Problem #2: Differential Amplifier (25 pts)

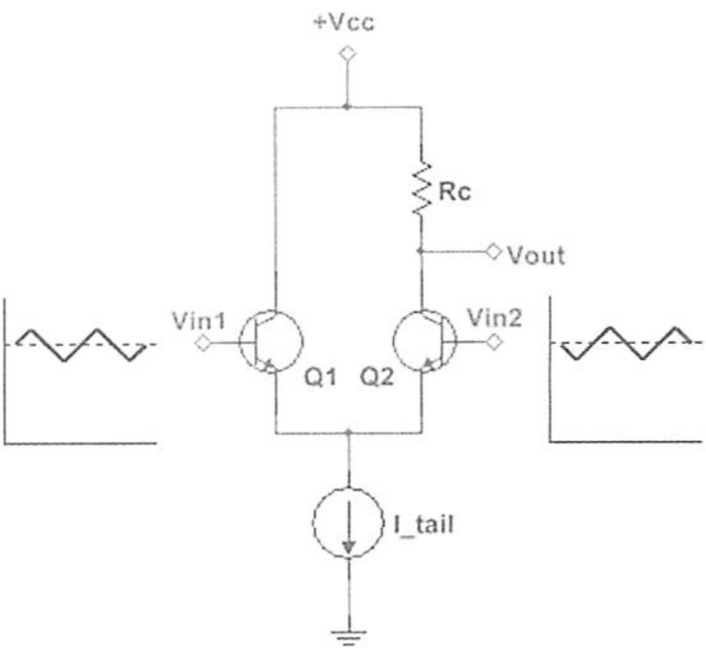
Your application requires a differential amplifier with Ad = +34 dB (+/- 0.5 dB is OK). Suppose Vcc = +15V and a 0.2 mA current sink produces the tail current. Assume Q1 and Q2 have the same properties as the 2N3904. The voltage inputs are given by:

a) Compute the minimum and typical values for the amplifier input impedance Z_{IN}.

b) Choose a standard 5% value for Rc and compute the resulting differential gain. Assume typical transistor parameters. Show all work!

c) What is the minimum CMRR needed to ensure that ΔV_{OUT} < 10 mV for a 5V common-mode input? Express your answer in dB.

d) Suppose Vin1 = 5 + ΔV(t) and Vin2 = 5 – ΔV(t), where ΔV(t) is an 100 mV peak-to-peak triangle wave at 20 kHz. Compute and sketch V_{OUT} over a 150 μs time interval. You can assume $A_{CM} \approx 0$. Label important features!



ⓐ $Z_{IN} = 2(\beta+1) r_e' = 2(\beta+1)\frac{.026V}{\frac{1}{2} I_T}$ ← 0.2mA

+6

At $I_c \sim \frac{1}{2}(0.2mA) = .1mA$

$\beta_{min} = 40$

$\beta_{typ} = 230$

$\alpha = \frac{230}{231} = .996$

Min $Z_{IN} = 2(41)\underbrace{\frac{.026}{\frac{1}{2}(.2mA)}}_{.26K} = \boxed{21.3K}$

Typ $Z_{IN} = 2(231)(.26K) = \boxed{120.1K}$

ⓑ $20\log_{10} A_d = 34 dB \rightarrow A_d = 10^{34/20} = 50.1 = .996\frac{R_c}{2(.26K)}$

+6

$R_c = 26.2K$

Choose $\boxed{R_c = 27K}$

$A_d = .996\frac{27K}{2(.26K)} = 51.7 = \boxed{34.27 dB}$ ✓

within 0.5 dB

ⓒ Want $A_{CM} V_{CM} < .010V$

+5

$A_{CM} < \frac{.010}{5} = .002 \rightarrow CMRR > 20\log_{10}\left(\frac{51.7}{.002}\right) = \boxed{88.3 dB}$

(extra sheet for work)

ⓓ $\Delta V_{IN} = 2\Delta V(t) = 200\, mV_{pp}$ [Triangle wave] = $100\, mV_p$ [triangle wave]

SO, $V_{OUT} = \overset{\nearrow}{V_{CQ}} + A_d \Delta V_{IN} + \underbrace{A_{cm} V_{CM}}_{\approx 0\,!} = 12,31 + 51,7 \times 0.1V \times$ [Triangle Wave]

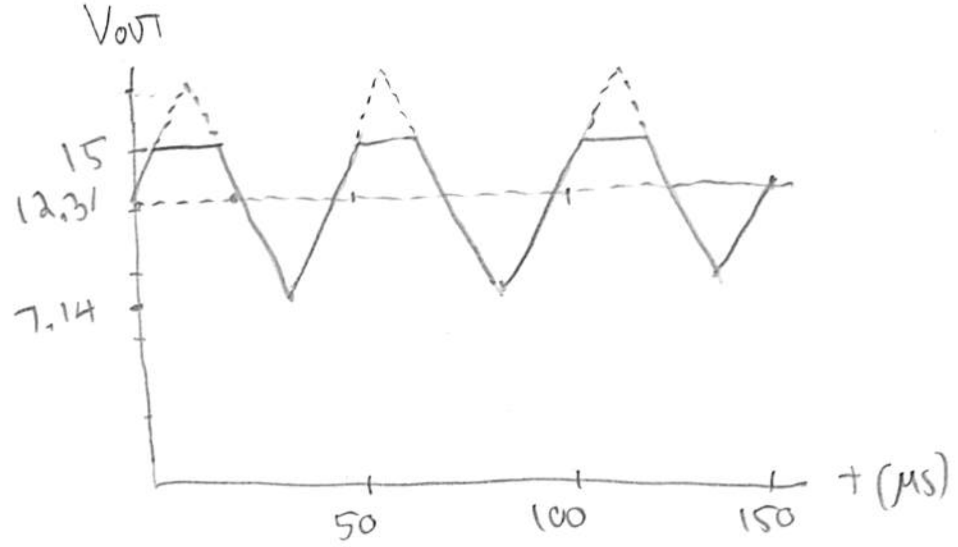
$\underbrace{15 - ,996 \frac{.2mA}{2}(27K)}_{12,31V}$

$= 12,31 + 5,17 \times$ [Triangle wave]

Max $V_{OUT} = 12.31 + 5.17 = 17.48V$ ✗ ← cannot exceed 15V due to Q_2 cut-off

Min $V_{OUT} = 12.31 - 5.17 = 7,14V$ ✓ ← Does not saturate Q_1

20kHz → 1cycle = 50μs

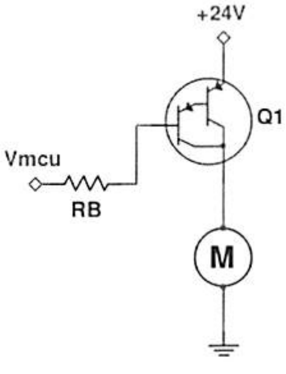


+8

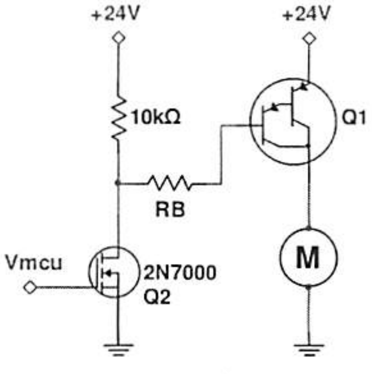
Problem #2: Transistor Switches (25 pts)

You are asked to design a circuit to allow a microprocessor unit (MCU) to operate a DC motor.

- The MCU output Vmcu is 5V logic with a 20 mA current limit.
- The motor is rated at 4A for voltages between 22 and 24V.
- The motor must be operated with a high-side transistor switch.



Circuit #1



Circuit #2

(a) Explain why Circuit #1 would not work while Circuit #2 would work OK.

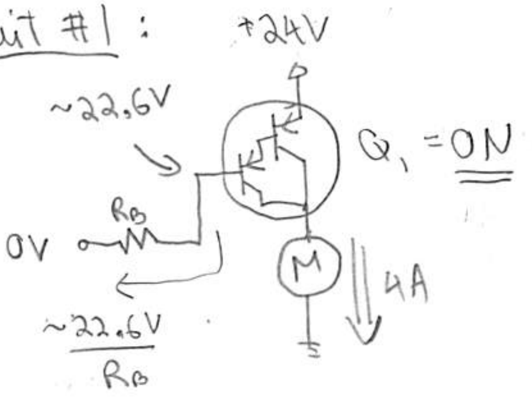
(b) Q1 must either be a TIP115 or TIP105 transistor. Choose the appropriate transistor by only considering max I_C and V_{CE}.

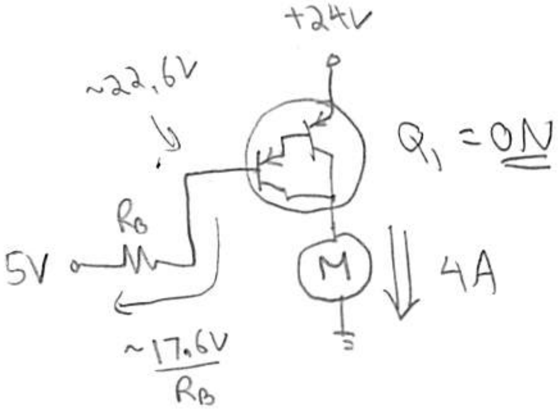
(c) Given your choice of Q1, would a 10, 15, or 20 °C/W heat sink be adequate? Assume typical Q1 properties.

(d) Compute the appropriate 5% standard resistor for RB. Assume typical Q1 and Q2 conditions.

ⓐ Circuit #1 :

+3

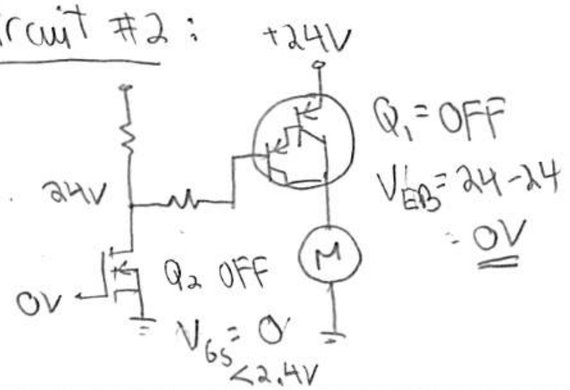


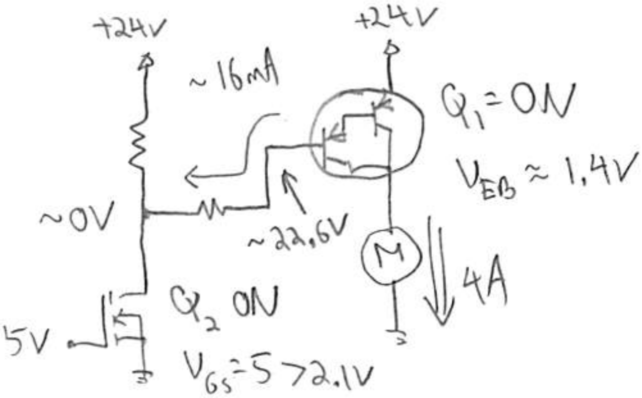


☆ Q_1 is always ON, so circuit #1 will not work! ☹

Circuit #2 :

+3





☆ Q_1 is OFF or ON, so circuit #2 will work! ☺

(extra sheet for work)

+4

ⓑ	Max I_c	Max V_{CE}
TIP115:	2A X	60V ✓
TIP105:	8A ✓	60V ✓

Choose $\boxed{\text{TIP105}}$

ⓒ $|V_{CE}| \sim 1.55V$, $|V_{BE}| \sim 2.1V$ @ $I_c = 4A$

$$P = \left(\frac{4A}{250}\right)(2.1V) + (4A)(1.55V) = \underline{\underline{6.23W}}$$

+5

$$25^\circ C + 6.23\,W\left(1.56^\circ C/W + 0.5^\circ C/W + \Theta_{SA}\right) < 100^\circ C$$

$$\Theta_{SA} < \frac{100 - 25^\circ C}{6.23W} - (1.56 + 0.5^\circ C/W)$$

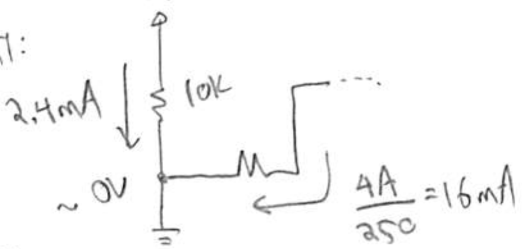
Choose 10°C/W heat sink

$$< \underbrace{9.98^\circ C/W}$$

+5

Close enough to 10°C/W

ⓓ Estimate Q_2 drain current:



$I_D \sim 18.4mA$

$$R_{DS,on} \sim \frac{0.5V}{0.3A} = 1.67\Omega$$

↗ Assuming $R_{DS,on} << R_B$,

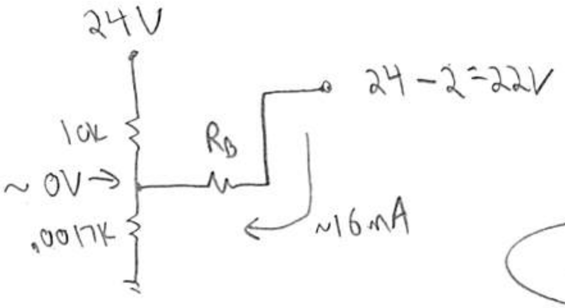
Check later

$$\frac{22-0}{R_B} = 16mA$$

$R_B = 1.375K$

↓

1.67Ω<<1.3K ✓



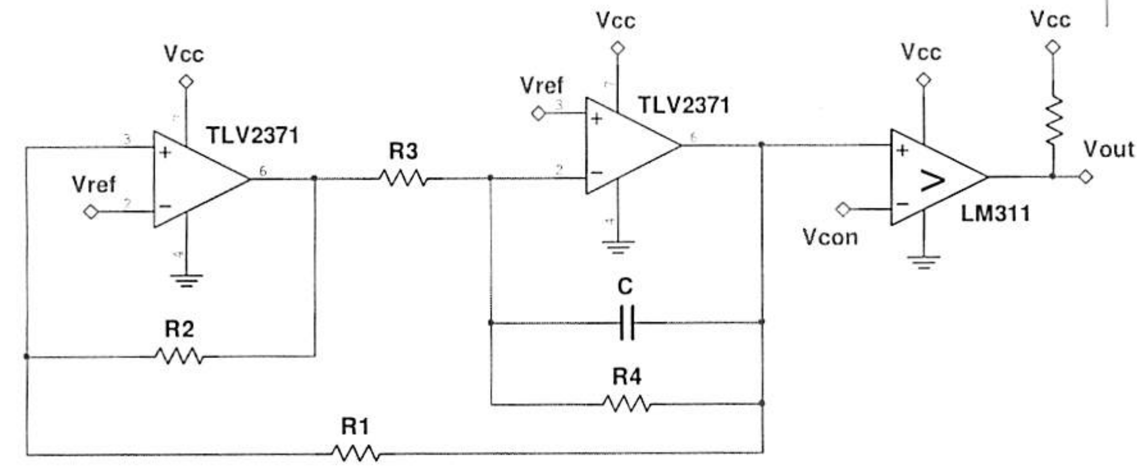
+5

Choose $\boxed{R_B = 1.3K}$

Problem #3: Servo Motor Controller (25 pts)

You are asked to design the PWM circuit for a digital servo motor controller. The triangle wave oscillator must have a frequency f = 50 Hz and peak-to-peak amplitude of $3V_{PP}$. Use TLV2371 op amps powered by +5V and GND. These rail-to-rail op amps have $V_{SAT(+)} = V_{CC}$ and $V_{SAT(-)} = 0$. Some useful formulas are shown below:

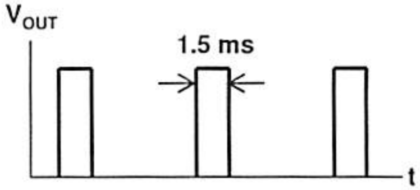
$V_{TH} = 0.5(V_{SAT(+)}-V_{SAT(-)})R_1/R_2$ $\quad$ $V_{REF} = 0.5(V_{SAT(+)}-V_{SAT(-)})$ $\quad$ $f = R_2/(4R_1R_3C)$



a) Choose 5% values for R_1 and R_2 such that the resulting triangle wave peak amplitude is **within 5% of the desired value.** Show all work!

b) Choose 5% values for R_3, R_4, and C and confirm the resulting triangle wave frequency is **within 5% of the desired value.** Show all work!

c) In many servos, a PWM pulse width (e.g. duration of the HIGH portion) of 1.5 ms puts the motor in the "home" position. What control voltage V_{CON} is needed to make this possible? Show all work!



ⓐ $V_{TH} = 1.5V = 0.5(5-0)\frac{R_1}{R_2} \Rightarrow \frac{R_1}{R_2} = 0.6$ or $\frac{R_2}{R_1} = 1.667$

R_1	R_2
10K	16.67K
11K	18.34K
→ 12K	20.0K

$2V_{TH} = 2 \times \frac{5-0}{2} \frac{12k}{20K}$

$= \underline{3V}$ ← 0% error!

Choose $\boxed{\begin{matrix} R_1 = 12K \\ R_2 = 20K \end{matrix}}$

+9

(extra sheet for work)

ⓑ $f = \frac{20K}{4(12K)R_3C} = 50Hz \rightarrow R_3C = 8.333 \times 10^{-3} s$

C	R_3	5% R_3	
100nF	83.33K	82K	-1.6%
120nF	69.44K	68K	-2.1%
150nF	55.55K	56K	-0.8%

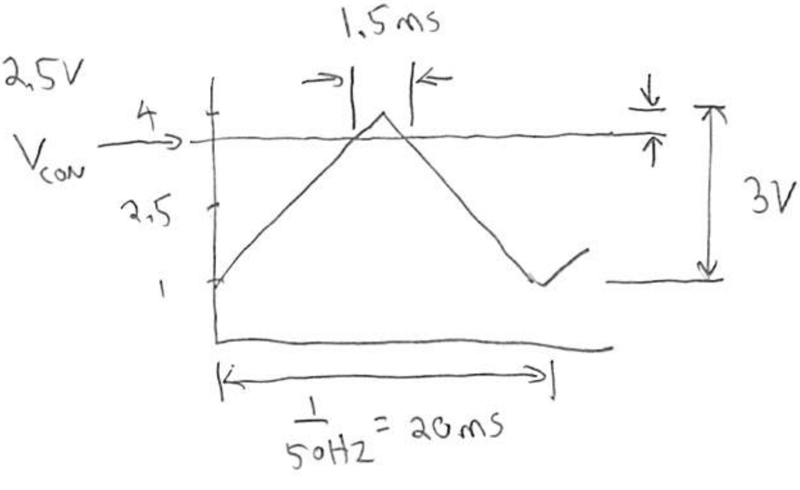
Choose $\boxed{\begin{array}{l} C = 150nF \\ R_3 = 56K \end{array}} \rightarrow$ 150nF

(+9)

$$f = \frac{20K}{4(12K)(56\times10^{3})(150\times10^{-9})} = \boxed{49.6Hz}$$

$$100 \times \frac{49.6-50}{50} = \boxed{-0.8\%}$$

ⓒ $V_{REF} = \frac{5-0}{2} = 2.5V$



Want $\frac{1.5ms}{20ms} = \frac{4 - V_{CON}}{4 - 1V}$

$4 - V_{CON} = 3 \frac{1.5}{20}$

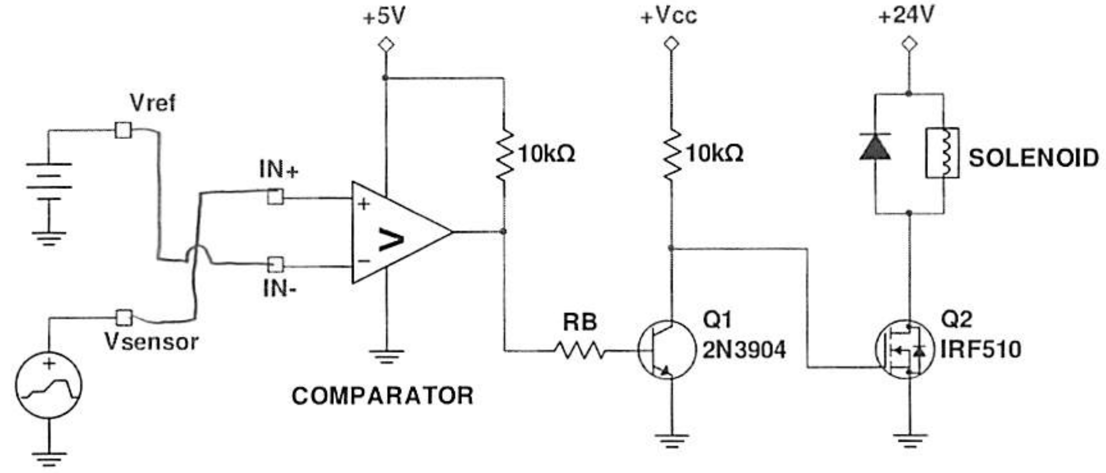
$V_{CON} = 4 - 3 \cdot \frac{1.5}{20} = \boxed{3.775V}$

(+7)

Problem #4: Water Valve Controller (25 pts)

A greenhouse needs an automatic sprinkler system. Here's how it works: when the plants are too dry, a solenoid valve turns on and water flows through the sprinkler system. The system has four parts:

(1) Water-level sensor produces V_{SENSOR} between 1V (water = empty) and 2V (water = full).
(2) V_{SENSOR} and V_{REF} are inputs to a voltage comparator with open collector output.
(3) 2N3904 transistor switch drives an IRF510 power MOSFET.
(4) 24V, 1A solenoid turns on to allow water flow.



(a) How would you connect V_{SENSOR} and V_{REF} to the comparator?

(b) You must choose between V_{CC}= 5, 12, and 24V. Use the appropriate 2N3904 and IRF510 data sheet parameters to explain why your chosen V_{CC} works **and why the other two values do not**.

(c) Compute the appropriate 5% standard resistor for R_B. Assume typical Q1 conditions and keep in mind that the comparator has an open collector output.

ⓐ When dry: $V_{sensor} < V_{ref}$ → Comparator is LOW → Q_1 OFF → Q_2 ON

+6 wet: $V_{sensor} > V_{ref}$ → Comparator is HIGH → Q_1 ON → Q_2 OFF

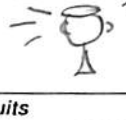
ⓑ Q_2 gate is the key!

Max $V_{GS,TH} = 4V$

Max $V_{GS} = 20V$

WINNER! → 12V

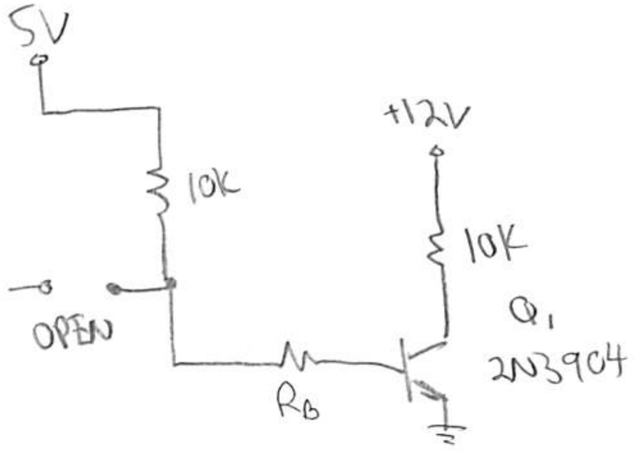
V_{cc}	V_{GS}
5V	5V ← Not much higher than 4V. May not fully turn ON Q_2
12V	12V ← Good! Fully turn on Q_2 without damage.
24V	24V ← Exceeds max allowable V_{GS}



+10

(extra sheet for work)

ⓒ Comparator HIGH output means open collector.



$I_c \sim \frac{12V}{10K} = 1.2mA$

$\left.\begin{array}{l} V_{CE} = .05V \\ V_{BE} = .7V \end{array}\right] @ \sim 1.2mA$

SO, want $I_B = \frac{I_c}{10}$

$$\frac{5-0.7}{10K+R_B} = \frac{1}{10}\ \frac{12-.05V}{10K} = .12mA$$

+9

$\rightarrow R_B = 25.98K$

choose $\boxed{R_B = 27K}$