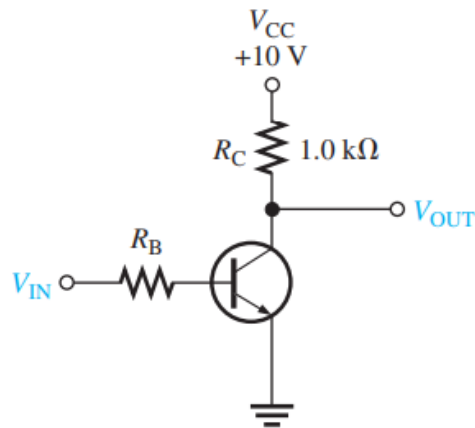


A. BJT Switching Applications

1. For the following BJT transistor circuit as given below, answer the following questions.



- What is V_{CE} when $V_{IN} = 0$ V? [2 marks]
- What minimum value of I_B is required to saturate this transistor if β_{DC} is 200? Neglect $V_{CE}(\text{sat})$. [4 marks]
- Calculate the maximum value of R_B when $V_{IN} = 5$ V. [4 marks]

Solution

- a. When $V_{IN} = 0$ V, the transistor is in cut-off (acts like an open switch) and

$$V_{CE} = V_{CC} = 10 \text{ V}$$

- b. Since $V_{CE}(\text{sat})$ is neglected (assumed to be 0 V), the saturation current at the collector is found from:

$$I_C(\text{sat}) = \frac{V_{CC}}{R_C} = \frac{10 \text{ V}}{1 \text{ k}\Omega} = 10 \text{ mA}$$

As a result, the minimum current at the base of transistor is found from:

$$I_B(\text{min}) = \frac{I_C(\text{sat})}{\beta_{DC}} = \frac{10 \text{ mA}}{200} = 50 \text{ }\mu\text{A}$$

This is the value of I_B necessary to drive the transistor to the point of saturation. Any further increase in I_B will ensure the transistor remains in saturation but there cannot be any further increase in I_C .

c. When the transistor is on, $V_{BE} \cong 0.7 \text{ V}$. The voltage across R_B is:

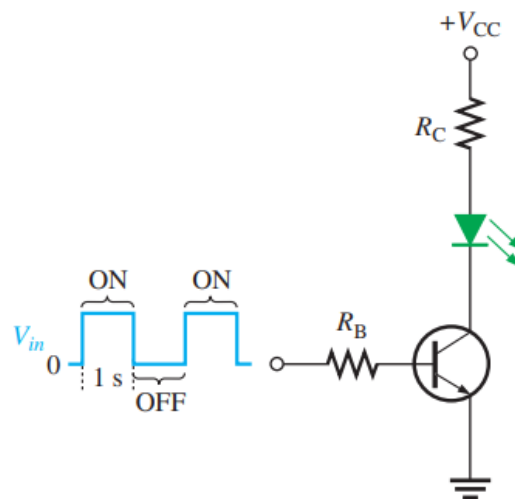
$$V_{R_B} = V_{IN} - V_{BE} \cong 5 \text{ V} - 0.7 \text{ V} = 4.3 \text{ V}$$

Calculate the maximum value of R_B needed to allow a minimum I_B of $50 \mu\text{A}$ using Ohm's law as follows:

$$R_B(\text{max}) = \frac{V_{R_B}}{I_B(\text{min})} = \frac{4.3 \text{ V}}{50 \mu\text{A}} = 86 \text{ k}\Omega$$

2. The LED in circuit given below requires 30 mA to emit a sufficient level of light. Therefore, the collector current should be approximately 30 mA . The values of the components in the circuit are $V_{CC} = 9 \text{ V}$, $V_{CE}(\text{sat}) = 0.3 \text{ V}$, $R_C = 220 \Omega$, $R_B = 3.3 \text{ k}\Omega$, $\beta_{DC} = 50$, and $V_{LED} = 1.6 \text{ V}$.

For the given component values, determine the amplitude of the square wave input voltage necessary to make sure that the transistor saturates. Use a double of the minimum value of base current as a safety margin to ensure saturation. [8 marks]



Solution

The collector current at saturation is found from the following equation:

$$I_C(\text{sat}) = \frac{V_{CC} - V_{LED} - V_{CE}(\text{sat})}{R_C} = \frac{9 \text{ V} - 1.6 \text{ V} - 0.3 \text{ V}}{220 \Omega} = 32.3 \text{ mA}$$

The minimum base current is found from:

$$I_B(\text{min}) = \frac{I_C(\text{sat})}{\beta_{DC}} = \frac{32.3 \text{ mA}}{50} = 646 \mu\text{A}$$

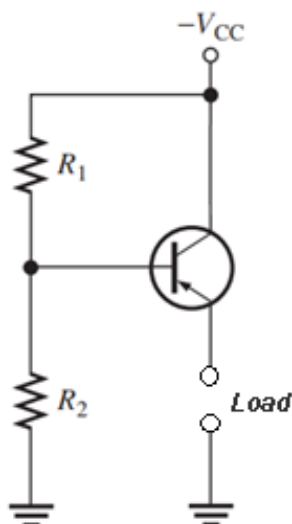
To ensure saturation, use twice the value of $I_B(\text{min})$, which is $(2)(646 \mu) = 1.29 \text{ mA}$. Use Ohm's law to solve for V_{in} .

$$I_B = \frac{V_{R_B}}{R_B} = \frac{V_{in} - V_{BE}}{R_B}$$

Rearrange the equation given above, the input voltage V_{in} is found from:

$$V_{in} = 2I_B(\text{min})R_B + V_{BE} = (1.29 \text{ mA})(3.3 \text{ k}\Omega) + 0.7 \text{ V} = 4.96 \text{ V}$$

3. The most commonly used PNP BJT transistor (e.g. 2N3906) as a switch is as shown in the figure below. If we have a load that requires 100 mA of current and a transistor with a minimum DC gain of 100, calculate the minimum base current required to saturate the transistor in the circuit and determine the values of R_1 and R_2 for supply voltage, V_{CC} is -12 V. [12 marks]



Solution

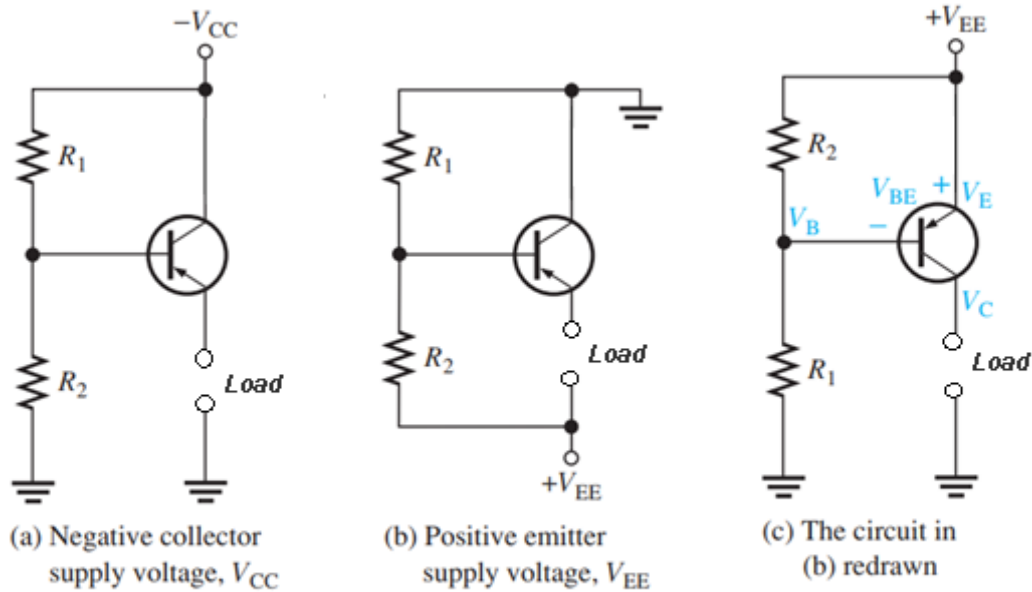
The secret to making a transistor switch work properly is to get the transistor in a saturation state.

For this to happen we need to know the maximum load current for the device to be turned on and the minimum DC gain of the transistor.

ON CHARACTERISTICS

| | | | | | |
|---------------|--------------------------------------|--|------|------|---|
| h_{FE} | DC Current Gain * | $I_C = 0.1 \text{ mA}, V_{CE} = 1.0 \text{ V}$ | 60 | 300 | |
| | | $I_C = 1.0 \text{ mA}, V_{CE} = 1.0 \text{ V}$ | 80 | | |
| | | $I_C = 10 \text{ mA}, V_{CE} = 1.0 \text{ V}$ | 100 | | |
| | | $I_C = 50 \text{ mA}, V_{CE} = 1.0 \text{ V}$ | 60 | | |
| | | $I_C = 100 \text{ mA}, V_{CE} = 1.0 \text{ V}$ | 30 | | |
| $V_{CE(sat)}$ | Collector-Emitter Saturation Voltage | $I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$ | | 0.25 | V |
| | | $I_C = 50 \text{ mA}, I_B = 5.0 \text{ mA}$ | | 0.4 | V |
| $V_{BE(sat)}$ | Base-Emitter Saturation Voltage | $I_C = 10 \text{ mA}, I_B = 1.0 \text{ mA}$ | 0.65 | 0.85 | V |
| | | $I_C = 50 \text{ mA}, I_B = 5.0 \text{ mA}$ | | 0.95 | V |

From the datasheet of 2N3906 BJT transistor, for $I_C = 100 \text{ mA}$, it is safe to assume that the DC gain of the transistor is selected to be 100 (e.g. more than 30 minimum value and less than 300 maximum value at $I_C = 100 \text{ mA}$ and $V_{CE} = 1 \text{ V}$).



If we transform the circuit from (a) to (b) as shown above, the minimum base current of the transistor is found from the following equation:

$$I_B(\text{min}) = \frac{I_C}{\beta_{DC}} = \frac{100 \text{ mA}}{100} = 1 \text{ mA}$$

In actual practice, it is best to calculate about 30% more current than we will need to guarantee our transistor switch is always saturated. In this case, we will use:

$$I_B = I_B(\text{min}) \times 1.3 = 1.3 \times 1 \text{ mA} = 1.3 \text{ mA}$$

Taking the KVL at the base of the transistor:

$$V_S = I_B R_1$$

We can now calculate resistor R_1 in the circuit as follows:

$$R_1 = \frac{V_S}{(I_C/\beta_{DC} \times 1.3)} = \frac{12}{(0.1/100 \times 1.3)} \cong 9.23 \text{ k}\Omega$$

Which its value is 10 k Ω to the nearest standard resistor value.

Resistor R_2 is generally required for stability and to ensure that the transistor switch is completely turned off. This resistor ensures that the base of the transistor does not go slightly negative which would cause a very small amount of collector current to flow.

The value of this resistor is not critical but a value about 10 times R_1 is normally chosen. Considering that input resistance looking at the internal of the base of the 2N3906 BJT transistor is equal to, the value of the resistors at the base should be less than 100 k Ω .

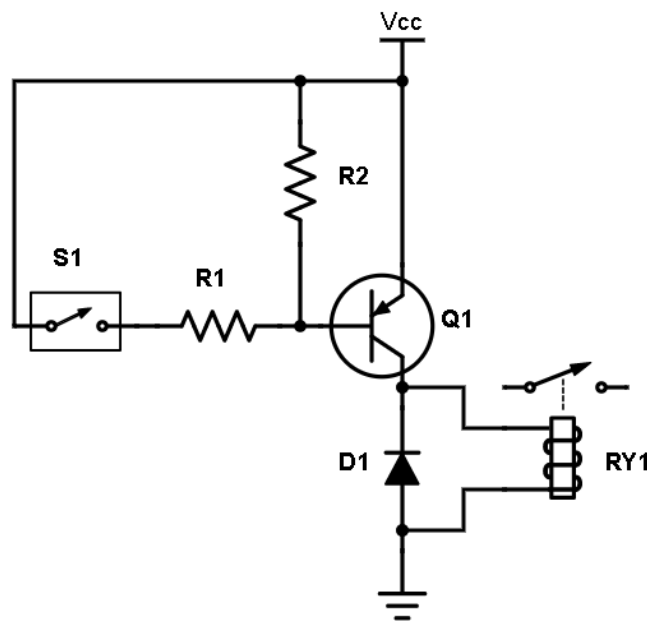
For this circuit, we will calculate R_2 to be 10 times R_1 as follows:

$$R_2 = 10 \times R_1 = 10 \times 10 \text{ k}\Omega = 100 \text{ k}\Omega$$

4. Transistor switches are used for a wide variety of applications. These transistors are commonly used to turn on transmitter circuits, LED's, cooling fans and even relays. Describe practical implementation of the PNP transistor circuit in the figure given in the previous question for driving a relay coil. [6 marks]

Solution

When using a transistor to turn on a relay coil, it is very important to use a diode (1N4001) reversed biased in parallel with the relay coil as shown in the figure below. This is to prevent the kickback voltage in the reverse polarity from destroying the transistor. This reverse voltage occurs momentarily when the normal current stops flowing through the coil. In the end, it is good practice to use a diode when turning on any inductive load.



The actual transistor used as a switch is not critical in these applications. Virtually any general purpose NPN or PNP transistor can be used as a switch. All that is needed is to know the minimum DC gain and the power dissipation of the transistor.

While most all transistors in a TO-92 case will have DC gain of at least 100, many power transistors in TO-220 cases often have an DC gain no greater than 25. It is essential to know the DC gain or Beta of a transistor, so that we can have a large enough base current to achieve saturation.

Transistor switches are often used to take the low-level output from logic circuits to turn on or turn off a particular device. This is especially important when using a low current logic output from a CMOS IC.

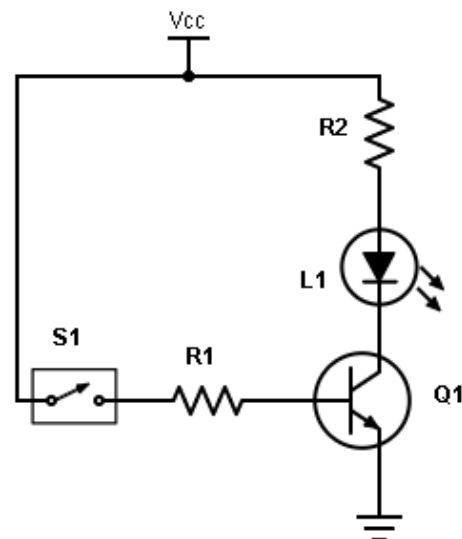
If a power transistor is used to turn on a high current device i.e. a high-power relay coil, it may be necessary to use another lower current transistor switch to drive a transistor switch used in a high current application (e.g. Darlington transistor circuit – back-to-back BJT transistors arrangement).

While there are a few applications where our transistor switches may not be suitable, it is usually a much more reliable and inexpensive alternative to using mechanical relays. These circuits are low in cost and offer ease of design.

5. Summarise common practical examples of BJT transistor as a switch by comparing the similarities and differences of its use for applications given below:
- a. Switch the LED. [2 marks]
 - b. Operate the relay. [2 marks]
 - c. Drive the motor. [2 marks]

Solution

- a. For transistor to switch the LED application, the schematic below shows how a transistor is used to switch the Light Emitting Diode (LED).



For this application, when the switch at the base terminal is open, no current flows through the base so the transistor is in the cut off state. Therefore, the circuit acts as open-circuit and the LED becomes OFF.

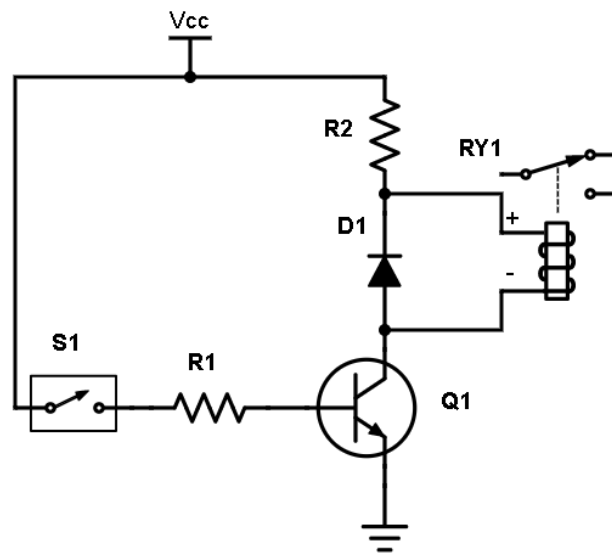
When the switch is closed, base current starts flowing through the transistor and then drives into saturation results to LED become ON.

Resistors are placed to limit the currents through the base and LED. It is also possible to vary the intensity of LED by varying the resistance in the base current path.

- b. For transistor to operate the relay application, it is also possible to control the relay operation using a transistor. For this application, with a small circuit arrangement of a transistor able to energise the coil of the relay so that the external load connected to it is controlled.

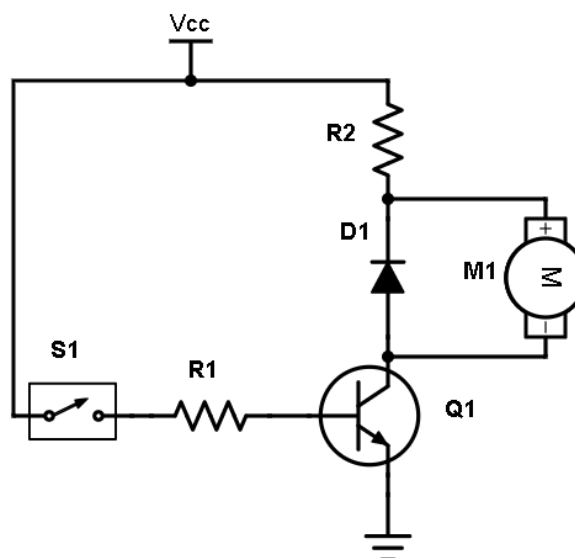
Consider the below circuit to know the operation of a transistor to energize the relay coil. The

input applied at the base causes to drive the transistor into saturation region, which further results the circuit becomes short circuit. So, the relay coil gets energized and relay contacts get operated.



In inductive loads, particularly switching of motors and inductors, sudden removal of power can keep a high potential across the coil. This high voltage can cause considerable damage to the rest circuit. Therefore, we must use the diode in parallel with inductive load to protect the circuit from induced voltages of the inductive load.

- c. For transistor to drive the motor application, a transistor can also be used to drive and regulate the speed of the DC motor in a unidirectional way by switching the transistor in regular intervals of time as shown in the below figure.



For this application, as mentioned in above, the DC motor is also an inductive load, so we have to place a freewheeling diode across it to protect the circuit.

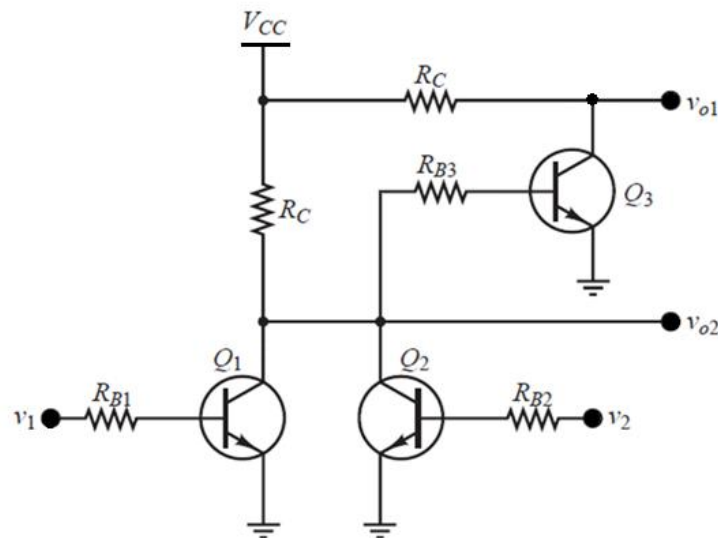
By switching the transistor in cut-off and saturation regions, we can turn ON and OFF the motor

repeatedly.

It is also possible to regulate the speed of the motor from standstill to full speed by switching the transistor at variable frequencies. We can get the switching frequency from control device or IC like microcontroller.

6. Show that the circuit of the figure below functions as an OR gate if the output is taken at v_{o1} .

[8 marks]



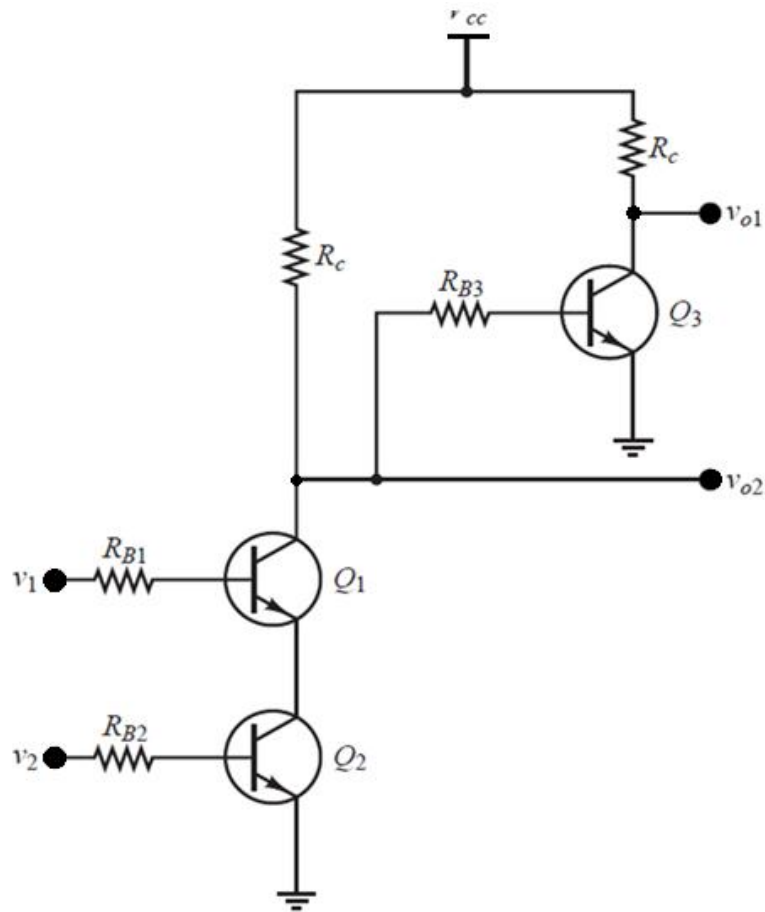
Solution

The conditions and states of the OR logic gate circuit are shown in the table below.

| v_1 | v_2 | Q_1 | Q_2 | Q_3 | v_{o1} | v_{o2} |
|-------|-------|-------|-------|-------|----------|----------|
| 0 | 0 | Off | Off | On | 0 | 5 |
| 0 | 5 | Off | On | Off | 5 | 0 |
| 5 | 0 | On | Off | Off | 5 | 0 |
| 5 | 5 | On | On | Off | 5 | 0 |

7. Show that the circuit of the figure below functions as a NAND gate if the output is taken at v_{o2} .

[8 marks]

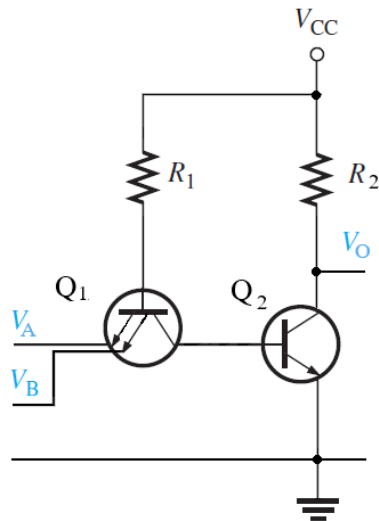


Solution

The conditions and states of the NAND logic gate circuit are shown in the table below.

| v_1 | v_2 | Q_1 | Q_2 | Q_3 | v_{o1} | v_{o2} |
|-------|-------|-------|-------|-------|----------|----------|
| 0 | 0 | Off | Off | On | 0 | 5 |
| 0 | 5 | Off | On | On | 0 | 5 |
| 5 | 0 | On | Off | On | 0 | 5 |
| 5 | 5 | On | On | Off | 5 | 0 |

8. There are several BJT logic device families and diode-transistor logic (DTL) and transistor-transistor logic (TTL) are two examples of them.
- What is transistor-transistor logic (TTL)? [3 marks]
 - Explain how the TTL is considered to be an improvement from the DTL. [3 marks]
 - Considering a basic transistor-transistor logic circuit diagram as shown in the figure below, describe its basic operations. [8 marks]



Solution

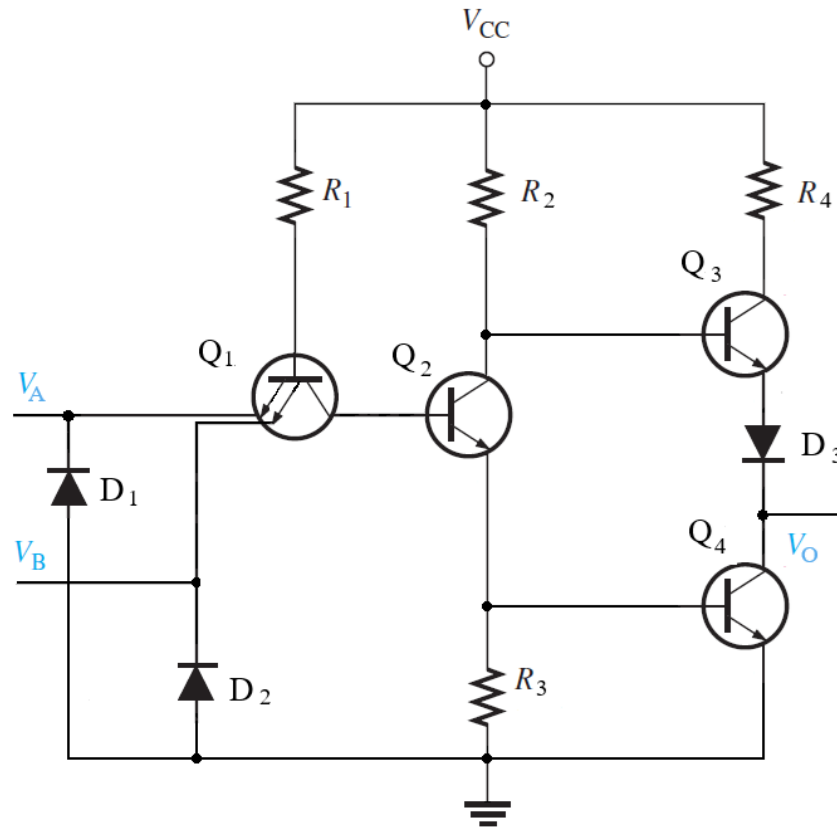
- a. Transistor-Transistor Logic (TTL) is one of the digital circuits designed from BJT (Bipolar Junction Transistor) and resistors. The operation principle of TTL is based on the switching function of logic gates and amplification performed by the transistors in the circuit.
- b. The basic diode-resistor logic formed with AND gate uses separate diodes for the inputs. Therefore, a bipolar junction transistor uses two junction diodes, which represent either NPN Or PNP transistors. So, the TTL (transistor-transistor logic) is formed when the input diodes of the DTL (Diode-Transistor Logic) are replaced with a single NPN transistor with multiple emitter inputs as shown in the above circuit.
- c. The circuit given above shows a simplified transistor-transistor logic which functions as a 2-input NAND gate. Here, T_1 with two input emitter terminals acts as an input transistor, and T_2 acts as a single-stage NPN inverting switching transistor.

When one or both emitter inputs A and B of T_1 is or are connected to the logic LOW level (0), T_1 's base current flows via the base or emitter junction to GND (0 V), T_1 saturated and is followed by the collector terminal. This causes the base of T_2 to be grounded (0 V).

Therefore, T_2 will be in the "OFF" state and the output at Q will be HIGH.

When both inputs " A " and " B " are at a logic HIGH level (1), the input transistor T_1 turns OFF and the primary switching transistor T_2 turns HIGH, making the Q output LOW due to the switching function of the transistor. Several emitters on T_1 are connected as inputs to create a NAND gate function.

9. To understand the working of a transistor-transistor logic (TTL), consider the circuit diagram of the standard TTL logic gate, which executes a positive NAND gate function as shown in the figure below. This standard TTL logic circuit is related to the Diode-Transistor Logic (DTL) circuit in some conditions. Describe how TTL circuit shown below works. [10 marks]

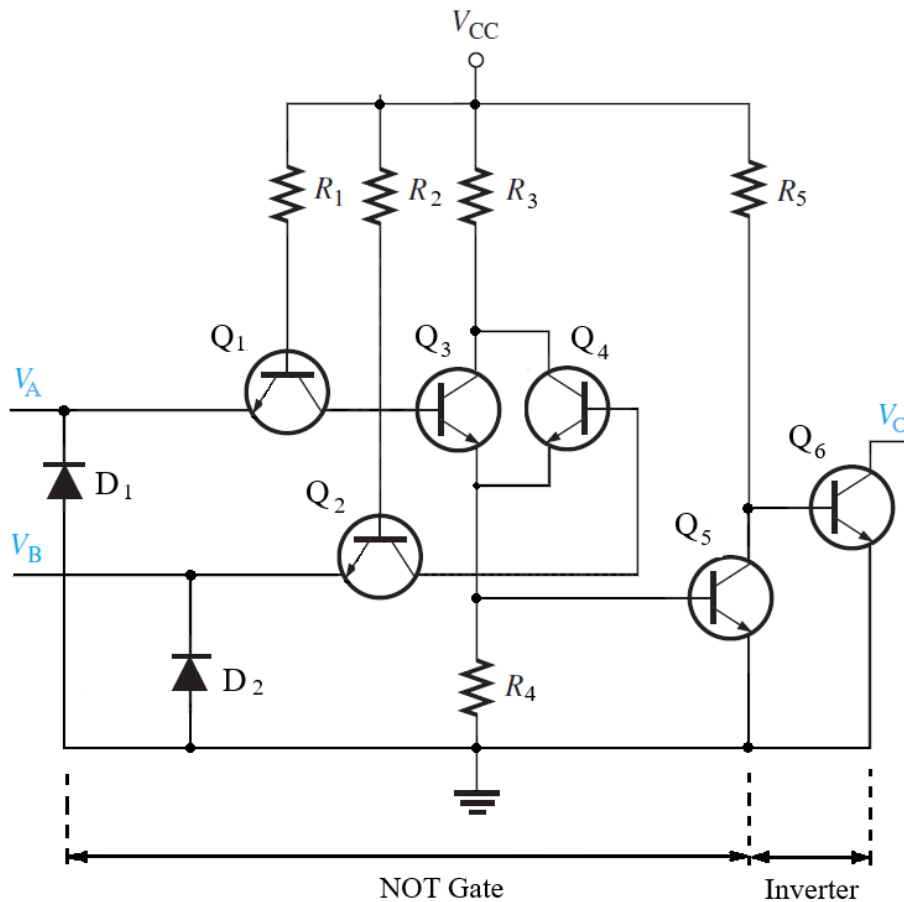


Solution

From the above figure, T_1 is the input transistor, which has an advantage in switching time. The transistor T_2 is a phase-splitter and the transistors T_3 and T_4 give totem-pole output. This TTL circuit has very low input impedance, high fan-out, and better noise immunity and is capable of a high capacitive drive.

- When the inputs A and B are HIGH, the transistors T_2 and T_3 turn ON and act as common-emitter amplifiers. The transistor T_4 and the diodes at the emitter are forward biased and a negligible amount of current flows. The output is LOW, which represents logic 0.
- When both the inputs are LOW, diodes D_1 and D_2 get forward biased. The current goes to the ground via the D_1 and D_2 and the resistor R_1 due to the supply voltage V_{CC} of 5 V. The voltage supply drops in R_1 and the transistor T_2 turns OFF because it has not had enough voltage to turn ON. Therefore, the transistor T_4 also turns OFF due to T_2 being OFF. The transistor T_3 turns ON (HIGH) and acts as an emitter follower. The output is HIGH, which represents a logic 1.
- When any one of the inputs A and B is low, then the diode gets forward biased due to the low input. The whole operation is the same as described above. Therefore, the output is HIGH (logic 1).

10. The following circuit given in the diagram below shows a transistor-transistor logic (TTL) OR gate with open collector output. Describe the mechanism of its operation. [12 marks]



Solution

The circuit diagram of the transistor-Transistor logic 2-input OR gate with TTL NOR gate stage and open collector output stage (NOR gate output is connected to another transistor/inverter stage to make a TTL OR gate) is shown in the figure above.

Transistors T_1 and T_2 are connected in the same way as seen for transistor T_1 in other TTL circuits. Instead of working as an amplifier, T_1 and T_2 are used as a two-diode “drive” circuit. To illustrate the working, T_1 and T_2 can be replaced with a set of diodes.

From the above circuit diagram, the TTL logic NOR gate stage is converted into TTL logic OR gate by connecting the output logic level of the NOR gate to another transistor stage (inverter stage). That means the output stage of the TTL NOR gate is added to an inverter stage to create the TTL OR gate. Since totem-pole output stages are possible in both TTL circuits using 2-input OR gate and NOR gates.

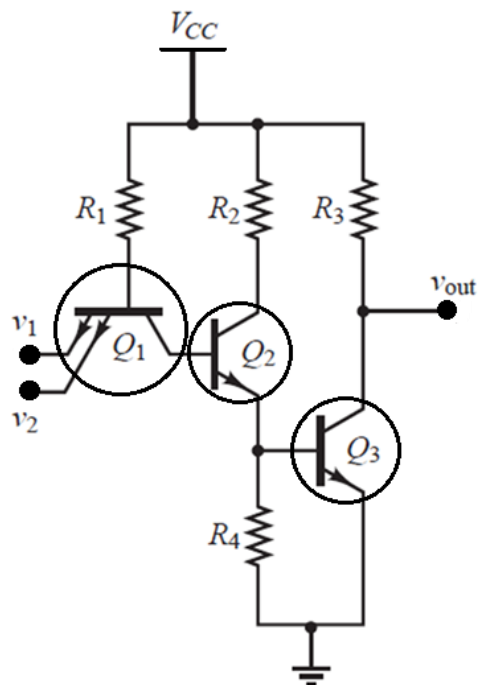
When input A is connected to V_{CC} , current flows through the base of transistor T_3 and saturates. When input A is grounded, this current gets diverted from the base of T_3 through the left control diode of T_1 , causing Q_3 to turn OFF (cut-off). The same way is done for input B and transistor T_4 . The logic level at input B gives the conductivity of T_4 , which is either in saturation or cut-off.

Observe how transistors T_3 and T_4 are connected in parallel at the collector and emitter terminals. Essentially, these two transistors act as parallel switches, allowing current via resistors R_3 and R_4 depending on the logic level of inputs A and B .

When one of the inputs is HIGH (1), both/anyone transistors (T_3 and/or T_4) saturate, allowing the current through resistors R_3 and R_4 and reaches the logic output LOW level (0) on the TTL NOR gate output transistor T_5 . The output of the transistor T_5 NOR gate circuit can only go high (1) when transistors T_3 and T_4 are OFF (cut-off). This means both inputs must be grounded or LOW (0) (TTL NOR gate condition to obtain output logic level HIGH).

The output (logic 0) of the transistor T_5 (TTL NOR gate output) obtained in the NOR gate stage is connected to transistor T_6 (inverting output stage of NOR gate) to get the final output at the open collector output will be logic HIGH (1). This will be the output of the TTL OR gate when any one of the inputs A and B is HIGH (1).

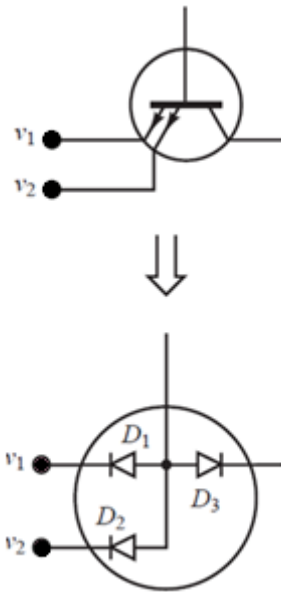
11. Determine v_{out} for each of the four combinations of v_1 and v_2 . Knowing that $R_1 = 5.7 \text{ k}\Omega$; $R_2 = 2.2 \text{ k}\Omega$; $R_3 = 2.2 \text{ k}\Omega$; $R_4 = 1.8 \text{ k}\Omega$; $V_{CC} = 5 \text{ V}$; $V_{BE(\text{on})} = V_Y = 0.7 \text{ V}$; $V_{CE(\text{sat})} = 0.2 \text{ V}$.



Treat the BE and BC junctions of Q_1 as offset diodes. Assume that the transistors are in saturation when conducting. TTL logic values are actually quite flexible, with v_{HIGH} as low as 2.4 V and v_{LOW} as high as 0.4 V. [24 marks]

Solution

The inputs to the TTL gate, v_1 and v_2 , are applied to the emitter of transistor Q_1 . The transistor is designed so as to have two emitter circuits in parallel. Transistor Q_1 is modelled by the offset diode model, as shown in the figure below. We now consider each of the four cases.



- Case 1: Voltage $v_1 = v_2 = 0$ V. With the emitters of Q_1 connected to ground and the base of Q_1 at 5 V, the BE junction will clearly be forward-biased and Q_1 is on. This result means that the base current of Q_2 (equal to the collector current of Q_1) is negative, and therefore Q_2 must be off. If Q_2 is off, its emitter current must be zero, and therefore no base current can flow into Q_3 , which is in turn also off. With Q_3 off, no current flows through R_3 , and therefore

$$v_{out} = V_{CC} - v_{R3} = 5 - 0 = 5 \text{ V}$$

- Case 2: Voltage $v_1 = 5$ V; $v_2 = 0$ V. Now, with reference to the figure above, we see that diode D_1 is still forward-biased, but D_2 is now reverse-biased because of the 5-V potential at v_2 . Since one of the two emitter branches is capable of conducting, base current will flow and Q_1 will be on. The remainder of the analysis is the same as in case 1, and Q_2 and Q_3 will both be off, leading to $v_{out} = 5$ V.
- Case 3: Voltage $v_1 = 0$ V; $v_2 = 5$ V. By symmetry with case 2, we conclude that, again, one emitter branch is conducting, and therefore Q_1 will be on, Q_2 and Q_3 will both be off, and $v_{out} = 5$ V.
- Case 4: Voltage $v_1 = 5$ V; $v_2 = 5$ V. When both v_1 and v_2 are at 5 V, diodes D_1 and D_2 are both strongly reverse-biased, and therefore no emitter current can flow. Thus, Q_1 must be off. Note, however, that while D_1 and D_2 are reverse-biased, D_3 is forward-biased, and therefore a current will flow into the base of Q_2 ; thus, Q_2 is on and since the emitter of Q_2 is connected to the base of Q_3 , Q_3 will also see a positive base current and will be on. To determine the output voltage, we assume that Q_3 is operating in saturation. Then, applying KVL to the collector circuit, we have:

$$V_{CC} = I_{C3}R_3 + V_{CE3}$$

Or

$$I_{C3} = \frac{V_{CC} - V_{CE3}}{R_C} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{5 - 0.2}{2,200} = 2.2 \text{ mA}$$

And

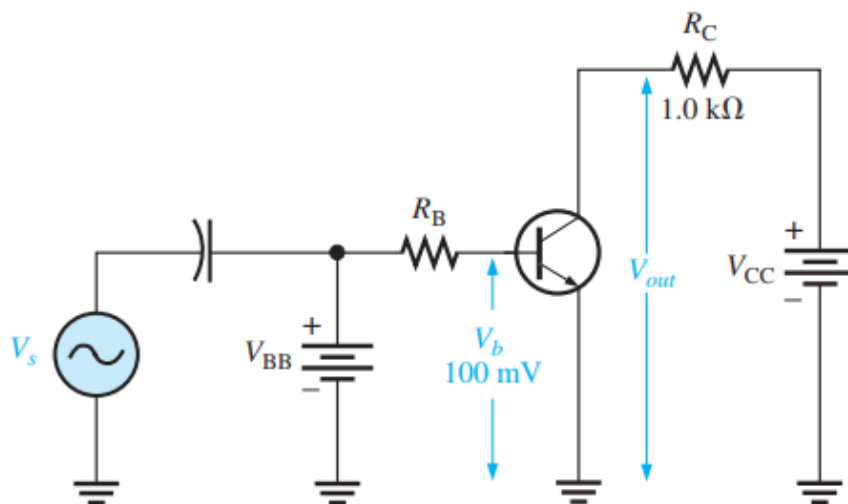
$$v_{out} = V_{CC} - I_C R_3 = 5 - (2.2 \times 10^{-3})(2.2 \times 10^3) = 5 - 4.84 = 0.16 \text{ V}$$

These results are summarised in the table below. The output values are consistent with TTL logic; the output voltage for case 4 is sufficiently close to zero to be considered zero for logic purposes.

| v_1 (Volt) | v_2 (Volt) | State of Q_1 | State of Q_2 | v_{out} (Volt) |
|--------------|--------------|----------------|----------------|------------------|
| 0 | 0 | Off | Off | 5 |
| 0 | 5 | Off | Off | 5 |
| 5 | 0 | Off | Off | 5 |
| 5 | 5 | On | On | 0.16 |

B. BJT Amplifier Applications

1. For amplifier analysis, the AC emitter resistance, r_e' is the most important of the r parameters in BJT amplifier analysis.
 - a. Derive the AC emitter resistance of a transistor. [14 marks]
 - b. Determine the r_e' of a transistor that is operating with a DC emitter current of 2 mA. [2 marks]
 - c. Determine the voltage gain and the AC output voltage in the figure given below if $r_e' = 50 \Omega$. [4 marks]



Solution

- a. Assuming an abrupt junction between n and p regions and it is also temperature dependent based on an ambient temperature of 20°C, derivation of AC emitter resistance of a transistor is found from the following process.

In the case of BJT, the Shockley equation for the transistor is:

$$I_C = I_S \left(e^{\left(\frac{V_{BE}}{nkT/q} \right)} - 1 \right)$$

Taking the derivative of the equation above and simplify the equation.

$$d(I_C) = d \left[I_s \left(e^{\left(\frac{V_{BE}}{nKT/q} \right)} - 1 \right) \right]$$

Since I_s is a constant

$$d(I_C) = I_s d \left[e^{\left(\frac{V_{BE}}{nKT/q} \right)} - 1 \right]$$

Knowing $d(e^x)/dx = e^x$

$$d(I_C) = I_s \left[e^{\left(\frac{V_{BE}}{nKT/q} \right)} - 1 \right] d \left(\frac{V_{BE}}{nKT/q} \right)$$

As a result, the first derivative of the Shockley equation for transistor is:

$$dI_C = I_C \left(\frac{dV_{BE}}{nKT/q} \right)$$

Knowing that $I_C \cong I_E$ and $nKT/q = V_T = 25 \text{ mV}$, as a result the above equation becomes:

$$g_m = \frac{dI_C}{dV_{BE}} = \frac{I_C}{V_T} = \frac{I_E}{25 \text{ mV}}$$

The transconductance of the transistor is $g_m = 1/r'_e$, rearranging the equation above:

$$r'_e \cong \frac{25 \text{ mV}}{I_E}$$

The numerator will be slightly larger for higher temperatures or transistors with a gradual (instead of an abrupt) junction.

Although these cases will yield slightly different results, most designs are not critically dependent on the value of r'_e and you will generally obtain excellent agreement with actual circuits using the equation as given.

- b. The equivalent resistance at the emitter of the transistor is found from the following:

$$r'_e \cong \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{2 \text{ mA}} = 12.5 \Omega$$

- c. The voltage gain of the given amplifier is:

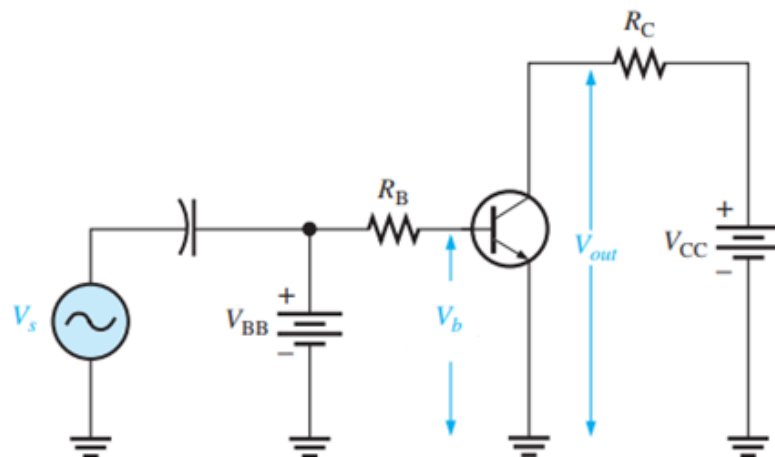
$$A_v \cong \frac{R_C}{r'_e} = \frac{1 \text{ k}\Omega}{50 \Omega} = 20$$

Therefore, the AC output voltage of the amplifier is:

$$V_{out} = A_v V_b = (20)(100 \text{ mV}) = 2 \text{ V rms}$$

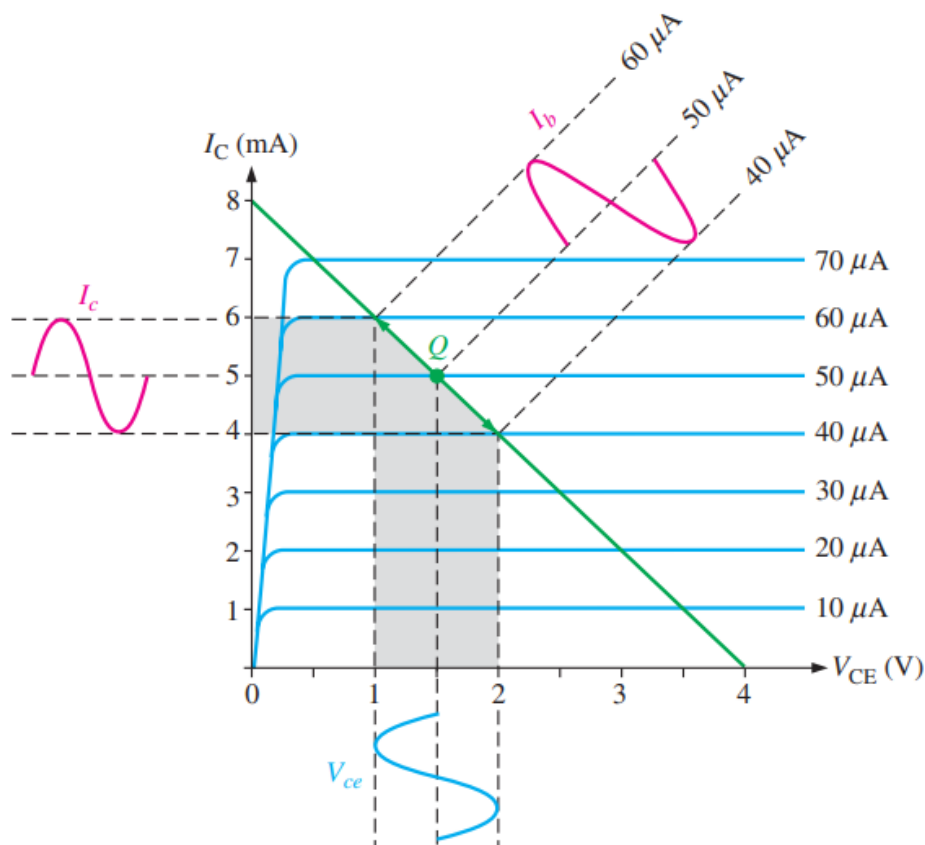
2. The AC load line of the amplifier is about the operational conditions of the amplifier circuit, and it shows the variation of the base current, collector current, and collector-to-emitter voltage

about their DC Q-point values.



The AC load line operation of a certain amplifier extends above and below the Q-point base current value of as shown in the figure given below.

- Determine the resulting peak-to-peak values of collector current and collector-to-emitter voltage from the graph. [2 marks]
- Determine maximum fluctuation of the output voltage. [2 marks]



Solution

- Projections on the graph of the figure given above show the collector current varying from 6 mA to 4 mA for a peak-to-peak value of 2 mA and the collector-to-emitter voltage varying

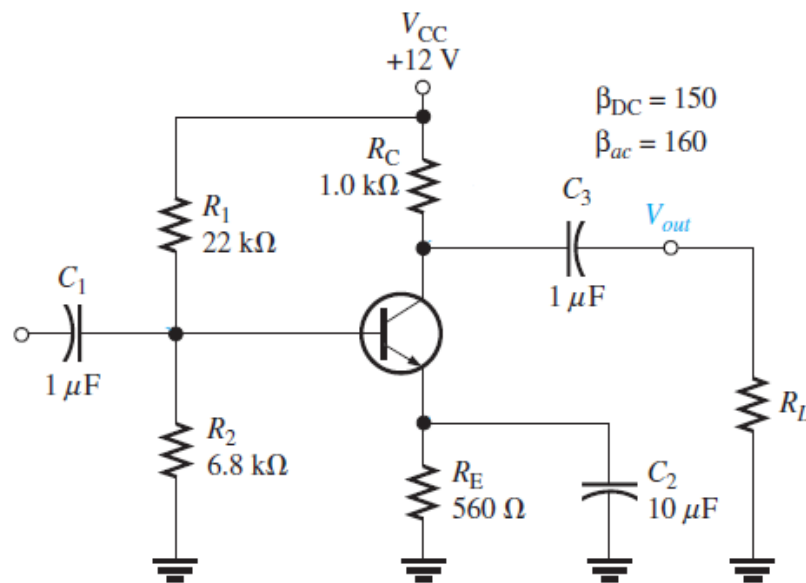
from 1 V to 2 V for a peak-to-peak value of 1 V.

- b. For the given load line graph, it looks like the Q-point is closer to the saturation region of the amplifier circuit rather than the cut-off region.

So, as the Q-point is at $V_{CE} = 1.5 \text{ V}$ and $I_C = 5 \text{ mA}$, the maximum fluctuation of output voltage of the amplifier circuit is calculated as:

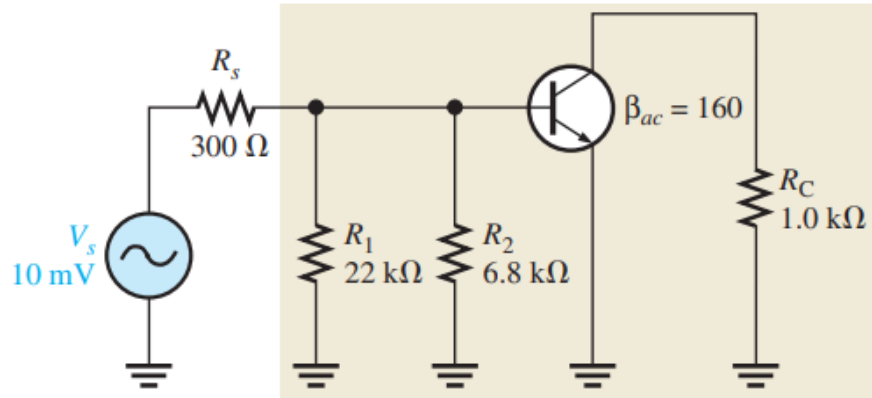
$$V_{out(peak-to-peak)max} = 3 \text{ V}$$

3. The amplifier given in the figure given below is supplied with a 10 mV rms and 300Ω signal source and the emitter current, I_E was previously found to be 3.80 mA.
- Sketch and briefly describe the AC equivalent circuit of the amplifier. [8 marks]
 - The AC emitter resistance of the amplifier circuit. [4 marks]
 - Total input resistance of the amplifier as viewed from the source. [2 marks]
 - Determine the signal voltage at the base of the transistor. Comment on the result of calculation. [4 marks]



Solution

- a. The circuit given below is the AC equivalent of the amplifier in the figure given above.



The AC equivalent circuit consists of the internal source resistance R_s , the resistor R_1 which is in parallel with R_2 and collector resistor R_C at the output of the amplifier circuit.

- b. First, determine the AC emitter resistance of the amplifier circuit.

$$r'_e \cong \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{3.80 \text{ mA}} = 6.58 \Omega$$

Then

$$R_{in}(\text{base}) = \beta_{ac} r'_e = 160(6.58 \Omega) = 1.05 \text{ k}\Omega$$

- c. Next, determine the total input resistance of the amplifier circuit as viewed from the source.

$$R_{in}(\text{tot}) = R_1 \parallel R_2 \parallel R_{in}(\text{base}) = \frac{1}{\left(\frac{1}{22 \text{ k}\Omega}\right) + \left(\frac{1}{6.8 \text{ k}\Omega}\right) + \left(\frac{1}{1.05 \text{ k}\Omega}\right)} = 873 \Omega$$

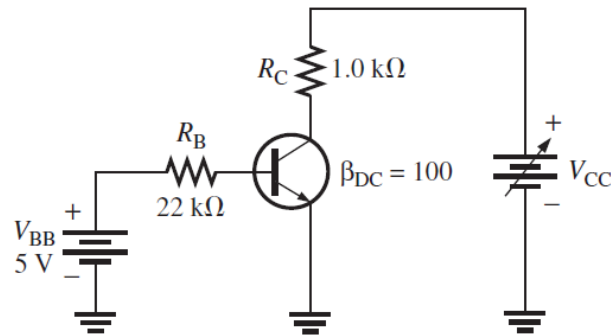
- d. The source voltage is divided down by R_s and $R_{in}(\text{tot})$, so the signal voltage at the base is the voltage across $R_{in}(\text{tot})$.

$$V_b = \left(\frac{R_{in}(\text{tot})}{R_s + R_{in}(\text{tot})}\right) \times V_s = \left(\frac{873 \Omega}{300 \Omega + 873 \Omega}\right) \times 10 \text{ mV} = 7.44 \text{ mV}$$

As you can see, there is significant attenuation (reduction) of the source voltage due to the source resistance and amplifier's input resistance combining to act as a voltage divider.

4. The transistor in this circuit has the following maximum ratings:

- $P(\text{max}) = 800 \text{ mW}$
- $V_{CE}(\text{max}) = 15 \text{ V}$
- $I_C(\text{max}) = 100 \text{ mA}$



- Calculate the collector current and comment whether it exceeds the maximum rating or not? [6 marks]
- Calculate the maximum value to which you can adjust V_{CC} without exceeding maximum ratings. [6 marks]
- What happens when the V_{BB} is reduced to zero? Would the rating of the transistor be exceeded or not? [4 marks]

Solution

- First, calculate the base current:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5\text{ V} - 0.7\text{ V}}{22\text{ k}\Omega} = 0.195\text{ mA}$$

For the transistor in active (linear) mode, I_C is then:

$$I_C = \beta_{DC} I_B = 100 \times 0.195\text{ mA} = 19.5\text{ mA}$$

This is significantly smaller than $I_C(\text{max})$, so maximum rating for I_C not exceeded.

- What is the maximum value of V_{CC} ?

For $I_C = 19.5\text{ mA}$, the voltage drop over resistor R_C is:

$$V_{R_C} = I_C R_C = (19.5\text{ mA})(1\text{ k}\Omega) = 19.5\text{ V}$$

For a maximum value of $V_{CE}(\text{max}) = 15\text{ V}$, the maximum value of V_{CC} is then:

$$V_{CC}(\text{max}) = V_{CE}(\text{max}) + V_{R_C} = 15\text{ V} + 19.5\text{ V} = 34.5\text{ V}$$

The power dissipation of transistor will then be:

$$P = I_C V_{CE} = (19.5\text{ mA})(15\text{ V}) = 292.5\text{ mW}$$

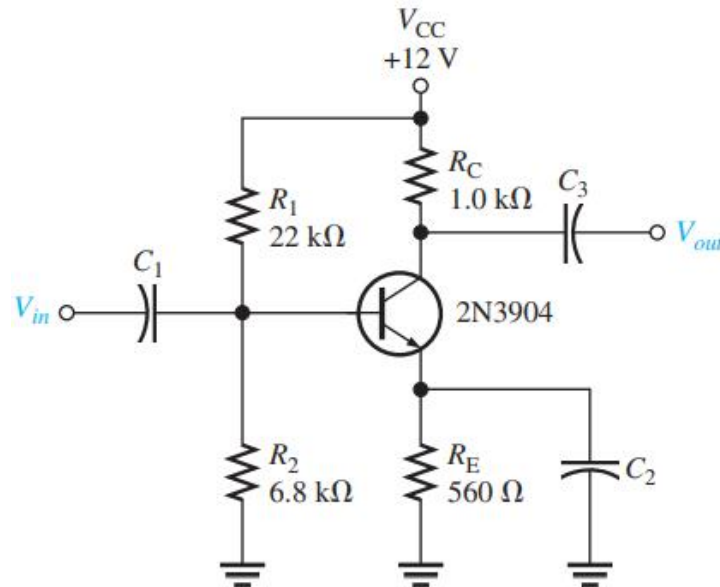
Which is well within limits of the transistor ($P(\text{max}) = 800\text{ mW}$)

- However, keep in mind what will happen if V_{BB} is reduced to 0 V. Thus, the BE junction will not be forward biased and the BE junction will be an open circuit. The I_C will then be 0 A, but the voltage V_{CC} will now in total be dropped over V_{CE} .

Thus, $V_{CE} = 34.5\text{ V}$ and the transistor ratings will be exceeded even though no power is

dissipated in transistor ($I_C = 0$).

5. For the BJT transistor-based amplifier as show below, attempt the following tasks:



- Select a minimum value for the emitter bypass capacitor, C_2 , if the amplifier must operate over a frequency range from 200 Hz to 10 kHz. [4 marks]
- Calculate the base-to-collector voltage gain of the amplifier both without and with an emitter bypass capacitor if there is no load resistor and $r'_e = 6.58 \Omega$. [4 marks]
- Calculate the base-to-collector voltage gain of the amplifier when a load resistance of 5 kΩ is connected to the output. The emitter is effectively bypassed and $r'_e = 6.58 \Omega$. [4 marks]

Solution

- a. The X_C of the bypass capacitor, C_2 , should be at least ten times less than R_E .

$$X_{C_2} = \frac{R_E}{10} = \frac{560 \Omega}{10} = 56 \Omega$$

Select a minimum value for the emitter bypass capacitor, C_2 , if the amplifier must operate over a frequency range from 200 Hz to 10 kHz. The minimum capacitance value at the at cut off frequency of 20 Hz (1/10 of the bandwidth of the amplifier) as follows:

$$C_2 = \frac{1}{2\pi f X_{C_2}} = \frac{1}{2\pi(20 \text{ Hz})(56 \Omega)} = 142 \mu\text{F}$$

This is the minimum value for the bypass capacitor for this circuit. You can always use a larger value, although cost and physical size may impose limitations.

- b. For this amplifier $r'_e = 6.58 \Omega$. Without C_2 , the gain is:

$$A_v = \frac{R_C}{r'_e + R_E} = \frac{1 \text{ k}\Omega}{6.58 \Omega + 560 \Omega} = 1.76$$

With C_2 , the gain is:

$$A_v = \frac{R_C}{r'_e} = \frac{1 \text{ k}\Omega}{6.58 \Omega} = 152$$

As you can see, the bypass capacitor makes quite a difference.

- c. When a load resistance of 5 kΩ is connected to the output of the amplifier and the emitter is effectively bypassed and $r'_e = 6.58 \Omega$. The AC collector resistance is:

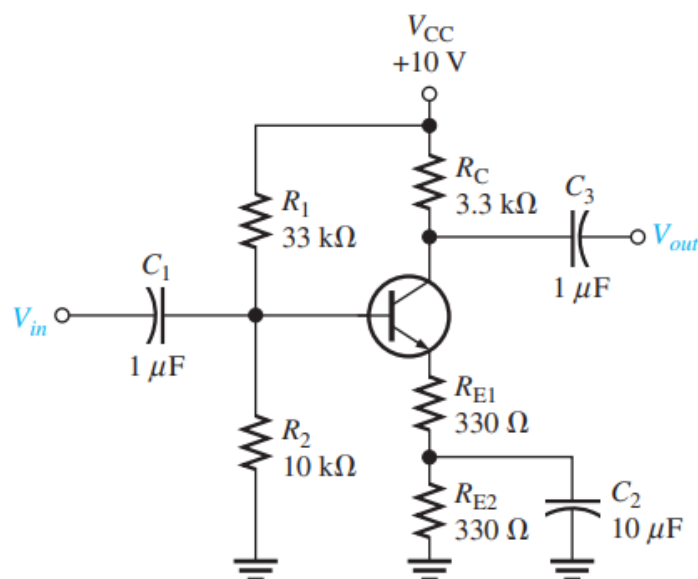
$$R_C = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L} = \frac{(1 \text{ k}\Omega)(5 \text{ k}\Omega)}{1 \text{ k}\Omega + 5 \text{ k}\Omega} = 833 \Omega$$

Therefore

$$A_v = \frac{R_C}{r'_e} = \frac{833 \Omega}{6.58 \Omega} = 127$$

The unloaded gain was found to be 152 in part (b).

6. Stability is a measure of how well an amplifier maintains its design values over changes in temperature or for a transistor with a different β .
- Although bypassing R_E does produce the maximum voltage gain, describe why this approach might cause a stability problem to the amplifier. [6 marks]
 - Describe what is swamping to stabilize the voltage gain. [6 marks]
 - Determine the voltage gain of the swamped amplifier in the figure given below. Assume that the bypass capacitor has a negligible reactance for the frequency at which the amplifier is operated. Assume $r'_e = 20 \Omega$. [2 marks]



Solution

- a. This is because the AC voltage gain is dependent on r_e' since:

$$A_v = \frac{R_C}{r_e'}$$

Furthermore, r_e' depends on I_E and hence on temperature. This causes the gain to be unstable over changes in temperature because when increases, the gain decreases and vice versa.

With no bypass capacitor, the gain is decreased because R_E is now in the AC circuit ($A_v = R_C/(r_e' + R_E)$).

However, with R_E unbypassed, the gain is much less dependent on r_e' . If $R_E \gg r_e'$, the gain is essentially independent of because:

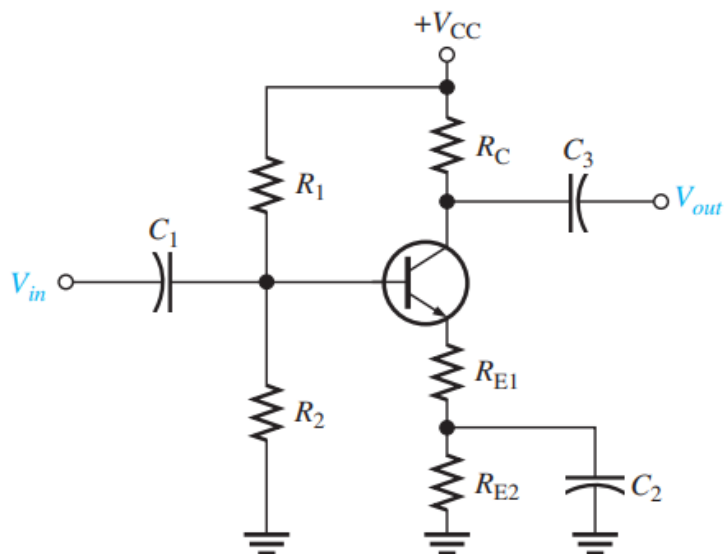
$$A_v = \frac{R_C}{r_e' + R_{E1}}$$

- b. Swamping is a method used to minimize the effect of without reducing the voltage gain to its minimum value.

This method “swamps” out the effect of on the voltage gain. Swamping is, in effect, a compromise between having a bypass capacitor across R_E and having no bypass capacitor at all.

In a swamped amplifier, R_E is partially bypassed so that a reasonable gain can be achieved, and the effect of r_e' on the gain is greatly reduced or eliminated.

The total external emitter resistance, R_E , is formed with two separate emitter resistors, R_{E1} and R_{E2} , as indicated in the figure below.



One of the resistors, R_{E2} , is bypassed and the other is not. Both resistors ($R_{E1} + R_{E2}$) affect the DC bias while only R_{E1} affects the AC voltage gain.

$$A_v = \frac{R_C}{r'_e + R_{E1}}$$

If R_{E1} is at least ten times larger than then the effect of r'_e is minimized and the approximate voltage gain for the swamped amplifier is:

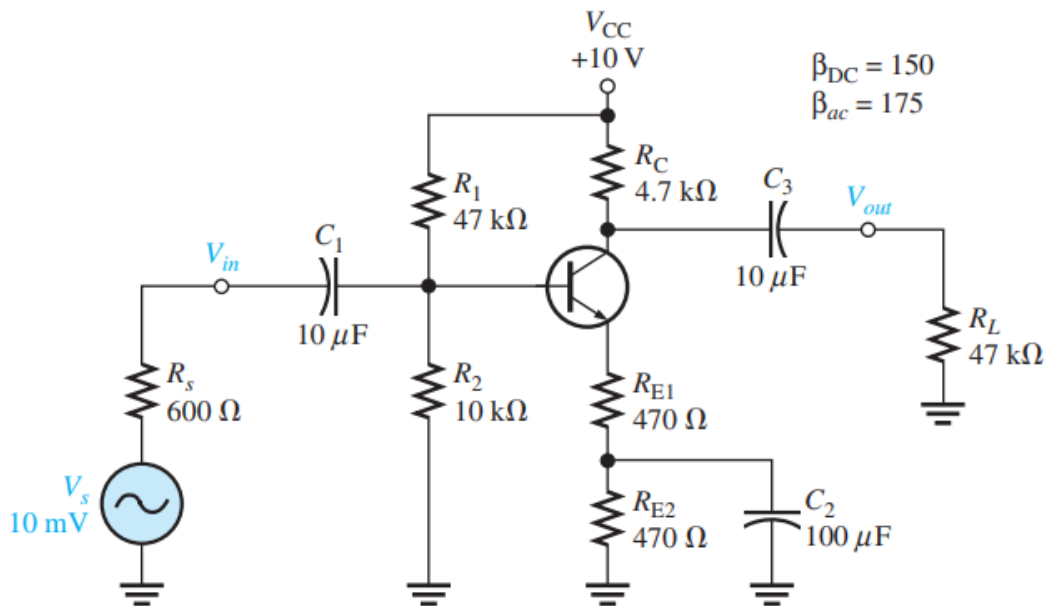
$$A_v \cong \frac{R_C}{R_{E1}}$$

- c. The R_{E2} is bypassed by C_2 . The R_{E1} is more than ten times r'_e (e.g. $r'_e = 20 \Omega$), so the approximate voltage gain is:

$$A_v \cong \frac{R_C}{R_{E1}} = \frac{3.3 \text{ k}\Omega}{330 \Omega} = 10$$

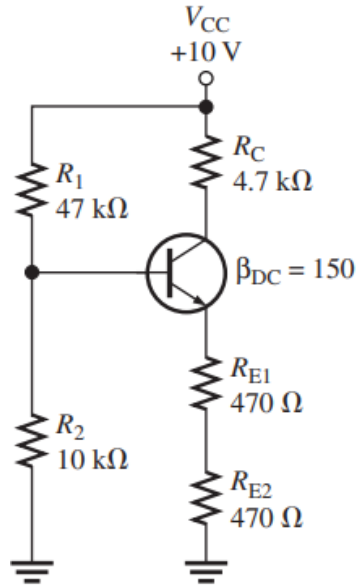
7. For the amplifier given in the figure below, perform the following tasks.

- Determine the DC collector voltage. [16 marks]
- Determine the AC collector voltage. [20 marks]
- Draw the total collector voltage waveform and the total output voltage waveform. [10 marks]



Solution

- a. Determine the DC bias values using the dc equivalent circuit as shown in figure below.



Apply Thevenin's theorem and Kirchhoff's voltage law to the base-emitter circuit in the figure above.

For a more precise calculation of the biasing circuit, we implement the Thevenin equivalent circuit of the biasing circuit at the input of the amplifier circuit.

The Thevenin resistance and voltage at the biasing circuit at the input of the amplifier circuit are:

$$R_{TH} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} = \frac{(47 \text{ k}\Omega)(10 \text{ k}\Omega)}{47 \text{ k}\Omega + 10 \text{ k}\Omega} = 8.25 \text{ k}\Omega$$

And

$$V_{TH} = \left(\frac{R_2}{R_1 + R_2} \right) \times V_{CC} = \left(\frac{10 \text{ k}\Omega}{47 \text{ k}\Omega + 10 \text{ k}\Omega} \right) \times 10 \text{ V} = 1.75 \text{ V}$$

The current at the emitter is determined from:

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} = \frac{1.75 \text{ V} - 0.7 \text{ V}}{(470 \Omega + 470 \Omega) + (8.25 \text{ k}\Omega/150)} = 1.06 \text{ mA}$$

The current at the collector is:

$$I_C \cong I_E = 1.06 \text{ mA}$$

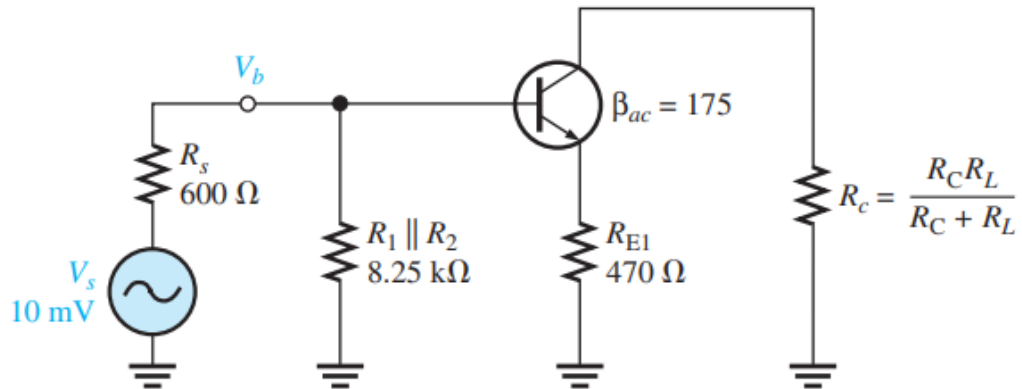
Voltages at the transistor are found from the following:

$$V_E = I_E(R_{E1} + R_{E2}) = (1.06 \text{ mA})(470 \Omega + 470 \Omega) = 1 \text{ V}$$

$$V_B = V_E - V_{BE} = 1 \text{ V} - 0.7 \text{ V} = 0.3 \text{ V}$$

$$V_C = V_{CC} - I_C R_C = 10 \text{ V} - (1.06 \text{ mA})(4.7 \text{ k}\Omega) = 5.02 \text{ V}$$

b. The AC analysis is based on the AC equivalent circuit given in the figure below.



The first thing to do in the AC analysis is calculate r'_e :

$$r'_e \cong \frac{25}{I_E} = \frac{25 \text{ mV}}{1.06 \text{ mA}} = 23.6 \Omega$$

Next, determine the attenuation in the base circuit. Looking from the 600 Ω source, the total R_{in} is:

$$R_{in}(\text{tot}) = R_1 \parallel R_2 \parallel R_{in}(\text{base})$$

Thus

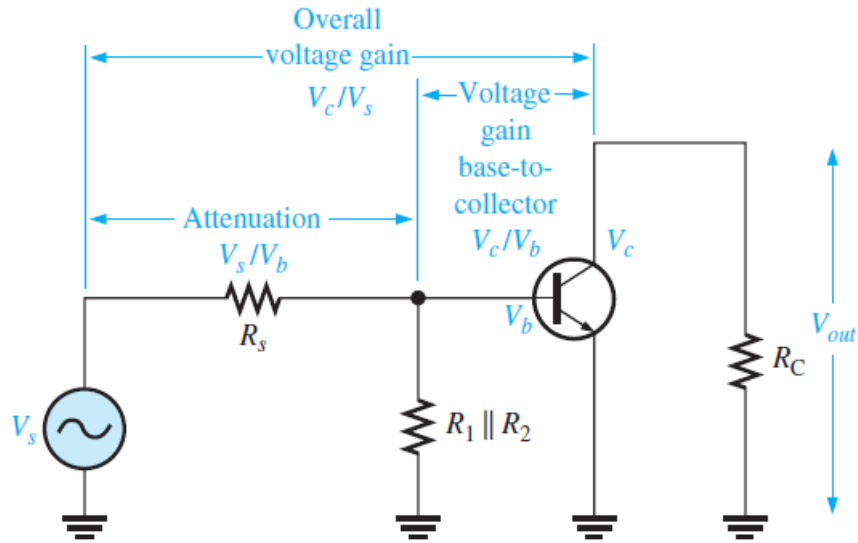
$$R_{in}(\text{base}) = \beta_{ac}(r'_e + R_{E1}) = 175(23.6 \Omega + 470 \Omega) = 86.5 \text{ k}\Omega$$

Therefore

$$\begin{aligned} R_{in}(\text{tot}) &= 47 \text{ k}\Omega \parallel 10 \text{ k}\Omega \parallel 86.5 \text{ k}\Omega \\ &= \frac{1}{\frac{1}{47 \text{ k}\Omega} + \frac{1}{10 \text{ k}\Omega} + \frac{1}{96.5 \text{ k}\Omega}} = 7.53 \text{ k}\Omega \end{aligned}$$

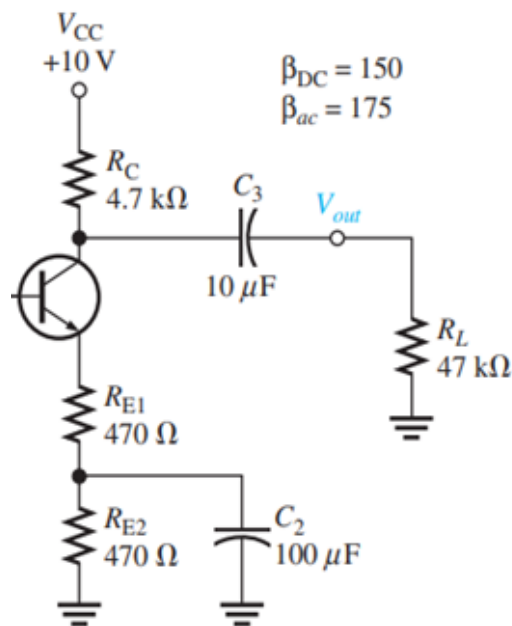
The attenuation from source to base is:

$$\text{Attenuation} = \frac{V_s}{V_b} = \frac{R_s + R_{in}(\text{tot})}{R_{in}(\text{tot})} = \frac{600 \Omega + 7.53 \text{ k}\Omega}{7.53 \text{ k}\Omega} = 1.08$$



Before A_v can be determined, you must know the AC collector resistance R_c .

$$R_c = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L} = \frac{(4.7 \text{ k}\Omega)(47 \text{ k}\Omega)}{4.7 \text{ k}\Omega + 47 \text{ k}\Omega} = 4.27 \text{ k}\Omega$$



The voltage gain from base to collector is:

$$A_v \cong \frac{R_c}{R_{E1}} = \frac{4.27 \text{ k}\Omega}{470 \Omega} = 9.09$$

The overall voltage gain is the reciprocal of the attenuation times the amplifier voltage gain.

$$A'_v = \left(\frac{V_b}{V_s}\right) A_v = \left(\frac{1}{1.08}\right) (9.09) = 8.45$$

The source produces 10 mV (rms), so the root mean square voltage at the collector is:

$$V_c = A'_v V_s = (8.45)(10 \text{ mV}) = 84.5 \text{ mV}$$

- c. The total collector voltage is the signal voltage of 84.5 mV (rms) riding on a DC level of $V_C = 5.02$ V, as shown in part (a) of the figure given below, where approximate peak values are determined as follows:

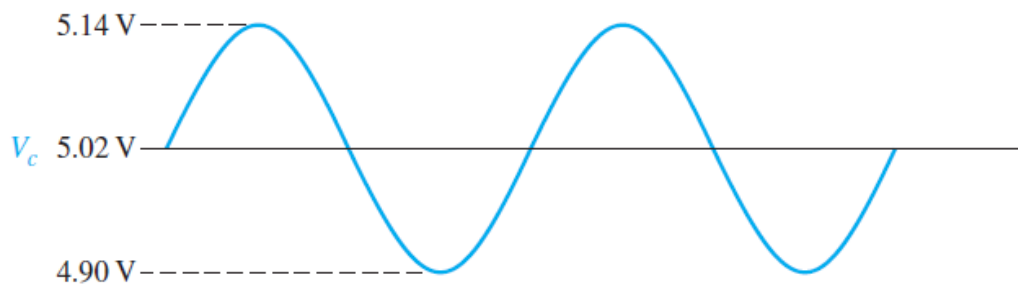
$$\text{Max } V_C(\text{peak}) = V_C + 1.414 V_c = 5.02 \text{ V} + (1.414)(84.5 \text{ mV}) = 5.14 \text{ V}$$

$$\text{Min } V_C(\text{peak}) = V_C - 1.414 V_c = 5.02 \text{ V} - (1.414)(84.5 \text{ mV}) = 4.90 \text{ V}$$

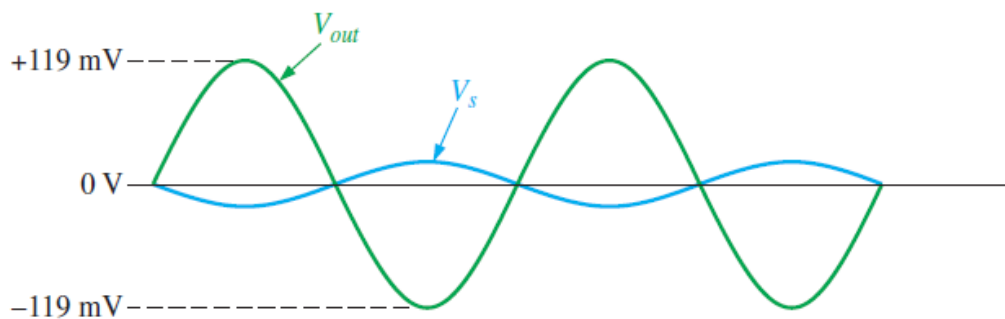
The coupling capacitor, C_3 , keeps the DC level from getting to the output. So, V_{out} is equal to the AC component of the collector voltage:

$$V_{out}(\text{peak}) = (84.5 \text{ mV})(1.414) = 119 \text{ mV}$$

As indicated in part (b) of the figure below, the source voltage, V_s , is shown to emphasize the phase inversion.



(a) Total collector voltage



(b) Source and output ac voltages