**Circuits Week 6: Op-Amps**

**Become excited!** After all this mucking about with passive (read: can't add power, only lose it) circuits, we're about to start on powered circuits. In particular, I'm skipping ahead to the EASIEST powered circuits, the golden land of "operational amplifiers" (see the picture on p 165 of the manual – we've skipped over everything in the lower hell, and right to the "golden rules" and "heavenly quad"), so-called op-amps. We can build amplifiers and radios with these.

I will go over how to use op-amps in class Tuesday; the book (& lab manual) assume you already understand transistors, which you don't (since they're harder, I skipped them for now :) It will turn out to be surprisingly simple; a lot moreso than the text makes it look.

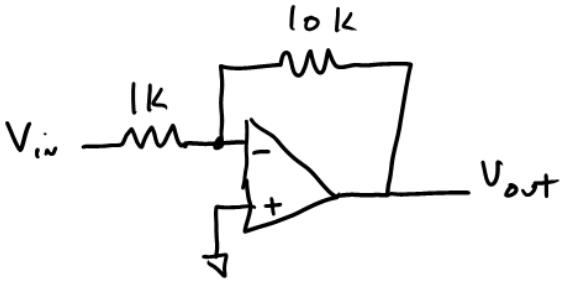
➔ Please read the material but DO NOT freak out if it seems too hard. Rather, read enough that what I say Tuesday falls on fertile ground.

Reading:

- Horowitz and Hill, Art of Electronics, Ch 4, - 4.06, pp. 176-180. Stop before §4.07.
- Read the lab manual first!
    - Horowitz and Hayes, Lab Manual, pp.163 – 172; 175-176 (worked examples).
    - ***** Especially to Golden Rules on p 169 !!**

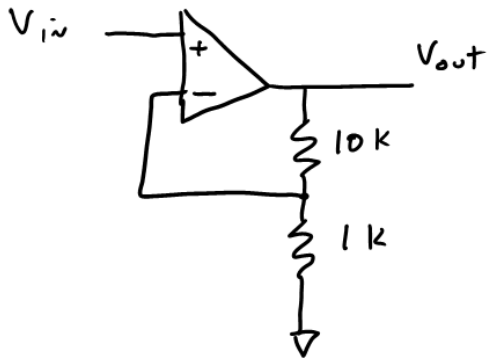
Exercises:
Due <u>Thursday</u> before class:

1. What is the gain, G, of the following circuit?




    a. Hints:
        i. If the "+" input is at ground (0V), what voltage is the "–" at?
            1. Use Golden Rule #1
        ii. Then what must the current be from $V_{in}$ to the "–" input?
        iii. But (Golden Rule #2), how much current goes into the "–" input?
        iv. Then what must be the current between "–" and $V_{out}$?
        v. The what must be the voltage, $V_{out}$?
        vi. Then what is the gain, G?

2. What is the gain G of the following circuit?




   a. Hints:
      i. If the "+" input is at $V_{in}$, what voltage is the "–" at?
         1. Use Golden Rule #1
      ii. Then what must the voltage output of the voltage divider consisting o the 1k and 10k resistors?
      iii. The what does $V_{out}$ have to be, given that you know the resistances in the voltage divider?

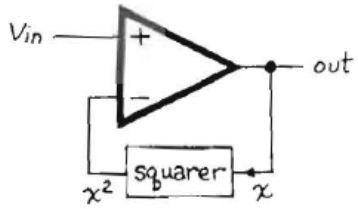
**Due Friday**, by 4:30 PM in the box outside my office (1010 Lab I)

3. Design a circuit (using an op-amp) that has an output as follows:
   a. Vin ≥ 2.5V  Vout = 5V
   b. Vin < 2.5V  Vout = 0V.

   Assume the op-amp is powered from 0 and 5V, so the highest it can go is 5V and the lowest is 0V, and you have two power supply voltages to work with: 0 and 5V.
   PS: this is an important circuit for digital logic, which is binary – i.e., can have only two values: on or off. It will output a "TTL low", i.e. 0V, when the input is below the 2.5V threshold, and a "TTL high", i.e. 5V when the input is above the threshold. This immunity to the exact input signal level is one of the important traits of digital logic – it's why one can transmit digital over a noisy line without problems, while an analog (e.g. voice) signal might get static-y.

4. Sometimes (usually) it is bad (very bad – the special smoke escapes from the op-amp, preventing it from working any more) for the input to go above the positive supply rail or below the negative supply rail. Design a simple addition to the input of your circuit for (3) that prevents the input, as seen from the op-amp, from ever going above 5V (or maybe a little lower…) or ever going below 0V (or maybe a tad higher…).

5. The Lab Manual shows that you can put all kinds of weird stuff in the feedback loop… c.f. p 173, Figs N8.12 and N8.13.
   What is the output of this circuit (here x = $V_{out}$)? Hint: remember Golden Rule #I: the system will do whatever is necessary to make the difference between the inputs zero…

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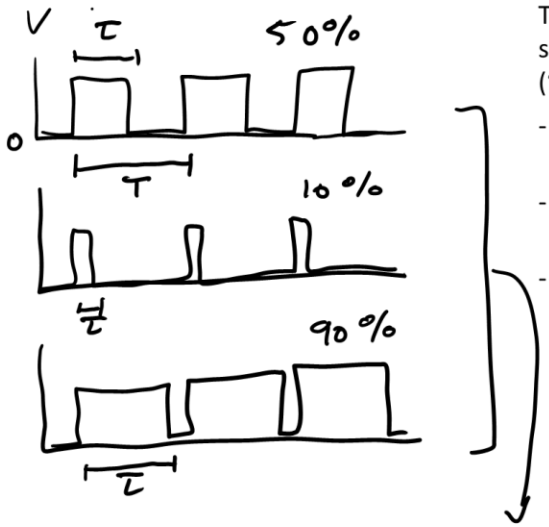
6. **Optional/Bonus:** Switching power supplies. Some of you asked me how these work. It's complicated, but let's take a simple example using a DC supply:
   a. You have an op-amp powered from the 0 and 15V lines, as shown. If the output is 5V, with a current of 100mA,
      i. How much power is being dissipated in the load?
      ii. How much power must be being dissipated in the op-amp?

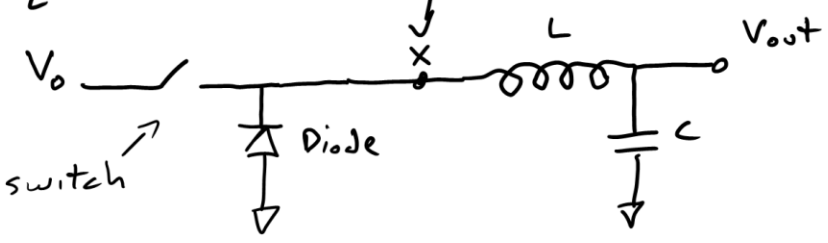
   With luck, you see the problem… The trick with a "switching" power supply is to apply either <u>all</u> of the voltage or <u>none</u>, so that effectively no power gets wasted in the op-amp (or other circuit part – actually usually a transistor). Imagine the following circuit:




The voltage at point X is set by $V_{in}$ and the switching frequency f = 1/T and fraction of time ("duty cycle") d = τ/T that the switch is closed.

- The switch is opened and closed at a frequency $\omega = 2\pi f = 2\pi/T$
- The diode makes the voltage at X = 0 (roughly) when the switch is open
- The voltage at X can be represented as a series:

$$V(t) = V_0\left[\frac{\tau}{T} + \sum_{n=1}^{\infty} \frac{2}{n\pi}\sin(n\pi d)\cos(n\omega t)\right]$$



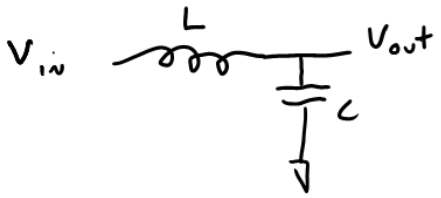
When the switch (usually a transistor) is closed, the input voltage, say 15V, is applied to the point X. When it's open, the inductor will try to keep the current flowing (remember, V = L dI/dt – if you try to suddenly reduce I, a big voltage V will be produced, and the sign of that voltage is just right to try to keep the original current going. This is sometimes known as Lenz's Law.)

So, when the switch opens, the inductor will try to keep the current going, which will suck current up through the diode, and thus the voltage at X will just be 0.6V, one diode-drop above ground. If we simplify this by assuming a perfect diode (0V diode drop) the voltage will look like that shown in the figure.

Since the switch never drops any voltage across it (it's either open, with no current, so P=IV = 0 in the switch) or closed, so $\Delta V = 0$ across the switch, and hence P = IV = 0 in the switch), there is no loss there. Since inductors and capacitors are lossless components, so there is no loss there either – hence such supplies can deliver power at very high (up to nearly 90%) efficiency.

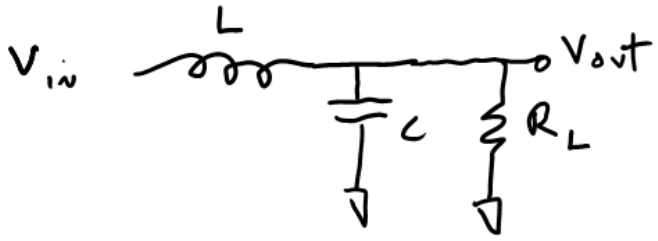
You are probably aware that you can add up a lot of sine (or cosine) waves to get any function you want – this is known as a Fourier series. The Fourier Series for a train of pulses of width $\tau$ at frequency $\omega = 2\pi f$ is given in the figure above. Notice that the sin term does not depend on the time t… it's just a constant. All that depends on t is the cosine function, for which there is one at every harmonic (multiple by n) of the frequency $\omega$.

b. So the input to this part of the circuit (shown below) consists of a constant proportional to $V_0 \tau/T$ and a bunch of $\cos(n\omega t)$ terms.
   i. What is the gain, |G|, of this circuit?
   ii. What is its resonant frequency?




c. For a 15V input power supply, producing $V_{out}$ = 5V at 500mA, typical values of L and C might be L = 150µH and C = 220µF, with a switching frequency of 50kHz.
   i. What is the gain for the DC term (i.e., the only term that does not change in time)?
   ii. What is the gain for the first harmonic, at frequency $\omega = 2\pi f$? How about the 2nd harmonic?
      1. The ripple voltage will be bigger than this – it's a more complicated for various reasons, but you get the idea.

d. The model circuit above isn't that great; we left off the load (and/or the finite resistances of the inductor and capacitor), which limit the height of the resonance peak.




i. Find the gain for the circuit above

ii. For values of L = 150μH, C = 220μF, and R = 10Ω (the $R_L$ that would draw 500mA at 5V), what is |G| at exactly the resonant frequency $\omega_R$?

Take-home: one way to view this use of the LC circuit is to use lossless components to low-pass filter the switching-modulated input voltage waveform, leaving only the DC term (roughly). Another way of thinking of this is that at DC there is no current through the capacitor because it's like an open circuit. At high frequency there's no current through the inductor, since it resists current change (or you can say iωL is large for large ω)… so very little current ever flows to ground – it all ends up in the capacitor or your load. This would not be true, e.g., if you used an RC low-pass filter instead – then most of the AC would go through the capacitor, roughly speaking, and that AC current would go through (and thus dissipate power in) the resistor. There's more to be said here, but that's a start.

PS: Also, in general you enclose all this in a feedback loop that adjusts τ to keep the $V_{out}$ where you want it as the load (or $V_{in}$) changes