Homework #2
ECE 363 (F19)
9 problems for 100 pts
Due Sep 27

A. <u>Useful Op Amp Circuits</u>

1) A difference amplifier (Fig. 1) does exactly what it says – it amplifies the difference between two voltages. This is a very useful function – a differential voltage signal is produced by many types of sensors and data transmission lines.

   (a) Derive the expression: $V_{OUT} = (R_2/R_1)*(V_A - V_B)$.

   (b) Let R_1 = 10 kohm and R_2 = 100 kohm. Suppose $V_A = 3 + 0.1*\text{rect}(t/T)$ and $V_B = 3 - 0.1*\text{rect}(t/T)$, where T = 1 ms. Sketch V_{OUT} from -1.5 to 1.5 ms.

   NOTE: It turns out this simple difference amplifier is not that great, because resistor matching errors make it difficult to obtain good CMRR. We'll talk about CMRR later in the course.

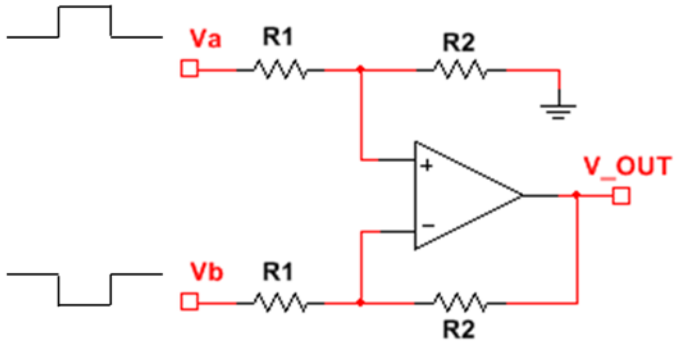

Fig. 1: Difference amplifier using a single op amp.

2) Current sources are super useful! LEDs need constant current to maintain constant brightness and color. Motors need constant current to achieve a desired torque (rather than speed). Transistor amplifiers often perform better when they are biased with current sources rather than resistors (e.g. voltage divider). The list goes on and on!

   - An accurate current source can be made from an op amp. Use the Golden Rules to show that the circuit in Fig. 2a produces a current given by $I = V_{IN}/R$. NOTE: The disadvantage of this circuit is that the load must be "floating", meaning there is no ground or power connection to either terminal of the load.
   - The current source in part (a) is fine for small load currents (e.g. < 1 mA). If you need more current, then slap on an external transistor! Use the Golden Rules to show that the circuit in Fig. 2b produces $I = \alpha V_{IN}/R$.
   - Technically, the circuit in part (b) is a current *sink*, since it "pulls" current from the load. Fig. 2c uses a pnp transistor to make a current *source* to "push" current into the load. Derive the expression for the load current I.

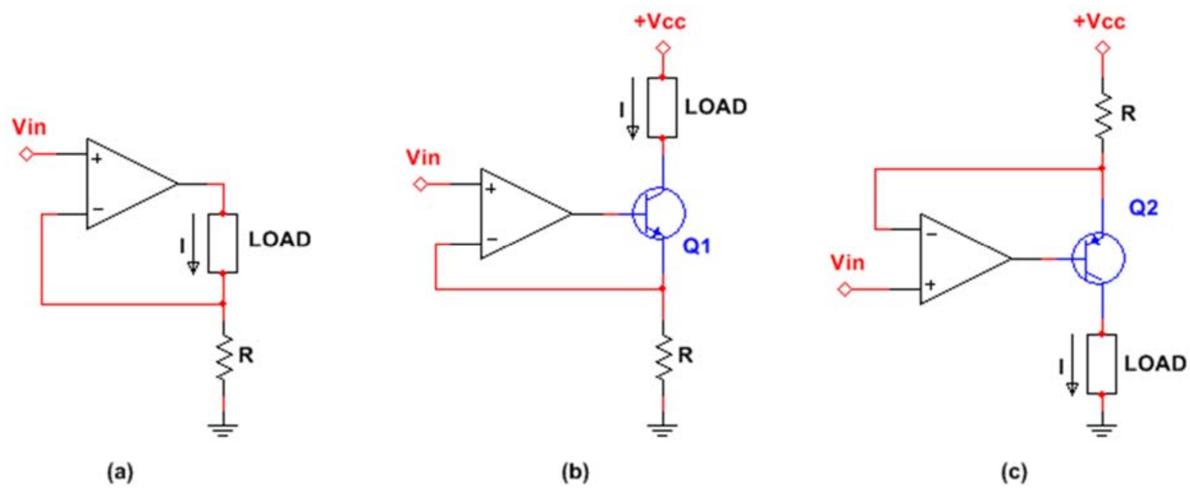

Fig. 2: Current sources using an op amp.

3) An integrator (Fig. 3) produces an output voltage V_{OUT} that is related to the integral of V_{IN}. One application of an integrator is to generate a ramp waveform by integrating a square wave. Another application is being part of an analog PID (proportional-integral-derivative) control loop.

(a) Derive: $V_{OUT} = -\frac{1}{R\,C}\int V_{IN}\,dt$. Hint: Think about how voltage and current are related in a capacitor!

(b) Let R = 100 kohm and C = 100 nF. Suppose V_{IN} is a +/- 5V square wave with a 100 Hz frequency (see figure). Sketch the input and output voltages over a 30 ms duration. Assume V_{OUT} = 0 as an initial condition. Make sure to label important features!

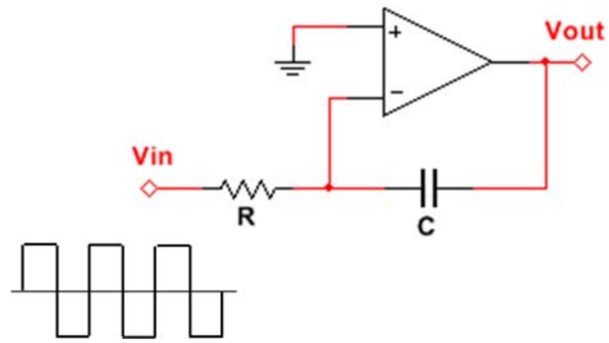

Fig. 3: Integrator circuit using an op amp.

NOTE: It turns out this "ideal" integrator is not very useful because at DC, the capacitor C1 is an open-circuit – this means the negative feedback path is broken! ☹ As a result, imperfections in real op amps cause the output voltage to wander with time. Practical integrators use a couple of extra components in parallel with C, such as a JFET reset switch and a large resistor.

4) A differentiator produces an output voltage that is the derivative of the input. One application is being part of an analog PID control loop.

(a) Derive the expression: $V_{OUT} = -RC*dV_{IN}/dt$

(b) Let R = 100 kohm and C = 100 nF. Suppose V_{IN} is a "trapezoidal wave" with a 4V peak-to-peak amplitude and 10 Hz frequency (Fig. 4). Sketch the input and output voltages over a 200 ms duration. Assume V_{OUT} = 0 as an initial condition. Make sure to label important features!

NOTE: It turns out this ideal differentiator is not very useful because it amplifies high frequency noise. Practical differentiators use an extra resistor and capacitor (see "AppNote20" on course website).

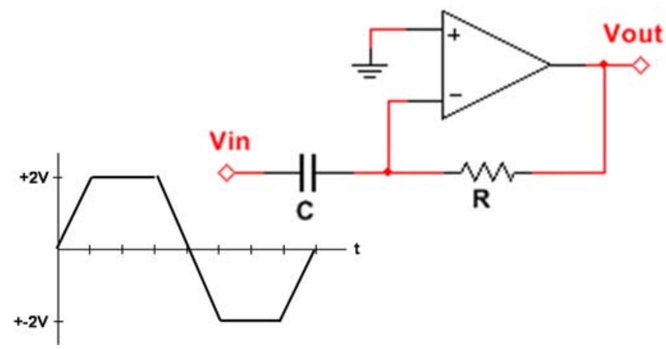

Fig. 4: Differentiator circuit using an op amp.

5) Recall the "half-wave rectifier" consisting of a diode and a resistor (Fig. 5a). Suppose the input is a 1V sine wave with a 1 kHz frequency.

(a) Sketch V_{IN} and V_{OUT} over a 2 ms duration. Assume the diode has a 0.7V drop when it is on.

(b) An "active" half-wave rectifier uses an op amp, a diode, and a resistor (Fig. 5b). Explain why $V_{OUT} = V_{IN}$ when $V_{IN} \geq 0$, while $V_{OUT} = 0$ when $V_{IN} < 0$. Hint: The diode allows current to flow in only one direction – this means the Golden Rules are only valid when $V_{IN} \geq 0$.

(c) Assuming the same input sine wave, sketch V_{IN} and V_{OUT} over a 2 ms duration.

NOTE: This active half-wave rectifier works fine for slow signals (e.g. few hundred Hz), but has problems with fast signals. We'll talk about the effects of an op amp's "slew rate" later in the course.

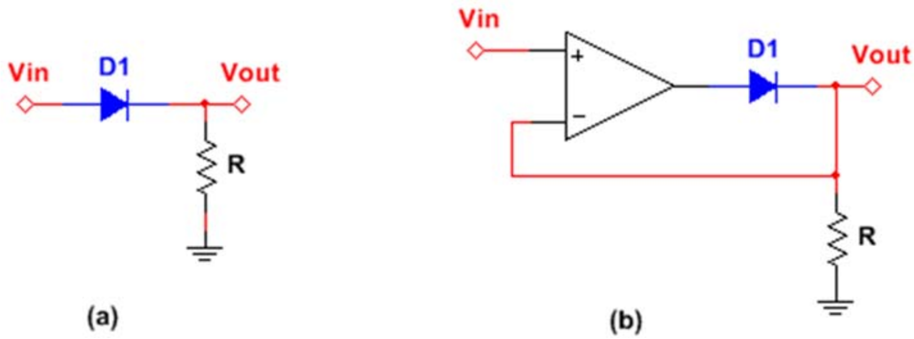

Fig. 5: (a) Half-wave rectifier. (b) Active half-wave rectifier using an op amp.

B. <u>Current Booster Analysis</u>

6) Consider the current booster shown in Fig. 6. Assume an ideal op amp with V_{CC} = 9V. The transistor is a 2N3904, and **use "typical" data sheet values at 25 °C.**

NOTE: You want to use h_{FE} (e.g. DC current gain, or pulsed current gain) rather than h_{fe} (e.g. small signal AC current gain).

(a) Use the Golden Rules to determine V_{OUT}/V_{IN}.

(b) The input voltage is V_{IN} = 500 mV and the load is R_L = 100 ohm. Compute V_{OUT} and I_{LOAD}.

(c) Compute the op amp output current. Express your answers in mA.

(d) Compute the transistor power dissipation in mW. Hint: Around 200 mW.

(e) Does the transistor need a heat sink?

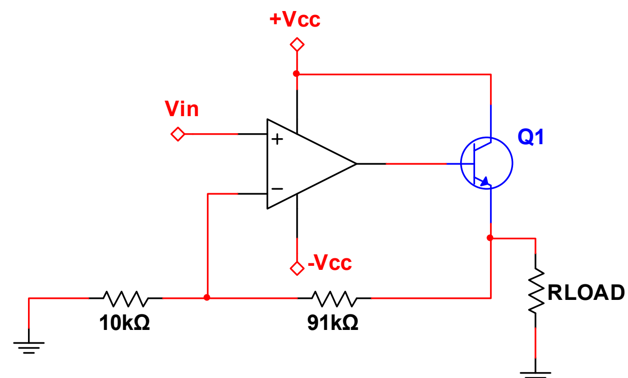

Fig. 6: Vin is a constant voltage for this op amp current booster.

7) We've seen how a Class B push-pull stage (by itself) suffers from crossover distortion for *analog* signals. However, totem-pole stages work extremely well for *digital* signals. Suppose V_{IN} is a 25% duty cycle square wave (see Fig. 4) that alternates between +13V (HIGH) and -13V (LOW). These voltage levels are typical of RS-232 communication lines. The load is R_L = 75 ohm. The transistors are 2N4401 and 2N4403.

(a) You must choose between V_{CC} = 12, 15, or 18V. Use the "quick" analysis approach we've done in class (e.g. with head room). Hint: You should choose 15V.

(b) Sketch V_{IN}, V_{OUT}, i_{E1} (Q1 emitter current), and i_{E2} (Q2 emitter current). **Assume typical values for V_{BE} from the data sheet**. You can assume the 2N4401 and 2N4403 have identical $|V_{BE}|$. Label important features.

(c) Given your choice of V_{CC}, estimate the AVERAGE power dissipation in Q1 and Q2 **assuming worst-case V_{BE} and h_{FE}**. Hint: Q1 ≈ 120 mW and Q2 ≈ 360 mW.

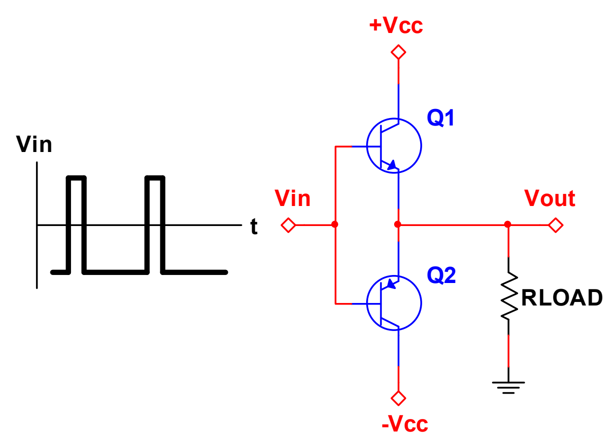

Fig. 7: Vin is a square wave with 25% duty cycle.

C. Op Amp Circuit Design

8) Design a photodiode amplifier using the BPV22F photodiode and LF356 JFET-input op amp (see course website for datasheets). The amplifier output must be a POSITIVE voltage.

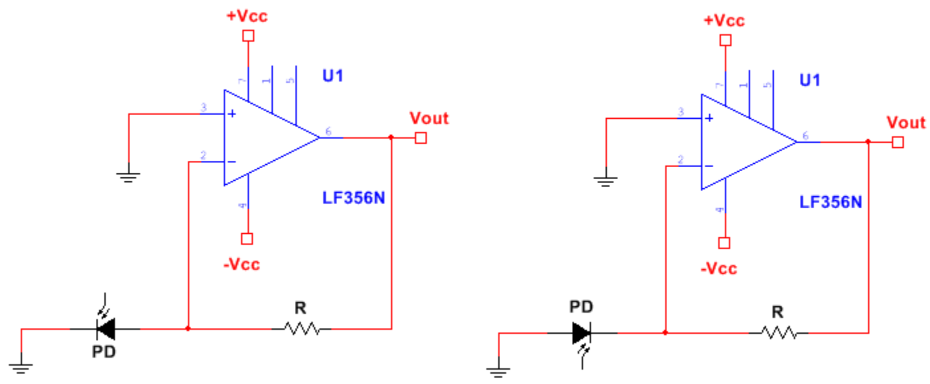

Fig. 8: Which photodiode amplifier configuration gives a positive voltage output? Choose wisely …

(a) You must choose either the left or right circuit shown above. Which one should you use? Hint: Due to the built-in electric field of a pn-junction, the photocurrent flows from the n-side to the p-side of the photodiode.

(b) Choose the feedback resistor R (5% standard value) that gives an output voltage of 5V (or slightly higher) when the incoming light irradiance is 0.1 mW/cm^2 at $\lambda = 950$ nm. Hint: The "Reverse Light Current vs Irradiance" plot in the BPF22F datasheet is useful.

(c) Now assume the light has a different wavelength ($\lambda = 850$ nm) but the same irradiance (0.1 mW/cm^2). Based on your chosen resistor, what is the expected output voltage? Hint: The "Reverse Light Current vs Irradiance" and the "Relative spectral sensitivity vs wavelength" plots in the BPF22F datasheet are useful.

9) Design a non-inverting voltage amplifier based on an op amp and Class B current booster (see Fig. 9). The design requirements are the following:

- Voltage gain is $G \geq +12$ dB
- The signal is a PWM waveform (e.g. it is NOT sinusoidal).
- The amplifier can drive 300 mW into a 75 ohm load when the PWM duty cycle is 100% (e.g. DC signal).

The design constraints are the following:

- Q1 must be a 2N3904, 2N4401, or TIP31 transistor.
  - NOTE: The pnp versions are the 2N3906, 2N4403, and TIP32.
- V_{CC} must be 4.5, 6, 9, or 12V.
- The op amp is the LF411.
- All resistors are standard 5% tolerance.

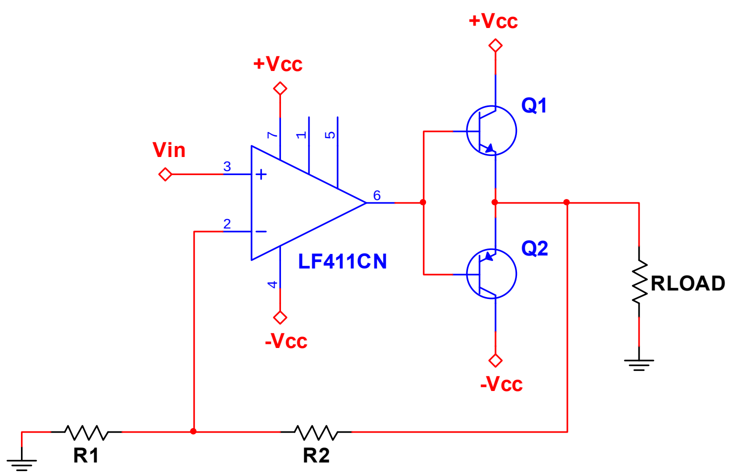

Fig. 9: Non-inverting op amp with totem-pole stage.

(a) Find the max load voltage and current. Hint: Around 4.7V and 60 mA.

(b) Based on the available V_{CC}, which is the best choice? Assume "quick" analysis parameters and explain your choice.

(c) Choose Q1 assuming "quick" analysis parameters and explain why. Assume the pnp versions have comparable properties. Hint: It is OK to ignore the current through R2 since it is usually tiny in comparison to the load current.

(d) Show that the op amp can produce the desired output voltage and current with your choice of V_{CC}. Assume "quick" analysis parameters.

(e) Choose values for R1 and R2. Keep in mind that R1 is typically (but not always) between 1 kohm and 10 kohm.