energy. This is the crucial point: because power P = I * V, you can move the same amount of power at high voltage but low current (avoiding losses), or at low voltage but high current (incurring losses). Poor Edison, who had to send power to his customers at a safe low voltage, was stuck in the second scenario, burning up his product in the wires as resistive heating. Remember also that resistance scales with the length of the wire. The further away Edison's customers were, the worse his losses would become. He was therefore restricted to transferring power only over very short distances. His power distribution system was better than a belt drive, but not by much! Edison had failed to tap into the main advantage of electricity, that it allows moving power over large distances.

The modern electrical system avoids this problem by using a variety of different voltages. *(Here the analogy with a river breaks down, since the electrical transformer can swap current for voltage, while you cannot of course swap the height of the river for the water flowing in it.)* The wires from a power plant carry electricity at extremely high voltage, over 100,000 V (where V here is the total voltage drop to ground). That is not safe at all to touch – touching a high-voltage line (if your feet are on the ground) is generally fatal, and at best leaves extreme burns. So you have, between the high voltage line and your house, various stations or devices that successively lower the voltage until what reaches you is a safe 110V. Those transformations don't throw power away: each one just trades off current and voltage, reducing V and correspondingly raising I.



A. Read the required readings, including the 1882 article, and comment on something interesting on each one. For extra credit, also read and comment on the clip of the PBS "American Experience" series on Edison that cover the lighting of Manhattan: http://www.pbs.org/wgbh/americanexperience/features/edison-manhattan/.

B. The 1882 article on Edison's first generating company in New York that was posted on the website gives the boundaries of Edison's service area. Print out a map of modern Manhattan (the street plan is the same) and color in Edison's service area. State its dimensions. What was the longest distance he was sending power over?

C. (Optional) Write an expression for Edison's fractional line losses (P_{loss}/P_{total}, where P_{total} is the total power generated) in terms of P_{total}, the voltage, and the resistance of his wires.