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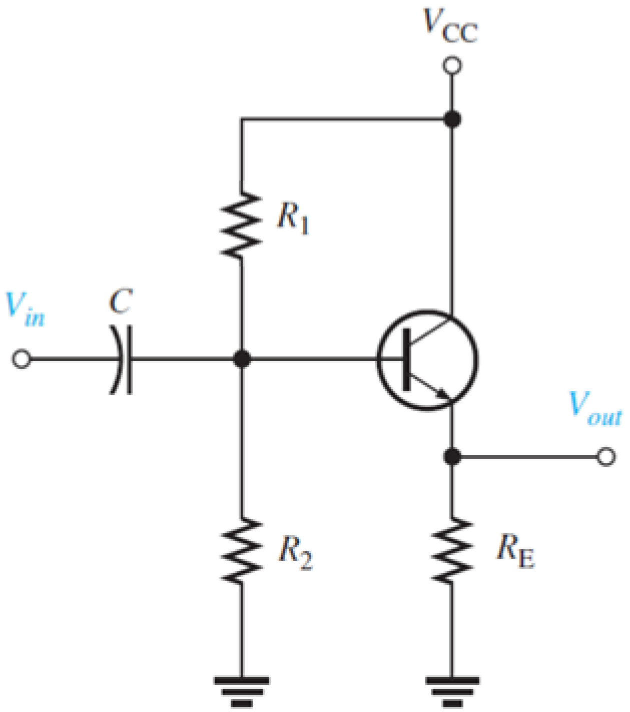
XMUT204 Electronic Design

Lecture 3g – BJT Further Circuits

Overview

- Common Collector (Emitter Follower) Amplifier.
- Common Base Amplifier.
- Cascaded Amplifier.
- Darlington Transistors (Pairs).
- Transistor as Constant Current Source.
- Current Mirror.
- Differential Amplifier.
- Phase Splitter.
- Voltage Regulator.
- Switches and Logic Gates.

1. Common-Collector Amplifier

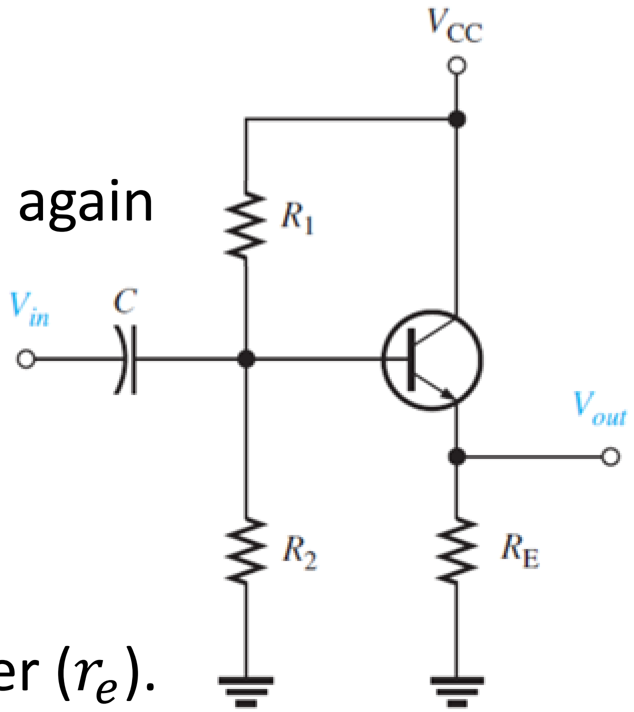


Two changes from CE with feedback:

1. The output is now taken at the emitter.
2. The collector resistor has been removed.

- The collector connected to positive supply which is at ground for AC signals as there are no AC signals between supply and ground.
- As the collector is at ground potential, for small signals, it is common to both input and output circuits e.g. hence called a common-collector amplifier.

1. Common-Collector Amplifier (cont.)



- If we use a small-signal model, we can again show that the **input resistance** is:

$$r_{in} \approx R_1 \parallel R_2$$

- The **output resistance** is given by the parallel combination of R_E and the resistance looking back into the emitter (r_e).

- This value of r_e is typically very low (e.g. few ohms) and will thus dominate.
- As a result, the amplifier has a very low output impedance:

$$r_{out} \approx R_E \parallel r_e$$

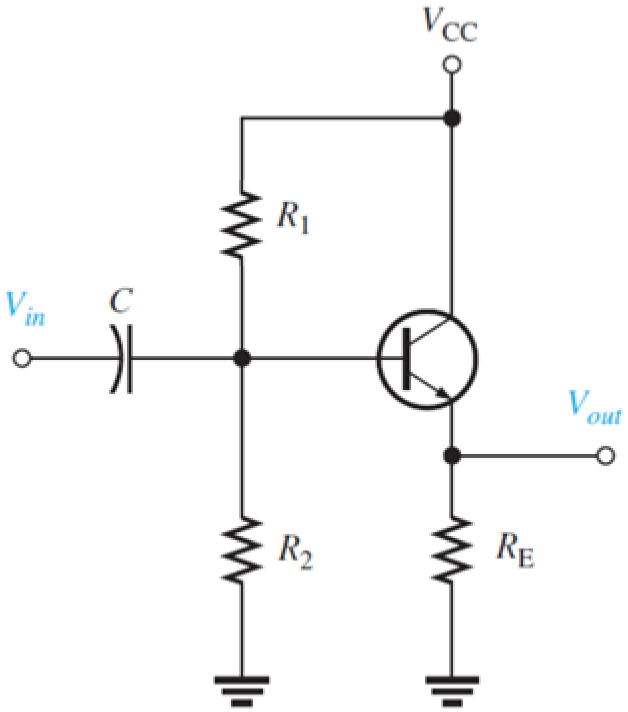
1. Common-Collector Amplifier (cont.)

- The small-signal voltage gain can be calculated by considering the input signal is applied at the base of the transistor so that:

$$V_i \approx V_b \approx V_\epsilon$$

- So that voltage gain $A_v \approx 1$.

- We thus have a unit gain amplifier (emitter follower) with low output impedance.
- This results in **a unity gain buffer.**

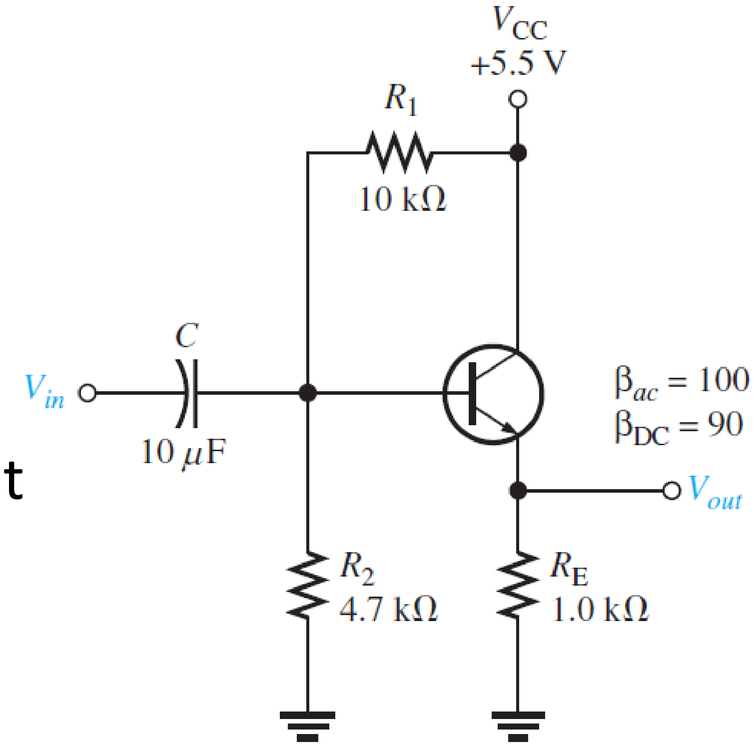


Example 1 – Common Collector BJT Circuit

For the common collector (emitter follower) circuit given below, perform the following tasks:

a. Determine the exact voltage gain for the circuit when it is unloaded. [8 marks]

b. What is the total input resistance in the circuit? What is the dc output voltage? [4 marks]



Answer

a. The amplifier circuit employs a voltage divider biasing configuration, so the voltage at the base is:

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC} = \left(\frac{4.7\ \text{k}\Omega}{10\ \text{k}\Omega + 4.7\ \text{k}\Omega}\right)5.5\ \text{V} = 1.76\ \text{V}$$

The current that flows in the emitter of the amplifier circuit is:

$$I_E = \frac{V_B - V_{BE}}{R_E} = \frac{1.76\ \text{V} - 0.7\ \text{V}}{1\ \text{k}\Omega} = 1.06\ \text{mA}$$

The ac emitter resistance of the BJT is:

$$r_e' \cong \frac{25\ \text{mV}}{1.06\ \text{mA}} = 23.6\ \Omega$$

The voltage gain of the amplifier circuit is:

$$A_v = \frac{R_E}{R_E + r_e'} = \frac{1\ \mathrm{k\Omega}}{1\ \mathrm{k\Omega} + 23.6\ \Omega} = 0.977$$

b. The total input resistance of the amplifier circuit is:

$$R_{in} = R_1 \parallel R_2 \parallel \beta_{ac}(r_e' + R_E) \cong R_1 \parallel R_2 \parallel \beta_{ac} R_E$$

$$= 10\ \mathrm{k\Omega} \parallel 4.7\ \mathrm{k\Omega} \parallel 100\ \mathrm{k\Omega} = 3.1\ \mathrm{k\Omega}$$

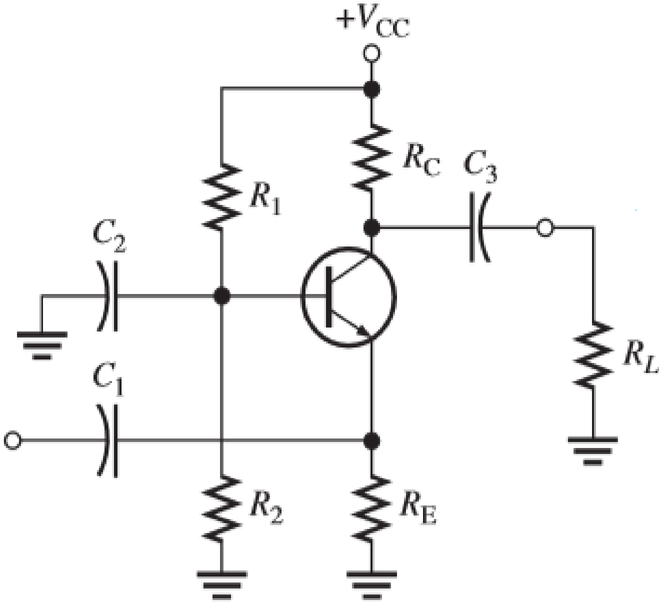
The output voltage of the amplifier circuit is:

$$V_{out} = V_B - V_{BE} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} - V_{BE}$$

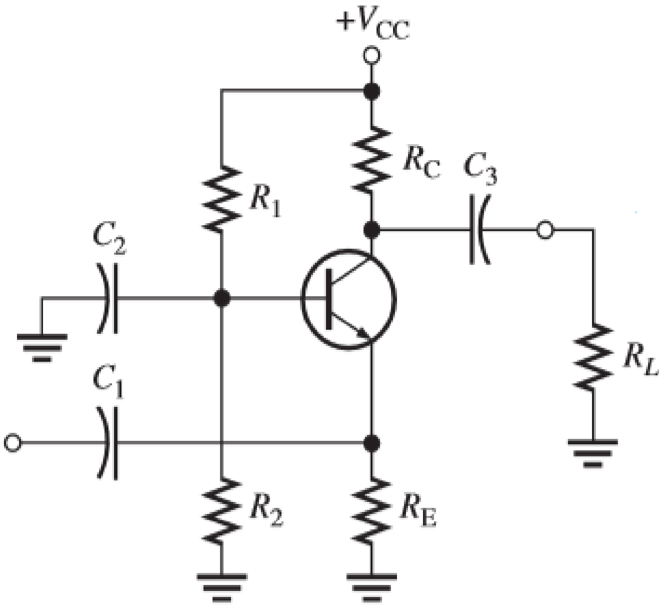
$$= \left(\frac{4.7\ \mathrm{k\Omega}}{10\ \mathrm{k\Omega} + 4.7\ \mathrm{k\Omega}}\right) 5.5\ \mathrm{V} - 0.7\ \mathrm{V} = 1.06\ \mathrm{V}$$

2. Common-Base Amplifier

- The base is the common terminal and is at AC ground because of capacitor C_2.
- The input signal is capacitively coupled to the emitter by capacitor C_1.
- The output is capacitively coupled from the collector to a load resistor by capacitor C_3.



2. Common Base Amplifier (cont.)



- The voltage gain from emitter to collector is (if $R_E \gg r_e'$):

$$A_v \approx \frac{R_c}{r_e'}$$

  Like the common-emitter amplifier, but with no phase inversion from emitter to collector.

- The input resistance, looking in at the emitter (e.g. if $R_E \gg r_e'$), is:

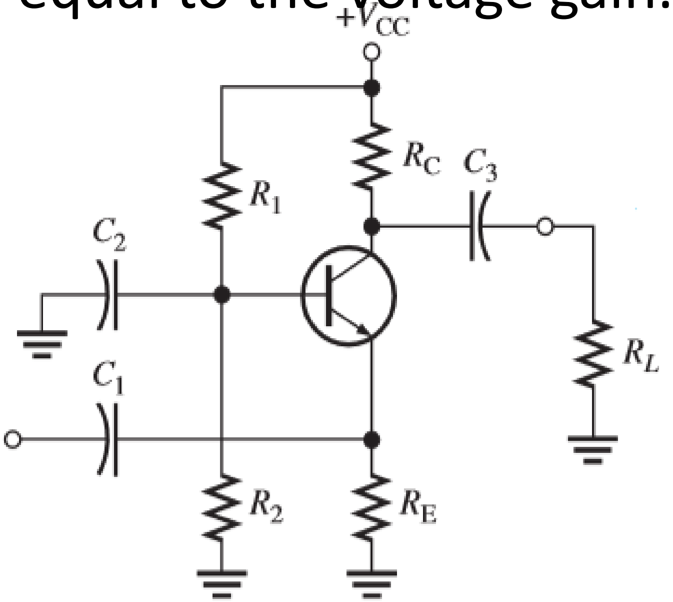
$$R_{in(emitter)} \approx r_e'$$

2. Common Base Amplifier (cont.)

- Looking into the collector, the AC collector resistance, appears in parallel with R_C, typically, much larger than R_C.
- So, a good approximation for the output resistance is:

$$R_{out} \approx R_C$$

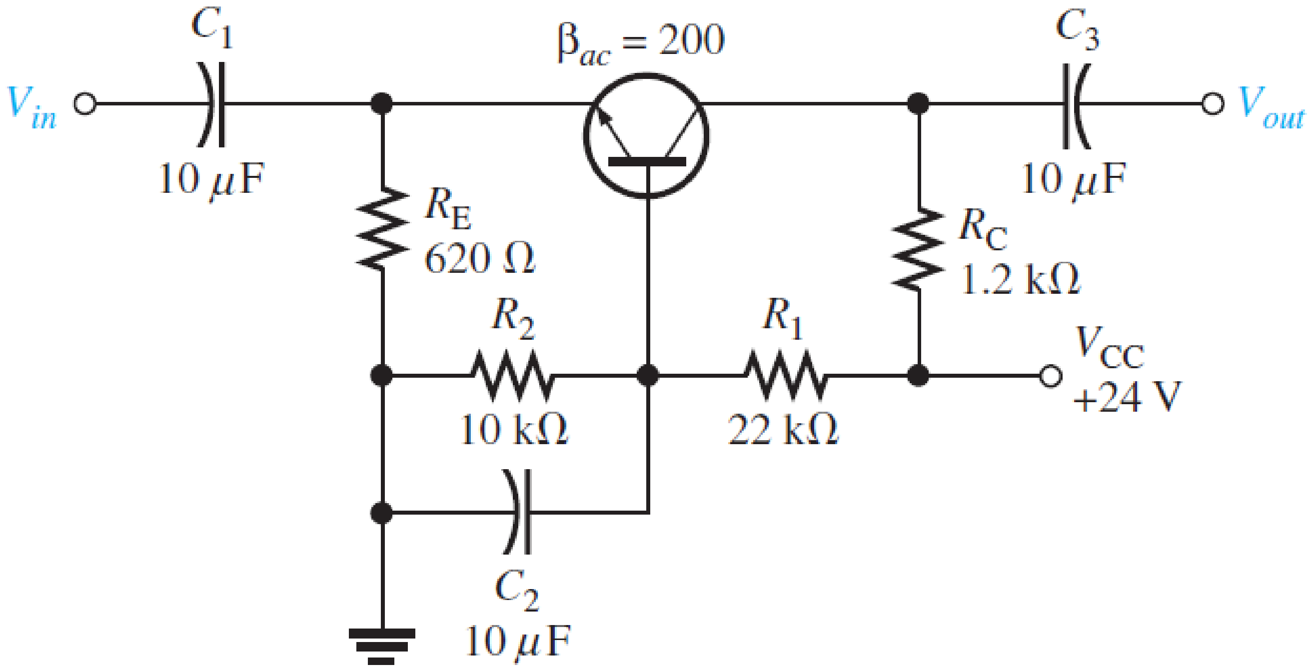
- Current gain is approximately 1, so the power gain is approximately equal to the voltage gain.



Example 2 – Common Base BJT Circuit

Find $R_{in}(\text{emitter})$, A_v, A_i, and A_p for the unloaded common base BJT amplifier as shown in the figure below.

[12 marks]



Answer

The voltage at the emitter is calculated from the following equation.

$$V_E = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC} - V_{BE} = \left(\frac{10\ \mathrm{k\Omega}}{22\ \mathrm{k\Omega} + 10\ \mathrm{k\Omega}}\right) 24\ \mathrm{V} - 0.7\ \mathrm{V}$$

$$= 6.8\ \mathrm{V}$$

Thus, the current that flows in the emitter is:

$$I_E = \frac{V_E}{R_E} = \frac{6.8\ \mathrm{V}}{620\ \Omega} = 10.97\ \mathrm{mA}$$

Knowing the value of the current in the emitter, the resistance at the emitter is calculated as:

$$R_{in(\mathrm{emitter})} = r_e' = \frac{25\ \mathrm{mV}}{I_E} = \frac{25\ \mathrm{mV}}{10.97\ \mathrm{mA}} = 2.28\ \Omega$$

As a result, the voltage, current, and power gains of the amplifier circuit are:

Voltage gain:

$$A_v = \frac{R_C}{r'_e} = \frac{1.2\ \text{k}\Omega}{2.28\ \Omega} = 526$$

Current gain:

$$A_i \cong 1$$

Power gain:

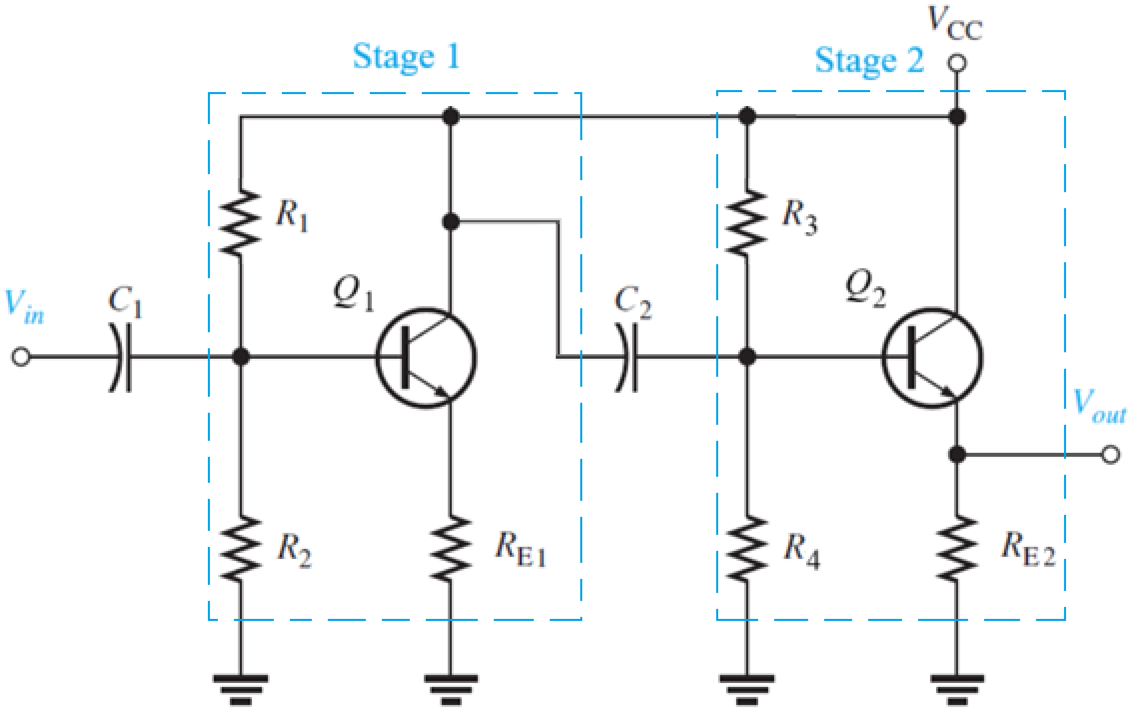
$$A_p = A_i A_v = (1)(526) = 526$$

3. Cascaded Amplifiers

- If more gain is required than can be supplied by a single gains stage, several stages can be connected (cascaded) in series.

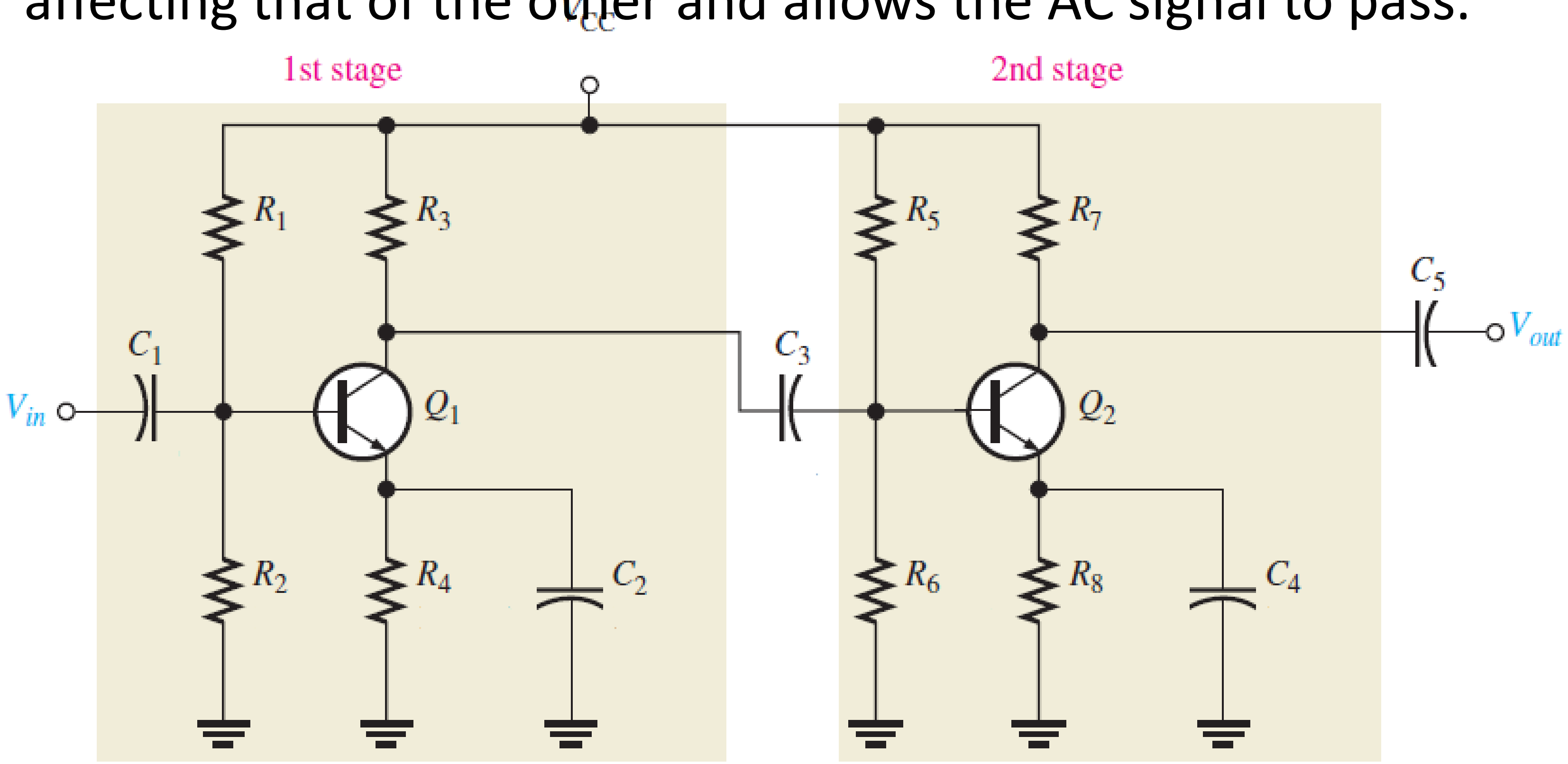
$$A_{V(tot)} = A_{V1} \times A_{V2}$$

Where: A_{V1} = Gain of stage 1 and A_{V2} = Gain of stage 2.

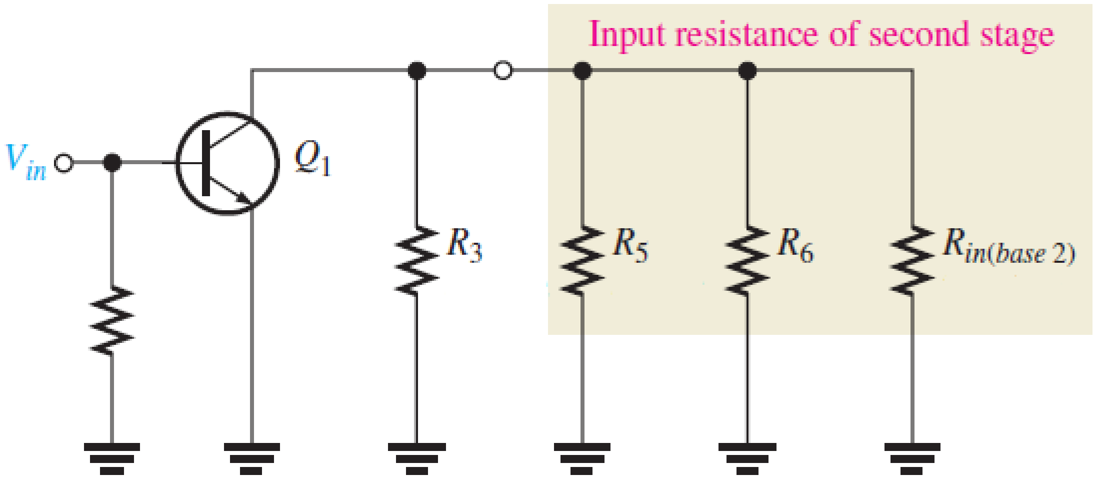


3.1. Capacitively Coupled Multistage Amplifier

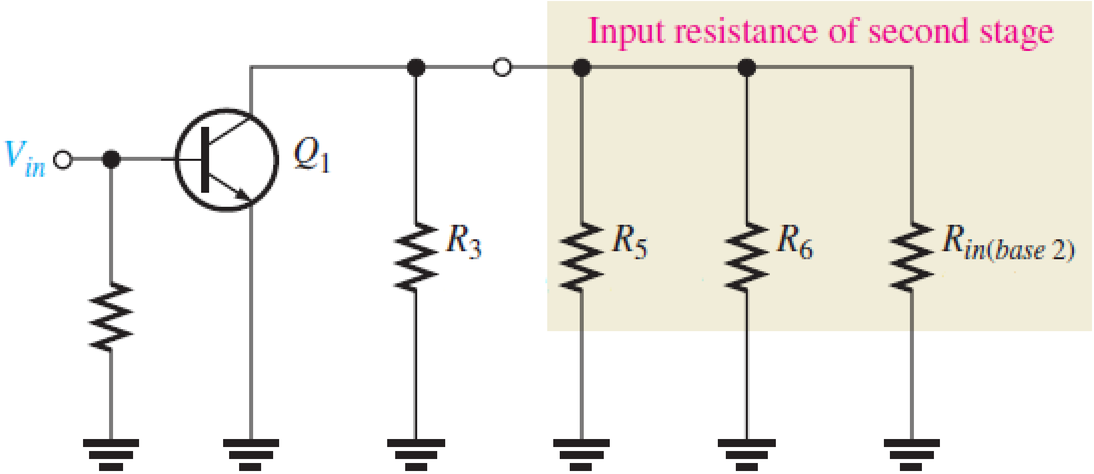
- Both stages are identical common-emitter amplifiers with the output of the first stage capacitively coupled to the input of the second stage.
- Capacitive coupling prevents the DC bias of one stage from affecting that of the other and allows the AC signal to pass.



- To work out voltage gain of multistage amplifier, consider the loading effect of the second stage.
- The coupling capacitor C_3 effectively appears as a short at the signal frequency.
- The total input resistance of the second stage presents an AC load to the first stage.



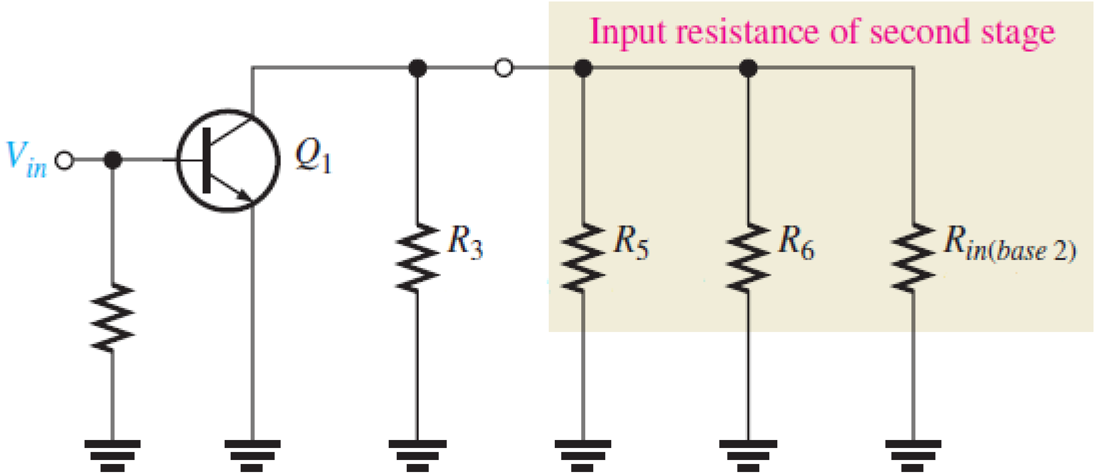
- Looking from the collector of Q_1, the two biasing resistors in the second stage, R_5 and R_6, appear in parallel with the input resistance at the base of Q_2.
- In other words, the signal at the collector of Q_1 "sees" R_3, R_5, R_6, and $R_{in(base2)}$ of the second stage all in parallel to AC ground.
- Thus, the effective AC collector resistance of Q_1 is the total of all these resistances in parallel.



- The voltage gain of the first stage is reduced by the loading of the second stage

- This is because the effective AC collector resistance of the first stage is less than the actual value of its collector resistor, R_3.

- Remember that $A_v = R_c/r_e'$.



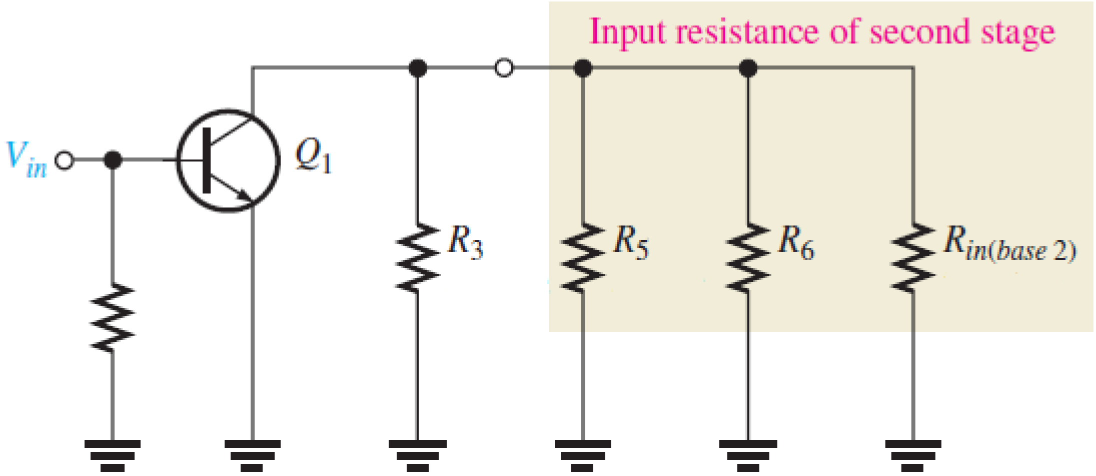
Voltage Gain of the First Stage

- The AC collector resistance of the first stage is:

$$R_{C1} = R_3 \parallel R_5 \parallel R_6 \parallel R_{in(base2)}$$

- Therefore, the base-to-collector voltage gain of the first stage is:

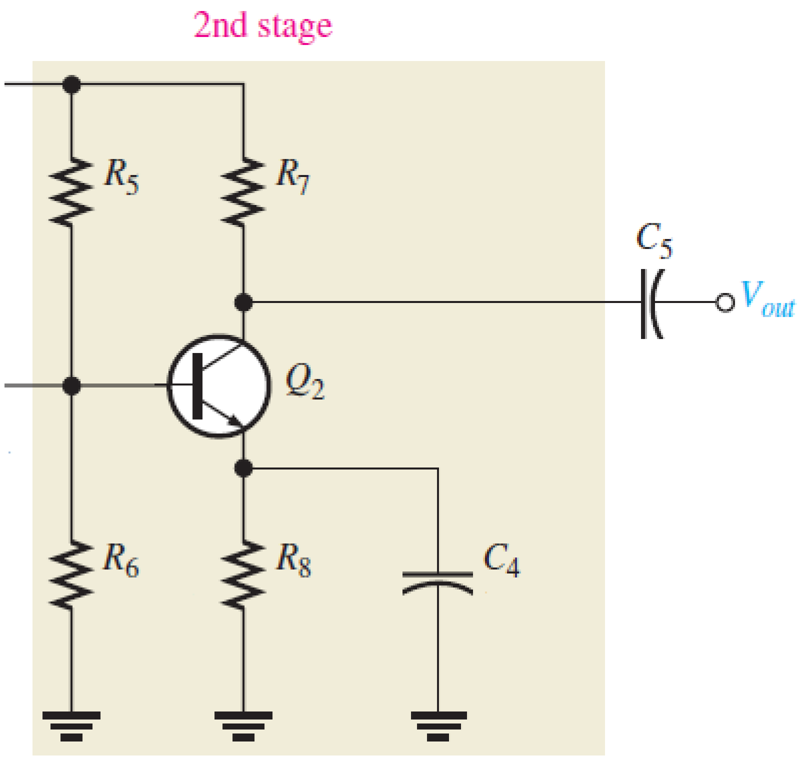
$$A_{v1} = \frac{R_{C1}}{r_e'}$$



Voltage Gain of the Second Stage

- The second stage has no load resistor, so the AC collector resistance is R_7, and the gain is:

$$A_{v2} = \frac{R_7}{r'_e}$$



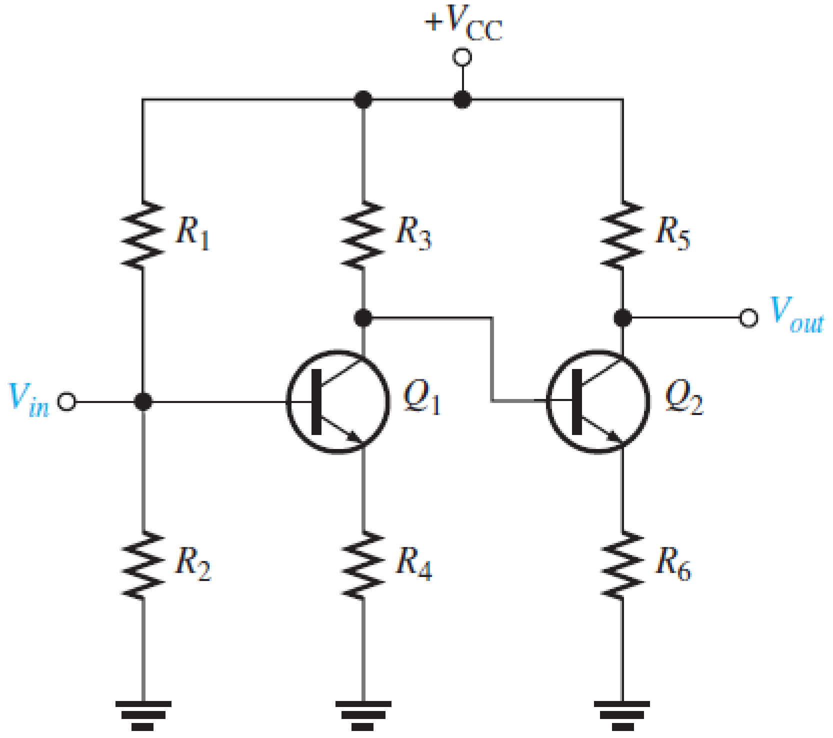
Overall Voltage Gain

- The overall amplifier gain with no load on the output is:

$$A_{v(total)} = A_{v1}A_{v2}$$

3.2. Direct Coupled Multistage Amplifier

- Notice that there are no coupling or bypass capacitors in the direct couple multistage amplifier circuit.
- The DC collector voltage of the first stage provides the base-bias voltage for the second stage.



- 1st stage voltage gain:

$$A_{v1} = \frac{R_3}{r_e' + R_4}$$

- 2nd stage voltage gain:

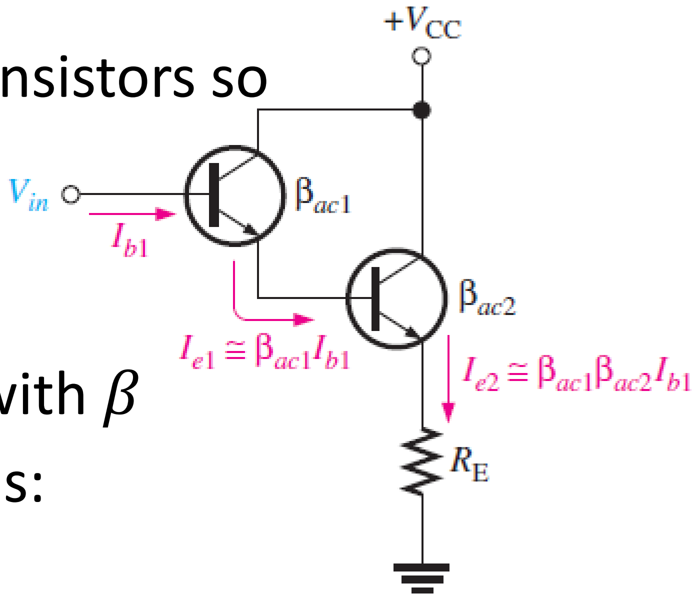
$$A_{v2} = \frac{R_5}{r_e' + R_6}$$

- Overall gain:

$$A_{v(total)} = A_{v1}A_{v2}$$

- Due to direct coupling, it has a better low-frequency response than the capacitively coupled type e.g. reactance of coupling and bypass capacitors at very low frequencies may become excessive.
- The increased reactance of capacitors at lower frequencies produces gain reduction in capacitively coupled amplifiers.
- Direct-coupled amplifiers can be used to amplify low frequencies all the way down to DC (0 Hz) without loss of voltage gain as there are no capacitive reactance in the circuit.
- The disadvantage is that small changes in the DC bias voltages from temperature effects or power-supply variation are amplified by the succeeding stages e.g. can result in a significant drift in the DC levels throughout the circuit

4. Darlington Transistors (Pairs)



The basic Darlington configuration.

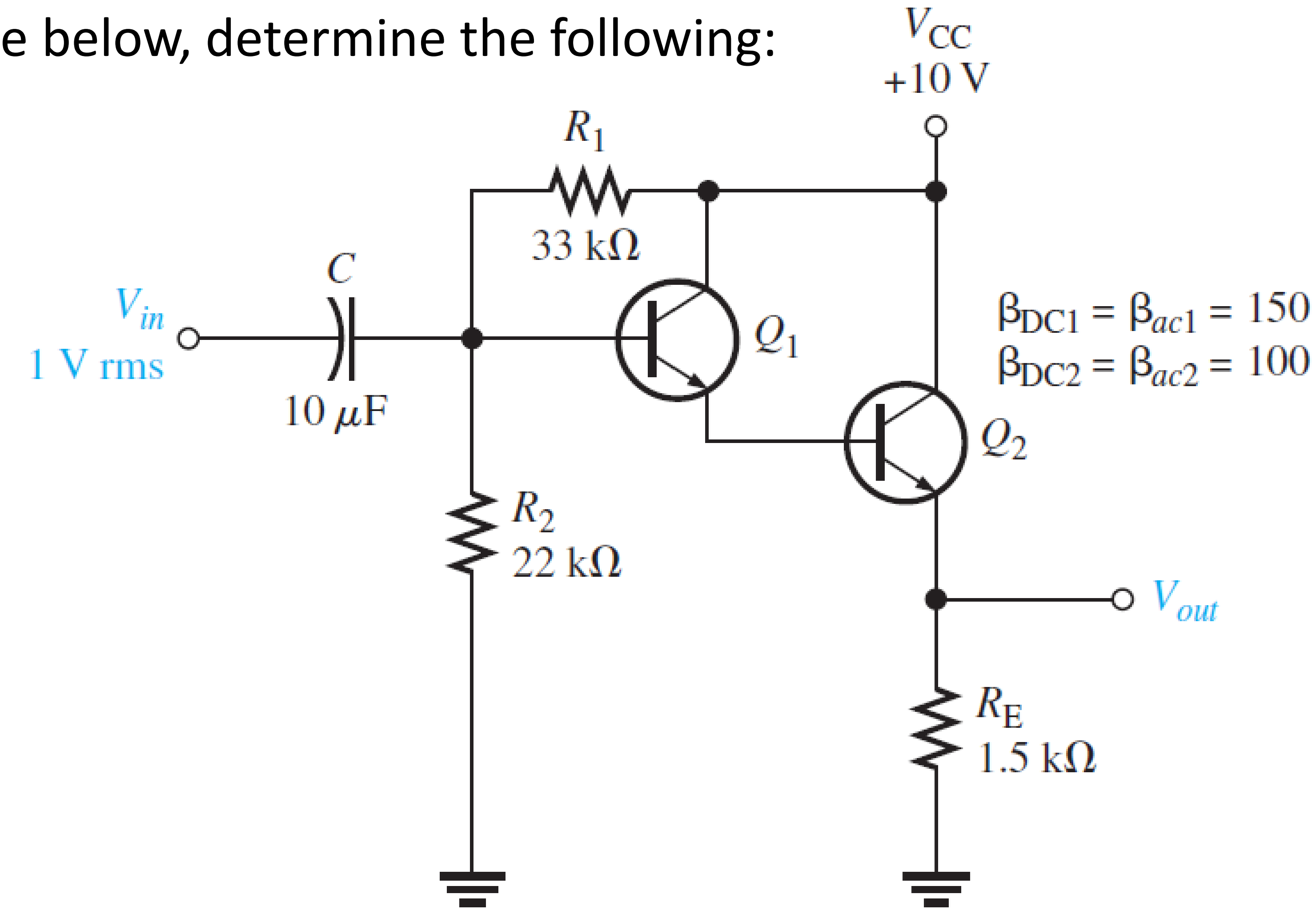
- This is a method to combine two transistors so that the gain of the first transistor is multiplied by the second transistor.
- So that it acts as a single transistor with β equal to the product of the two gains:

$$\beta_{TOT} = \beta_1 \times \beta_2$$

- Note that the voltage offset between base emitter will now be 1.4 V.
- Produce a device (single package) with very high gain and high input resistance.
- Commonly used for high-gain power transistors.

Example 3 – Multistage BJT Amplifiers

For a multistage amplifier circuit with pair of Darlington transistors in the figure below, determine the following:



a. The Q_1 and Q_2 DC terminal voltages. [8 marks]

b. The overall β_{ac}. [2 marks]

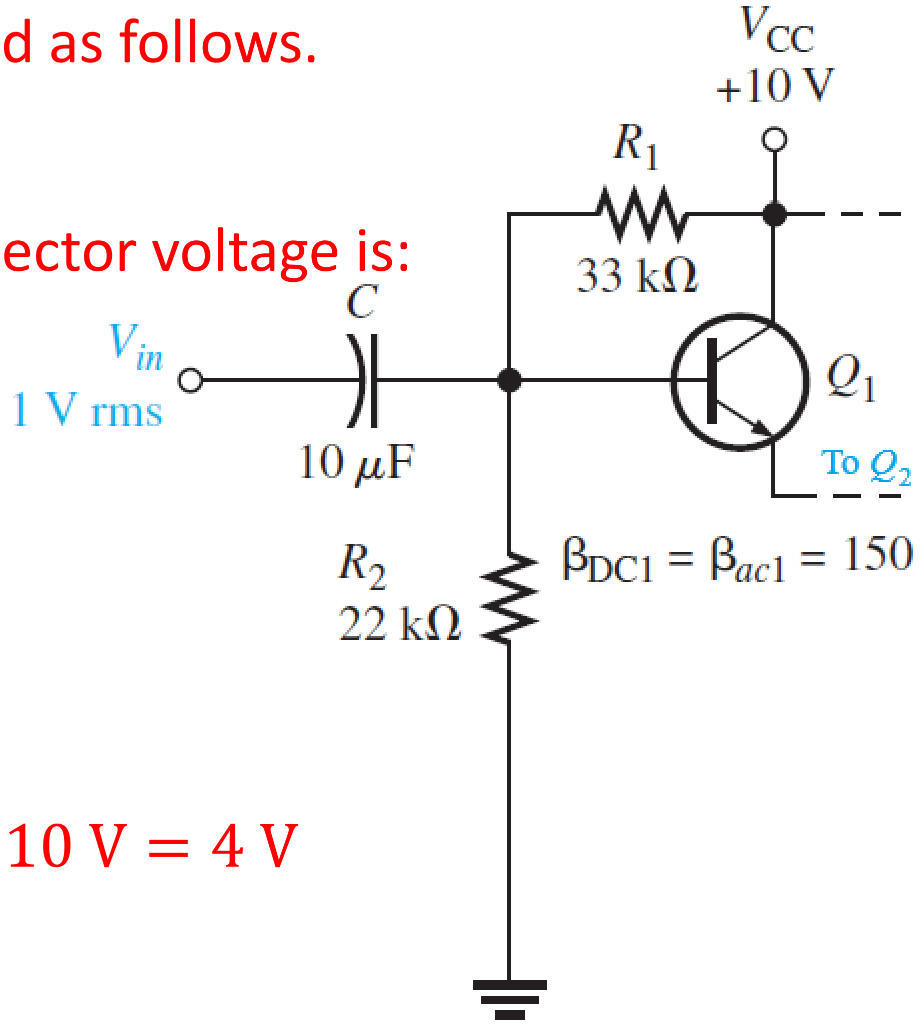
c. The r_e' for each transistor. [8 marks]

d. Total input resistance. [4 marks]

e. Find the overall current gain A_i. [12 marks]

Answer

a. The Q_1 and Q_2 DC terminal voltages of the Darlington pair BJT amplifier circuit are calculated as follows.



The First Transistor Q_1:

For the first transistor, its collector voltage is:

$$V_{c1} = 10\text{ V}$$

Its base voltage is:

$$V_{B1} = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$= \left(\frac{22\text{ k}\Omega}{33\text{ k}\Omega + 22\text{ k}\Omega}\right) 10\text{ V} = 4\text{ V}$$

The voltage at its emitter is:

$$V_{E1} = V_{B1} - V_{BE} = 4\text{ V} - 0.7\text{ V} = 3.3\text{ V}$$

The Second Transistor Q_2:

For the second transistor, its collector voltage is:

$$V_{C2} = 10\text{ V}$$

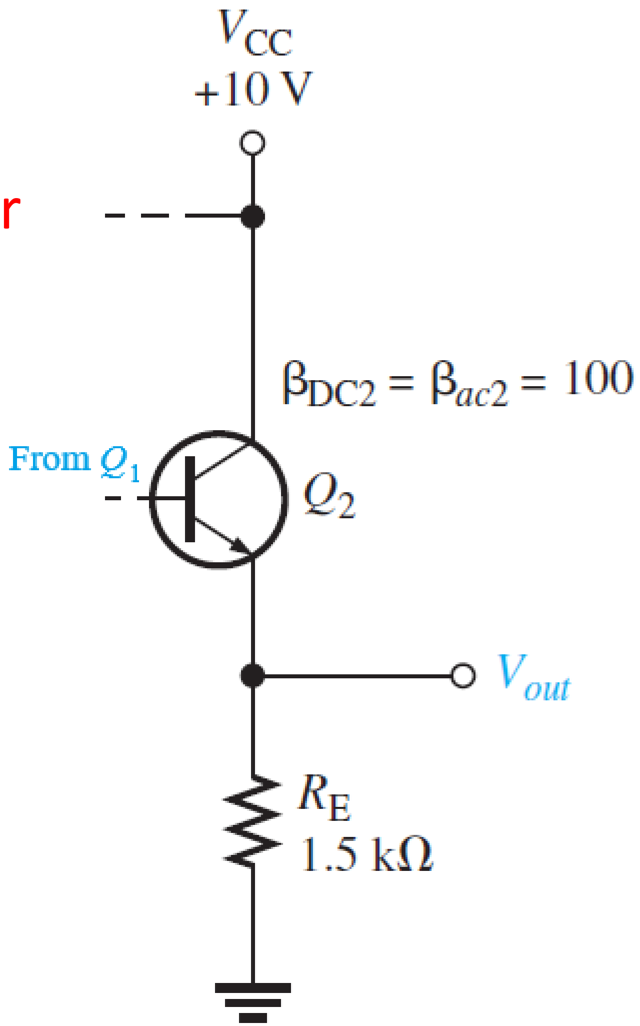
Its base voltage is:

$$V_{B2} = V_{E1} = 3.3\text{ V}$$

The voltage at its emitter is:

$$V_{E2} = V_{B2} - V_{BE}$$

$$= 3.3\text{ V} - 0.7\text{ V} = 2.6\text{ V}$$



b. The overall AC gain of the Darlington pair BJT amplifier circuit, β_{ac} is calculated as:

$$\beta'_{DC} = \beta_{DC1}\beta_{DC2} = (150)(100) = 15{,}000$$

c. The AC emitter resistance, r'_e for each transistor in the Darlington pair BJT amplifier circuit is calculated as follows.

The First Transistor Q_1:

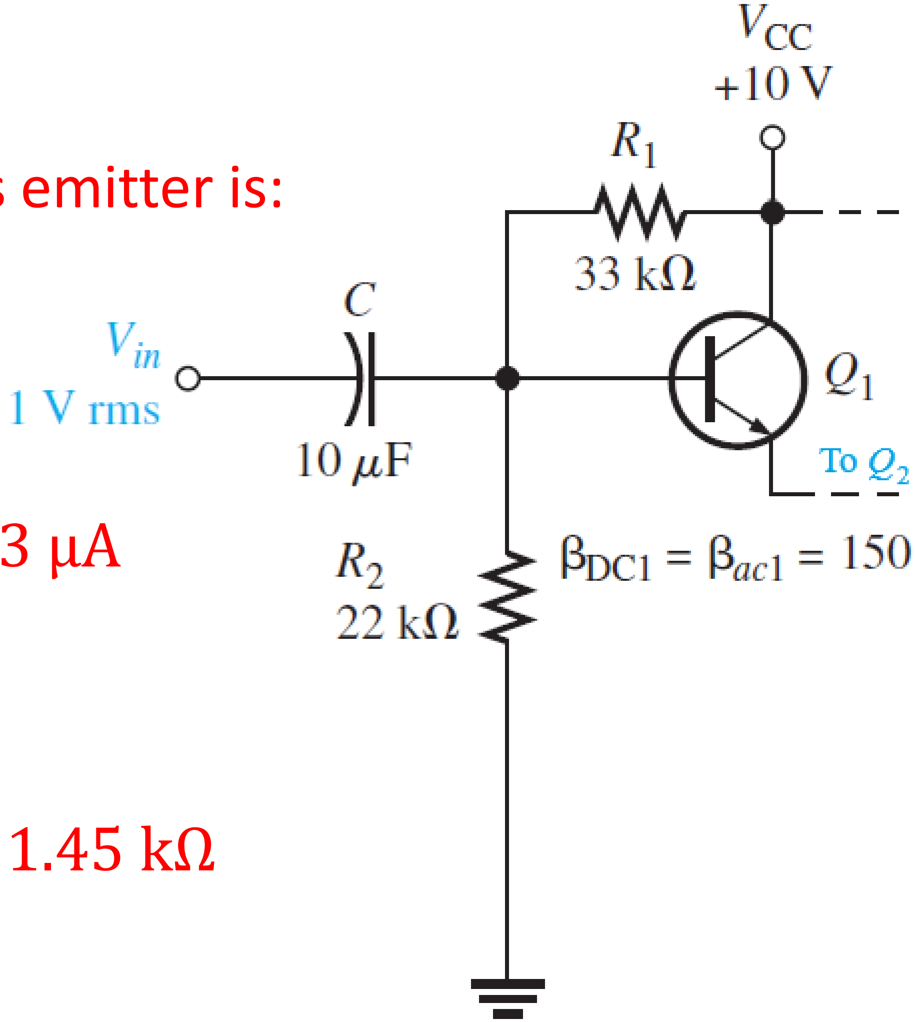
The current that flows in its emitter is:

$$I_{E1} = \frac{V_{E1} - V_{BE}}{\beta_{DC2} R_E}$$

$$= \frac{3.3\text{ V} - 0.7\text{ V}}{(100)(1.5\text{k}\Omega)} = 17.3\ \mu\text{A}$$

And

$$r'_{e1} = \frac{25\text{ mV}}{I_{E1}} = \frac{25\text{ mV}}{17.3\ \mu\text{A}} = 1.45\text{ k}\Omega$$



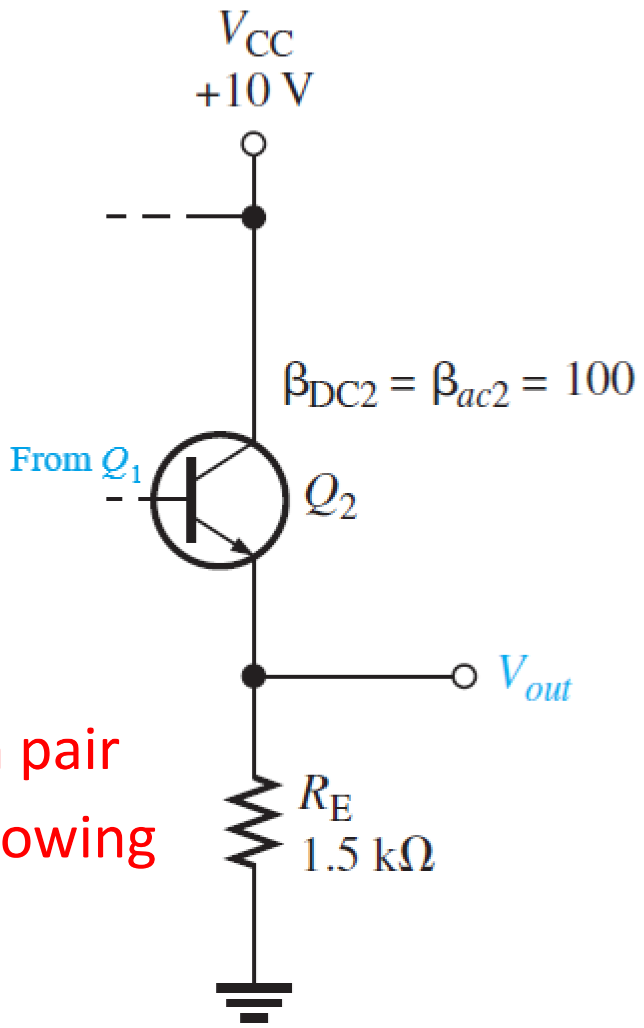
The Second Transistor Q_2:

The current that flows in its emitter is:

$$I_{E2} = \frac{V_{E2}}{R_E} = \frac{2.6\ \mathrm{V}}{1.5\ \mathrm{k\Omega}} = 1.73\ \mathrm{mA}$$

And

$$r'_{e2} = \frac{25\ \mathrm{mV}}{I_{E2}} = \frac{25\ \mathrm{mV}}{1.73\ \mathrm{mA}} = 14.5\ \Omega$$



d. Total input resistance of the Darlington pair BJT amplifier is calculated from the following equation:

$$R_{in} = R_1 \parallel R_2 \parallel R_{in}(\text{base1})$$

As a result, the input resistance at the base is:

$$R_{in(\text{base1})} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\ \text{k}\Omega) = 22.5\ \text{M}\Omega$$

Thus, the total input resistance of the amplifier is:

$$R_{in} = 33\ \text{k}\Omega \parallel 22\ \text{k}\Omega \parallel 22.5\ \text{M}\Omega = 13.2\ \text{k}\Omega$$

e. For finding the overall current gain A_i of the Darlington pair BJT amplifier circuit, we need to determine the currents that flow in the input and the output.

The resistance at the base of the amplifier circuit is:

$$R_{in(\text{base})} = \beta_{ac1}\beta_{ac2}R_E = (150)(100)(1.5\ \text{k}\Omega) = 22.5\ \text{M}\Omega$$

The total input resistance of the amplifier circuit is:

$$R_{in} = R_1 \parallel R_2 \parallel R_{in(\text{base})} = 22\ \text{k}\Omega \parallel 33\ \text{k}\Omega \parallel 22.5\ \text{M}\Omega = 13.2\ \text{k}\Omega$$

Thus, the AC current that flows in the input of the amplifier circuit is:

$$I_{in} = \frac{V_{in}}{R_{in}} = \frac{1\ \mathrm{V\ (rms)}}{13.2\ \mathrm{k\Omega}} = 75.8\ \mathrm{\mu A\ (rms)}$$

The AC current in the base of the transistor Q_1 is:

$$I_{in(\mathrm{base1})} = \frac{V_{in}}{R_{in(\mathrm{base1})}} = \frac{1\ \mathrm{V\ (rms)}}{22.5\ \mathrm{M\Omega}} = 44.4\ \mathrm{nA\ (rms)}$$

The AC current in the emitter (output) of the amplifier is:

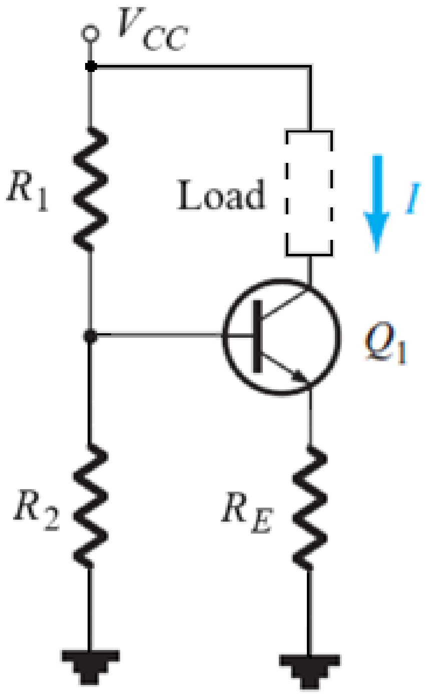
$$I_e \cong \beta_{ac1}\beta_{ac2}I_{in(\mathrm{base1})} = (150)(100)(44.4\ \mathrm{nA}) = 667\ \mathrm{\mu A\ (rms)}$$

As a result, the current gain of the amplifier circuit is:

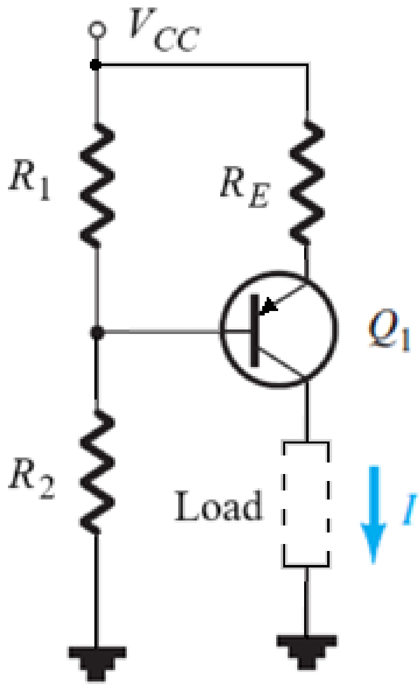
$$A_i' = \frac{I_e}{I_{in}} = \frac{667\ \mathrm{\mu A}}{75.8\ \mathrm{\mu A}} = 8.8$$

5. Transistor as a Constant-Current Source

- The constant current through the base will also ensure a constant emitter voltage, which will ensure a constant current through the load e.g. current sink/current source.



Current Sink



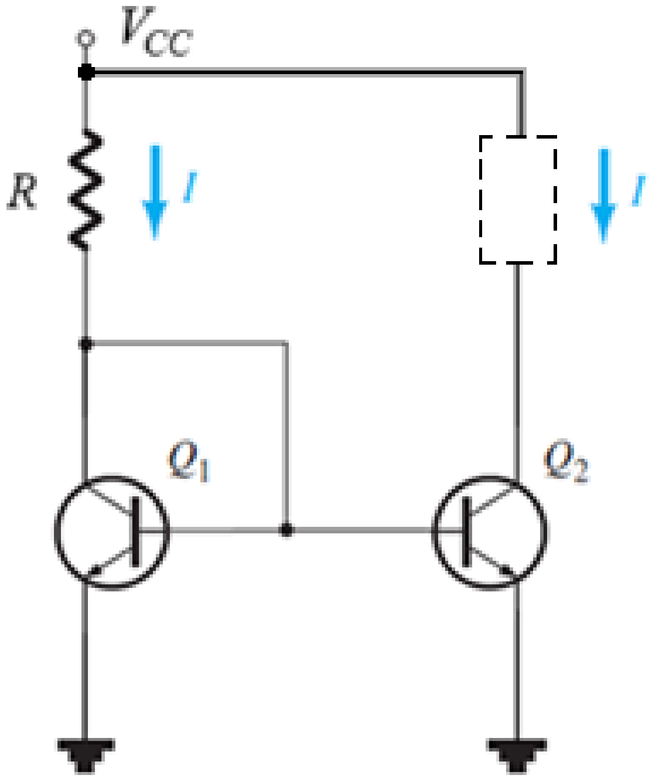
Current Source

- We can improve circuit by using a Zener diode in the place of R_2 to ensure a constant emitter voltage.

6. Current Mirror

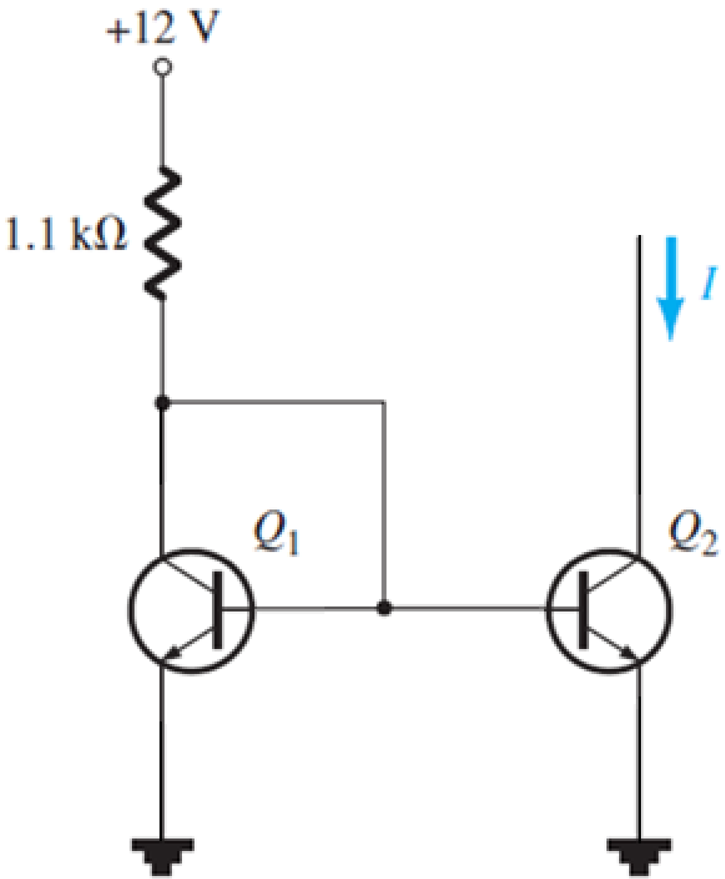
- A current mirror can be considered as a constant current source in which the current produced is equal to some input current.
- It can create equal currents in a circuit.

- Current that flows in the load is equal to the current that flows in R.
- Set value of R, so you could determine the amount of current that flows in the load.



Example 4 – BJT Current Mirror Circuit

Calculate the mirrored current I in the circuit shown in the figure below. [5 marks]



Answer

For a current mirror circuit, the current I in the circuit must be equal to $I_{control}$, so:

$$I = I_{control}$$

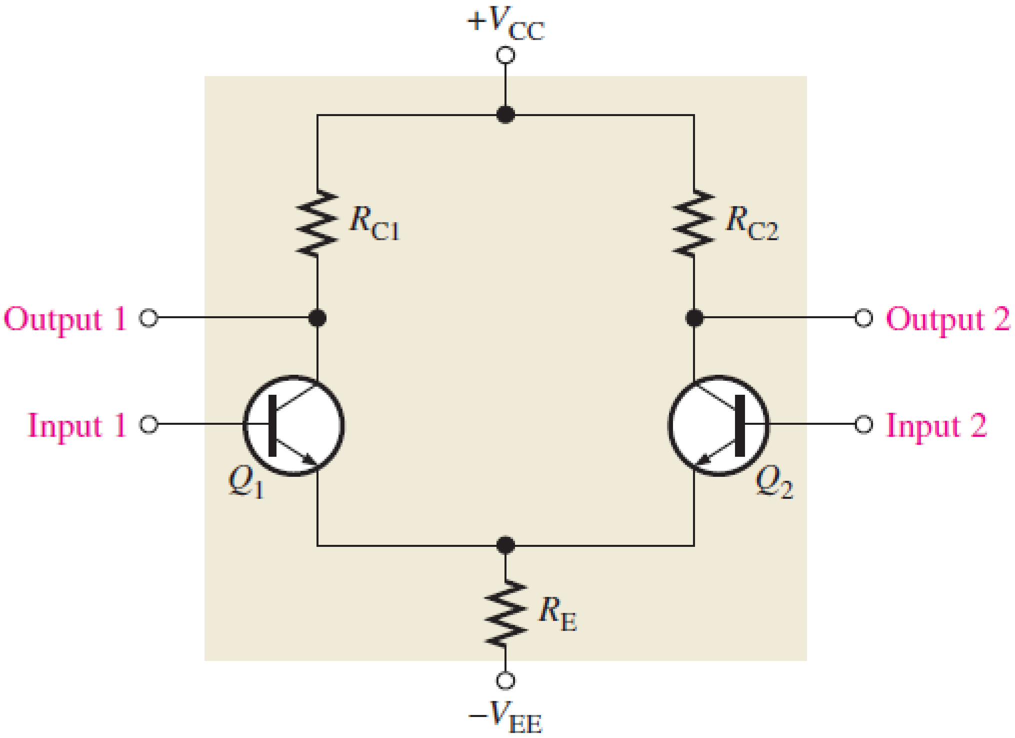
Thus

$$I = \frac{V_{CC} - V_{BE}}{R} = \frac{12\text{ V} - 0.7\text{ V}}{1.1\text{ k}\Omega}$$

$$= 10.27\text{ mA}$$

7. Differential Amplifier

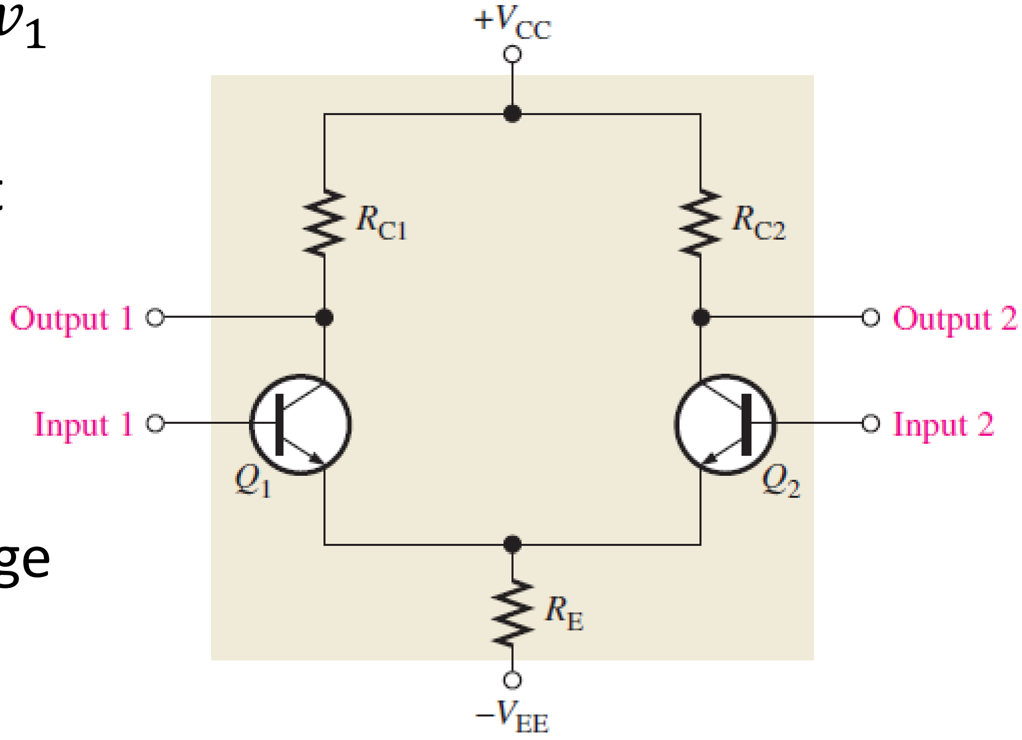
- Differential amplifiers produce an output signal that is proportional to the difference between two input signals.
- This circuit ignores the signal component that is common to both signals.



- The two transistors share the current that flows through the single emitter resistor.
- With perfectly matched transistors, resistors and equal input voltages, the outputs (v_3 and v_4) will be equal (i.e. zero differential voltage).

7. Differential Amplifier (cont.)

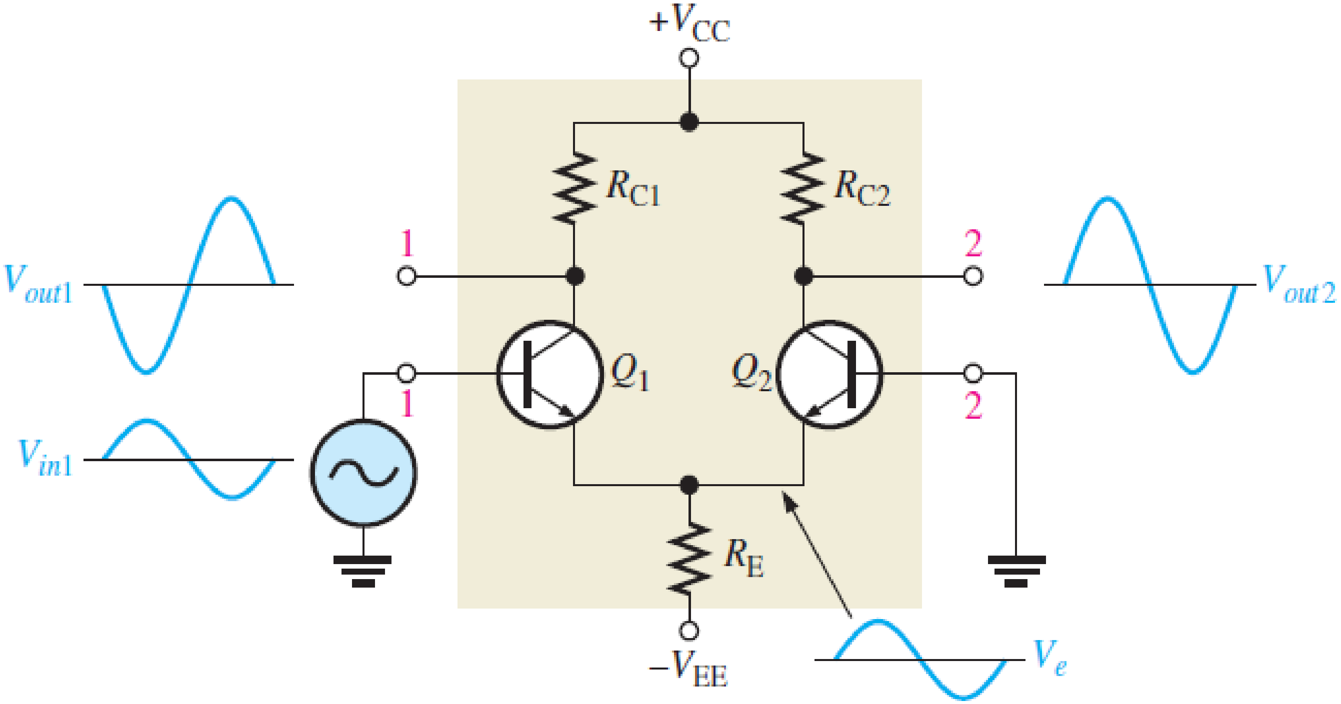
- If the input voltage on v_1 now rises, the current through R_E will be split unevenly with more of the current going through T_1.
- This will lead to a voltage difference between v_3 and v_4.



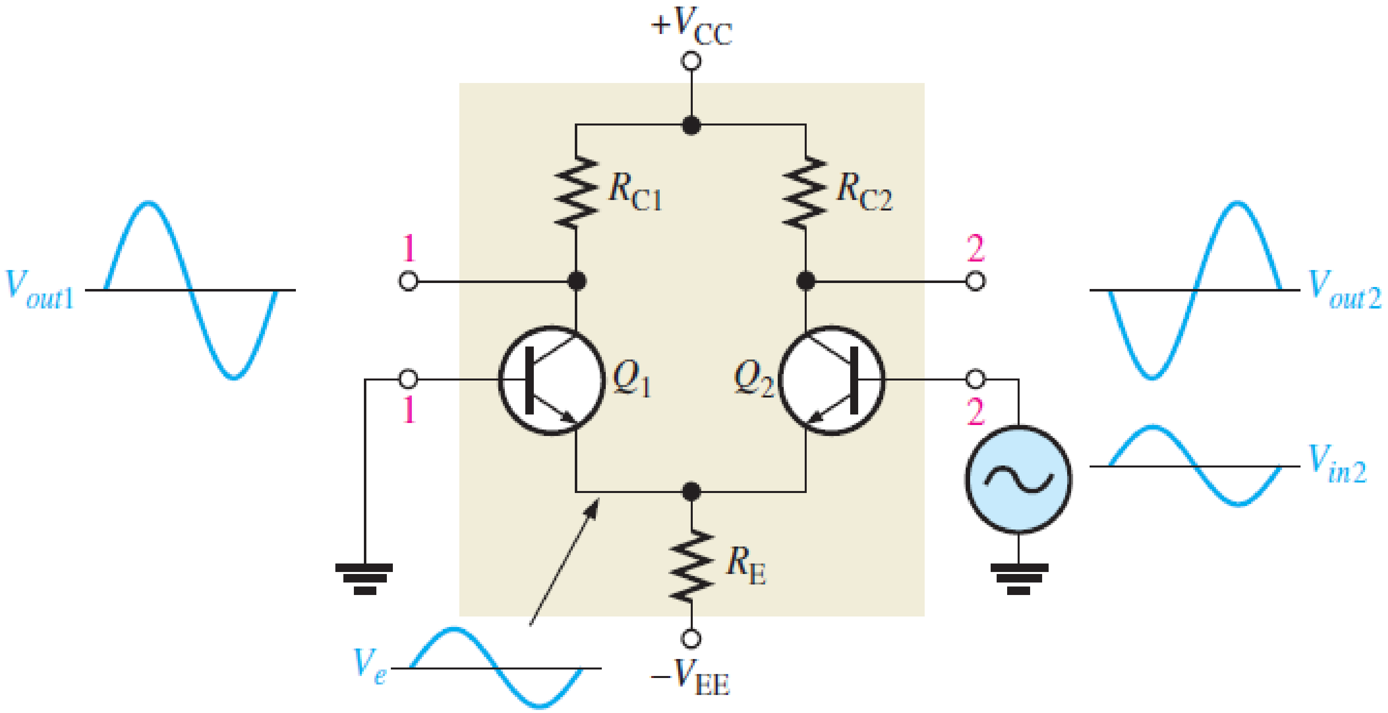
- This forms the principle of operation for bipolar operational amplifiers (op amps).

7.1. Differential Amplifier - Single-Ended Differential Input

- One of the inputs is grounded and the signal voltage is applied only to the other input.
- Signal voltage is applied to input 1, and an inverted and amplified signal voltage appears at output 1.

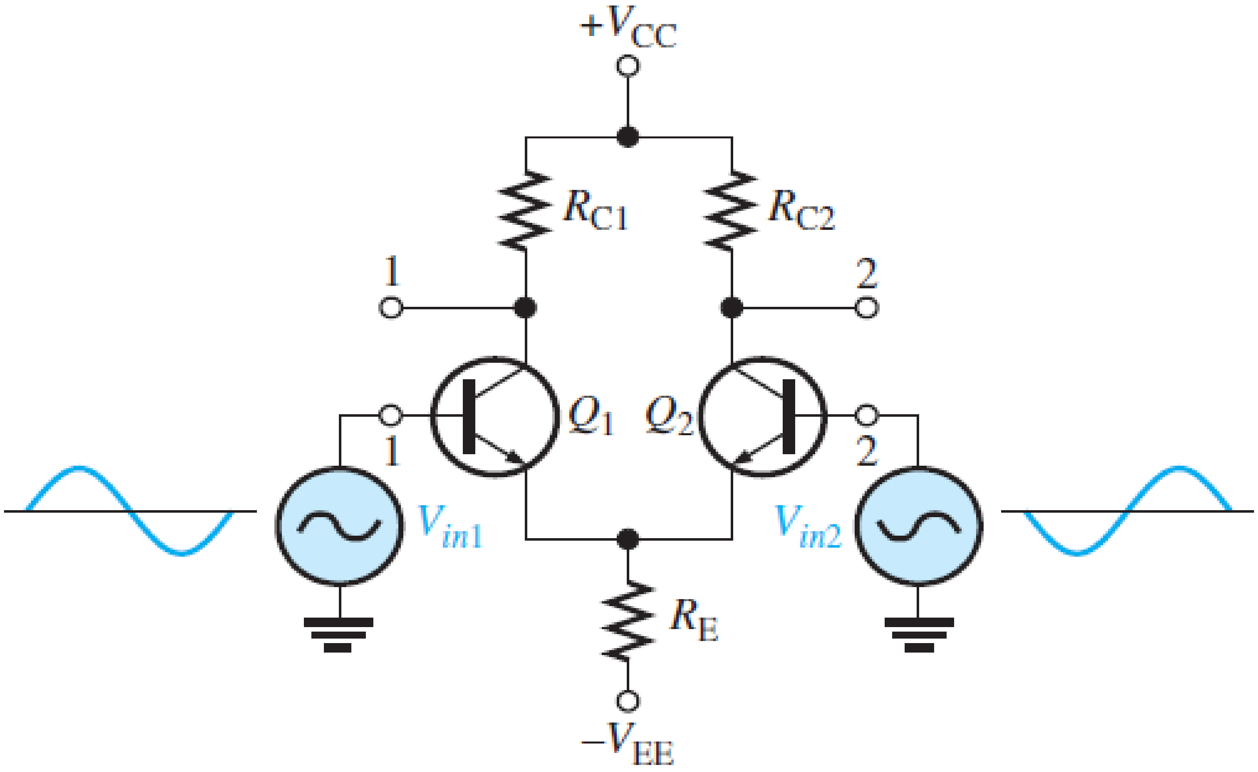


- The signal is applied to input 2 with input 1 grounded, and an inverted and amplified signal voltage appears at output 2.

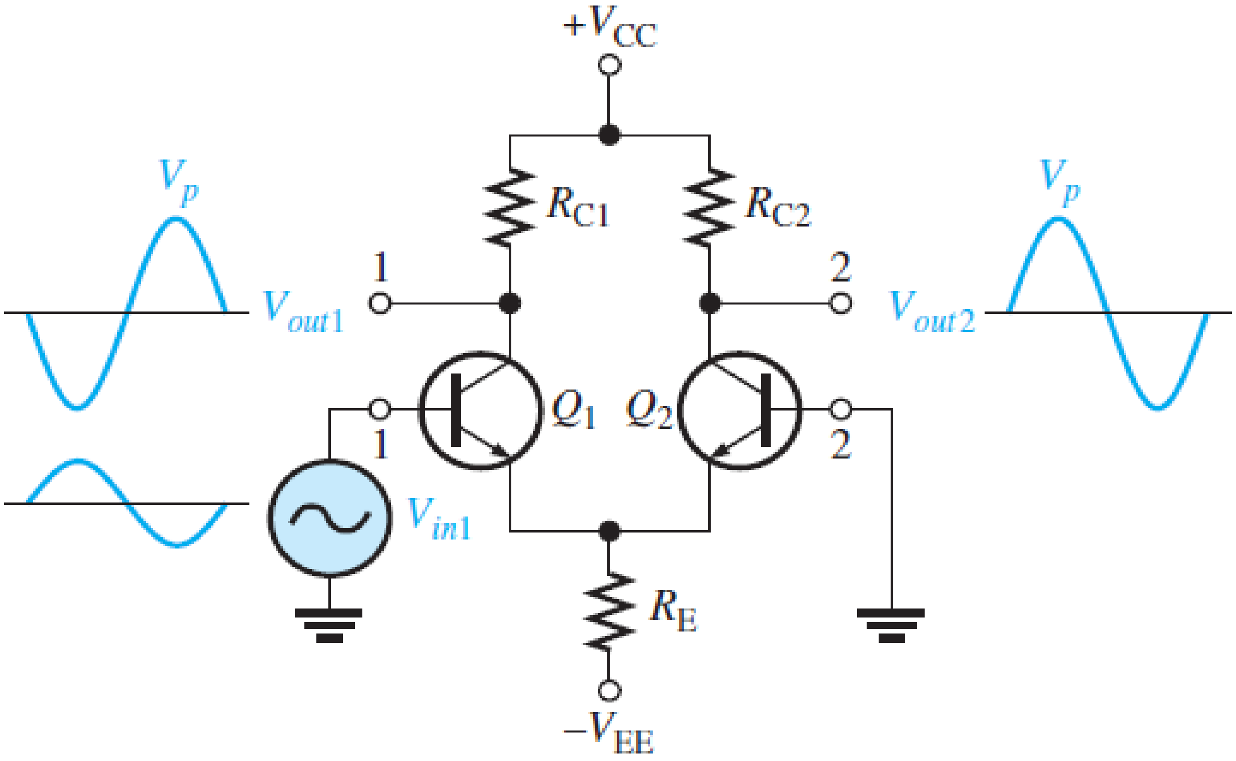


7.2. Differential Amplifier - Double-Ended Differential Input

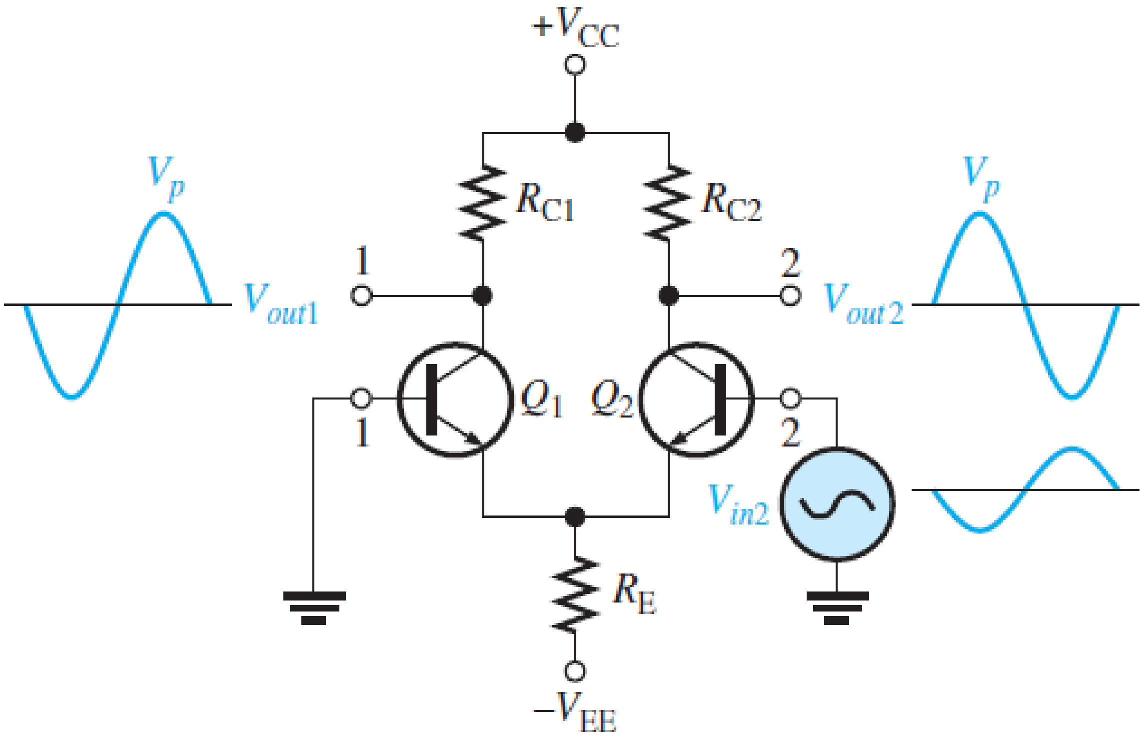
- Two opposite-polarity (out-of-phase) signals are applied to the inputs.



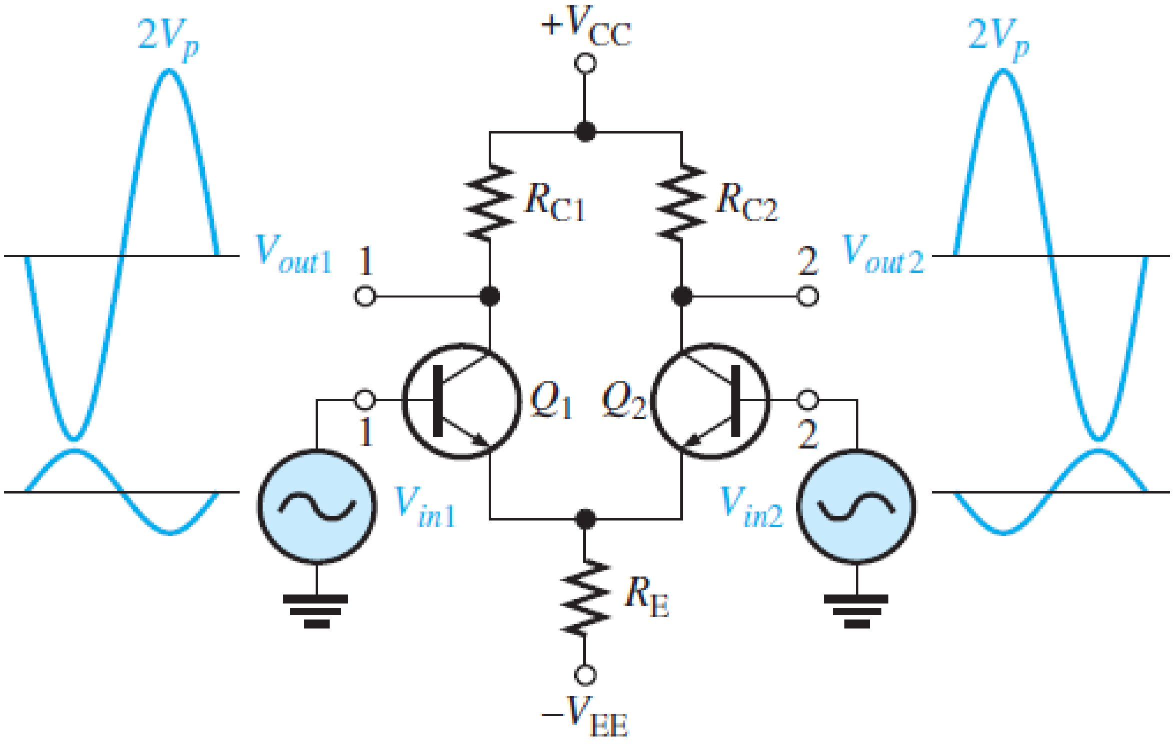
- The output signals due to the signal on input 1 acting alone as a single-ended input.



- The output signals due to the signal on input 2 acting alone as a single-ended input.
- Notice that the signals on output 1 and output 2 are of the same polarity.

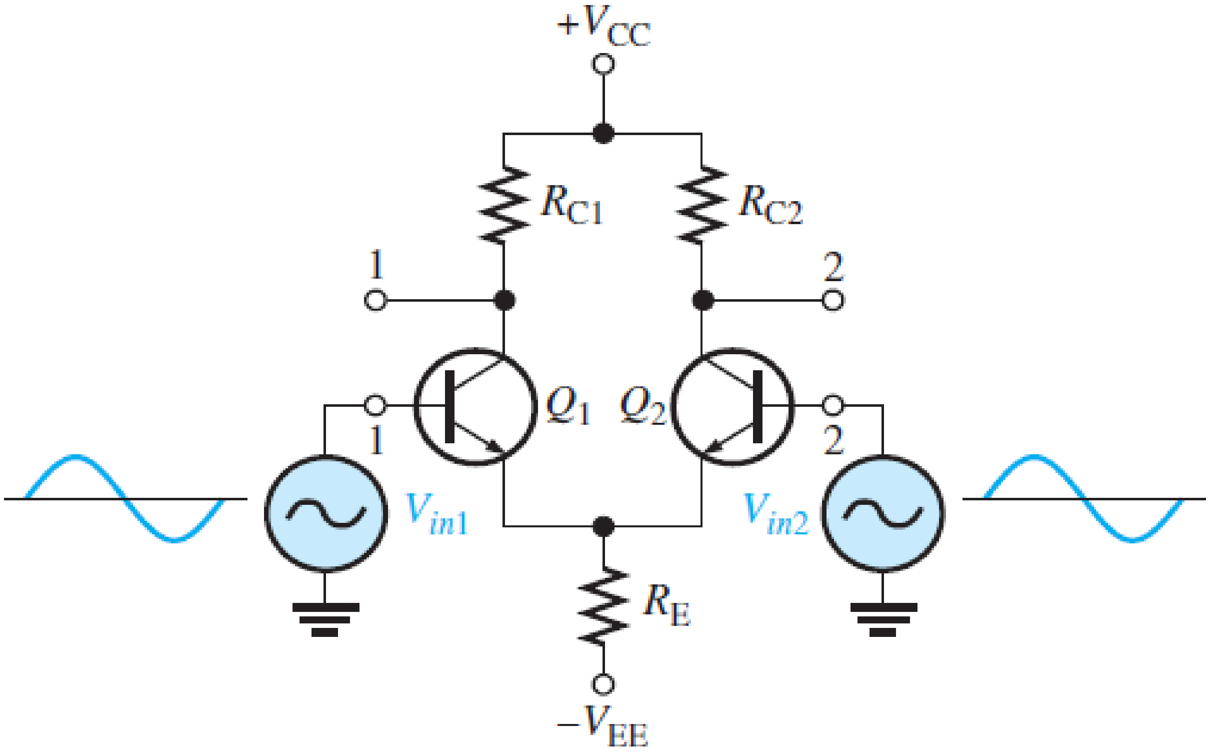


- By applying the superposition theorem and summing both output 1 signals and both output 2 signals, you get the total output signals.

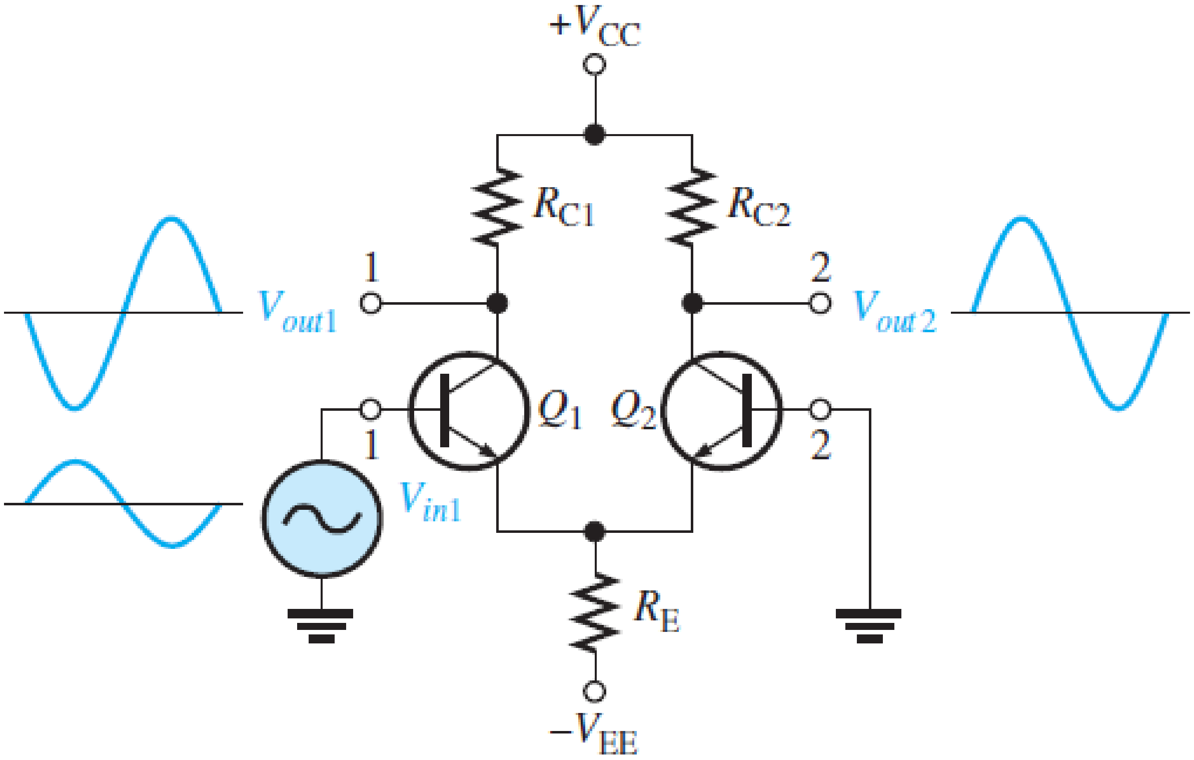


7.3. Differential Amplifier - Common Mode Inputs

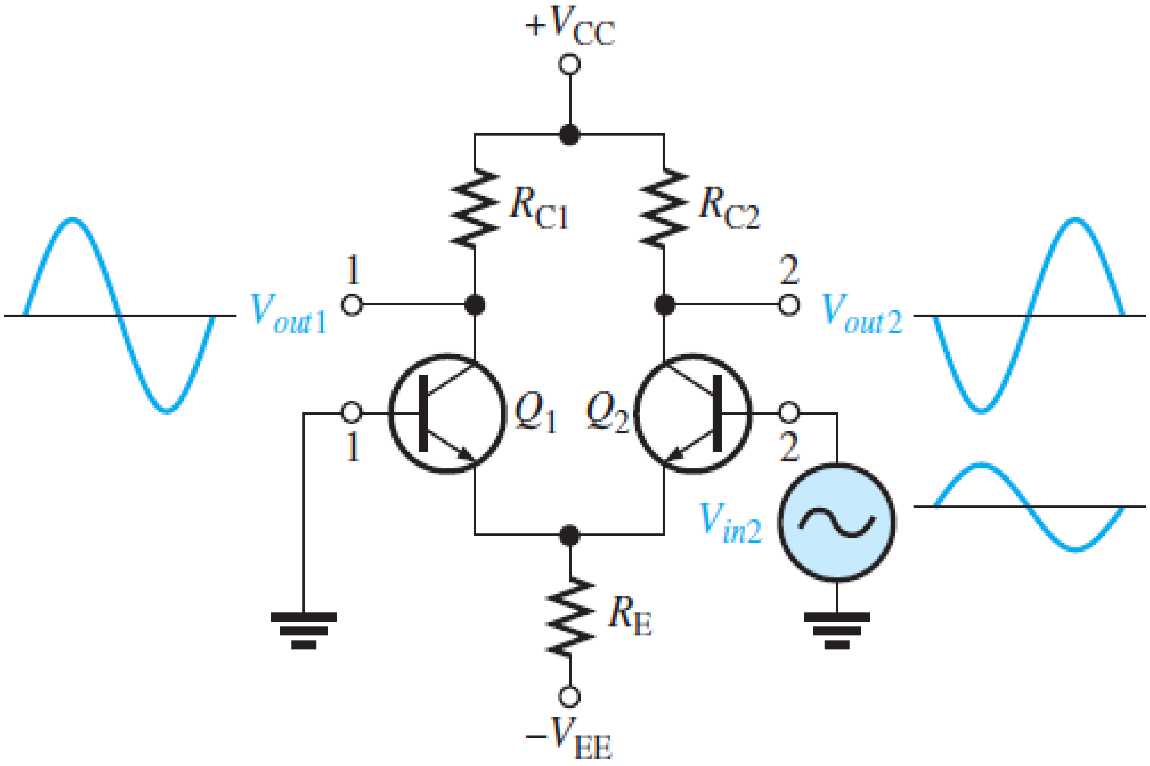
- Two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs.



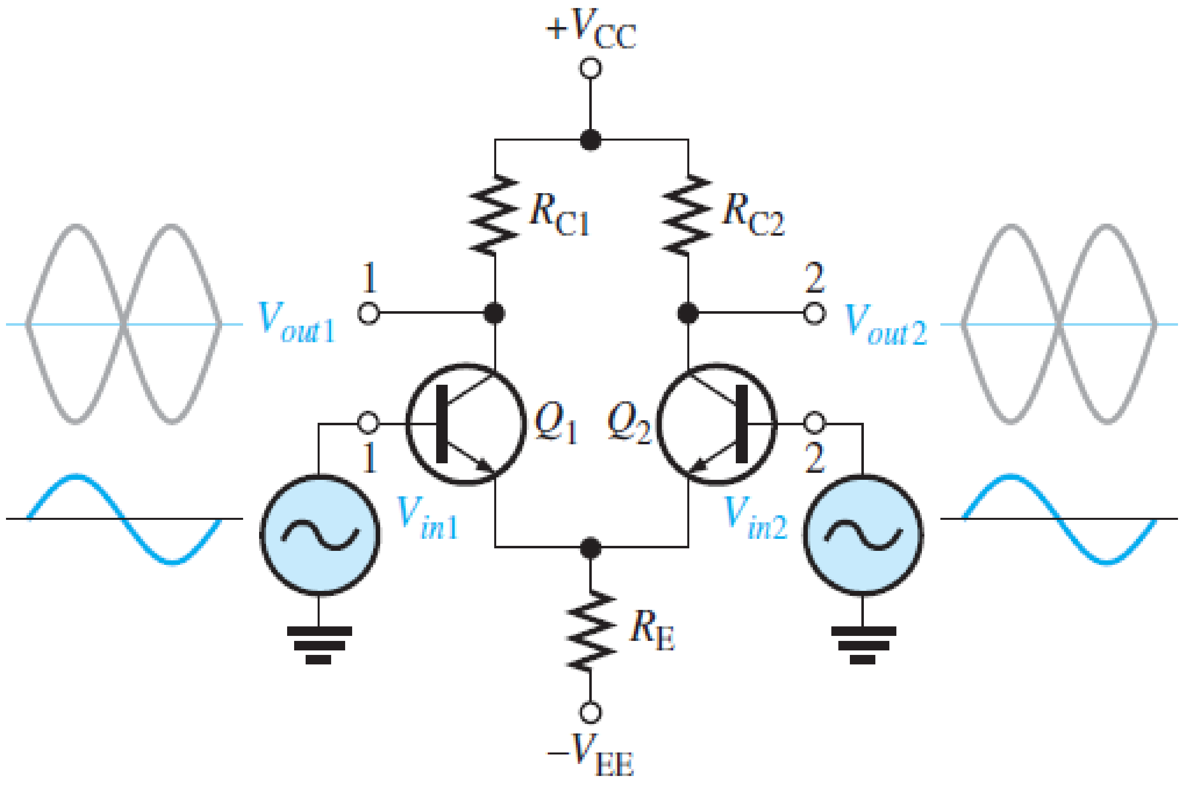
- The output signals due to the signal on only input 1.



- The output signals due to the signal on only input 2.
- Notice that the corresponding signals on output 1 are of the opposite polarity, and so are the ones on output 2.



- When the input signals are applied to both inputs, the outputs are superimposed and they cancel, resulting in a zero-output voltage.



- This action is commonly termed as common-mode rejection.
- The common-mode rejection means that this unwanted signal will not appear on the outputs and distort the desired signal e.g. radiated energy on the input lines from adjacent lines, the 60 Hz power line, or other sources.
- Ideal differential amplifiers - a very high gain for desired signals (single-ended or differential) and zero gain for common-mode signals.
- Practical differential amplifiers - a very small common-mode gain (usually much less than 1), while providing a high differential voltage gain (usually several thousand).

- The higher the differential gain with respect to the common-mode gain, the better the performance of the differential amplifier in terms of rejection of common-mode signals.
- The ratio between differential mode gain (A_{dm}) and common mode gain (A_{cm}) is termed the common-mode rejection ratio, CMRR:

$$\mathrm{CMRR} = \frac{A_{dm}}{A_{cm}}$$

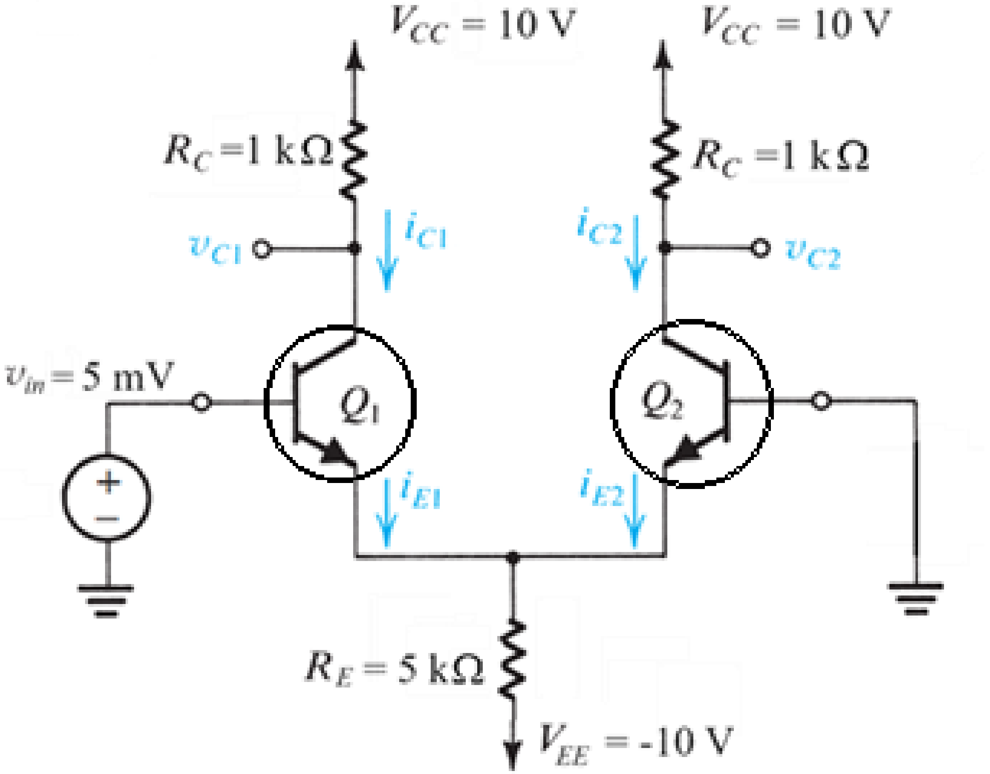
- The higher the CMRR, the better. A high CMRR means that the differential gain A_{dm} is high and the common-mode gain A_{cm} is low. The CMRR is often expressed in decibels (dB) as:

$$\mathrm{CMRR} = 20 \log\left(\frac{A_{dm}}{A_{cm}}\right)$$

Example 5 – BJT Differential Amplifier

For the differential amplifier circuit given below, considering identical transistors used in the circuit, the DC gain of the BJT is $\beta_{Q1} = \beta_{Q2} = 100$ and V_{BE} = 0.7 V.

Due to high DC gain of the transistors, assume that currents $I_{C1} = I_{C2} = I_{E1} = I_{E2}$.



Calculate the following circuit parameters of the differential amplifier:

a. The input impedance (Z_{in}) if terminal voltage V_T = 25 mV. [8 marks]

b. The AC output voltage if the output is taken across the terminals v_{C1} and v_{c2}. [6 marks]

Answer

a. For the given differential amplifier circuit, the tail current is:

$$I_T = \frac{V_{CC}}{R_E} = \frac{10\ \mathrm{V}}{5\ \mathrm{k\Omega}} = 2\ \mathrm{mA}$$

Assuming identical transistors, the current that flows in the emitter is:

$$I_{E1} = I_{E2} = \frac{I_T}{2} = \frac{2\ \mathrm{mA}}{2} = 1\ \mathrm{mA}$$

If terminal voltage, V_T = 25 mV, the AC emitter internal resistance is:

$$r_e' = \frac{25\ \mathrm{mV}}{I_E} = \frac{25\ \mathrm{mV}}{1\ \mathrm{mA}} = 25\ \Omega$$

The input impedance of the differential amplifier is:

$$Z_{in} = 2\beta r_e' = 2(100)(25\ \Omega) = 5\ \text{k}\Omega$$

b. As currents $I_E = I_C$, the voltage at the collector is:

$$V_C = V_{CC} - I_C R_C = 10\ \text{V} - (1\ \text{mA})(1\ \text{k}\Omega) = 9\ \text{V}$$

For the given common emitter leg of the circuit, the AC voltage gain is:

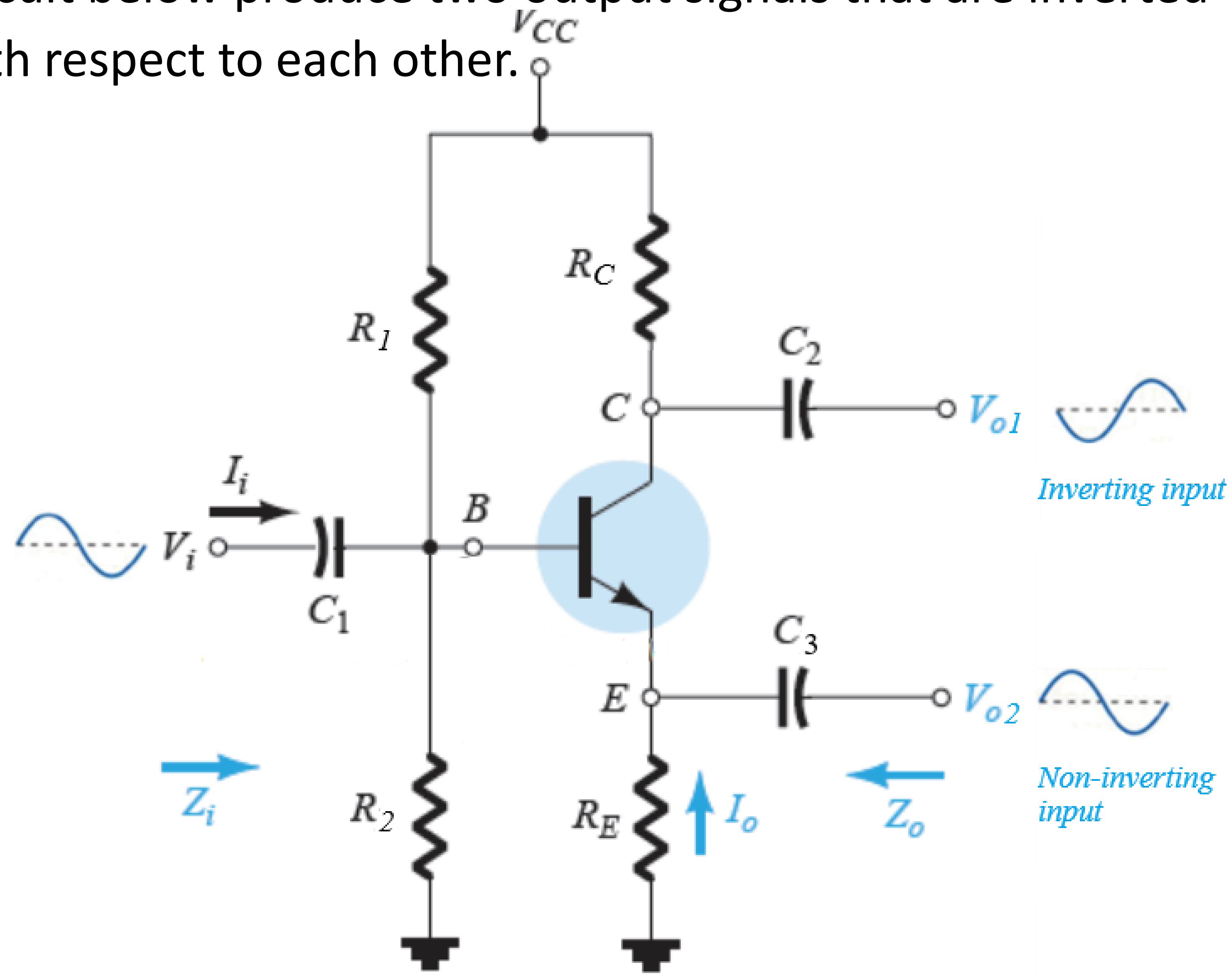
$$A_v = \frac{R_C}{r_e'} = \frac{1\ \text{k}\Omega}{25\ \Omega} = 40$$

Considering V_{in} = 5 mV, the AC output voltage is:

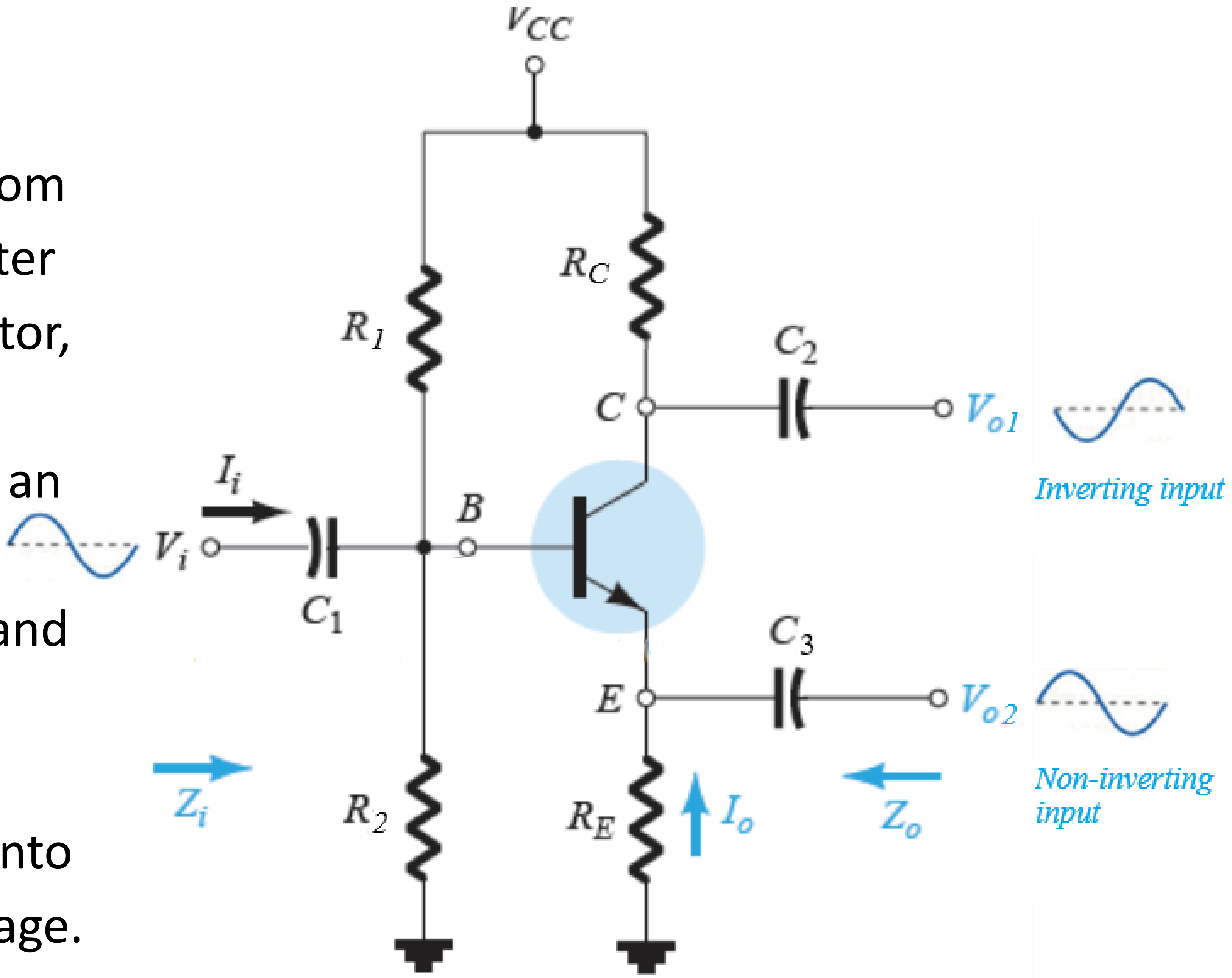
$$V_{out} = A_v V_{in} = 40(5\ \text{mV}) = 200\ \text{mV}$$

8. Phase Splitter

- Circuit below produce two output signals that are inverted with respect to each other.



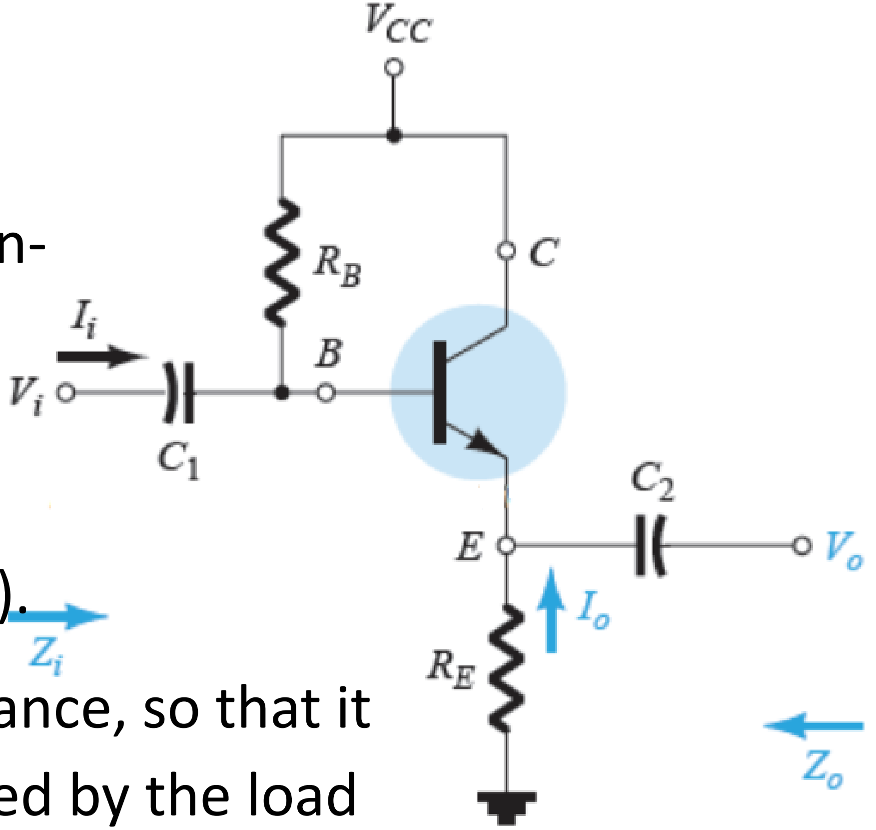
- By taking outputs from both emitter and collector, we have combined an inverting amplifier and a non-inverting amplifier into a single stage.



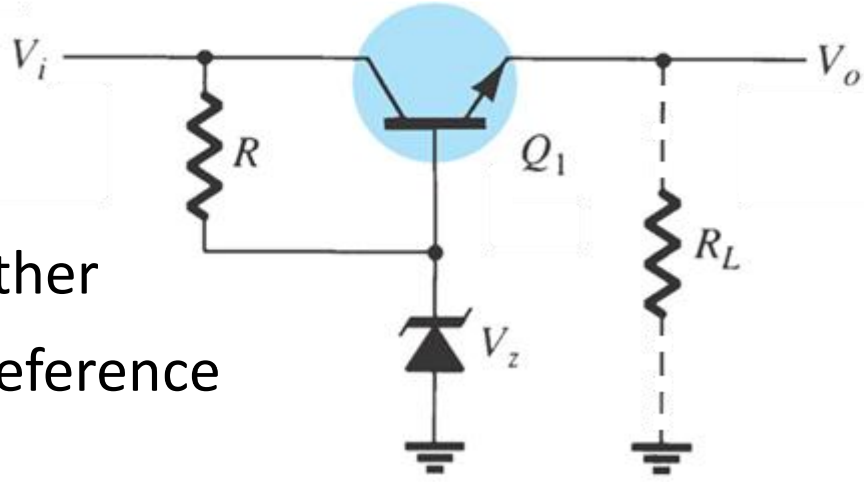
- Make R_E = R_C = R to give a voltage gain of -1 for inverting output e.g. two signals are of identical amplitude but opposite in phase.

9. Voltage Regulator

- The emitter follower (common-collector amplifier) as discussed before produces a voltage that is determined by its input voltage (-0.7 V offset).

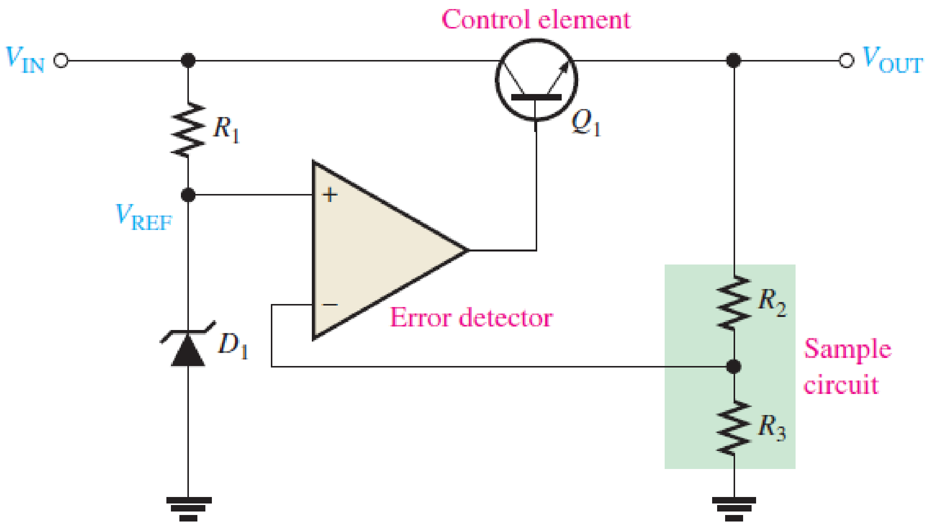


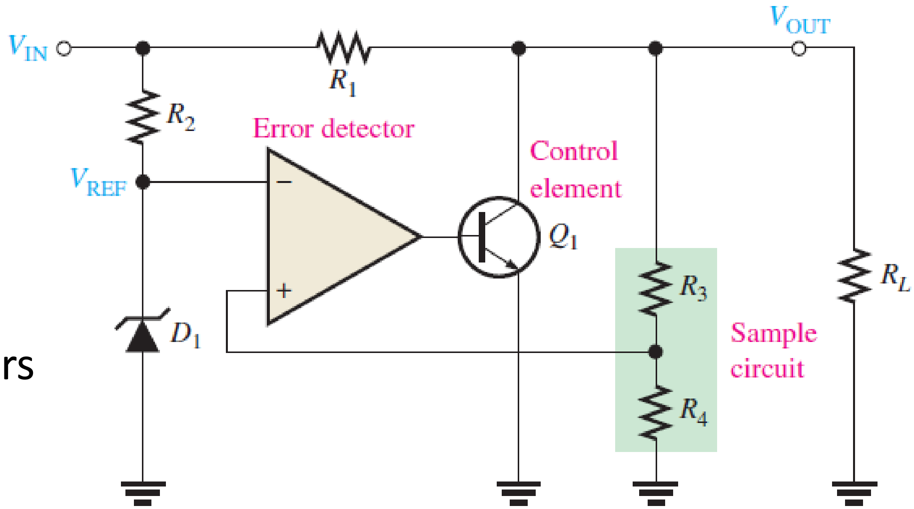
- It also has a low output resistance, so that it will not be significantly affected by the load connected to it.
- It can then be used as voltage regulator e.g. use of a Zener diode, or on input which together with resistor forms a voltage reference for the base input.



9. Voltage Regulator (cont.)

- In practice, with op amp as error detector amplifier, there are two types of series voltage regulator:
  - Series voltage regulator.
  - Shunt voltage regulator.

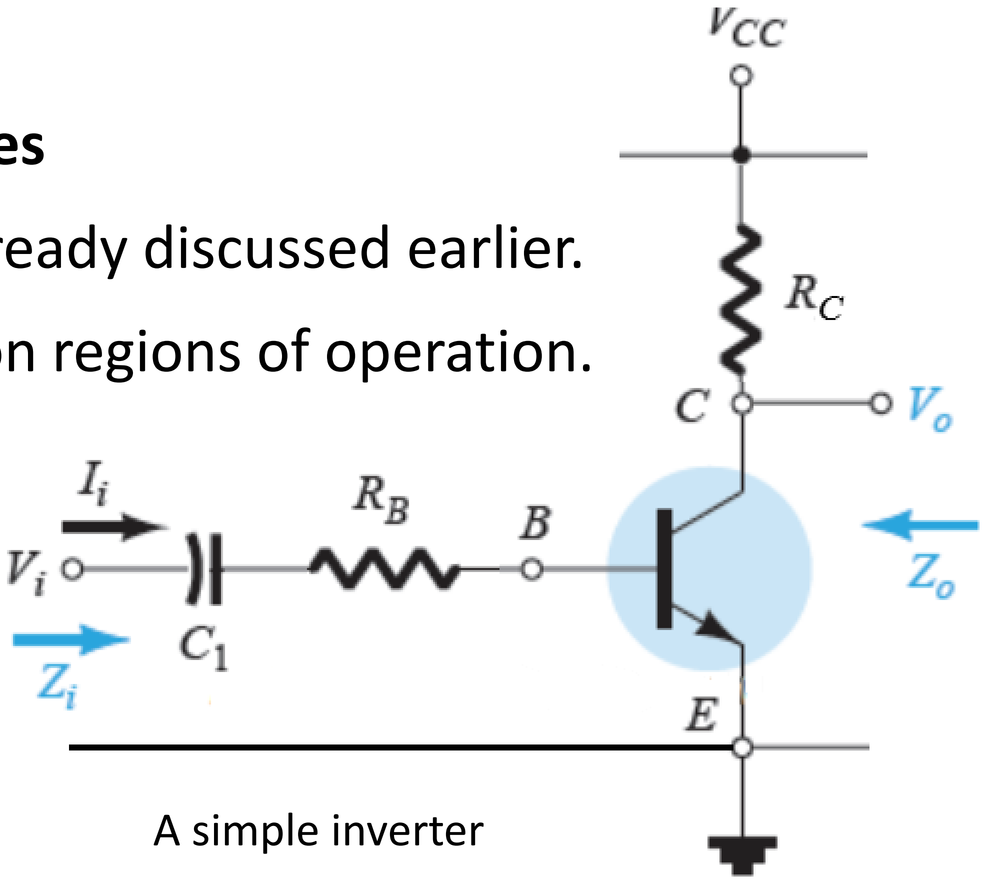




Two examples of basic voltage regulators using a NPN transistor: series (left) and shunt (right) voltage regulators

10. Switches and Logic Gates

- Use of BJT as a switch already discussed earlier.
- Use cut-off and saturation regions of operation.
- A simple inverter circuit i.e. BJT as a common-emitter amplifier circuit.

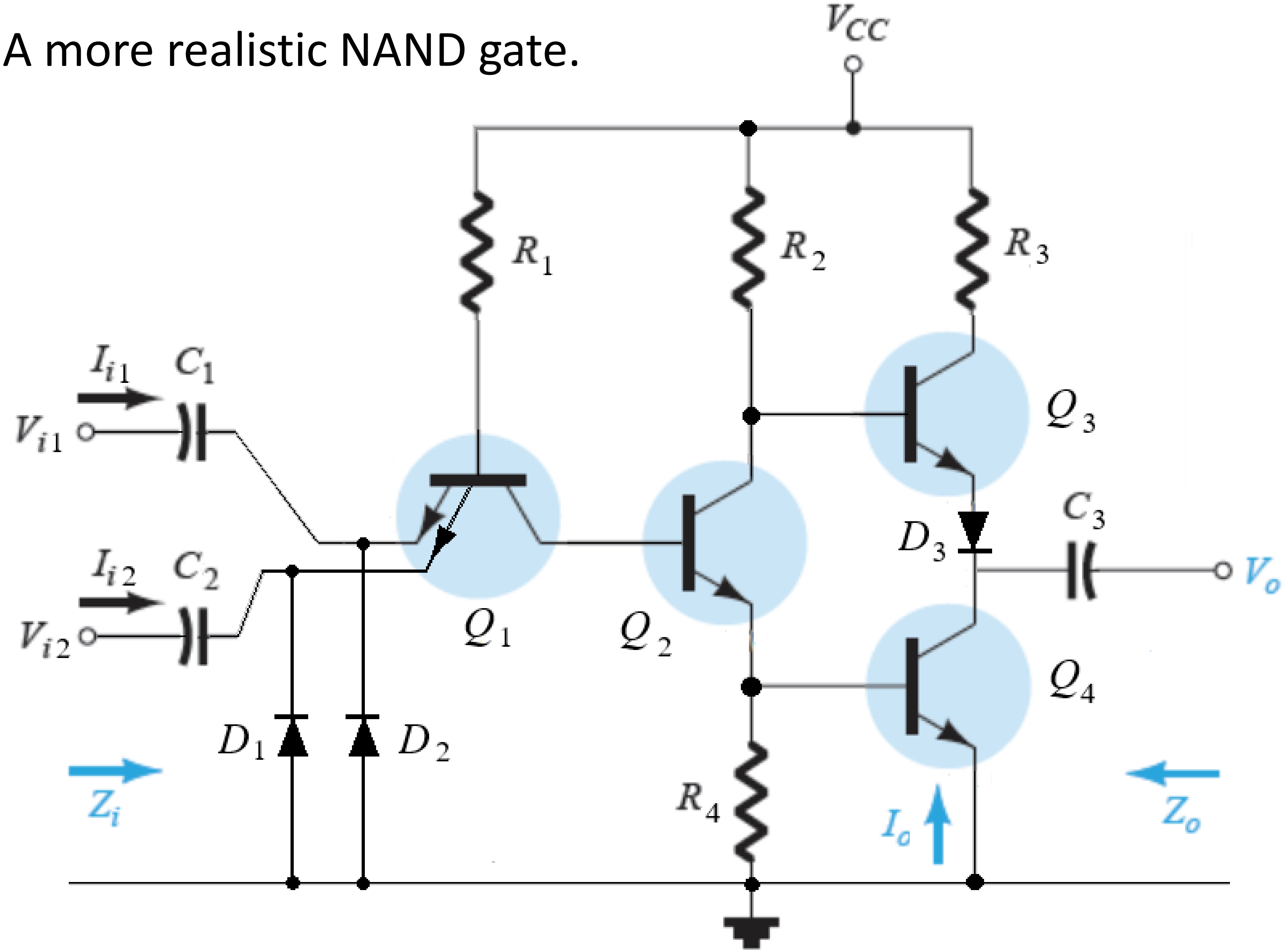


A simple inverter

- The inversion of common-emitter configuration makes V_o as the amplified and inverted version of V_i.

10. Switches and Logic Gates (cont.)

- A more realistic NAND gate.



10. Switches and Logic Gates (cont.)

Input stage:

- Both input signals are “High” voltage -> T_1 is on.
- If only one of input is “High” or both are “Low” -> T_1 is off.
- D_1 and D_2 - pull-up diode for preventing any negative voltages.

Buffer stage:

- T_1 is on -> T_4 is off and T_3 is off.
- T_1 is off -> T_3 is on and T_4 is off.

A	B	X
0	0	1
0	1	1
1	0	1
1	1	0

Output stage:

- T_2 is on -> both of T_3 and T_4 are on.
- D_3 is biasing diode e.g. when T_2 is on, only T_4 is on, not both of T_3 and T_4 and when T_2 is off, only T_3 is on whereas T_4 is off.