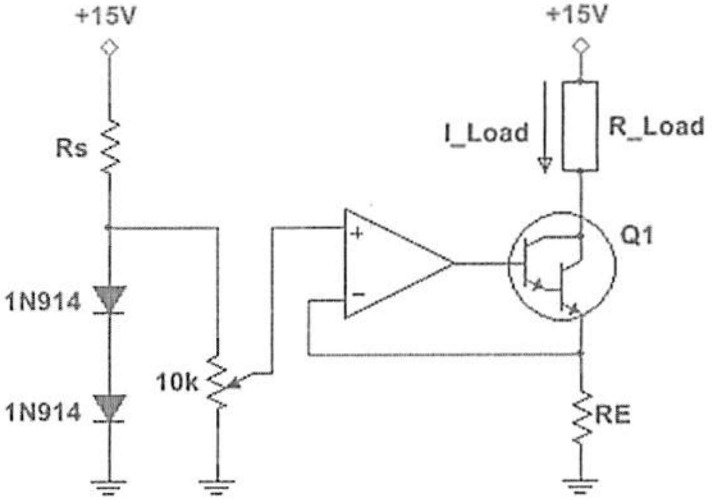
ECE 363 EXAM #1 (F19)

NAME: Solutions

4 problems for 100 pts

Problem #1: Adjustable Current Source (25 pts)

You are asked to design a DC current source that can produce up to 1.2A for a 10 ohm load. Consider the circuit shown to the right, where the load current comes from the Q1 collector. The current is made adjustable by the 10 kohm potentiometer, which samples a portion of the fixed voltage established by the pair of diodes. The design specs are:



- I_Load = 1.2A (+/- 5% is fine) when the potentiometer is set to 100%.
- Darlington is either a BC517 or TIP120
- Available heat sinks are 5, 10, 15, and 20 °C/W.
- All resistors are standard 5% values with available power ratings of ¼, ½, 1, 2, and 5W.

(a) Perform a "quick" analysis to choose Q1. You must explain why you chose one transistor and not the other one. If Q1 needs a heat sink, you must choose the proper value (assume $T_A = 25°C$ and $\theta_{CS} = 0.5°C/W$).

(b) **Based on "typical" Q1 and diode parameters**, choose the resistances and power ratings for R_E and R_S.

(c) Suppose your customer wants a current source to produce 1.2A in a 12 ohm load. Would you recommend using this same circuit you just designed? Explain why or why not.

ⓐ Max $I_L = 1.2A \xrightarrow{\times 2} 2.4A$ rating

(+10)

1.4V

$$P = \frac{1.2A}{2501}(1.4) + \frac{2500}{2501}(1.2A)(V_C - V_E) = 1.92W \xrightarrow{\times 2 \text{ Rating}} 3.84W$$

$15 - 1.2A \times 10\Omega = 3V$

	Max I_C	Max P (no HS)	Max P (w/HS)
BC517	1.2A X		
TIP120	5A ✓	2W X	65W ✓

Choose TIP120 + Heat Sink

$$T_J = 25°C + (1.92W)(1.92°C/W + 0.5°C/W + \Theta_{SA}) < 85°C$$

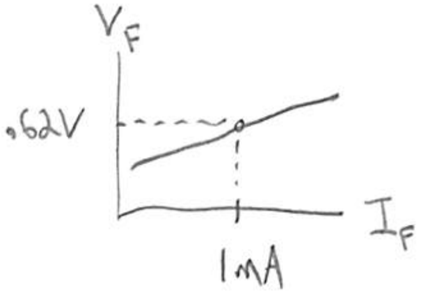
$\rightarrow \Theta_{SA} < 28.8°C/W$

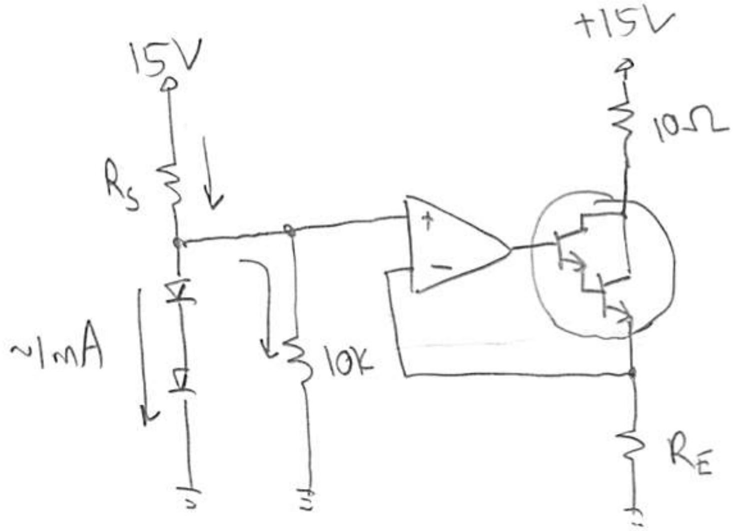
↳ Choose $\boxed{20°C/W}$

(extra sheet for work)

(b) Want ~1mA in diodes

(+10)

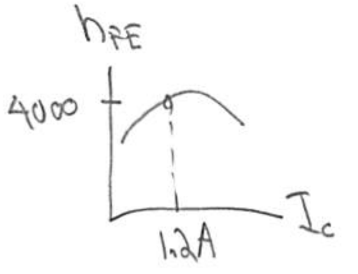




$$\frac{15 - \overbrace{2\times .62}^{1.24V}}{R_s} \sim 1mA + \frac{2\times .62V}{10K} \rightarrow R_s \approx 12.24K$$ Choose $\boxed{R_s = 12K}$

$$\frac{(15-1.24)^2}{12K} = 15.8mW \xrightarrow{\times 2} 31.6mW$$ $\boxed{\text{1/4W rating}}$

Want $I_c = \alpha I_E = \frac{4000}{4001} \cdot \frac{1.24V}{R_E} \sim 1.2A$



$R_E = 1.03\Omega \Rightarrow$ Choose $\boxed{R_E = 1.0\Omega}$

$$\frac{(1.24V)^2}{1\Omega} = 1.54W \xrightarrow{\times 2} 3.08W$$ $\boxed{\text{5W rating}}$

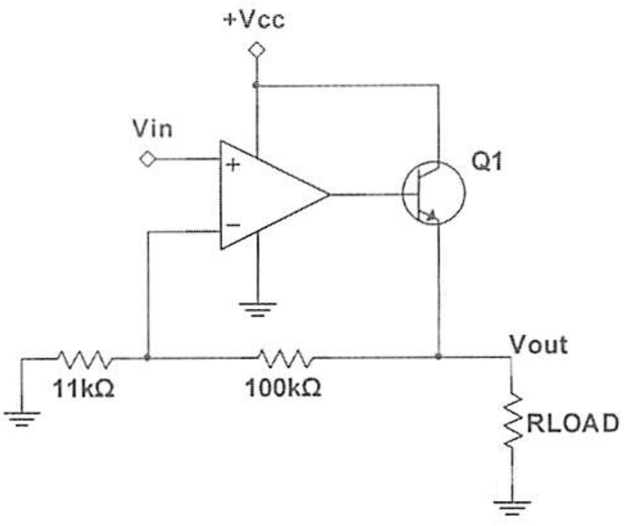
(c) $V_{Load} = 1.2A \times 12\Omega = 14.4V$

(+5)

Q_1's $V_{CE} = \underbrace{(15-14.4)}_{0.6V} - (1.24) < 0$!, Q_1 not in active mode ☹

NO, do not recommend same circuit.

Problem #2: Power Amplifier (25 pts)



You are asked to design a single-supply DC power amplifier with a voltage gain of 20 dB. The amplifier must deliver up to 8W into a 9 ohm load. You consider the circuit in the figure to the right:

The design constraints are the following:

- You must choose between the following:
  - TIP31 (power npn)
  - TIP110 (Darlington npn)
- The op amp output current must never exceed 10 mA.

(a) You must choose between Vcc = 9, 12, 15, or 18V. Show all calculations!

(b) Choose the appropriate transistor for Q1, keeping in mind the design constraint on the op amp's output current and **using worst-case transistor parameters.**

(c) Assuming an ambient temperature $T_A = 40°C$ and $\theta_{CS} = 0.5°C/W$, is a heat sink necessary for Q1? If so, you must choose between 6, 12, 18, and 24 °C/W. Show all work!

(d) Based on your chosen heat sink, what is the highest ambient temperature T_A that is safe for Q1?

ⓐ want $V_{cc} > V_{Load} + V_{CE,sat} + \overset{\text{Head room}}{2}$ $\Rightarrow V_{cc} > 8.49 + 2 = 10.49V$

$V_{CE,sat}$: 0V

$8W = \frac{V_L^2}{9\Omega}$

Max $V_L = 8.49V$

Choose $\boxed{V_{cc} = 12V}$

+7

ⓑ Max $I_L = \frac{8.49V}{9\Omega} = 0.94A \xrightarrow{\times 2} \underline{1.89A \text{ rating}}$

	Max I_c	Max P ← w/HS
TIP31	3A ✓	40W ✓
TIP110	2A ✓	50W ✓

TIP31: $P \sim \frac{.94A}{101}(0.7) + 0.99(.94)(12-8.49)$

$= 3.27W \xrightarrow{\times 2} 6.55W$ rating

TIP110: $P \sim \frac{.94A}{2501}(1.4) + \frac{2500}{2501}(.94)(12-8.49)$

$= 3.3W \xrightarrow{\times 2} 6.6W$ rating

Both OK, but what about BASE current?

(extra sheet for work)

$\underline{\min\beta @ I_C = 1A}$

TIP31 $\quad 25 \longrightarrow I_B = \frac{.94A}{26} = 36\,mA$ X

TIP110 $\quad 1000 \longrightarrow I_B = \frac{.94A}{1001} = \underline{\underline{.94\,mA}}$ ✓

(+7) Choose $\boxed{\text{TIP110}}$

(c) We already know Q_1 needs a HS for $T_A = 25°C$

(6.6W rating > 2W rating without HS)

$$P = \frac{.94A}{1001}(2.8V) + \frac{1000}{1001}(.94A)(12-8.49) = 3.3W$$

$$T_J = 40°C + 3.3W \times \left(2.5°C/W + 0.5°C/W + \theta_{SA}\right) < 85°C$$

$$\theta_{SA} < 10.6°C/W$$

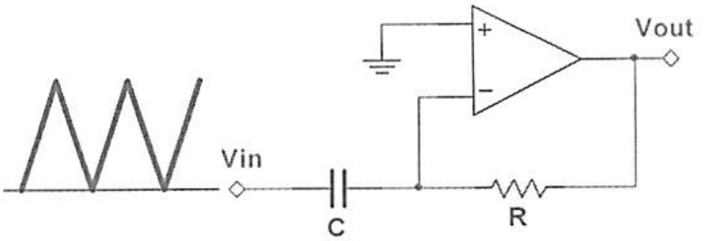
(+7) Choose $\boxed{6°C/W}$

(d) $T_{A,max} + 3.3(2.5 + .5 + 6) < 85$

(+4) $\boxed{T_A < 55.3°C}$

Problem #3: Differentiator (25 pts)

A differentiator has many applications, such as being part of a PID control loop. The circuit to the right uses an LM324 op amp. The input signal is a 200 mV_{PP} ramp waveform at 10 kHz.



(a) Use the Golden Rules to show that

$V_{OUT} = -RC\frac{dV_{IN}}{dt}$. Show all work!

(b) Let R = 2.2 Mohm and C = 470 pF. Assuming T_A = 25 °C, what is the worst-case DC output voltage error?

Hint: For DC analysis, what does the capacitor look like (open or short)?

(c) Keeping in mind the op amp's slew rate limitations, sketch the waveforms for V_{IN} and V_{OUT} over a 300 us time interval. Label important features!

ⓐ

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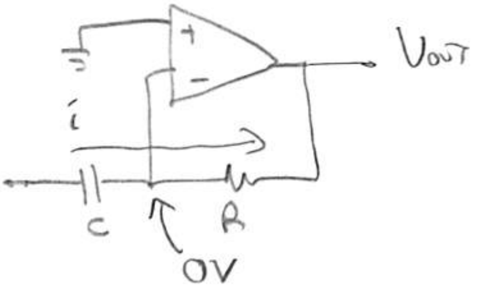
$$i = C\frac{d}{dt}(V_{IN}-0) = \frac{0-V_{OUT}}{R}$$

$$\boxed{V_{OUT} = -RC\frac{dV_{IN}}{dt}}$$



ⓑ

+9

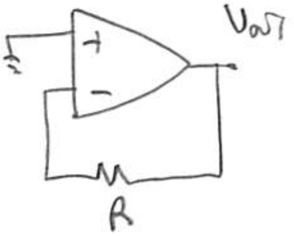
$T_A = 25°C$: $I_{IN(BIAS)} = 150\,nA$ (max) $R_{TH(+)} = 0$

$I_{IN(OS)} = 30\,nA$ (max) $R_{TH(-)} = 2.2M$

$V_{IN(OS)} = 7\,mV$ (max) Gain = 1

$$\Delta V_{OUT} = (150\times10^{-9})(2.2\times10^{6})\times1 + (30\times10^{-9})\left(\frac{2.2\times10^{6}+0}{2}\right)\times1 + .007\times1 = 0.33 + .033 + .007 = \boxed{0.37V}$$

Buffer (G=1)



(extra sheet for work)

ⓒ

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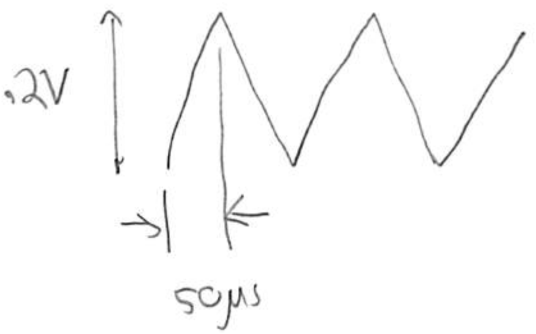
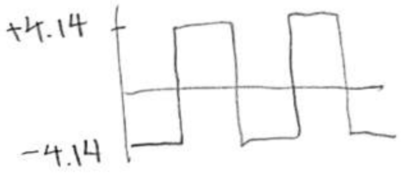
10kHz → 100μs period



$$\left|\frac{dV_{IN}}{dt}\right| = 4\times10^{3} \frac{V}{s}$$

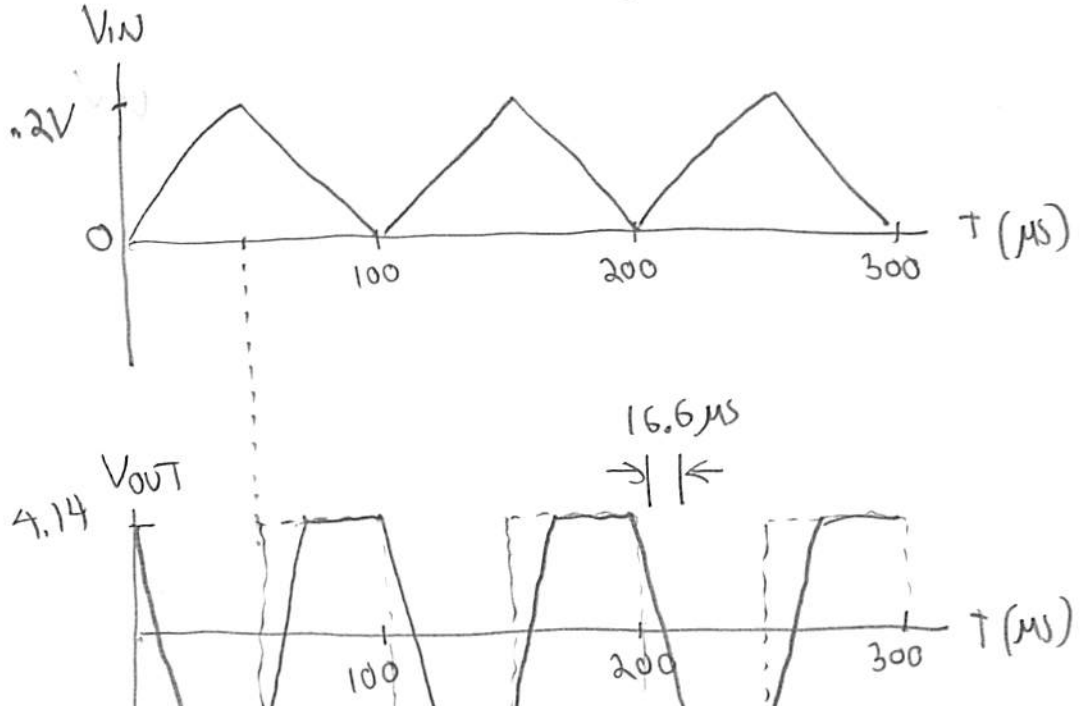
$$RC = (2.2\times10^{6})(470\times10^{-12}) = 1.03\times10^{-3}\ s$$

$V_{OUT} = \mp 4.14V$ (ideal)



BUT, SR = 0.4 V/μs

$$T_{SR} = \frac{0.8 \times 2 \times 4.14V}{.4\ V/\mu s} = \underline{\underline{16.6\mu s}}$$



Problem did not ask for this.

Does not include worst case ΔV_{OUT} error

Problem #4: Push-Pull Current Booster (25 pts)

Design an audio power amplifier to drive 125 mW into an 8 ohm load.

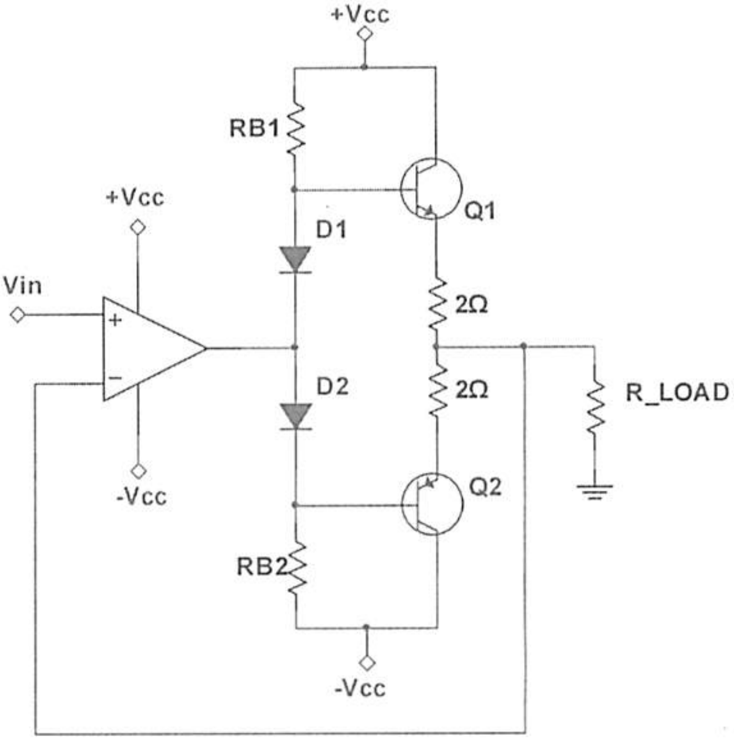
The design constraints are the following:

- Use an LF356 op amp.
- Q1 is a 2N4401, Q2 is a 2N4403.
- Assume the diodes have $V_F = 0.62V$ at 1 mA.
- V_{CC} is either 3, 5, 9, 12, or 15V.
- All resistors are 5% standard values.

(a) Perform a "quick" analysis to choose V_{CC}. Show all calculations!

(b) Choose RB1 and RB2 based on worst-case transistor conditions. You can assume Q1 and Q2 have matching properties.

(c) Show that the op amp can provide the required output voltage and current, **even under worst-case transistor conditions**.



ⓐ $$\frac{V_{max}^2}{2\times 8\Omega} = .125W \rightarrow V_{max} = \sqrt{.125\times 16} = \underline{1.41V}$$

+8

↖ For sine wave $\qquad I_{max} = \underline{.177A}$

Head room

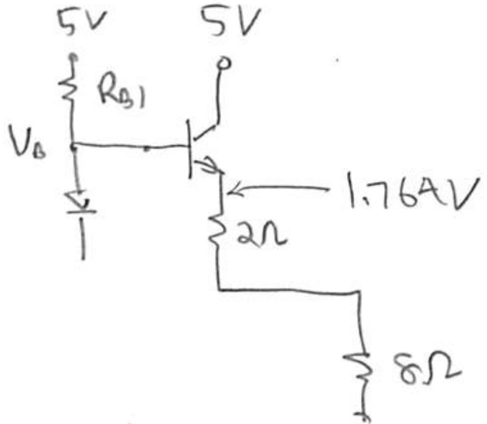
want $V_{CC} > 1.41 + (.177A)(2\Omega) + \underset{V_{CE,sat}}{0} + 2 = 3.76V$ $\boxed{\text{Choose } V_{CC} = 5V}$

ⓑ Max $V_B = 1.764 + \underbrace{\max V_{BE}}_{}$

+9

.95V @ 150mA (close enough)

= 2.714V



want $\frac{5-2.714}{R_{B1}} - \frac{.177A}{100} \gtrsim 1mA$

↑ min β @ 150mA

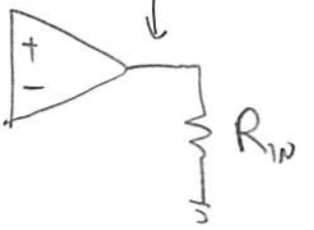
⇒ $R_{B1} \sim 825.3\Omega$

(extra sheet for work)

Choose $\boxed{R_{B1} = 820\Omega} = R_{B2}$

ⓒ

Max $V_o = 2.714 - .62$
$= \underline{\underline{2.094V}}$



$R_{IN} = 820 // 820 // (100+1)(r_e' + 2+8)$

$\uparrow \frac{.026V}{.177A} = .15\Omega$

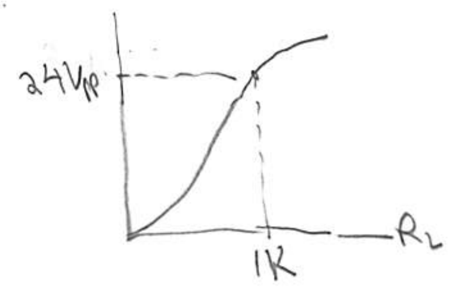
$= 292.9\Omega$

$\Rightarrow$ max $i_o = \frac{2.094V}{292.9\Omega} = \underline{\underline{7.15mA}}$

op amp head room: $5 - 2.094 = \underline{\underline{2.91V}}$

$V_{cc} = 15V$: max $V_o = 15 - 2.91 = \underline{\underline{12.1V_p}} \leftarrow$ $24V_{pp}$

Data sheet:



max $i_o = \frac{12V_p}{1K} = \underline{\underline{12mA}} > 7.15mA$ ✓

+8

YES, op amp is good! ☺