Homework #3
ECE 363 (F19)
9 problems for 100 pts
Due Oct 11

A. Class AB Analysis

1) Consider the Class AB current booster in Fig. 1. The input voltage is a $1V_{PP}$ sine wave at 2 kHz, the minimum load impedance is R_L = 50 ohm. The op amp output swing is shown in the plot below. Assume "quick" analysis parameters for all components (i.e. diodes have $V_F = 0.7V$, transistors have $|V_{BE,ON}| = 0.7V$, $|V_{CE,SAT}| = 0V$, and $\beta = 100$).

   (a) Compute the maximum load voltage and current (e.g. assume the entire circuit works properly). Hint: You know V_{IN}, and recall that an inverting amplifier has a gain G = -R2/R1.

   (b) We already have RB1 and RB2. You must choose between V_{CC} = 6, 9, 12, or 15V. Hint #1: What is the min V_{CC} needed to provide enough base current to Q1 when V_{LOAD} is maximum? Hint #2: Assume the 1 Mohm resistor current is so tiny it can be ignored. Hint #3: $V_{CC} > 8.3V$.

   (c) Using Fig. 1b, show the op amp can produce the necessary max V_O and I_O. Hint: Max I_O is ≈ 10 mA.

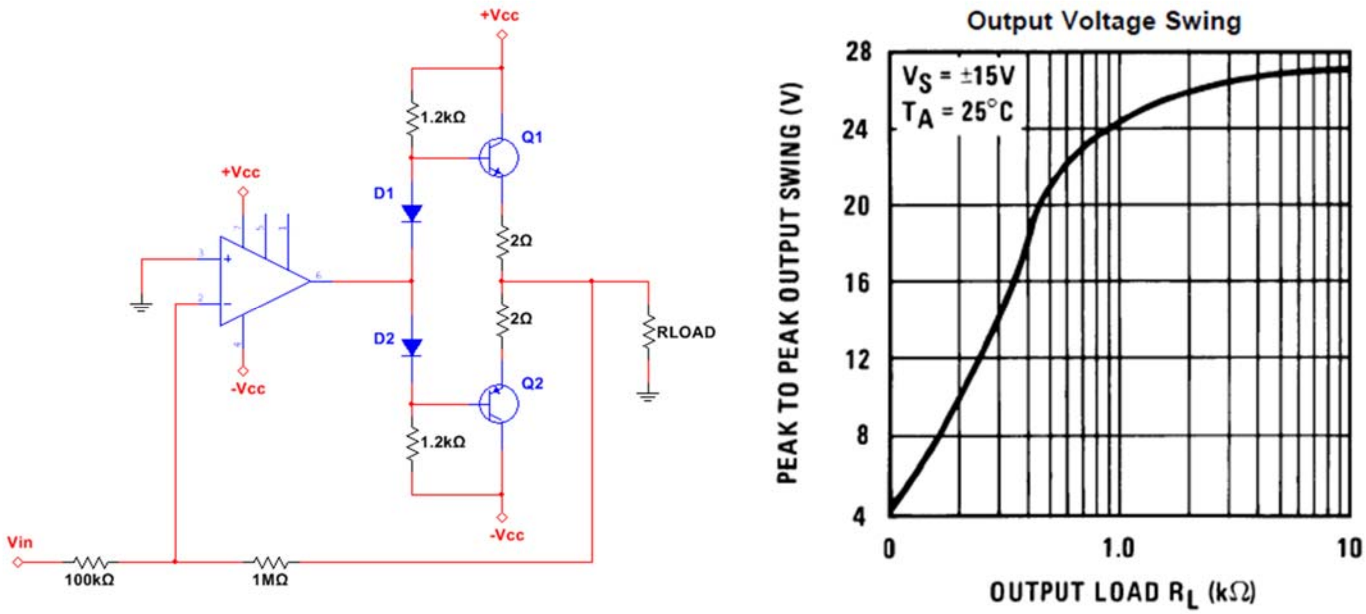

Fig. 1: (Left) Op amp with Class AB output stage. (Right) Op amp max output swing.

B. Class AB Design

2) Design an audio amplifier based on an op amp and Class AB stage (see Fig. 2). The design requirements are the following:

   - Drive up to 400 mW (but not more) into a 32 ohm load.
   - The input signal is a sine wave with a maximum amplitude of $1V_{PP}$.
   - The input impedance must be $R_{IN} \geq 10$ kohm.

- o The low frequency cut-off is < 200 Hz (see part (g)).

The design constraints are the following:

- Q1 must be a 2N3904 or 2N4401. NOTE: The pnp versions are the 2N3906 and 2N4403.
- V_{CC} must be 4.5, 6, 9, or 12V.
- Use an LM741 op amp and 1N914 diodes (see website).
- All resistors are standard 5% tolerance.
- C_{OUT} must be 1, 10, 47, 100, or 470 uF.

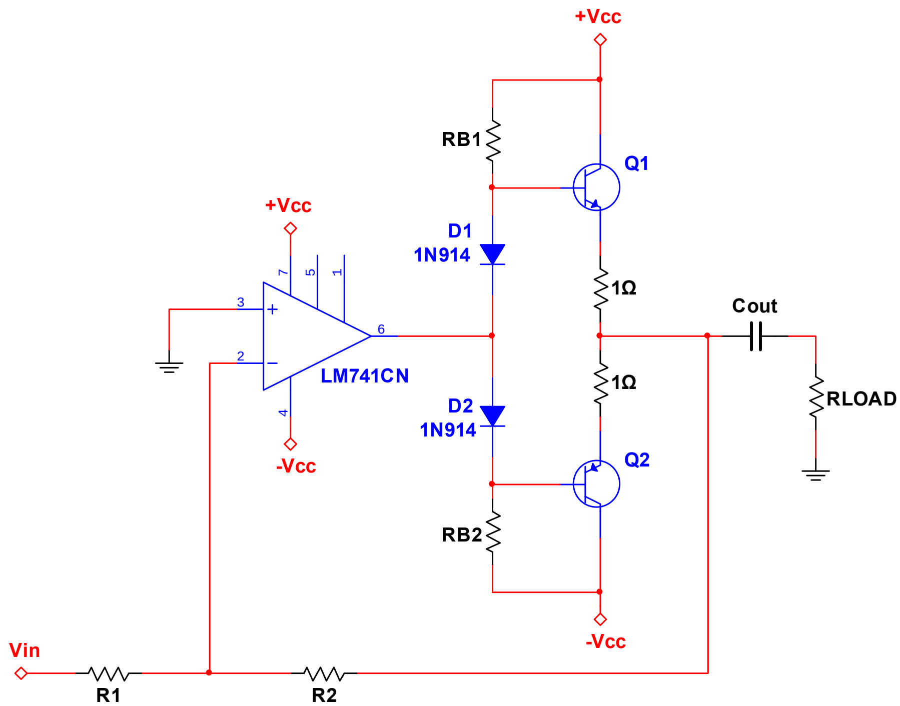

Fig. 2: Inverting amplifier with Class AB output stage. Remember that G = -R2/R1 for an inverting amplifier!

(a) Compute the max load voltage and current. Hint: Around 5.1V and 160 mA.

(b) Perform a "quick" analysis to find the minimum V_{CC} **and then choose a V_{CC}** (this may need to be changed later). Hint #1: As always, first assume C_{OUT} acts like a perfect short circuit (we'll choose a proper value later). Hint #2: $V_{CC} > 7V$.

(c) Choose Q1 and Q2. Show all work! Hint #1: Assume "quick" analysis parameters when computing power dissipation in Q1! Hint #2: As always, you can ignore R2 current since it is usually much smaller than the load current. Hint #3: The 2N4401 should work. If you need a heat sink, then you MUST compute the necessary θ_{SA}.

(d) Choose RB1 and RB2. Pick standard 5% values. Hint: Around 1 kohm.

(e) Show that the op amp can provide the required output voltage and current. **If it does not, then you must increase V_{CC} to a higher value and repeat part (c) and (d).**

(f) Choose R1 and R2. Remember that G = -R2/R1 and R_{IN} = R1for an inverting amplifier. Keep in mind that your Class AB stage assumed a maximum load power of 400 mW. This sets an upper limit to the value of |G|.

(g) How to choose C_{OUT}? At the lowest frequency of interest, we want the magnitude of the C_{OUT} impedance to be "small". Let's define "small" as less than $R_{LOAD}/10$. Choose C_{OUT}. Show all work!

3) Design a non-inverting voltage amplifier to drive a DC motor. The design requirements are the following:

- o The DC motor is rated at 6V with a stall current of 1.8 A. **Design for a max load current = 0.9A**.
- o The input signal is a DC voltage between -0.5V and +0.5V.

The design constraints are the following:

- Q1 must be a MPSA29 or TIP110 Darlington transistor (see Fig. 3).
  - ➢ NOTE: The pnp versions are the MPSA63 and TIP115.
- V_{CC} must be 4.5, 6, 9, or 12V.

- The op amp is the LF356.
- All resistors are standard 5% tolerance.

(a) Compute the max load voltage and current.

(b) Perform a "quick" analysis to find the minimum V_{CC} **and then choose a V_{CC}** (this may need to be changed later). NOTE: For a Darlington, "quick" parameters are $V_{BE} = 1.4V$, $\beta = 2500$, and $V_{CE(sat)} = 0.7V$.

(c) Choose Q1 and Q2. Show all work! Hint #1: Assume "quick" analysis parameters when computing power dissipation in Q1! Hint #2: As always, you can ignore R2 current since it is usually much smaller than the load current. Hint #3: The 2N4401 should work. If you need a heat sink, then you MUST compute the necessary θ_{SA}.

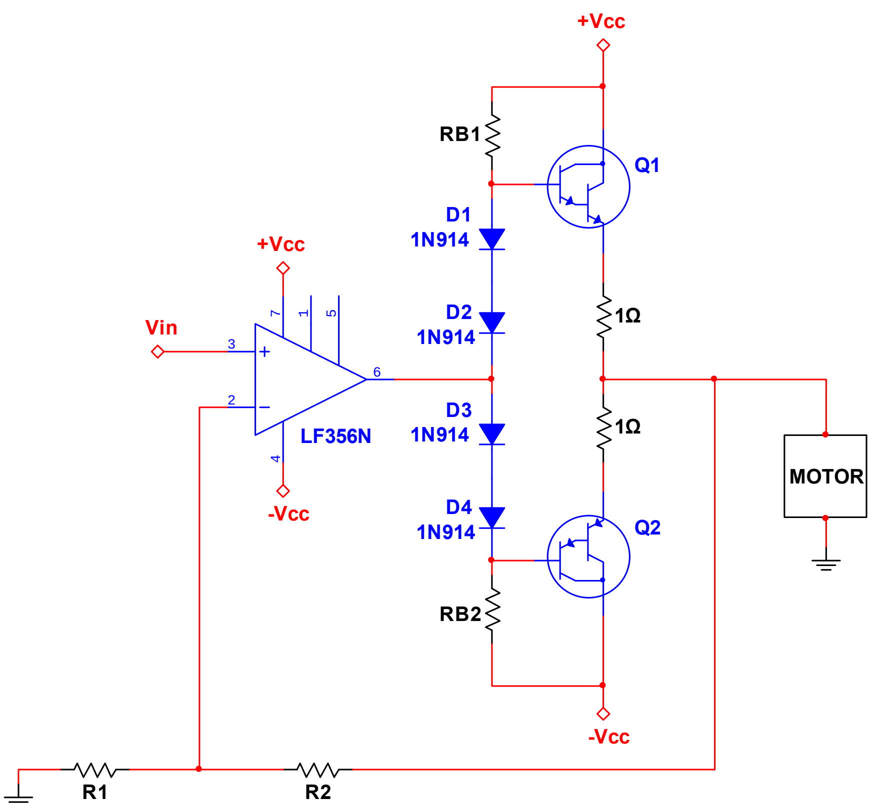

Fig. 3: Non-inverting amplifier with Darlington Class AB output stage.

(d) Choose RB1 and RB2. Pick standard 5% values. Hint: Around 1 kohm.

(e) Show that the op amp can provide the required output voltage and current. **If it does not, then you must increase V_{CC} to a higher value and repeat part (c) and (d).**

(f) Choose R1 and R2. Remember that G = 1+ (R2/R1) for a non-inverting amplifier. Your final gain should produce a maximum output voltage that is within +/- 5% of 6V.

C. <u>Real op amp effects</u>

4) The advantage of a non-inverting amplifier is the huge input impedance (well over 10 Mohm!). However, one still has to be careful about voltage errors!

   (a) Suppose $V_{SENSOR} = 0$. Given the LF356 (not the LF356B) op amp's worst-case values for $I_{in(bias)}$, $I_{in(os)}$, and $V_{in(os)}$, compute the output voltage offset due to each parameter.

   (b) Is the main source of error due to input bias current, input offset current, or input offset voltage?

   (c) What is the worst-case output voltage offset?

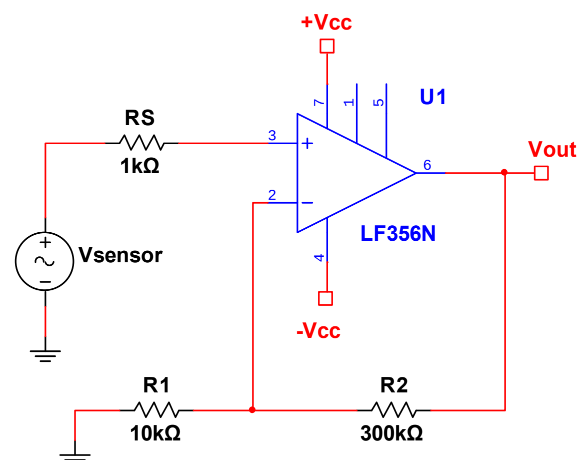

Fig. 4: Worst-case output voltage is the sum of the magnitudes of all three output errors!

5) The large input impedance of emitter followers make them useful as voltage buffers. However, they do have some drawbacks for small-signal DC applications …

(a) Consider the emitter follower in Fig. 5a. Suppose V_{IN} is a triangle waveform from 0 to 1V. Assume V_{BE} = 0.7V for the npn transistor. Sketch both V_{IN} and V_{LOAD} – you should find they are quite different from each other! ☹

(b) A much better circuit is shown in Fig. 5b. Use the Golden Rules to derive an expression for V_{OUT} in terms of V_{SENSOR}.

(c) What is the purpose of R? Choose the appropriate 5% resistor value for R.

(d) Assuming the 741C op amp (worst-case parameters) and your choice of resistor R from part (c), compute the worst-case output error of the voltage buffer.

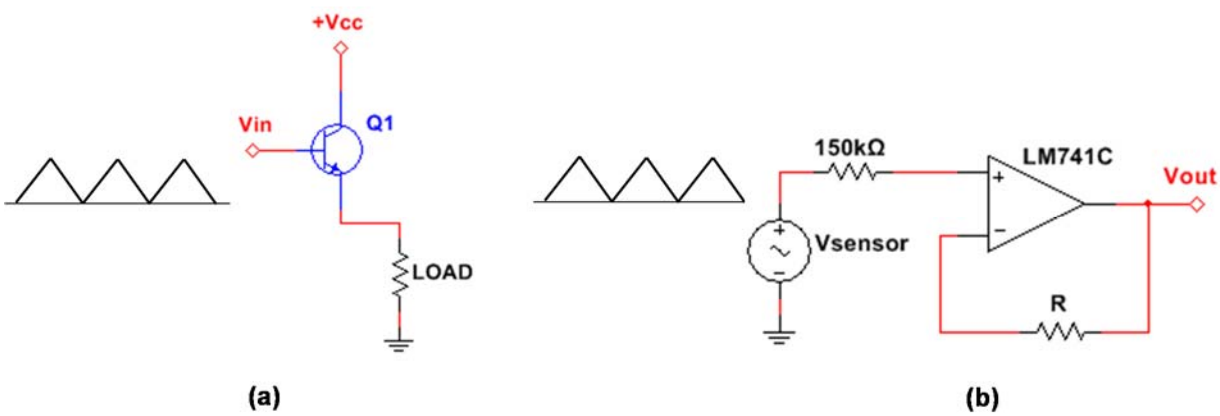

Fig. 5: (a) Emitter follower (b) Op amp follower using an LM741C.

6) Design a DC inverting amplifier with an input impedance of at least R_{IN} = 10 kohm and a gain of at least G = -50 (e.g. G = -51 is OK but G = -49 is not). Use an LF411 op amp (typical parameters). Also use standard 5% resistors.

(a) Determine R1and R2.

(b) Suppose V_{IN} comes from a sensor with an output impedance of 1 kohm. Compute the appropriate value for R3.

(c) What is the expected bandwidth from this amplifier?

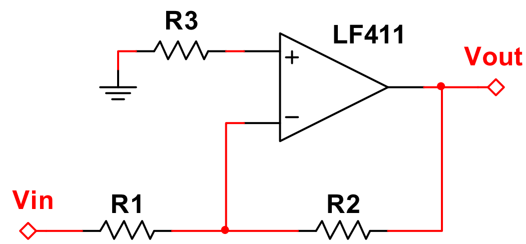

Fig. 6: DC inverting amplifier using an LF411.

D. Rise Time vs. Bandwidth

7) The output frequency response of most op amps can be described with a first-order low-pass filter. Consider a simple RC circuit. Suppose the input V_{IN} is a step function of amplitude V_O. The output voltage V_{OUT} does not change instantaneously! Instead, the output is given by $V_{OUT}(t) = V_O(1 - e^{-t/RC})$. The rise time can be defined as $T_R = T_{90} - T_{10}$, which is the time difference between V_{OUT} reaching $0.1V_O$ and $0.9V_O$.

a) Solve the above equation to determine T_{10}, which is when $V_{OUT} = 0.1V_O$.

b) Solve the above equation to determine T_{90}, which is when $V_{OUT} = 0.9V_O$.

c) Show that $T_R = T_{90} - T_{10} = \ln(9)*RC = 2.2RC$.

d) Using $f_C = 1/(2\pi RC)$, show that $T_R = 0.35/f_C$. NOTE: f_C is the -3dB bandwidth of the low-pass filter.

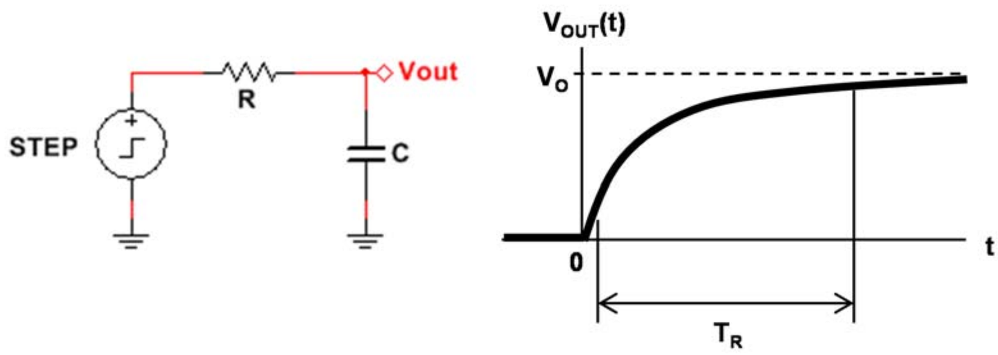

Fig. 7: Voltage waveform for a capacitor charged by a step voltage.

8) Consider an LM741 non-inverting amplifier with a gain G = +26 dB. The input V_{IN} is a 20 mV_{PP} square wave at 20 kHz. Ideally, the op amp output V_{OUT} is a perfect square wave. In reality, V_{OUT} takes a certain amount of time to swing up and down. See the course website for the LM741 data sheet.

a) Compute the small-signal bandwidth and associated rise time T_R.

b) Based on the LM741 slew-rate, compute the slew-rate limited rise time T_{SR}.

c) Is your amplifier limited by small-signal bandwidth or slew rate?

d) Sketch the amplifier output for 100 us. Label important features such as rise and fall times!

Note: If the amplifier is bandwidth limited, the V_{OUT} edges have "exponential decay". If the amplifier is slew-rate limited, the V_{OUT} edges have a linear ramp shape.

9) Consider an LF411 inverting amplifier with a gain |G| = +30 dB. The input V_{IN} is a 200 mV_{PP} sine wave at 300 kHz. See the course website for the LF411 data sheet.

a) Compute the large-signal bandwidth.

b) Compute the small-signal bandwidth.

c) Is the amplifier limited by slew-rate or small-signal bandwidth?