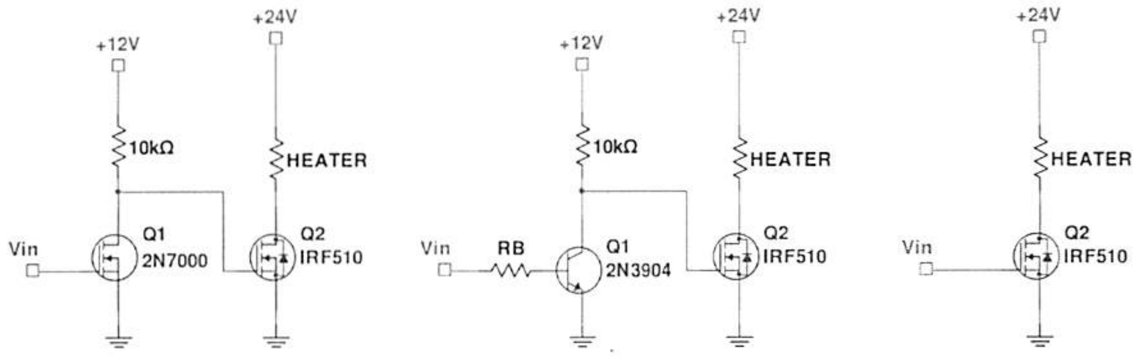
ECE 363 EXAM #2 (F19) NAME: Solutions

4 problems for 100 pts

Problem #1: Transistor Switch (25 pts)

You are asked to design a circuit to control a heater with a microcontroller unit (MCU). The heater is rated at 24V @ 60W while the MCU outputs 3.3V logic. You decide to drive the heater with an IRF510 power MOSFET, but you are wondering how exactly to hook up the MCU.



Circuit #1 Circuit #2 Circuit #3

(a) Explain why Circuit #2 is the best choice **and why Circuits #1 and #3 are not good choices.** Use the appropriate data sheet parameters, particularly worst-case transistor parameters.

(b) For Circuit #2, compute the appropriate 5% standard resistor for RB assuming typical Q1 parameters.

(c) Suppose T_A = 40 °C and the available heat sinks are θ_{SA} = ~~6~~ 4, ~~12~~ 8, ~~18~~ 12, and ~~24~~ 16 °C/W. You want your circuit to be capable of driving the heater with any duty cycle (e.g. 0 to 100%). Select the appropriate heat sink assuming worst-case Q2 parameters. Show all work!

(a) Circuit #1: 2N7000 has max $V_{GS,TH} = 3V$ ← Too close to 3.3V logic] Q_1 May not fully turn on :((+3)

Circuit #2:
- $V_{IN} = 3.3V$ is plenty to drive the Q_1 base ✓
- When $V_{IN} = 0$, Q_1 collector ≈ 12V = Q_2 gate ↑ Way above max $V_{GS,TH} = 4V$] Q_2 Fully Turns on :)
- When $V_{IN} = 3.3V$, Q_1 collector < 0.1V = Q_2 gate — Q_2 fully Turns OFF :)

(+4)

(+3) Circuit #3: $V_{IN} = 3.3V$ is below Q_2's max $V_{GS,TH} = 4V$ ← Q_2 cannot fully turn ON :(

(extra sheet for work)

$V_{CE,sat} \sim .05V$ @ 1.2mA

(b) Q_1: $I_C \sim \frac{12-0V}{10K} = 1.2mA$ $\qquad$ $I_C \sim \frac{12-.05}{10K} = 1.2mA$

2N3904: $V_{BE(sat)} \sim 0.7V$ @ $I_C = 1.2mA$

$$I_B = \frac{3.3-0.7}{R_B} \approx \frac{1.2mA}{10} \rightarrow R_B = 21.67K$$

+7 $\qquad$ Choose $\boxed{R_B = 22K}$

(c) Load: $R_L = \frac{(24V)^2}{60W} = 9.6\Omega$ $\qquad$ IRF510: Max $R_{DS,on} = .54\Omega$

$$I_L = \frac{60W}{24V} = 2.5A \qquad I_D \sim \frac{24-0}{9.6+.54} = 2.37A$$

+4 $\quad P = (2.37)^2(.54\Omega) = 3.03W$

$$T_J = 40 + (3.03W)(3.5°C/W + .5°C/W + \Theta_{SA}) < 85°C$$

$$\Theta_{SA} < 10.85°C/W$$

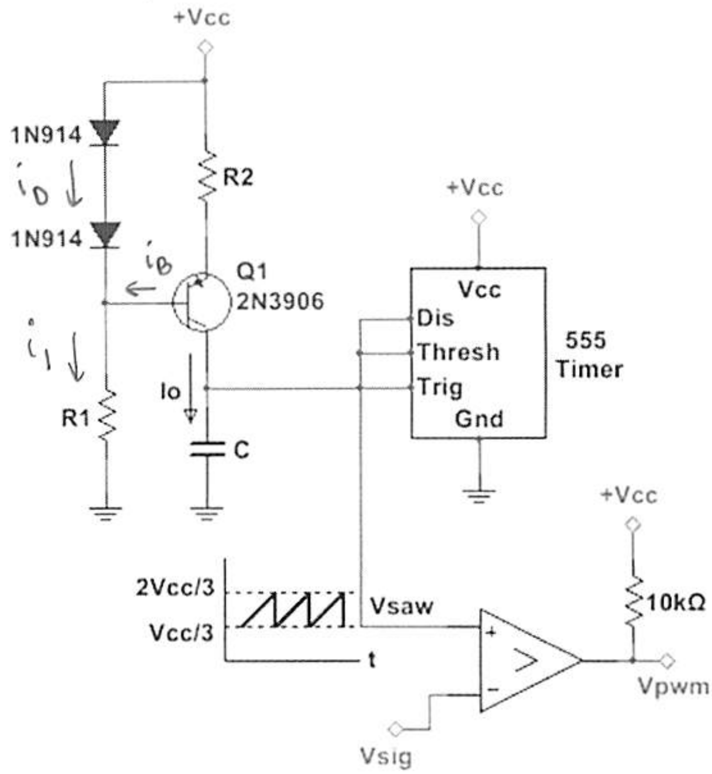
Choose $\boxed{\Theta_{SA} = 8°C/W}$

+4

Problem #2: Sawtooth Oscillator (25 pts)

You are asked to design a sawtooth oscillator for an LED PWM driver. You decide to use a 555 timer to operate at 20 kHz (+/- 2%). Let V_{CC} = 6V. Some comments:

- $f = 3 \cdot I_0/(C \cdot V_{CC})$
- The available capacitors are 1 nF, 10nF, and 100 nF.
- I_0 is typically between 0.1 to 1 mA.
- **Assume typical parameters for Q1 and both diodes.**



(a) Choose values for your capacitor C and current source value Io.

(b) Choose a standard 5% resistor for R2.

(c) Choose a standard 5% resistor for R1.

(d) Confirm your frequency satisfies the design requirement.

(e) Suppose Vsig = 2.5V. Compute the duty cycle and sketch Vpwm over a 200 us time interval. Label important features!

(a) $f = 20 \times 10^3 = \frac{3 I_o}{C \times 6V} \Rightarrow \frac{I_o}{C} = 4 \times 10^4 \ \frac{V}{s}$

C	I_o	
1nF	40μA	X
10nF	.4mA	✓
100nF	4mA	X

+6

Choose $C = 10nF$ and $I_o = 0.4mA$

(b) 1N914: $V_F \sim 0.62V$ @ 1mA

2N3906: $V_{BE} \sim 0.63V$ @ 0.4 mA

$\beta \sim 120 \Rightarrow \alpha = \frac{120}{121} = .992$

$I_o = 0.4mA = \alpha \frac{2 \times .62 - .63}{R_2}$

↑ .992

$R_2 = 1.51K$

+5

Choose $R_2 = 1.5K$

(c) $i_D + i_B = i_1$

$1mA + \frac{1}{121}(.4mA) = \frac{6 - 2 \times .62}{R_1}$

$R_1 = 4.74K \Rightarrow$ Choose $R_1 = 4.7K$ +5

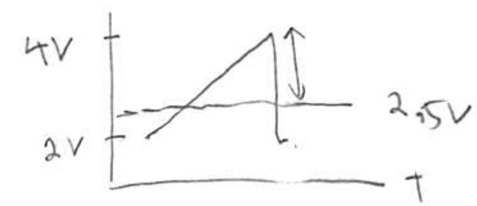
(extra sheet for work)

(d) Actual $I_o = .992 \dfrac{2 \times .62 - .63}{1.5K} = .403\,mA$

(+3) $f = \dfrac{3 \times (.403 \times 10^{-3})}{(10 \times 10^{-9})(6V)} = 2.02 \times 10^{4}\ Hz$

.75% error ✓

(e)

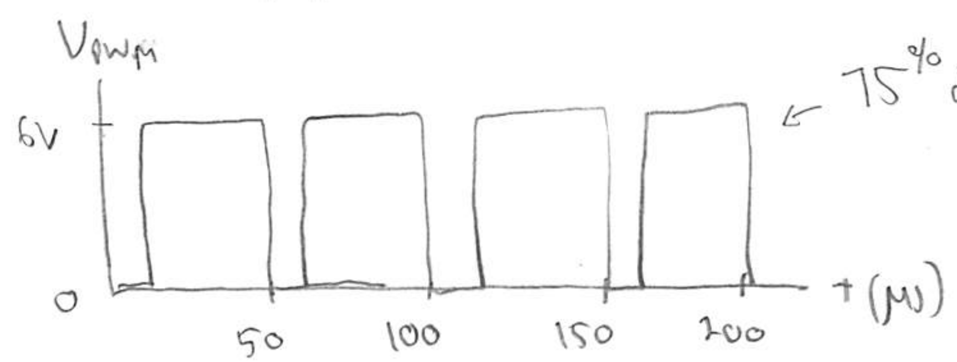


Duty Cycle $= \dfrac{4 - 2.5}{4 - 2} = $ **75%**

(+2)

20 kHz → 1 cycle = 50 μs

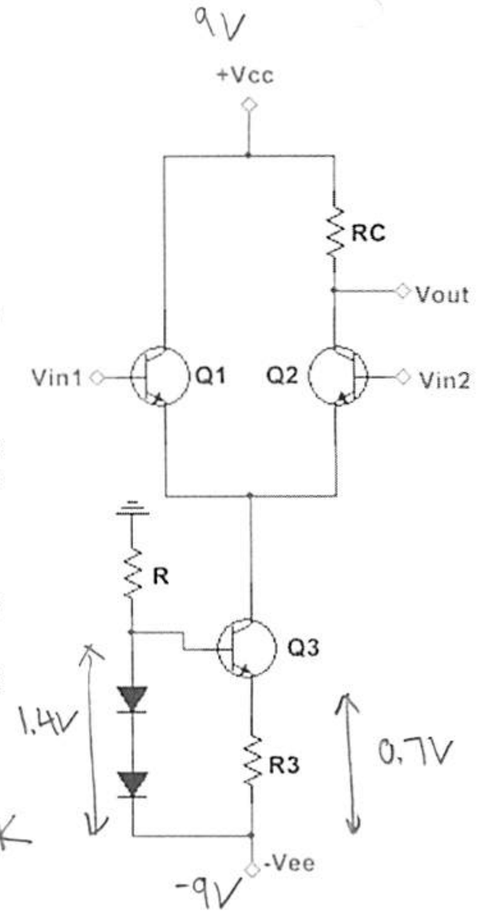
4 cycles = 200 μs



← 75% duty cycle

(+4)

Problem #3: Differential Amplifier (25 pts)



Your application requires a differential amplifier with the following specs:

- Ad = + 37.5 dB (+/- 0.4 dB is OK)
- $Z_{IN} \geq 75$ kohm
- Assume quick analysis parameters for all transistors and diodes.
- Vin1 = 3 + Vsig/2 and Vin2 = 3 – Vsig/2.

a) You must choose between R3 = 4.3 kohm or 5.6 kohm. Which is the best choice? **You must also show why the other value is a bad choice.** Show all work!

b) Choose an appropriate 5% standard value for R. Show all work!

c) Choose the appropriate 5% standard value for R_C **and show that you have satisfied the design requirement.** Show all work!

d) Assuming $A_{CM} \approx 0$, compute the maximum amplitude of Vsig that does not result in a clipped Vout.

(a) $Z_{IN} = 2(\beta+1)r_e' = 2(\beta+1)\frac{.026}{\frac{1}{2}I_T} \geq 75K$ (β = 100)

$I_T \leq 0.14\text{ mA}$ current source: $I_T = .99\frac{.7V}{R_3}$

(+6) $R_3 = 4.3K \Rightarrow I_T = .16\text{mA}$ X TOO HIGH

$5.6K \Rightarrow I_T = .124\text{mA}$ ✓ :)

(b) $i_R = i_D + i_B$

$\frac{0-(-9+1.4)}{R} = 1\text{mA} + \frac{.124\text{mA}}{100}$ (+5)

$R = 7.59K$ Choose $\boxed{R = 7.5K}$

(c) $37.5\text{ dB} = 20\log_{10}A_d \rightarrow A_d = 10^{37.5/20} = 74.99 = \alpha\frac{R_c}{2r_e'}$

$r_e' = \frac{.026}{.5(.124\text{mA})} = .419K \Rightarrow R_c = \frac{74.99}{.99}2(.419K) = 63.5K$

(extra sheet for work)

(+6)

Choose $\boxed{R_C = 62K}$

Check: $A_d = .99 \dfrac{62K}{2(.419K)} = 73.25$

$20\log_{10}(73.25) = 37.3\text{ dB}$

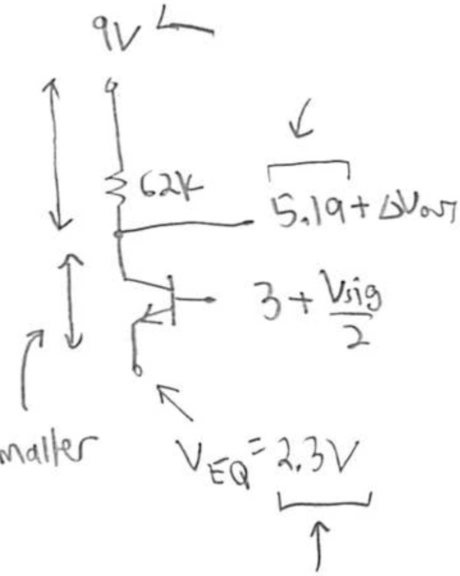
(+2)

−0.2 dB error ✓

ⓓ $V_{OUT} = V_{CQ} + \underbrace{\Delta V_{OUT}}_{A_d \Delta V + \underbrace{A_{CM} V_{CM}}_{\sim 0}}$

$V_{CQ} = 9 - .99 \dfrac{.124\text{ mA}}{2}(62K) = \underline{\underline{5.19V}}$

$V_E \sim 3 - 0.7 = \underline{\underline{2.3V}}$



☆ Don't want to saturate Q_2!

(+6)

$5.19 - |\Delta V_{OUT}| > 2.3V$

$|\Delta V_{OUT}| < 2.89V$

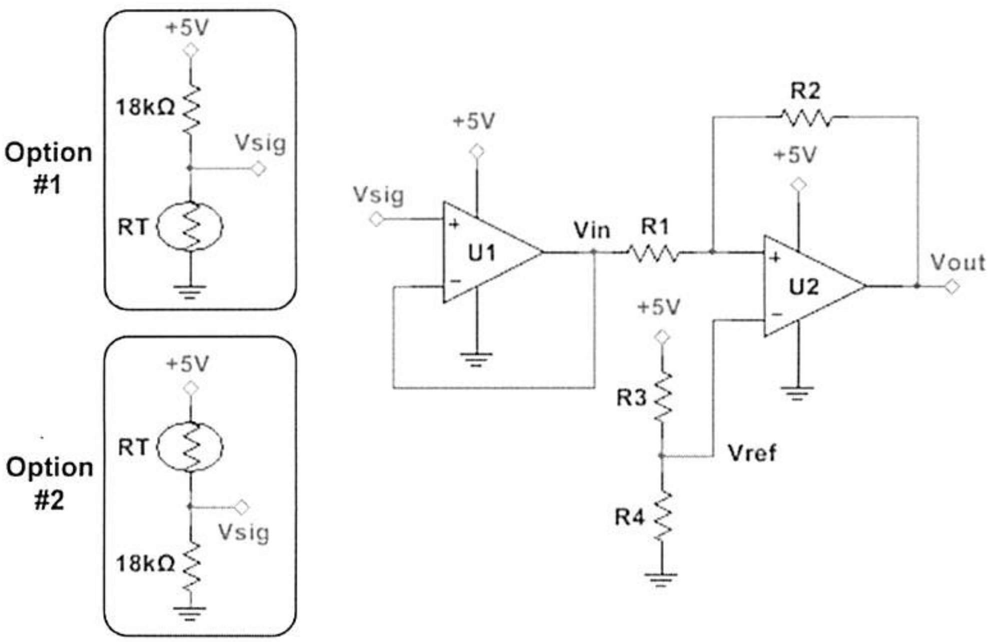
$\Delta V_{IN} = \left(3 + \frac{V_{sig}}{2}\right) - \left(3 - \frac{V_{sig}}{2}\right) = V_{sig} \Rightarrow |V_{sig}| < \dfrac{2.89}{73.25} = .0395V$

$\boxed{|V_{sig}| < 39.5\text{ mV}}$

Problem #4: Thermostat (25 pts)

A chemical processing machine requires cooling a sample and maintaining the temperature within a certain range. Temperature is measured with a thermistor (thermally sensitive resistor). The specs are the following:

- Temperature sensor:
  - The thermistor resistance is R_T = 12.49 kohm @ 20℃ and R_T = 25.34 kohm @ 5℃.
  - The thermistor R_T is either in the bottom (Option #1) or top (Option #2) of a voltage divider.
- Both op amps are operated from a single-supply. Assume $V_{SAT(+)} = V_{CC} - 1V$ and $V_{SAT(-)} = 0V$.
  - Op amp U1 is just a buffer. Op amp U2 is a Schmitt trigger with V_{OUT} being:
    - HIGH when the temperature rises above 20℃
    - LOW when the temperature dips below 5℃
- Some useful formulas for the Schmitt trigger are:
  - Upper Trip Point: $UTP = (1 + R_1/R_2)\cdot V_{REF} - (R_1/R_2)\cdot V_{SAT(-)}$
  - Lower Trip Point: $LTP = (1 + R_1/R_2)\cdot V_{REF} - (R_1/R_2)\cdot V_{SAT(+)}$



(a) Would you use Option #1 or Option #2 to produce Vsig? **Explain your reasoning (e.g. a table helps).**

(b) Compute the UTP and LTP values for Vsig **to 3 decimal places** (e.g. 1.234V) based on your answer to (a).

(c) Based on the UTP and LTP formulas, choose appropriate 5% values for R_1 and R_2. NOTE: R_2 should be in the 100 kohm range.

(d) Determine V_{REF}, and choose 5% values for R_3 and R_4. NOTE: R_4 should be in the 100 kohm range.

+5

(a) Higher — want V_{sig} for T = 20°C

T	R_T	V_{sig} (option #1)	(option #2)
20°C	12,49K	$5 \times \frac{12{,}49}{12{,}49+18} = 2{,}048$ ×	$5 \times \frac{18}{18+12{,}49} = 2{,}952$ ✓
5°C	25,34K	$5 \times \frac{25.34}{25.34+18} = 2{,}923$	$5 \times \frac{18}{18+25.34} = 2{,}077$

Choose option #2

(extra sheet for work) (b) From Table:

(+5)

$$UTP = 2.952V$$
$$LTP = 2.077V$$

(c)

$$2.952 = \left(1 + \frac{R_1}{R_2}\right) V_{REF} - 0$$
$$- \quad 2.077 = \left(1 + \frac{R_1}{R_2}\right) V_{REF} - \frac{R_1}{R_2} 4$$

(+8)

$$0.875 = 4 \frac{R_1}{R_2} \Rightarrow \frac{R_1}{R_2} = 0.219$$

Let $R_2 = 100K$, $R_1 = 22K$ $\Rightarrow \frac{R_1}{R_2} = 0.22$ ✓

(d)

$$2.952 = (1 + 0.22) V_{REF} \Rightarrow V_{REF} = 2.420V = 5 \frac{R_4}{R_3 + R_4}$$

(+7)

$$\frac{R_3 + R_4}{R_4} = 1 + \frac{R_3}{R_4} = 2.066$$

$$\frac{R_3}{R_4} = 1.066$$

R_4	R_3	R_4/R_3
100K	110K	1.1
110K	120K	1.09
120K	130K	1.083
130K	150K	1.154
150K	160K	1.067 ✓

+