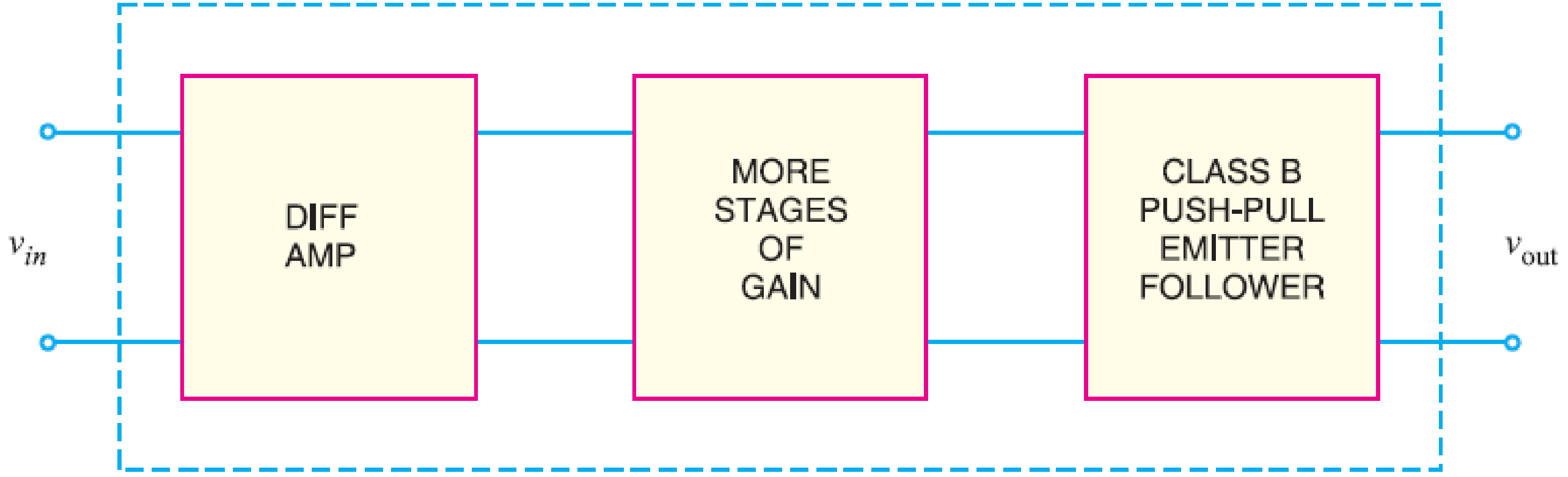
Differential and Operational Amplifier

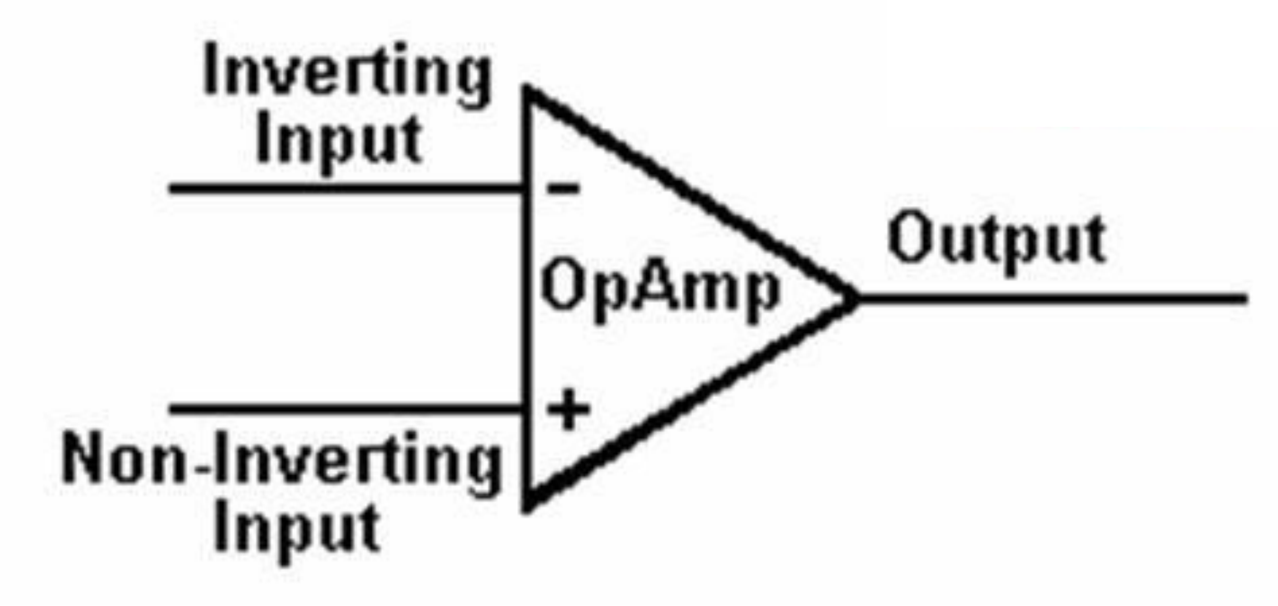
Operational Amplifier (Op Amp)

- An operational amplifier was designed to perform such mathematical operations as *addition, subtraction, integration and differentiation*. Hence, its name is operational amplifier.
- An operational amplifier is a very high gain differential amplifier with high input impedance and low output impedance.



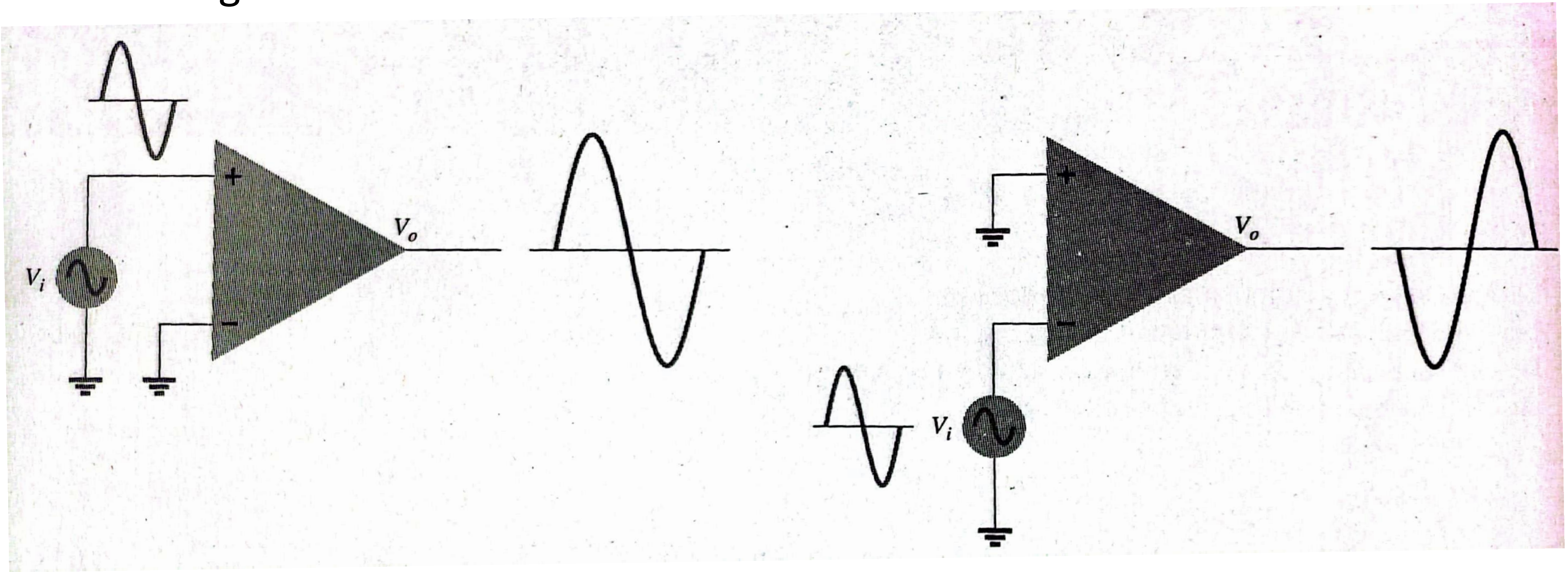
Block diagram of OP-Amp

Basic Op-Amp



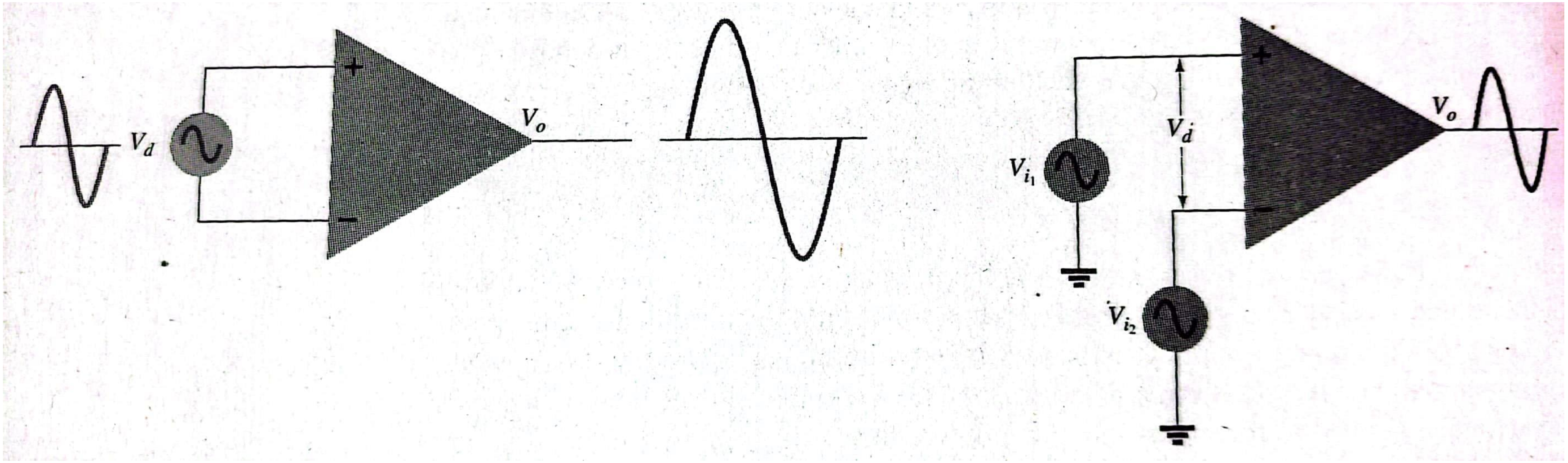
Op-Amp

- Single Ended Input
  - The input signal is connected to one input with the other input is connected to the ground.



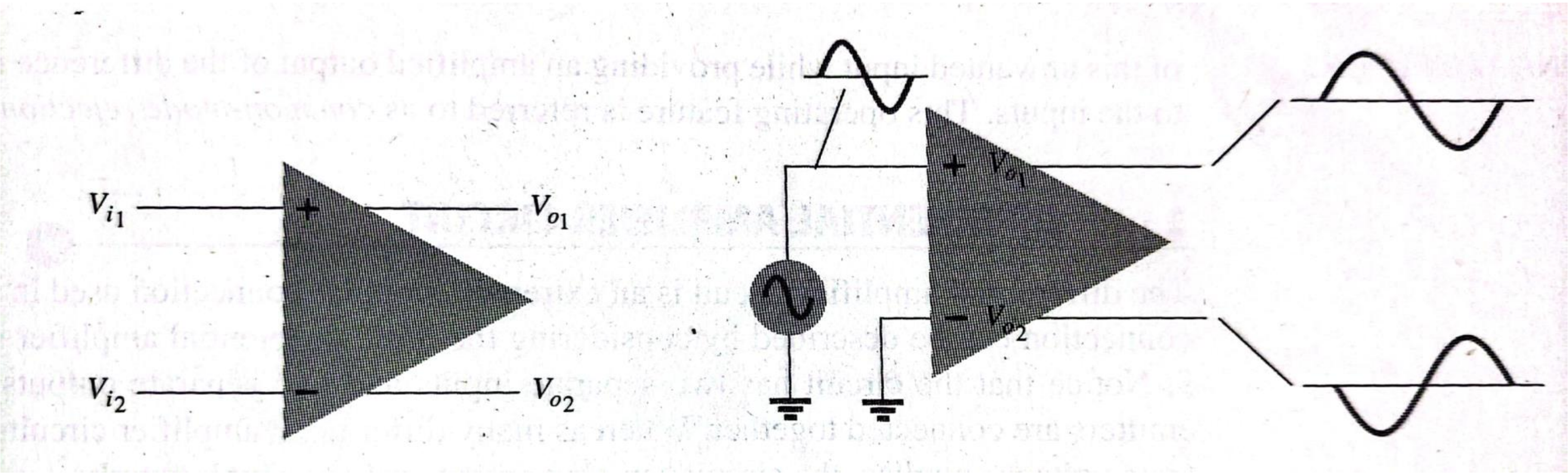
Op-Amp

- Double Ended (Differential) Input
  - Each input is connected to an input signal, neither input is at ground.



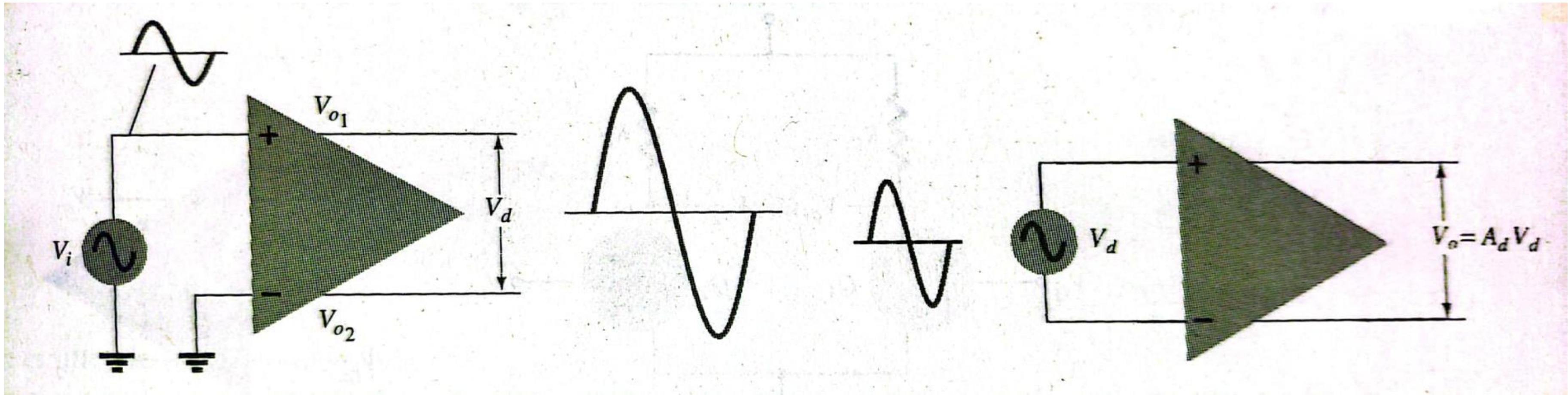
Op-Amp

- Double Ended Output



Op-Amp

- Double Ended Output



The difference output signal is $V_{o_1} - V_{o\,2}$. It is called *floating signal* since neither output terminal is the ground terminal.

The difference output is twice as large as either output because they are of opposite polarity and subtracting them results in twice of their amplitude.

Basic Op-Amps Concepts

1) The Ideal Op-amp

The IC Op-amp comes so close to ideal performance that it is used to state the characteristics of an ideal amplifier without regard to what is inside the package.

Characteristics of Ideal Op-amp:

i. Infinite voltage gain
ii. Infinite input impedance
iii. Zero output impedance
iv. Infinite bandwidth
v. Zero input offset voltage (i.e. exactly zero output when no input)

Basic Op-Amps Concepts

2) The Op-amp Golden Rules

For an Op-amp with external feedback

i. Voltage Rule

"The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

The voltage gain of a real Op-amp is so high that a fraction of a millivolt input will swing the output over its full range.

ii. Current Rule

The inputs draw no current.

The input current is so low, microamps to pico amps.

Basic Op-Amps Concepts

3) The Real Op-amp

The modern integrated circuit version is typified by the famous 741 Op-amp. Some of the general characteristics of the IC version are:

i. High gain, about million
ii. High input impedance
iii. Low output impedance
iv. Used with split supply, usually $\pm$15 V
v. Used with feedback, with gain determined by the feedback network.

Basic Op-Amps Concepts

4) Op-amp Notation and Parameters

A typical circuit symbol for an Op-amp is shown below:

Terminals are:

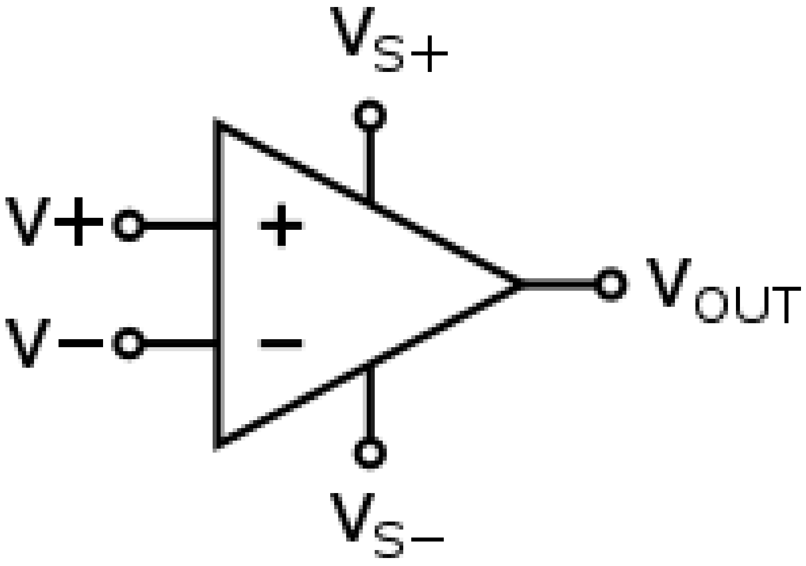
$\mathrm{V}^{+} = \mathrm{non} - \mathrm{inverting\ input}$

$\mathrm{V}^{-} = \mathrm{inverting\ input}$

$\mathrm{V}_{\mathrm{s}+} = \mathrm{positive\ power\ supply}$

$\mathrm{V}_{\mathrm{s}-} = \mathrm{negative\ power\ supply}$

$\mathrm{V}_{\mathrm{out}} = \mathrm{output}$



Basic Op-Amps Concepts

4) Op-amp Notation and Parameters

- Differential Input (V_d):

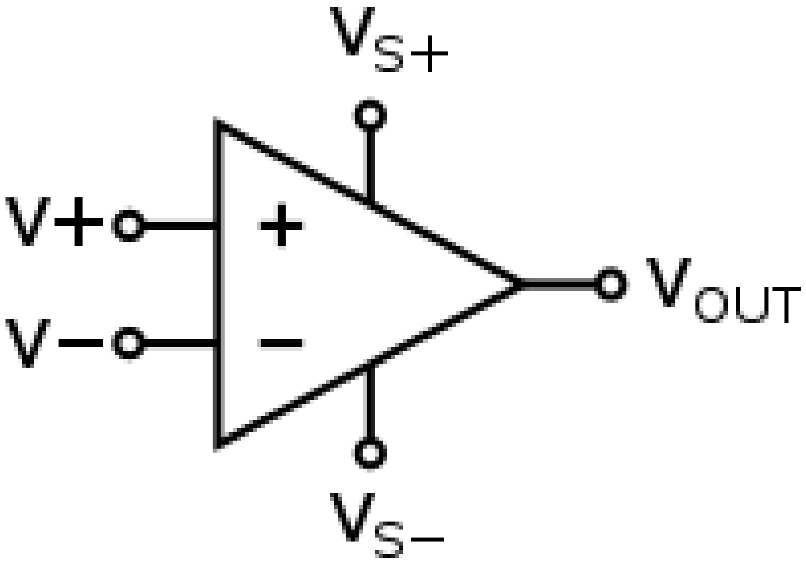
$$V_d = \mathrm{V}^+ - \mathrm{V}^-$$

- Common Input (V_c):

$$V_c = \frac{1}{2}(V^+ + V^-)$$

- Output Voltage

$$V_o = A_d V_d + A_c V_c$$



Differential Amplifier (DA)

A ***differential amplifier*** *is a circuit that can accept* ***two input signals*** *and amplify the* ***difference*** *between these two input signals.*

Fig. 25.2 shows the block diagram of an ordinary amplifier. The input voltage v is amplified to Av where A is the voltage gain of the amplifier. Therefore, the ouput voltage is $v_0 = Av$.

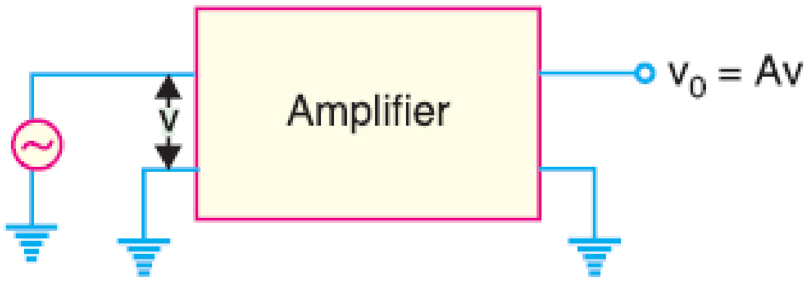


Fig. 25.2

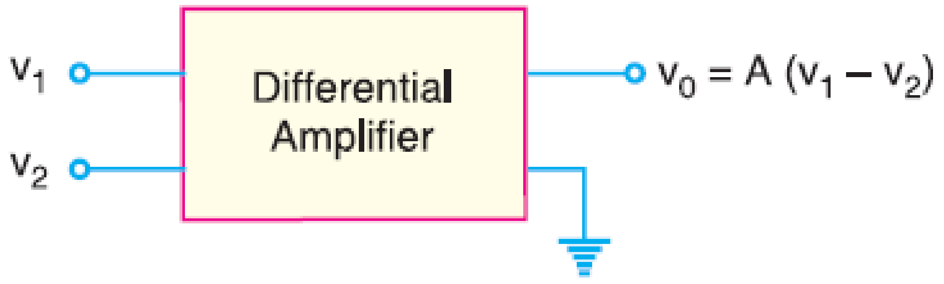


Fig.25.3

Fig. 25.3 shows the block diagram of a differential amplifier. There are two input voltages v_1 and v_2. This amplifier amplifies the difference between the two input voltages. Therefore, the output voltage is $v_0 = A(v_1 - v_2)$ where A is the voltage gain of the amplifier.

Example

1) A differential amplifier has an open-circuit voltage gain of 100. The input signals are 3.25 V and 3.15V. Determine the output voltage.

$$\text{Output voltage, } v_0 = A(v_1 - v_2)$$

$$A = 100 \; ; v_1 = 3.25 \text{ V} : v_2 = 3.15\text{V}$$

$$v_0 = 100(3.25 - 3.15) = \mathbf{10V}$$

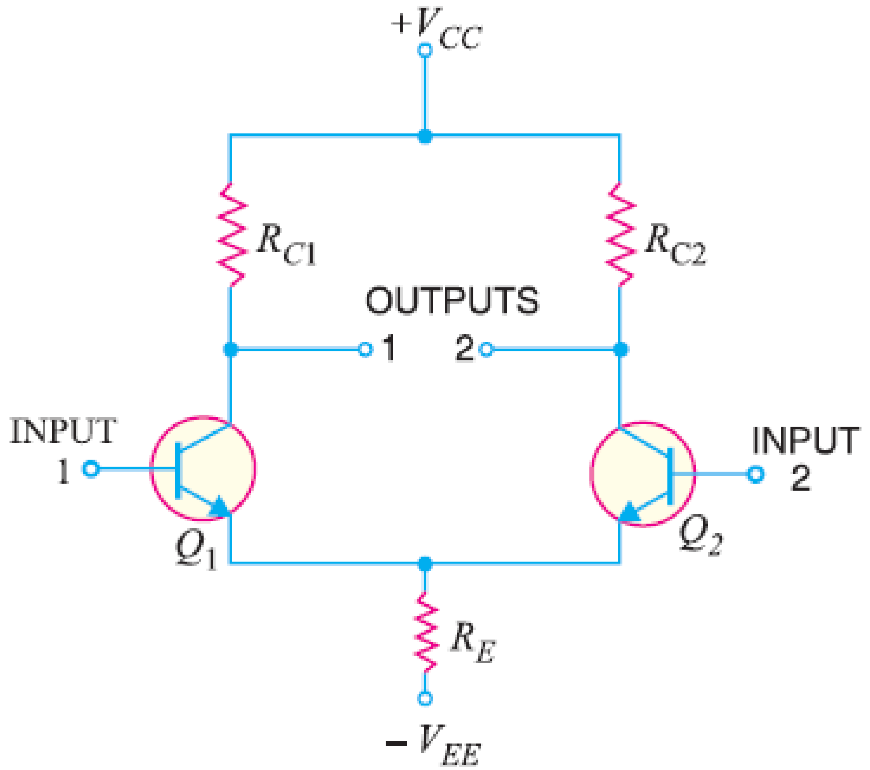
Ans.

10 V

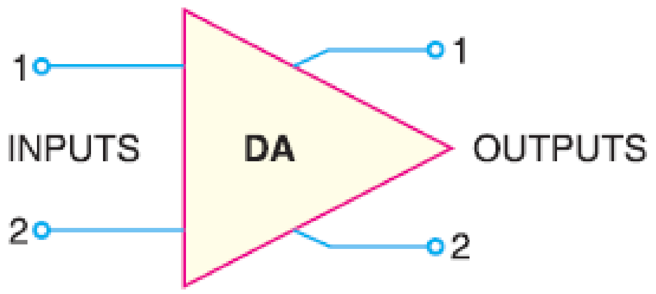
Basic Circuit of Differential Amplifier

Figure (i) shows the basic circuit of a differential amplifier.

Figure (ii) shows the symbol of differential amplifier.

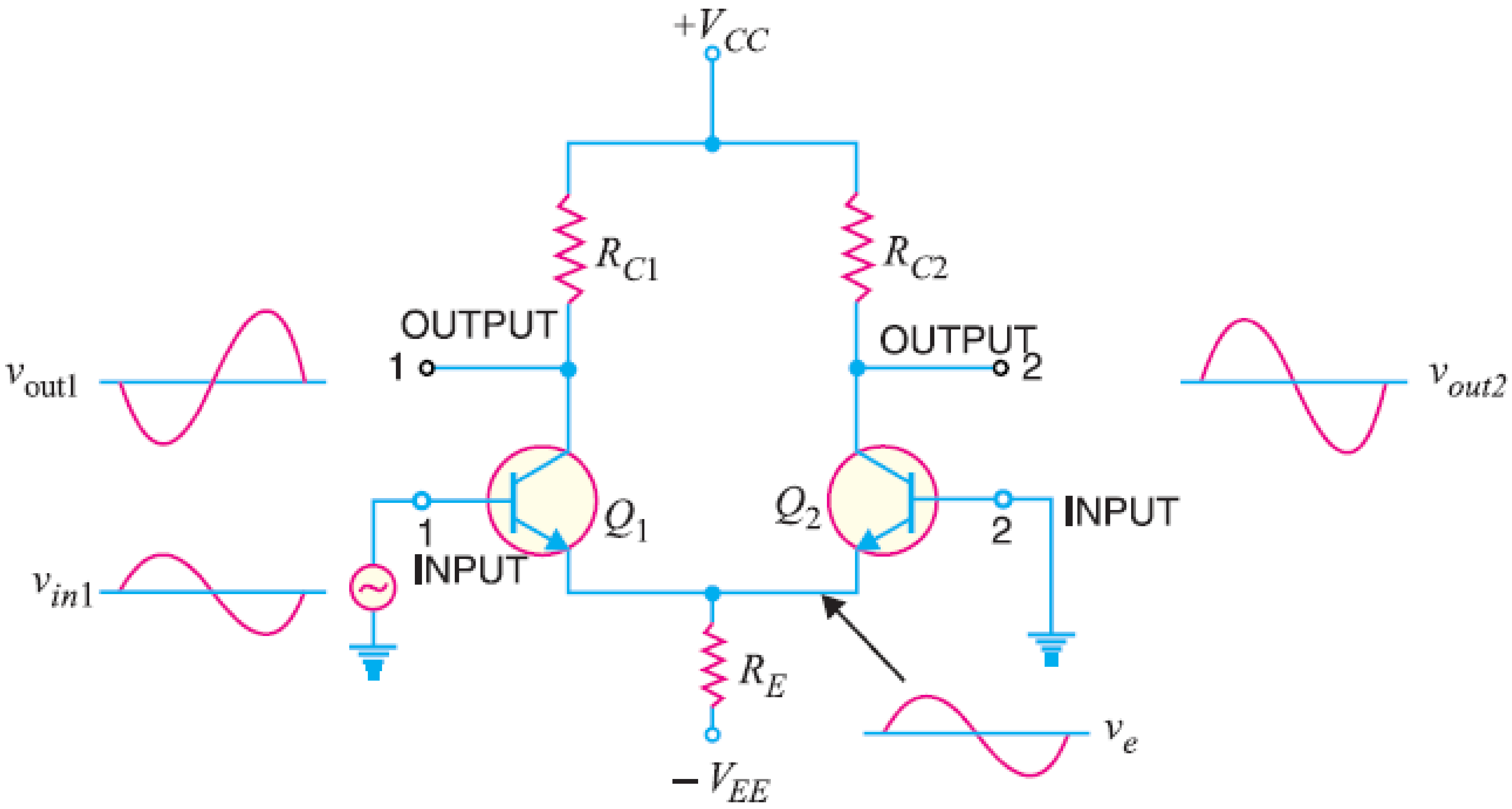


(i)

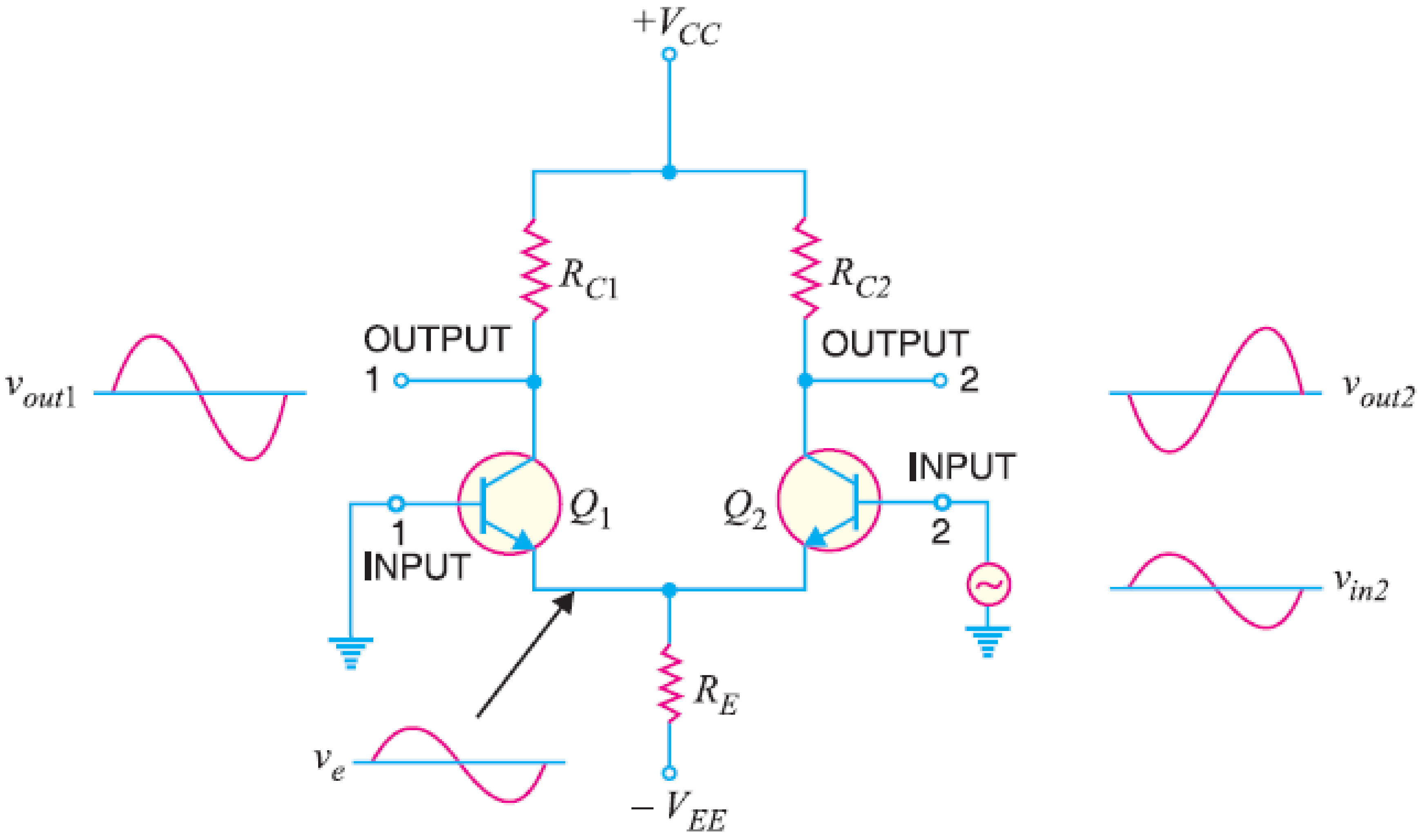


(ii)

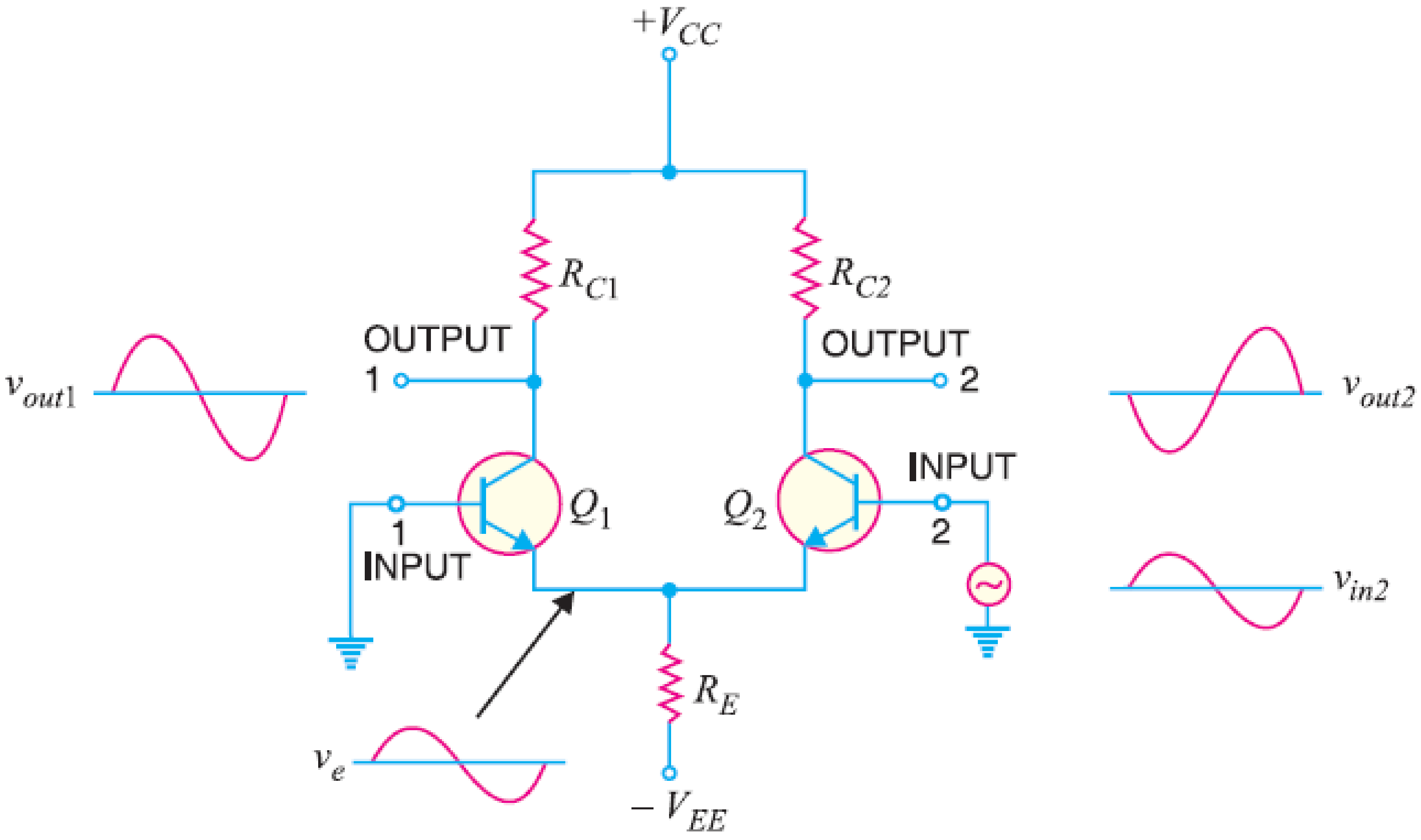
Operation of Differential Amplifier



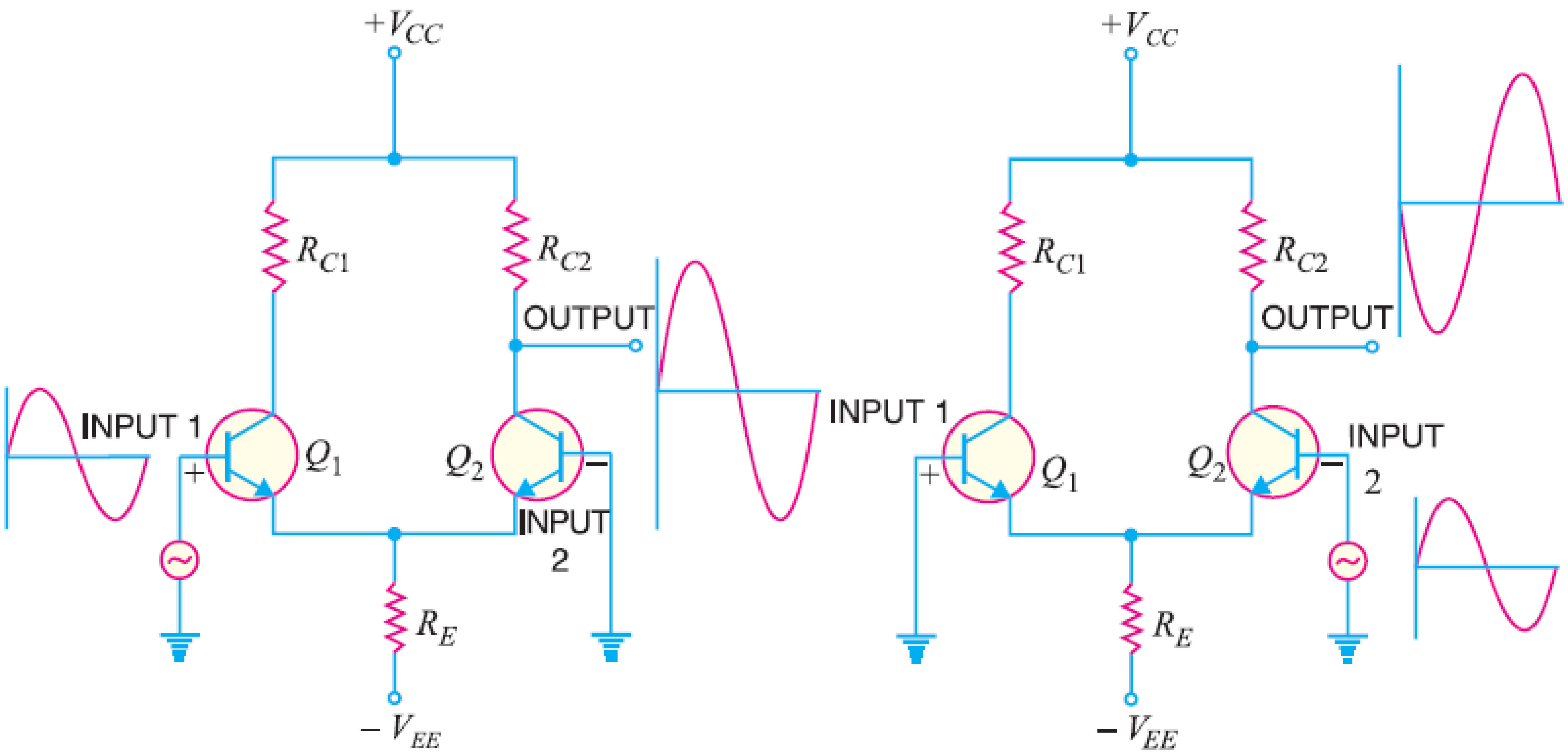
Operation of Differential Amplifier



Operation of Differential Amplifier



Operation of Differential Amplifier



(*i*) Noninverting input

(*ii*) Inverting input

Common-mode and Differential-mode Signals

The input signals to DA are defined as:

i. Common-mode signals
ii. Differential signals

i. Common-mode signals

- When the input signals to a *DA* are in phase and exactly equal in amplitude, they are called *common-mode signals.*
- The common-mode signals are rejected (not amplified) by the differential amplifier. It is because a differential amplifier amplifies the difference between the two signals ($v1 – v2$) and for common-mode signals, this difference is zero. Note that for common-mode operations, $v1 = v2$.

Common-mode and Differential-mode Signals

The input signals to DA are defined as:

i. Common-mode signals
ii. Differential signals

ii. Differential signals

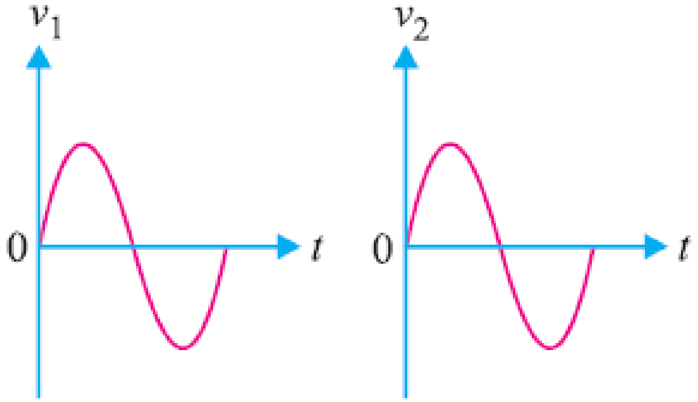
- When the input signals to a DA are 180° out of phase and exactly equal in amplitude, they are called differential-mode signals.
- The differential-mode signals are amplified by the differential amplifier. It is because the difference in the signals is twice the value of each signal. For differential-mode signals, $v1 = -v2$.

Common-mode and Differential-mode Signals

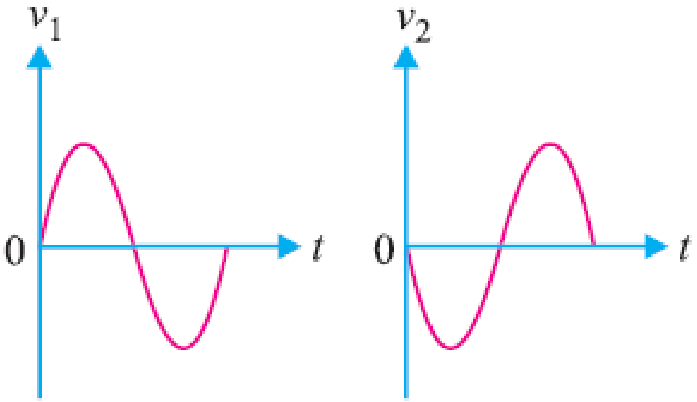
The input signals to DA are defined as:

i. Common-mode signals
ii. Differential signals

Thus we arrive at a very important conclusion that a differential amplifier will amplify the differential-mode signals while it will reject the common-mode signals.



Common-mode signals

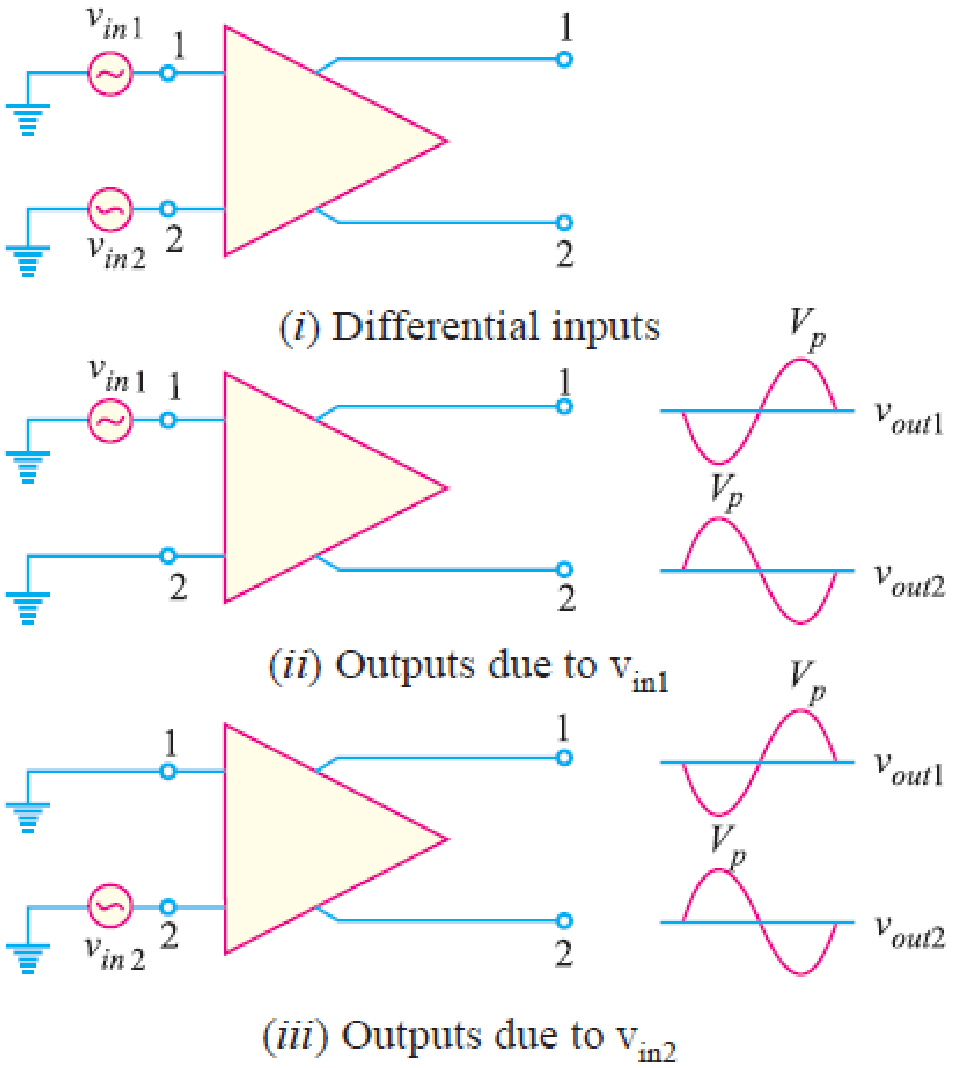


Differential-mode signals

Double-ended Input Operation of DA

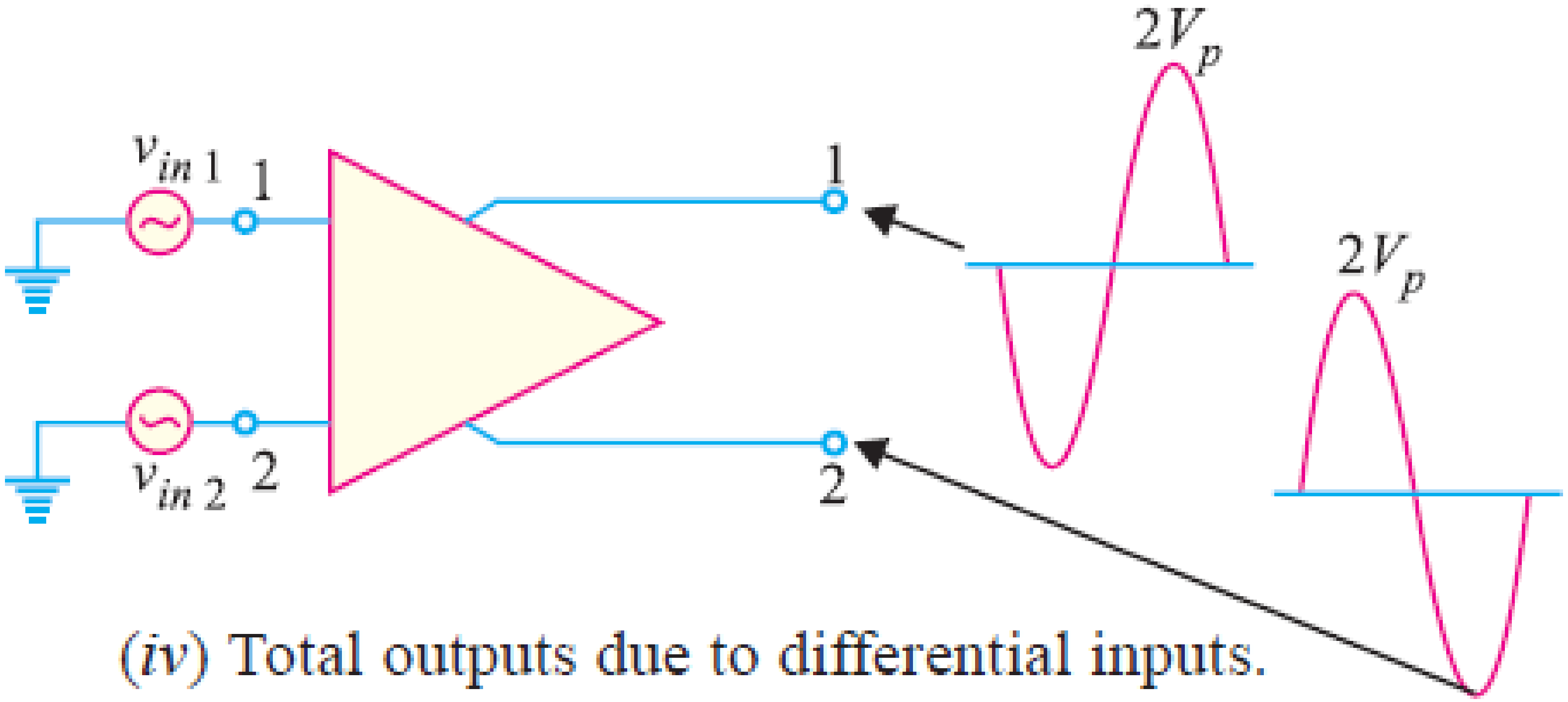
Differential Input

- In this mode (arrangement), two opposite-polarity (180° out of phase) signals are applied to the inputs of DA as shown in the figure.



Double-ended Input Operation of DA

Differential input

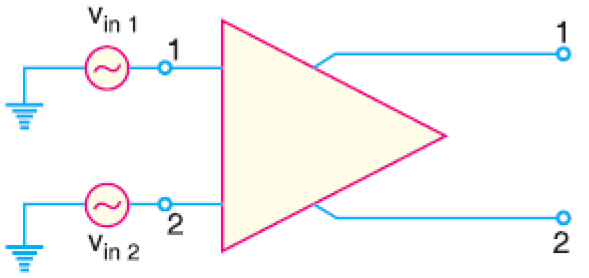


(*iv*) Total outputs due to differential inputs.

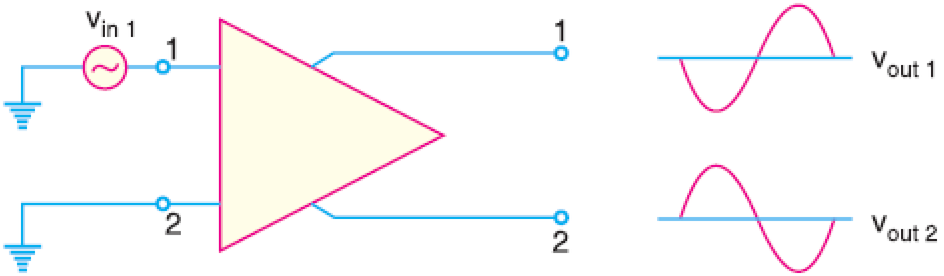
Double-ended Input Operation of DA

Common-mode Input

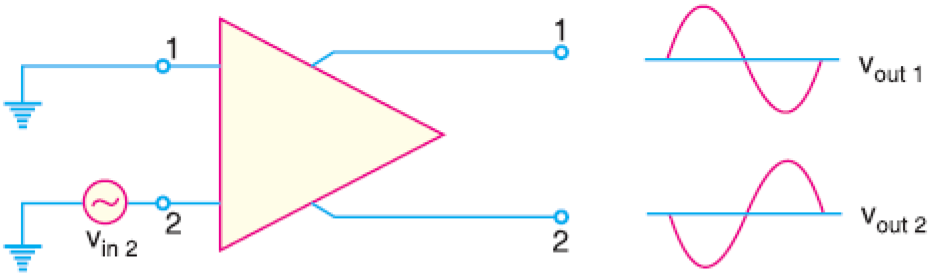
- In this mode, two signals equal in amplitude and having the same phase are applied to the inputs of DA as shown in the figure.



(*i*) Common-mode inputs



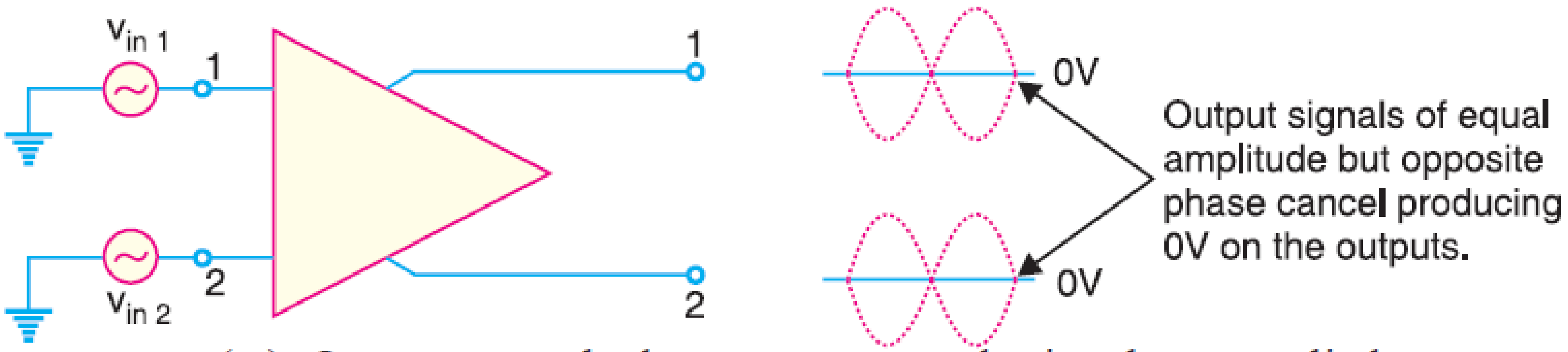
(*ii*) Outputs due to v_{in1}



(*iii*) Outputs due to v_{in2}

Double-ended Input Operation of DA

Common-mode Input



(iv) Outputs cancel when common-mode signals are applied.

Voltage Gains of DA

The voltage gain of a *DA* operating in differential mode is called *differential-mode voltage gain* and is denoted by A_{DM}.

The voltage gain of *DA* operating in common-mode is called *common-mode voltage gain* and is denoted by A_{CM}.

Ideally, a *DA* provides a very high voltage gain for differential-mode signals and zero gain for common-mode signals.

However, practically, differential amplifiers do exhibit a very small common-mode gain (usually much less than 1) while providing a high differential voltage gain (usually several thousands).

The higher the differential gain w.r.t. the common-mode gain, the better the performance of the *DA* in terms of rejection of common-mode signals.

Common-mode Rejection Ratio (CMRR)

A differential amplifier should have high differential voltage gain (*ADM*) and very low common-mode voltage gain (*ACM*).

The ratio *ADM*/*ACM* is called common-mode rejection ratio (*CMRR)*:

$$CMMR = \frac{A_{DM}}{A_{CM}}$$

Very often, the CMRR is expressed in decibels (dB):

$$CMMR_{dB} = 20\log\left(\frac{A_{DM}}{A_{CM}}\right) = 20\log(CMMR)$$

Importance of CMMR

CMRR is the ability of a DA to reject the common-mode signals.

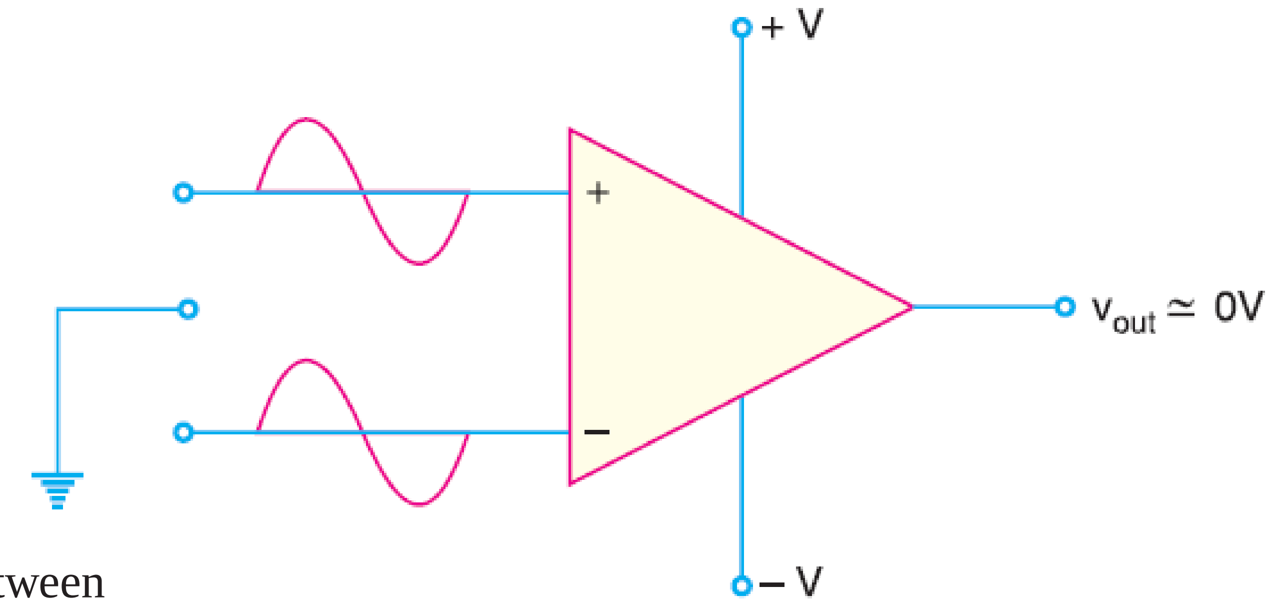
The larger the CMRR, the better the DA is at eliminating common-mode signals.

The ability of the *DA* to reject common-mode signals is one of its main advantages. Common-mode signals are usually *undesired signals* caused by external interference. For example, any *RF* signals picked up by the *DA* inputs would be considered undesirable.

The *CMRR* indicates the *DA*'s ability to reject such unwanted signals.

Example

2) Suppose the differential amplifier in Figure has a differential voltage gain of 1500 (i.e., ADM = 1500) and a common-mode gain of 0.01 (i.e., ACM = 0.01), determine the CMMR.



Ans.

CMMR = 150,000

This means that the output produced by a difference between the inputs would be 150,000 times as great as an output produced by a common-mode signal.

Example

3) A certain differential amplifier has a differential voltage gain of 2000 and a common mode gain of 0.2. Determine CMRR and express it in dB.

Ans.

$$\mathrm{CMMR}_{\mathrm{dB}} = 80\mathrm{dB}$$

Example

4) A differential amplifier has an output of 1V with a differential input of 10 mV and an output of 5 mV with a common-mode input of 10 mV. Find the CMRR in dB.

Ans.

$$\mathrm{CMMR_{dB}} \cong 46\mathrm{dB}$$

Example

5) A differential amplifier has a voltage gain of 150 and a CMRR of 90 dB. The input signals are 50 mV and 100 mV with 1 mV of noise on each input. Find *(i) the output signal (ii) the noise on the output.*

Ans.

$i)\ V_o = 7.5\ V$

$ii)\ Noise\ on\ output = 4.7\ \mu V$

D.C. Analysis of Differential Amplifier (DA)

The current through the emitter resistor R_E is called †**tail current.** For the circuit values considered in Fig.25.15, we have,

$$\text{Tail current, } I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{(15 - 0.7)\text{V}}{25\text{ k}\Omega} = \mathbf{0.572\ mA}$$

Because of the symmetry in the circuit, I_E must split equally between Q_1 and Q_2.

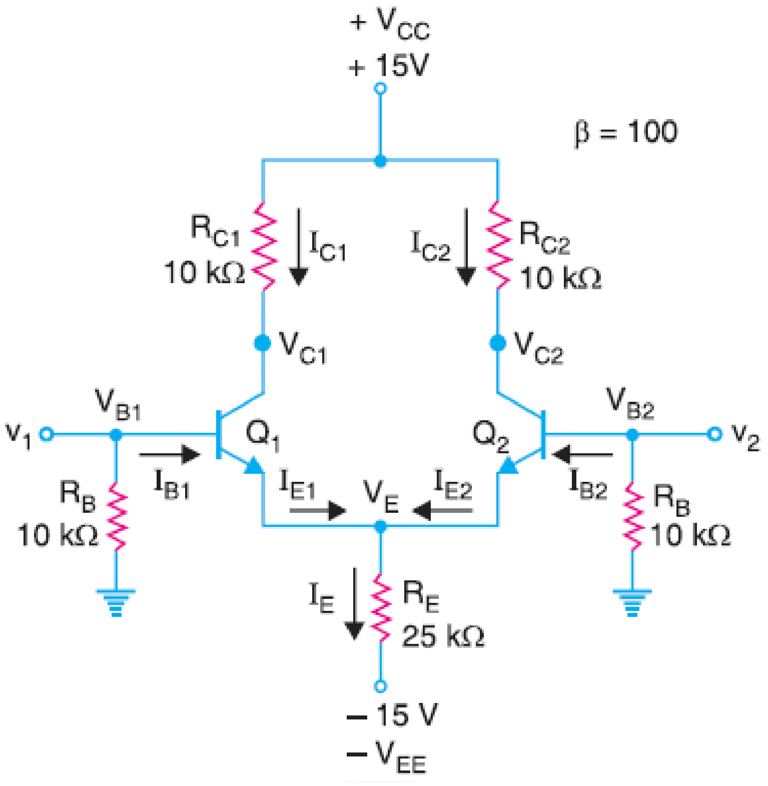
$$\therefore \quad I_{E1} = I_{E2} = \frac{I_E}{2} = \frac{0.572\text{ mA}}{2} = \mathbf{0.286\ mA}$$

Now $\quad I_{C1} \simeq I_{E1} = \mathbf{0.286\ mA}\ ;\ I_{C2} \simeq I_{E2} = \mathbf{0.286\ mA}$

Also $\quad I_{B1} = \frac{I_{C1}}{\beta} = \frac{0.286\text{ mA}}{100} = \mathbf{2.86\ \mu A}\ ;\ I_{B2} = \frac{I_{C2}}{\beta} = \mathbf{2.86\ \mu A}$

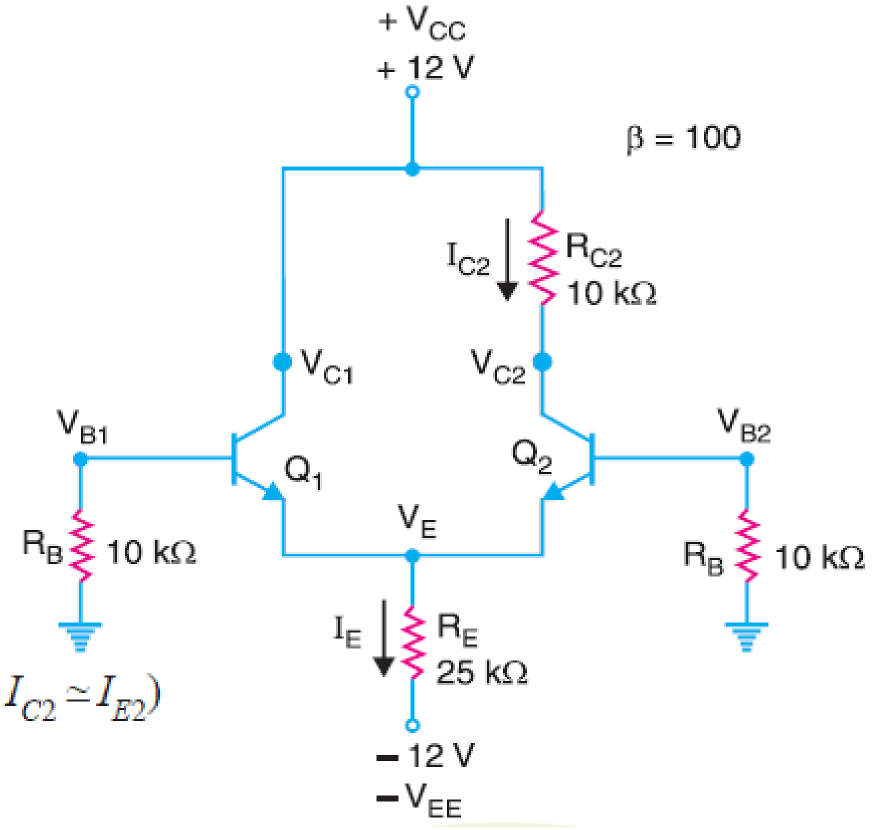
$$V_{C1} = V_{CC} - I_{C1} R_{C1} = 15\text{ V} - 0.286\text{ mA} \times 10\text{ k}\Omega = \mathbf{12.1\ V}$$

$$V_{C2} = V_{CC} - I_{C2} R_{C2} = 15\text{ V} - 0.286\text{ mA} \times 10\text{ k}\Omega = \mathbf{12.1\ V}$$



Example

Find the bias voltages and currents for the differential amplifier circuit shown in Figure.



Ignoring the base current, the emitter voltage for both transistors is $V_E = -\,0.7$ **V.**

Now, Tail current, $I_E = \dfrac{V_{EE} - V_{BE}}{R_E} = \dfrac{(12-0.7)V}{25\text{ k}\Omega} = \mathbf{0.452\ mA}$

$\therefore \quad I_{E1} = I_{E2} = I_E/2 = 0.452\text{ mA}/2 = \mathbf{0.226\ mA}$

Now, $I_{C1} = I_{C2} = \mathbf{0.226\ mA}$ $\quad (\because I_{C1} \simeq I_{E1} \text{ and } I_{C2} \simeq I_{E2})$

$\therefore \quad I_{B1} = I_{B2} = 0.226\text{ mA}/\beta = 0.226\text{ mA}/100 = \mathbf{2.26\ \mu A}$

$V_{C1} = V_{CC} = \mathbf{12V}\ ;\ V_{C2} = V_{CC} - I_{C2}R_{C2} = 12 - 0.226\text{ mA} \times 10\text{ k}\Omega = \mathbf{9.7V}$

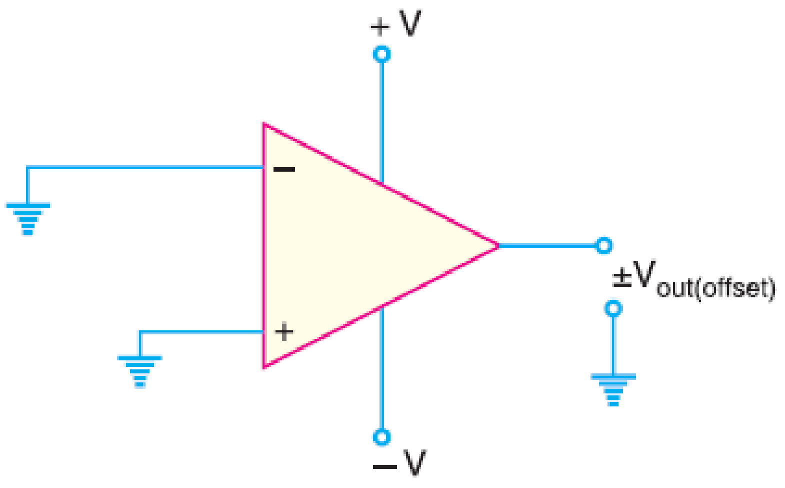
Parameters of DA (or OP–amp) due to Mismatch of Transistors

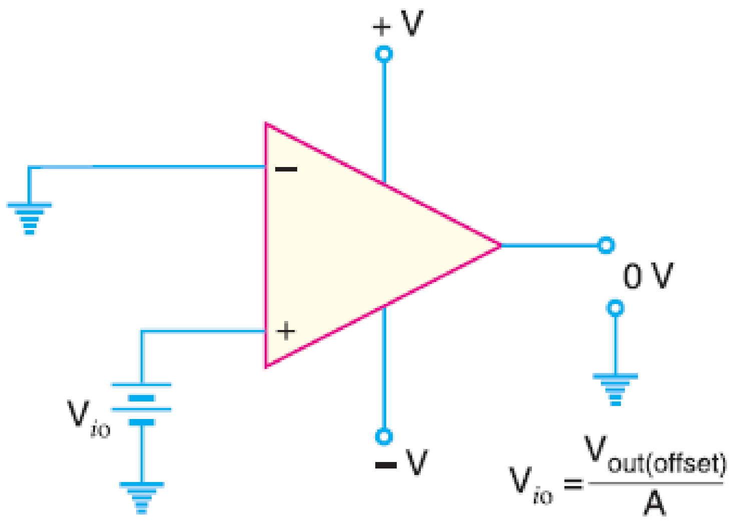
a) Output Offset Voltage ($V_{out(offset)}$)

- The output voltage present in an op-amp when there is no applied voltage in the input.

b) Input Offset Voltage (V_{os})

- The differential dc voltage required between the inputs to force the output voltage become zero.





Parameters of DA (or OP–amp) due to Mismatch of Transistors

c) Input Bias Current ($I_{in(bias)}$)

- The dc current required by the inputs of the amplifier to properly operate the first stage.
- It is the average of both the input currents.

$$I_{in(bias)} = \frac{I_1 + I_2}{2}$$

For example, if IB1 = 85 µA and IB2 = 75 µA, then the input bias current is

$$I_{in(bias)} = \frac{85\ \mu A + 75\ \mu A}{2} = 80\ \mu A$$

Parameters of DA (or OP–amp) due to Mismatch of Transistors

d) Input Offset Current ($\mathrm{I}_{\mathrm{in(offset)}}$)

- The difference of the input bias currents, expresses as an absolute value.

$$\mathrm{I}_{\mathrm{in(offset)}} = |\mathrm{I}_1 - \mathrm{I}_2|$$

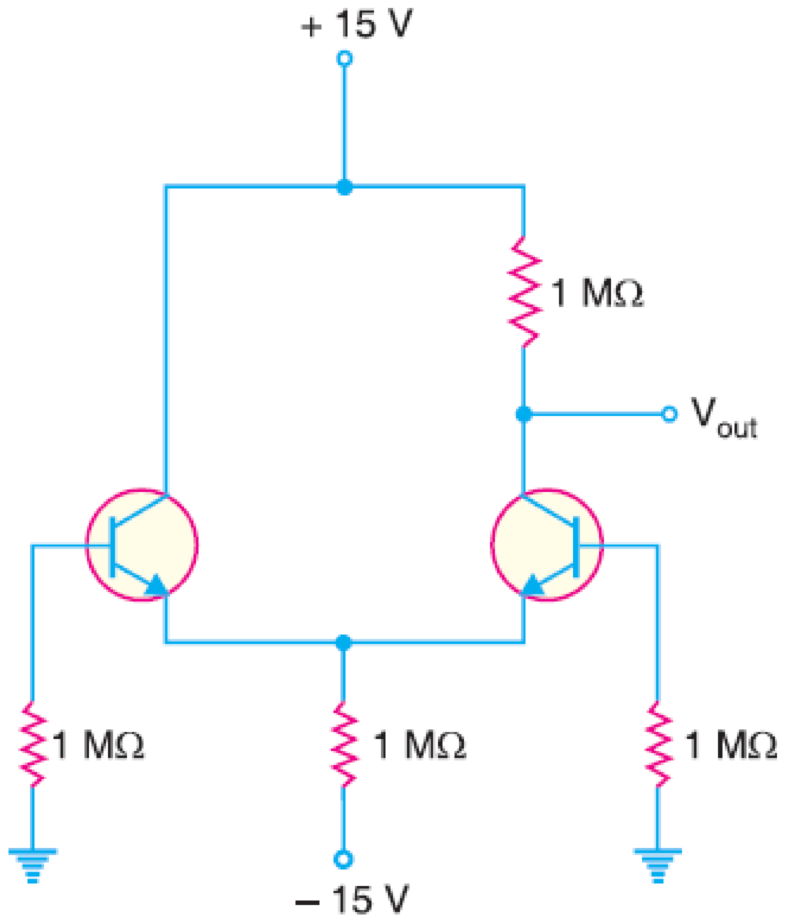
Example

In figure below, the left transistor has βdc = 90 and the right transistor has βdc = 110.

Find: (Neglect V_{BE})

(i) the input offset current

(ii) input bias current.



Ans.

(i) 15.1 nA

(ii) 75.8 nA

Example

The data sheet of an IC OP-amp gives these values : Iin(offset) = 20 nA and Iin(bias) = 80 nA. Find the values of two base currents.

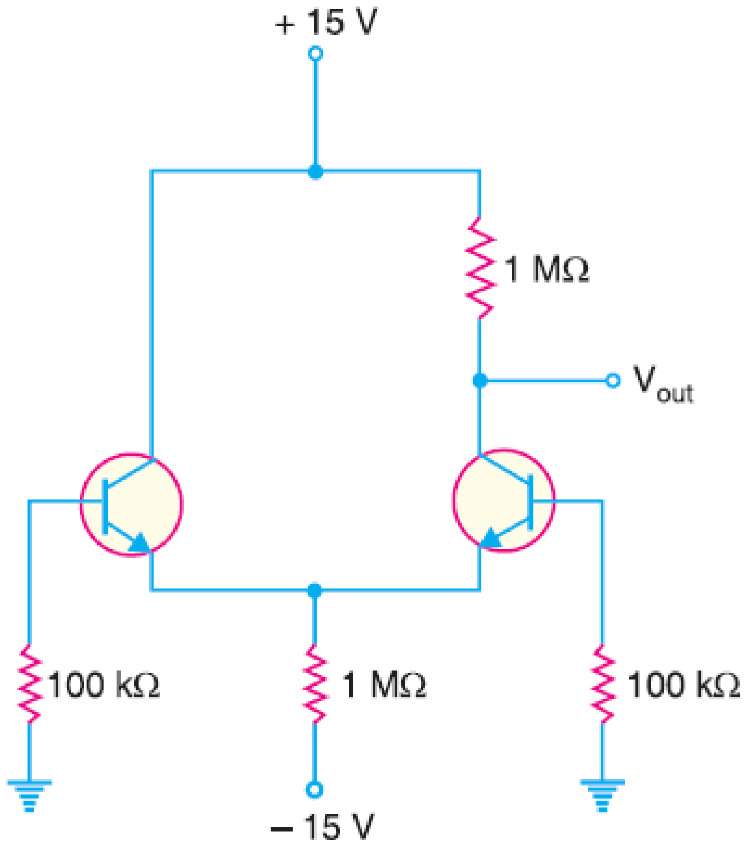
Ans.

I1 = 90 nA

I2 = 70 nA

Example

In figure below, what is the output offset voltage if Iin(bias) = 80 nA and Iin(offset) = 20 nA? Assume that voltage gain is A = 150. Assume only βdc differences exist.

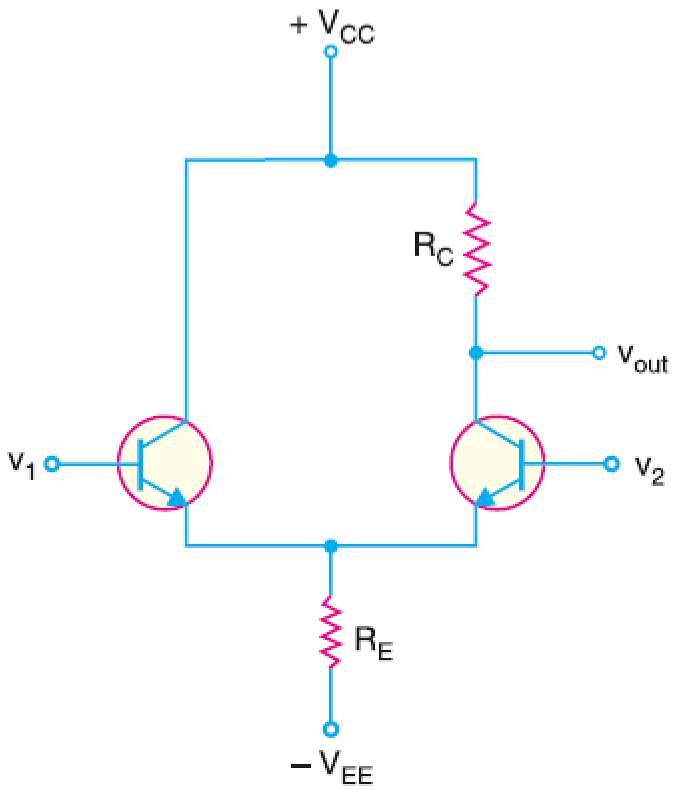


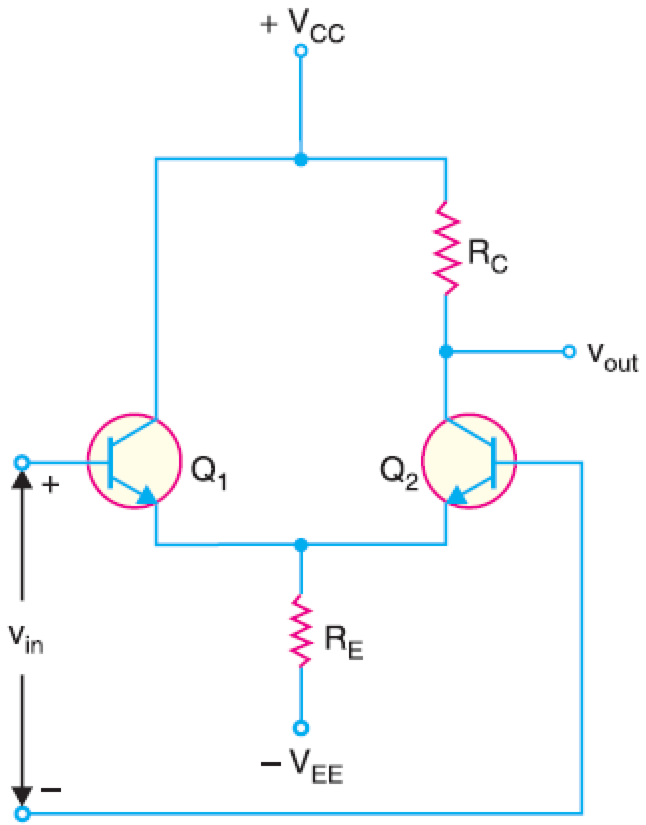
Ans.

0.3 V

A.C. Analysis of Differential Amplifier

- If you look at the differential amplifier circuit in the figure, it responds to the difference between the voltages at the two input terminals. In other words, *DA* responds to *vin* (= *v*1 – *v*2).





A.C. Equivalent Circuit

- AC emitter current (i_e):

$$i_e = \frac{V_{in}}{2r'_e}$$

- Output Voltage (V_{out}):

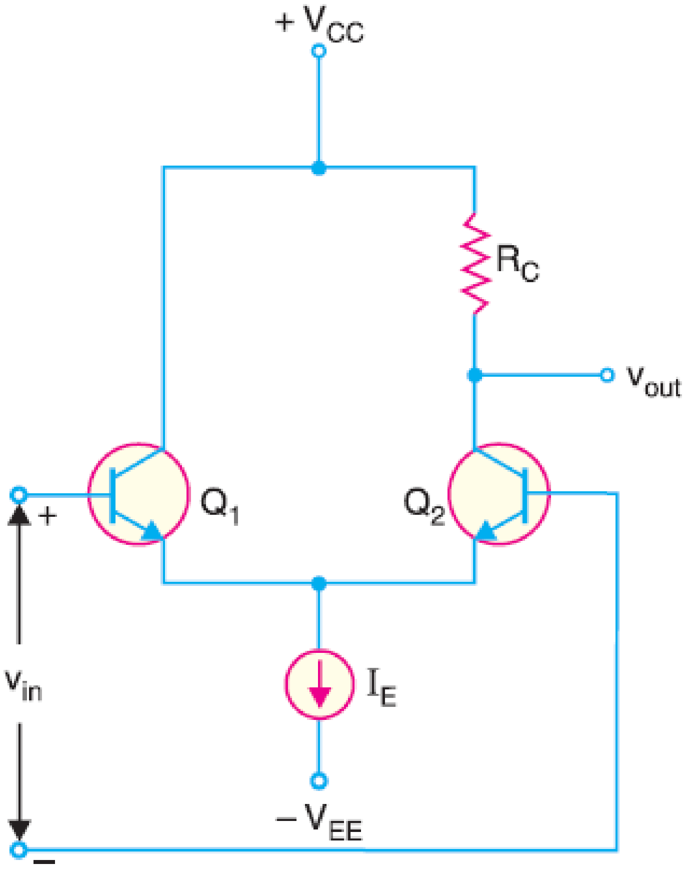
$$V_{out} = i_C R_C = \frac{V_{in}}{2r'_e} R_C$$

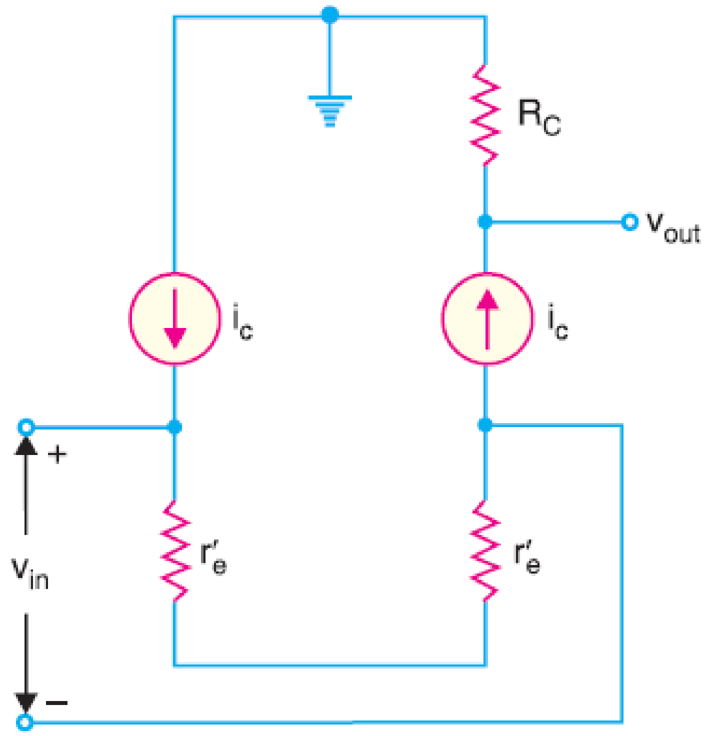
- Voltage Gain (A):

$$A = \frac{V_{out}}{V_{in}} = \frac{R_C}{2r'_e}$$

- Input Impedance (Z_i):

$$Z_i = \frac{V_{in}}{I_b} = 2\beta r'_e$$





Gain **A** is referred to as differential-mode voltage gain and is usually denoted by A_{DM}.

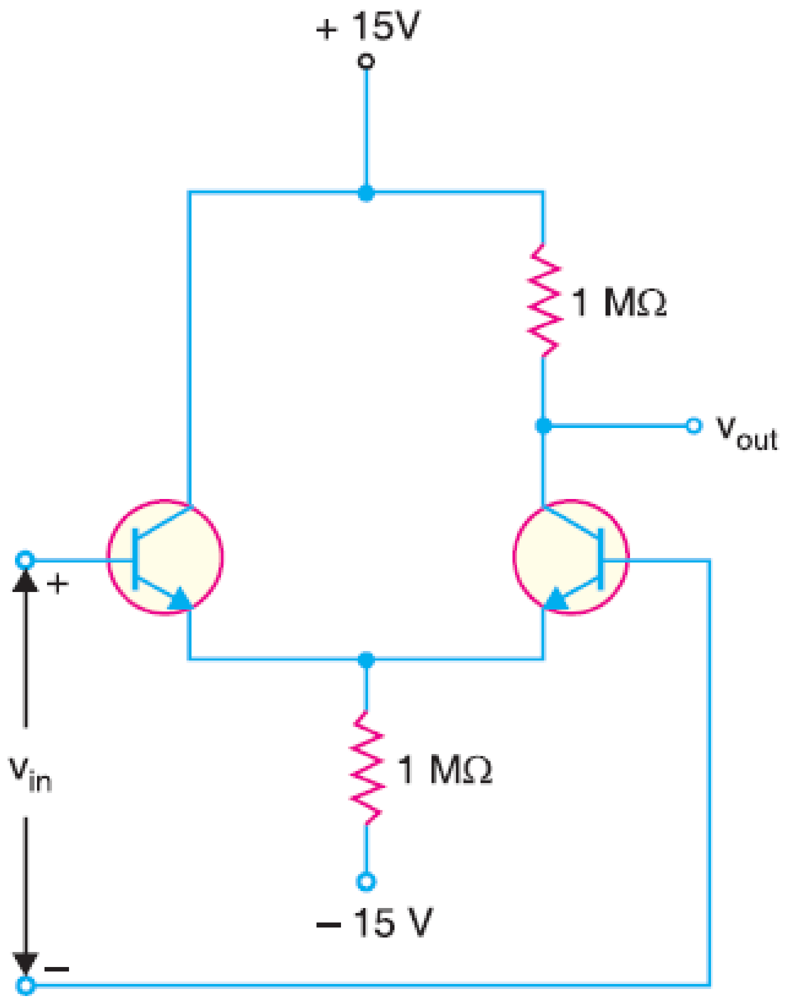
$$i_e = \frac{v_{in}}{2r'_e} \simeq \beta\, i_b \qquad (\because\ i_c = \beta i_b \simeq i_e)$$

Example

What is Vout in figure when

(i) Vin = 1mV

(ii) Vin = –1mV



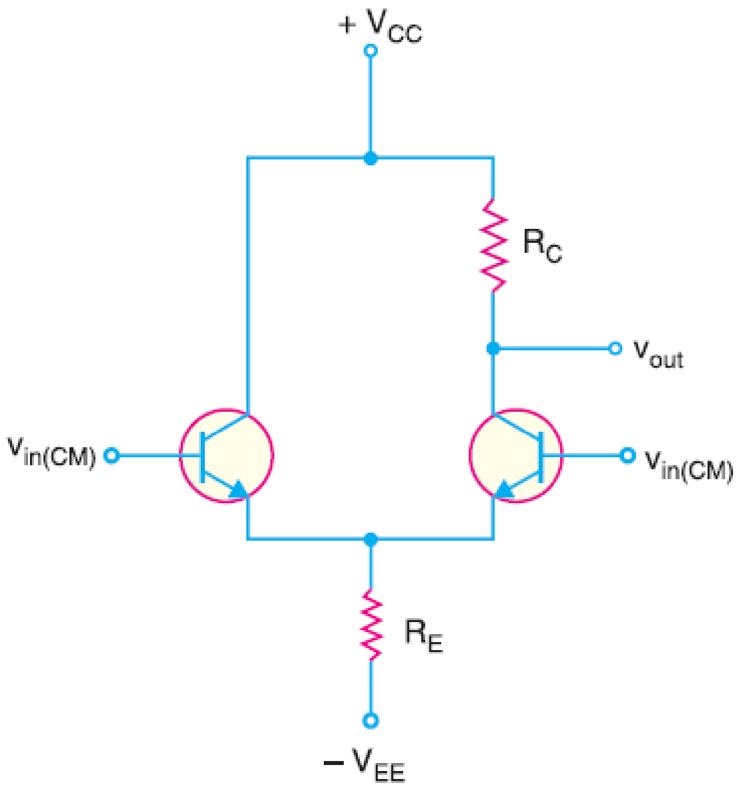
Ans.

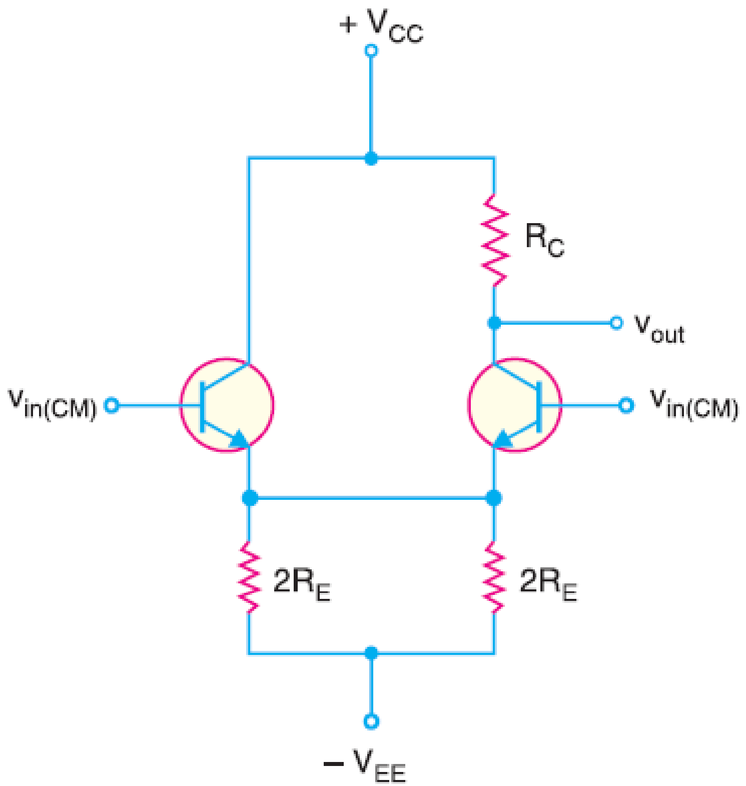
(i) 0.15 V

(ii) -0.15 V

Common-mode Voltage Gain ($\mathbf{A_{CM}}$)

- The common-mode signals are equal in amplitude and have the same phase.
- Ideally, there is no a.c. output voltage with a common-mode input signal.
- In practice, the two halves of the differential amplifier are never completely balanced and there is a very small a.c. output voltage for the common-mode signal.

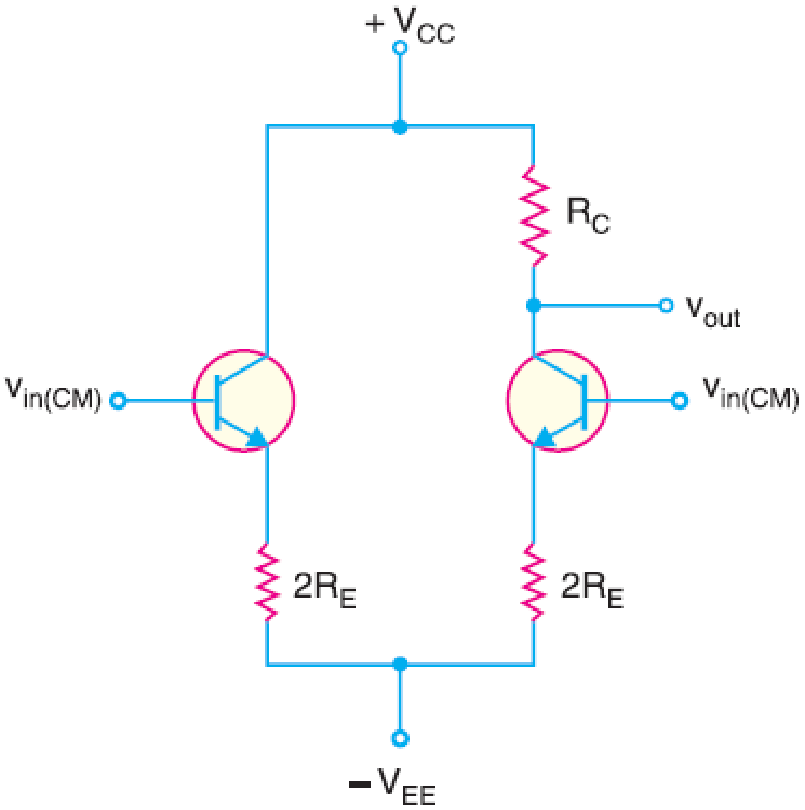


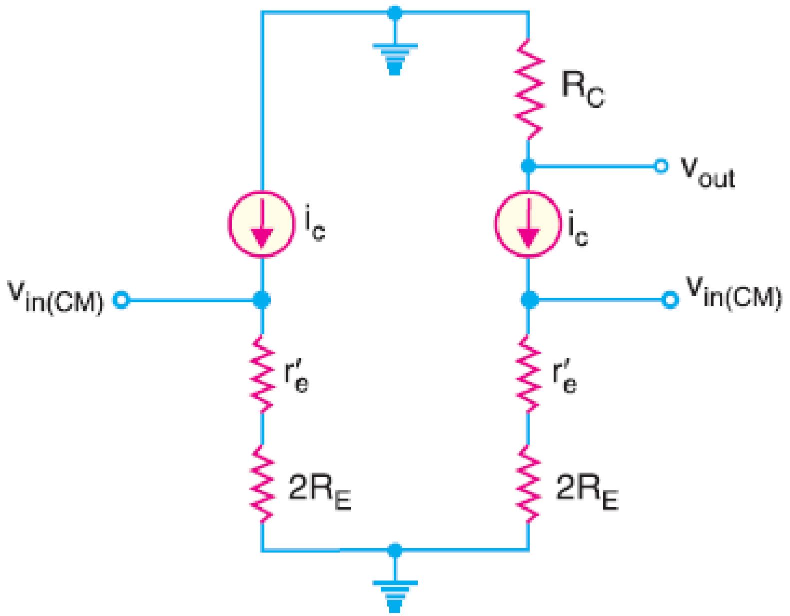


Common-mode Voltage Gain ($\mathbf{A_{CM}}$)

- Common-mode Voltage Gain (A_{CM}):

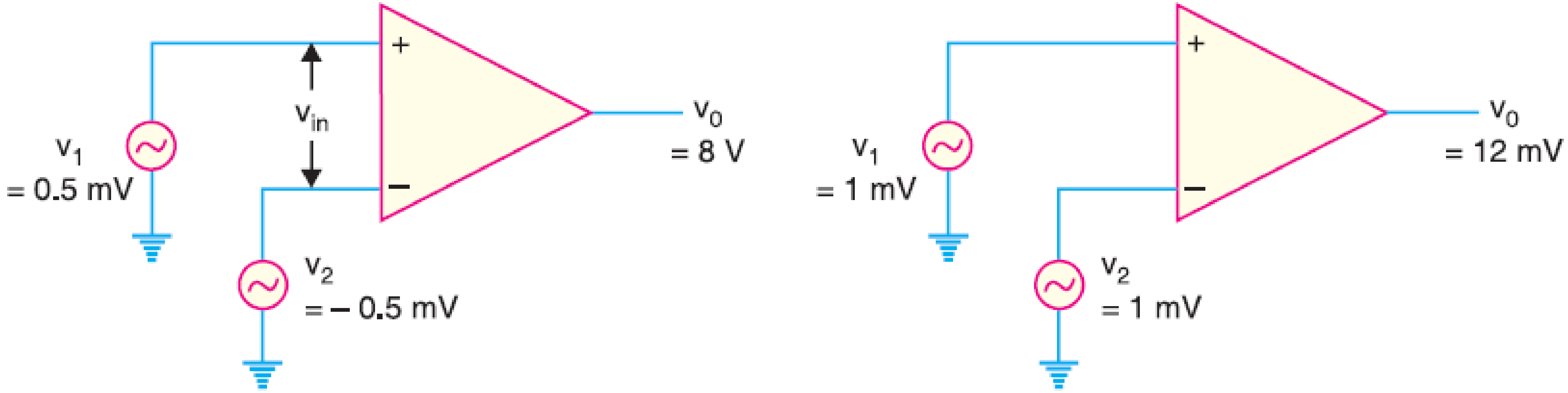
$$A_{CM} = \frac{V_{out}}{V_{in}} = \frac{R_C}{r'_e + 2R_E} \cong \frac{R_C}{2R_E}$$





Example

Calculate the CMRR for the circuit measurements shown in the figure.



Ans.

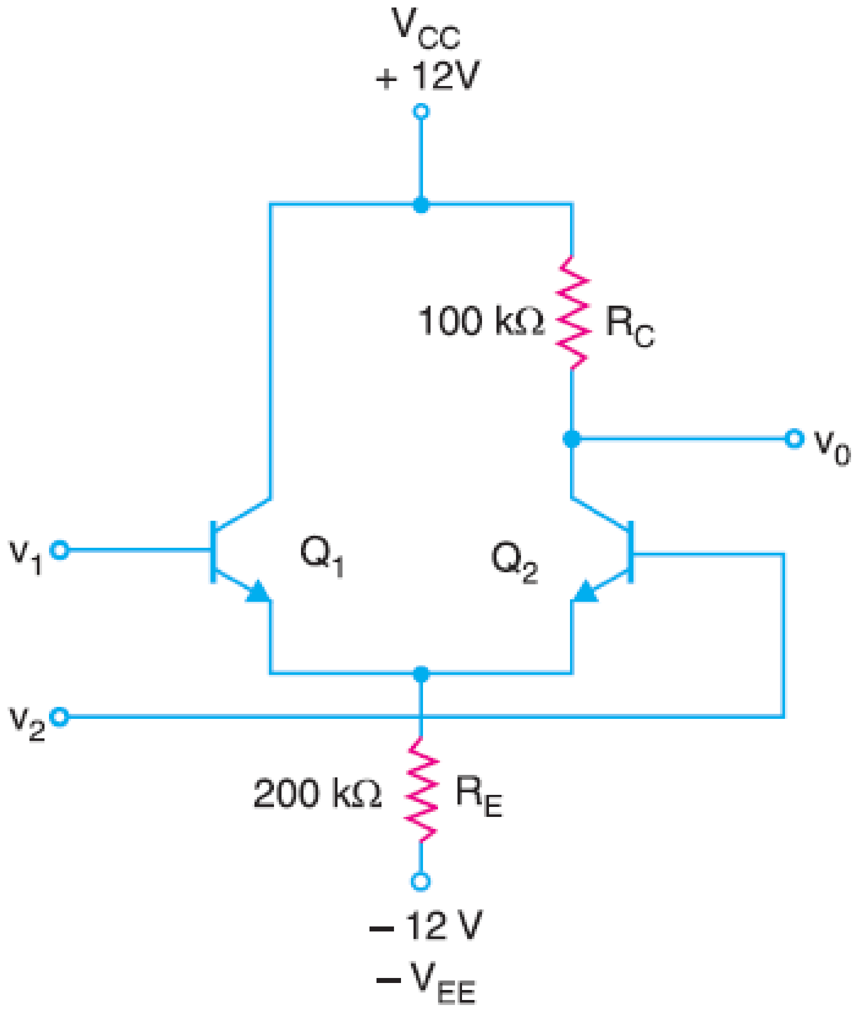
CMRR = 666.7 or 56.48 dB

Example

For the circuit shown in Fig. 25.37, find

(i) The common-mode voltage gain

(ii) The CMRR in dB



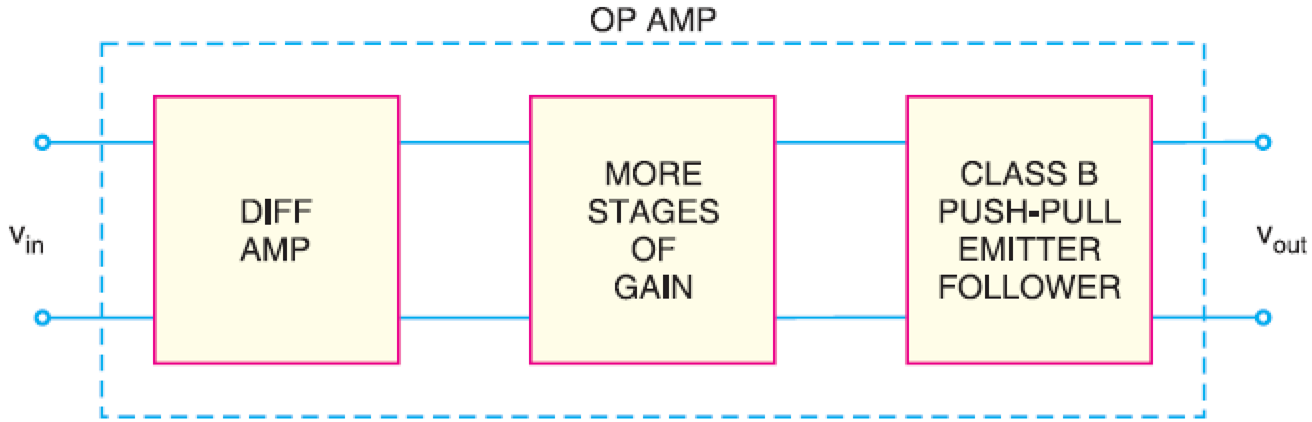
Ans.

(i) 0.25 V

(ii) 47.09 dB

Operational Amplifier (OP- Amp)

- The figure shows the block diagram of an operational amplifier (OP-amp).
- The input stage of an OP- amp is a differential stage followed by more stages of gain and a class B push-pull emitter follower.



Operational Amplifier (OP- Amp)

The following are the important properties common to all operational amplifiers (*OP*-amps):

- An operational amplifier is a multistage amplifier. The input stage of an *OP*-amp is a differential amplifier stage.
- An inverting input and a noninverting input.
- A high input impedance (usually assumed infinite) at both inputs.
- A low output impedance (< 200 Ω).
- A large open-loop voltage gain, typically 105.
- The voltage gain remains constant over a wide frequency range.
- Very large *CMRR* (> 90 dB).

Output Voltage From OP-Amp

The output voltage from an *OP*-amp for a given pair of input voltages depends mainly on the following factors:

1. The voltage gain of *OP*-amp.
2. The polarity relationship between $v1$ and $v2$.
3. The values of supply voltages, $+V$ and $–V$.

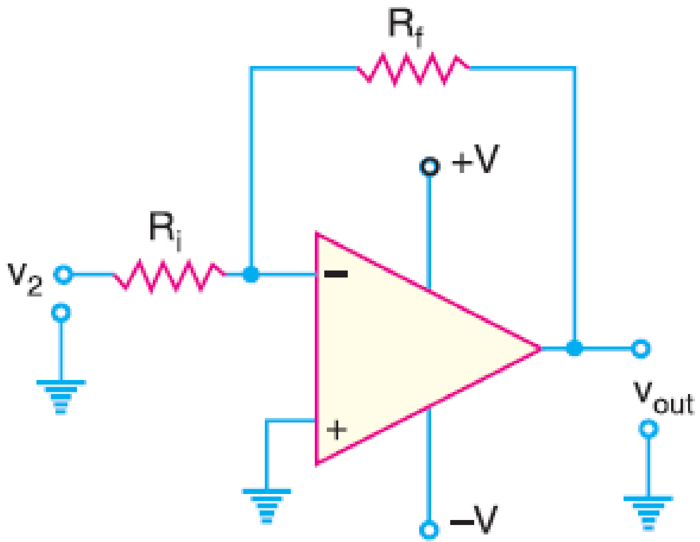
The voltage gain of *OP*-amp

1. Voltage gain of OP-amp

- The *maximum* possible voltage gain from a given OP-amp is called *open-loop voltage gain* and is denoted by the symbol A_{OL}. The value of A_{OL} for an *OP*-amp is generally greater than 10,000.
- When a feedback path is present such as *Rf* connection in the figure, the resulting circuit gain is referred to as *closed-loop voltage gain* (A_{CL}).

The following points may be noted :

(*i*) The maximum voltage gain of given OP-amp is A_{OL}. Its value is generally greater than 10,000.
(*ii*) The actual gain (A_{CL}) of an OP-amplifier is reduced when negative feedback path exists between output and input.



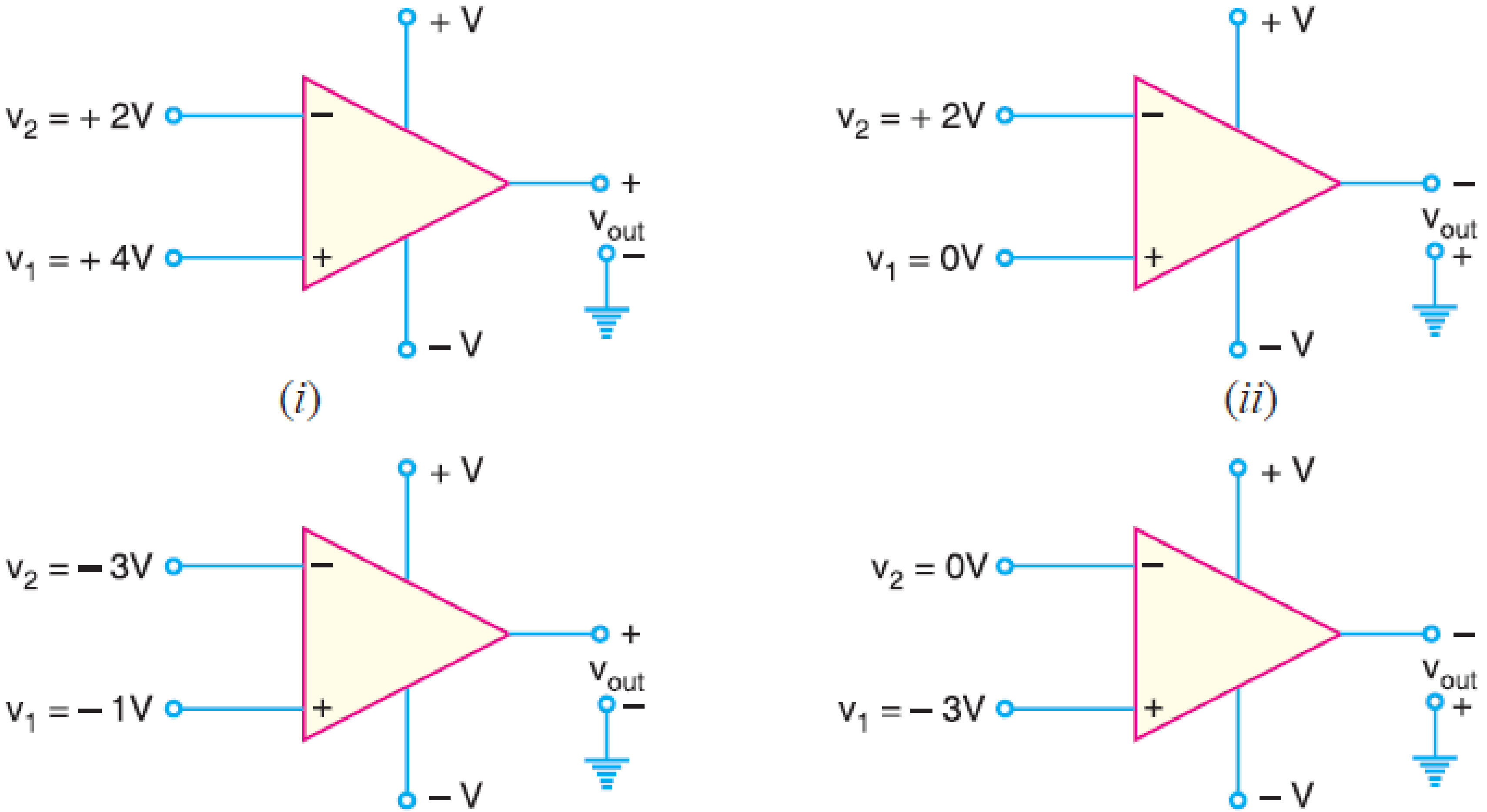
The voltage gain of *OP*-amp

2. OP-Amp Input/Output Polarity Relationship

- We know the differential input voltage v_{in} is the difference between the non-inverting input (V_1) and inverting input (V_2) *i.e.*, $V_{in} = V_1 - V_2$
- When the result of this equation is *positive*, the OP-amp output voltage will be *positive*. When the result of this equation is *negative*, the output voltage will be *negative*.

Example

Determine the polarity of the output voltage for:



Ans.

i. P

ii. N

iii. P

iv. N

The voltage gain of *OP*-amp

3. OP-Amp Input/Output Polarity Relationship

The supply voltages for an *OP*-amp are normally equal in magnitude and opposite in sign *e.g.*, ± 15V, ± 12V, ± 18*V*. These supply voltages determine the limits of output voltage of *OP*-amp. These limits, known as *saturation voltages,* are generally given by;

$$+V_{sat} = +V_{supply} - 2V$$

$$-V_{sat} = -V_{supply} + 2V$$

Suppose an *OP*-amplifier has $V_{supply} = \pm 15V$ and open-loop voltage gain $A_{OL} = 20{,}000$. Let us find the differential voltage v_{in} to avoid saturation.

$$V_{sat} = V_{supply} - 2 = 15 - 2 = 13V$$

$$\therefore \quad V_{in} = \frac{V_{sat}}{A_{OL}} = \frac{13V}{20{,}000} = 650\ \mu\text{V}$$

If the differential input voltage V_{in} exceeds this value in an *OP*-amp, it will be driven into saturation and the device will become non-linear.

The voltage gain of *OP*-amp

3. OP-Amp Input/Output Polarity Relationship

Note : Although input terminals of an *OP*-amp are labeled as + and –, this does not mean you have to apply positive voltages to the + terminal and negative voltages to the –terminal. Any voltages can be applied to either terminal. The true meaning of the input terminal labels (+ and –) is that a *positive voltage applied to the + terminal drives the output voltage towards +V of d.c. supply; a positive voltage applied to the – terminal drives the output voltage towards –V of d.c. supply.

Bandwidth of an OP-Amp

All electronic devices work only over a limited range of frequencies. This range of frequencies is called **bandwidth.** Every *OP*-amp has a bandwidth *i.e.*, the range of frequencies over which it will work properly. The bandwidth of an *OP*-amp depends upon the closed-loop gain of the *OP*-amp circuit. One important parameter is **gain-bandwidth product (GBW).** It is defined as under :

$$A_{CL} \times f_2 = f_{unity} = \text{GBW}$$

where

A_{CL} = closed-loop gain at frequency f_2

f_{unity} = frequency at which the closed-loop gain is unity

It can be proved that the gain-bandwidth product of an OP-amp is constant. Since an *OP*-amp is capable of operating as a d.c. amplifier, its bandwidth is $(f_2 - 0)$. The gain-bandwidth product of an OP-amp is an important parameter because it can be used to find :

Example

An OP-amp has a gain-bandwidth product of 15 MHz.

i. Determine thebandwidth of OP-amp when ACL = 500.

ii. Also find the maximum value of ACL when f2 = 200 kHz.

$$f_2 = \frac{f_{unity}}{A_{CL}} = \frac{15\text{MHz}}{500} = 30\text{ kHz}$$

Since the *OP*-amp is capable of operating as a d.c. amplifier, bandwidth BW = **30 kHz**

$$A_{CL} = \frac{f_{unity}}{f_2} = \frac{15\text{MHz}}{200\text{ kHz}} = \mathbf{75 \text{ or } 37.5 \text{ db}}$$

Example

An OP-amp has a gain-bandwidth product of 1.5 MHz. Find the operating bandwidth for the following closed-loop gains

(i) ACL = 1

(ii) ACL = 10

(iii) ACL = 100

$$\text{For } A_{CL} = 1,\ BW = \frac{1.5\ \text{MHz}}{1} = \mathbf{1.5\ MHz}$$

$$\text{For } A_{CL} = 10,\ BW = \frac{1.5\ \text{MHz}}{10} = \mathbf{150\ kHz}$$

$$\text{For } A_{CL} = 100,\ BW = \frac{1.5\ \text{MHz}}{100} = \mathbf{15\ kHz}$$

Slew Rate

- A measure of *how fast the output voltage can change* and is measured in volts per microsecond (V/µs).
- If the slew rate of an *OP*-amp is 0.5V/µs, it means that the output from the amplifier can change by 0.5 V every µs.

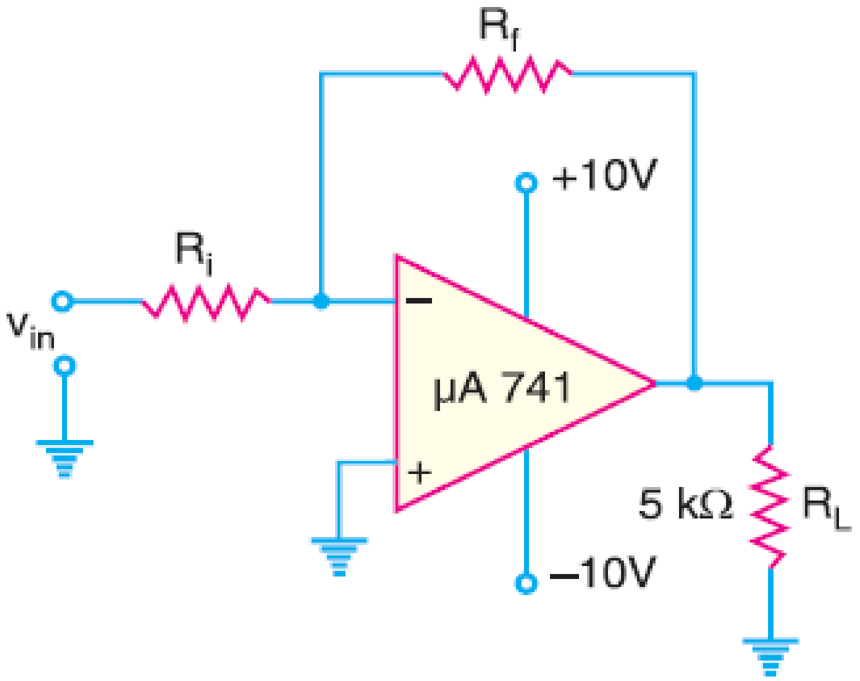
- Since frequency is a function of time, the *slew rate can be used to determine the maximum operating frequency of the OP-amp* as follows:

$$\text{Maximum operating frequency, } f_{max} = \frac{\text{Slew rate}}{2\pi \, V_{pk}}$$

Here V_{pk} is the peak output voltage.

Example

Determine the maximum operating frequency for the circuit shown in in the figure. The slew rate is 0.5 V/μs.

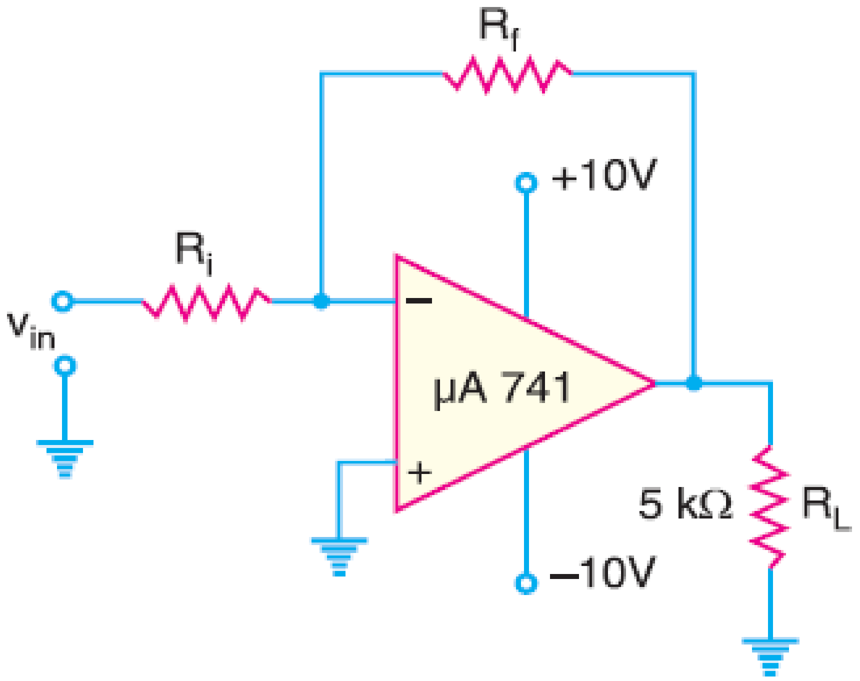


Ans.

9.95 kHz

Example

The amplifier in the figure is being used to amplify an input signal to a peak output voltage of 100 mV. What is the maximum operating frequency of the amplifier?



Ans.

796 kHz

Frequency Response of an OP-Amp

The operating frequency has a significant effect on the operation of an *OP*-amp. The following are the important points regarding the frequency response of an *OP*-amp :

(*i*) The maximum operating frequency of an *OP*-amp is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi V_{pk}}$$

Thus, the *peak output voltage limits the maximum operating frequency.*

(*ii*) When the maximum operating frequency of an *OP*-amp is exceeded, the result is a distorted output waveform.

(*iii*) Increasing the operating frequency of an *OP*-amp beyond a certain point will :

(*a*) Decrease the maximum output voltage swing.

(*b*) Decrease the open-loop voltage gain.

(*c*) Decrease the input impedance.

(*d*) Increase the output impedance.

OP-Amp with Negative Feedback

- With negative feedback, the voltage gain (A_{CL}) can be reduced and controlled so that OP-amp can function as a linear amplifier.
- In addition to providing a controlled and stable gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth.

The table below shows the general effects of negative feedback on the performance of OP-amps:

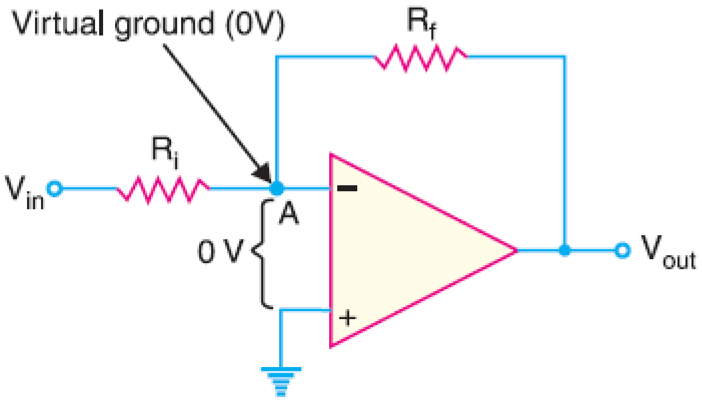
	Voltage gain	Input Z	Output Z	Bandwidth
Without negative feedback	A_{OL} is too high for linear amplifier applications	Relatively high	Relatively low	Relatively narrow
With negative feedback	A_{CL} is set by the feedback circuit to desired value	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

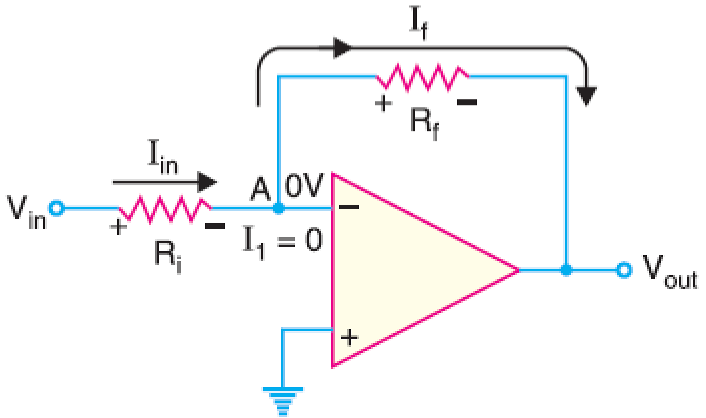
Applications of OP-Amps

Applications of OP-Amps

- The operational amplifiers have many practical applications.
- The *OP*-amp can be connected in a large number of circuits to provide various operating characteristics.

Inverting Op-amp





Now $$I_{in} = \frac{\text{Voltage across } R_i}{R_i} = \frac{V_{in} - V_A}{R_i} = \frac{V_{in} - 0}{R_i} = \frac{V_{in}}{R_i}$$

and $$I_f = \frac{\text{Voltage across } R_f}{R_f} = \frac{V_A - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$, $$-\frac{V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

$\therefore$ Voltage gain, $$A_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

Inverting Op-amp

The negative sign indicates that output signal is inverted as compared to the input signal. The following points may be noted about the inverting amplifier :

(*i*) The closed-loop voltage gain (A_{CL}) of an inverting amplifier is the ratio of the feedback resistance R_f to the input resistance R_i. *The closed-loop voltage gain is independent of the OP-amp's internal open-loop voltage gain.* Thus the negative feedback stabilises the voltage gain.

(*ii*) The inverting amplifier can be designed for unity gain. Thus if $R_f = R_i$, then voltage gain, $A_{CL} = -1$. Therefore, the circuit provides a unity voltage gain with 180° phase inversion.

(*iii*) If R_f is some multiple of R_i, the amplifier gain is constant. For example, if $R_f = 10\ R_i$, then $A_{CL} = -10$ and the circuit provides a voltage gain of exactly 10 along with a 180° phase inversion from the input signal. If we select precise resistor values for R_f and R_i, we can obtain a wide range of voltage gains. *Thus the inverting amplifier provides constant voltage gain.*

Input and Output Impedance of Inverting Amplifier

- Input Impedance (Z'_{in})

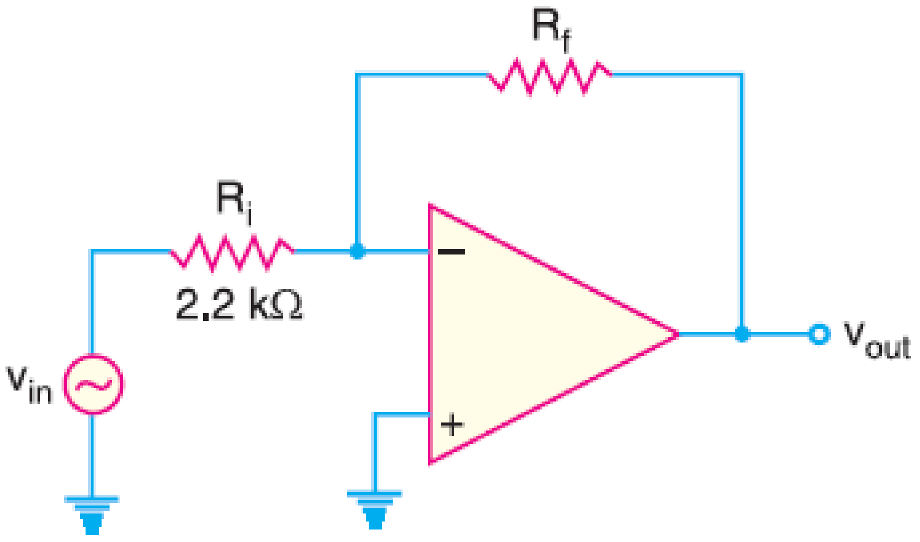
$$Z'_{in} \cong R_{in}$$

- Output Impedance (Z'_{out})

$$Z'_{out} = Z_{out} \parallel R_f$$

Example

Given the OP-amp configuration in the figure below, determine the value of Rf required to produce a closed-loop voltage gain of –100.

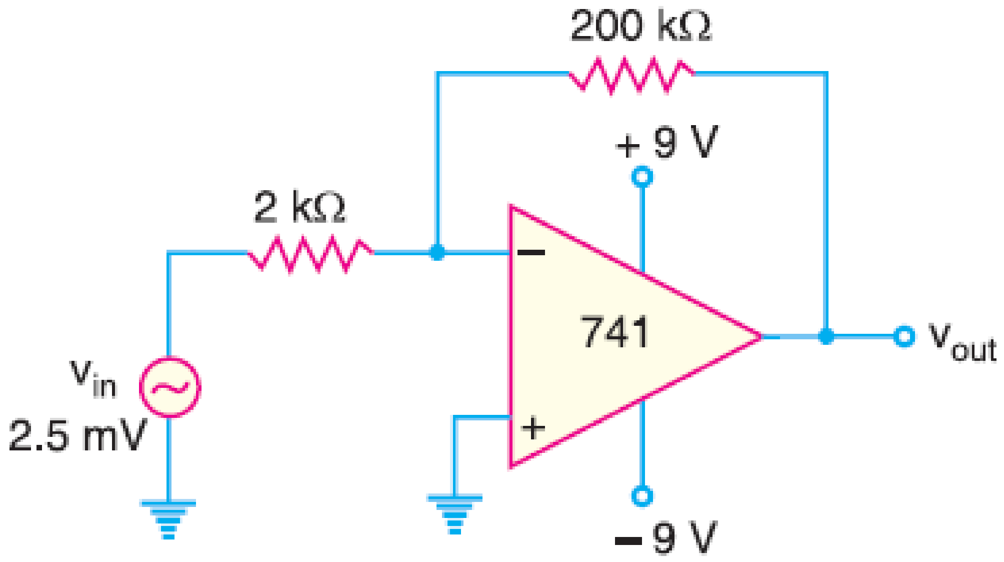


Ans.

$$R_f = 220\ \text{k}\Omega$$

Example

Determine the output voltage for the circuit.

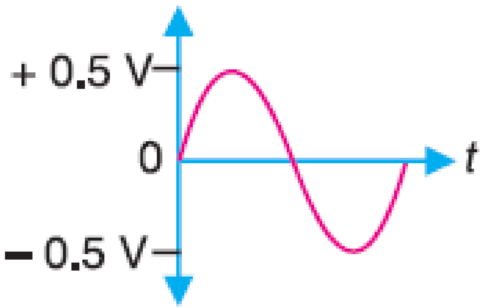


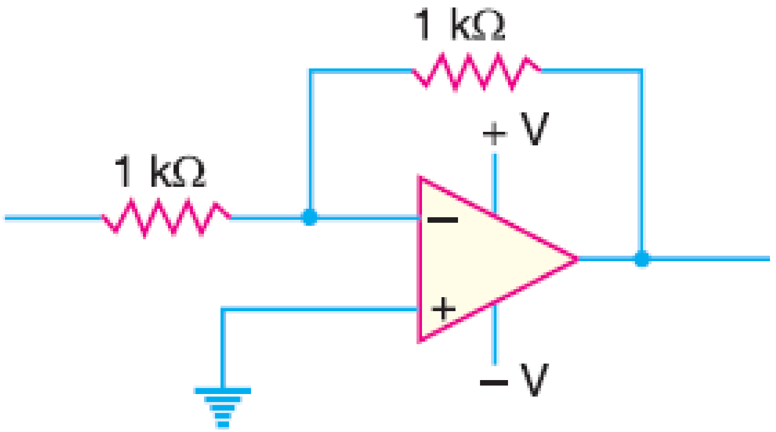
Ans.

$$V_{out} = -0.25 \text{ V}$$

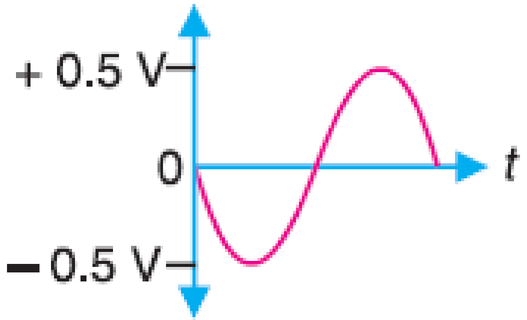
Example

Find the output voltage waveform for the circuit show.



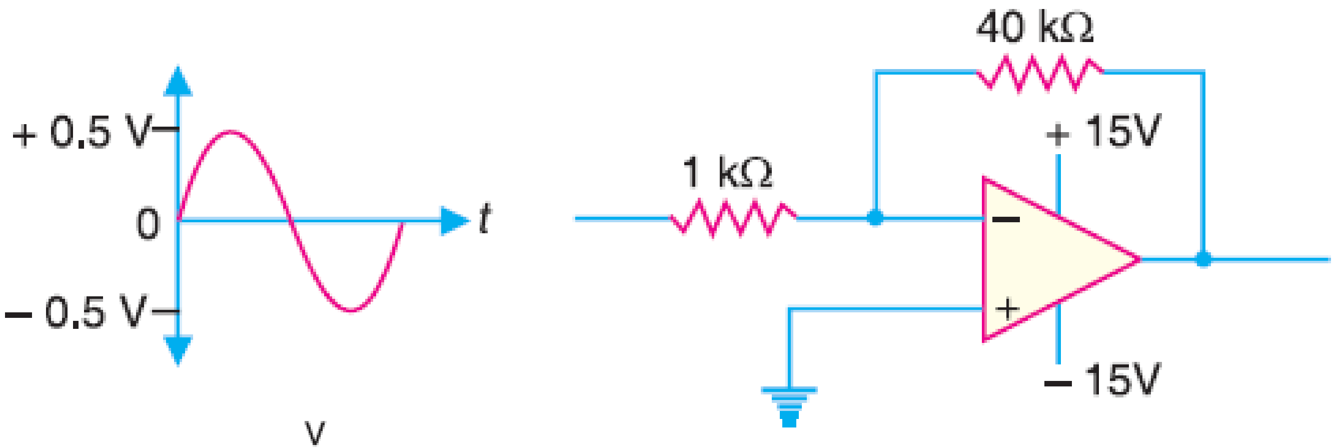


Ans.

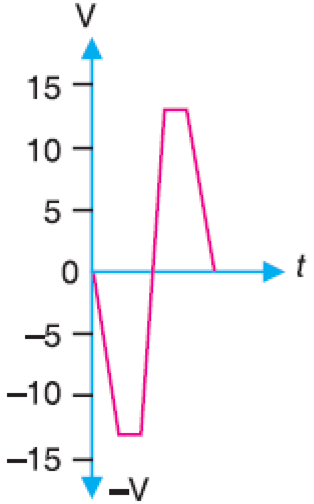


Example

Find the output voltage waveform for the circuit shown.



Ans.



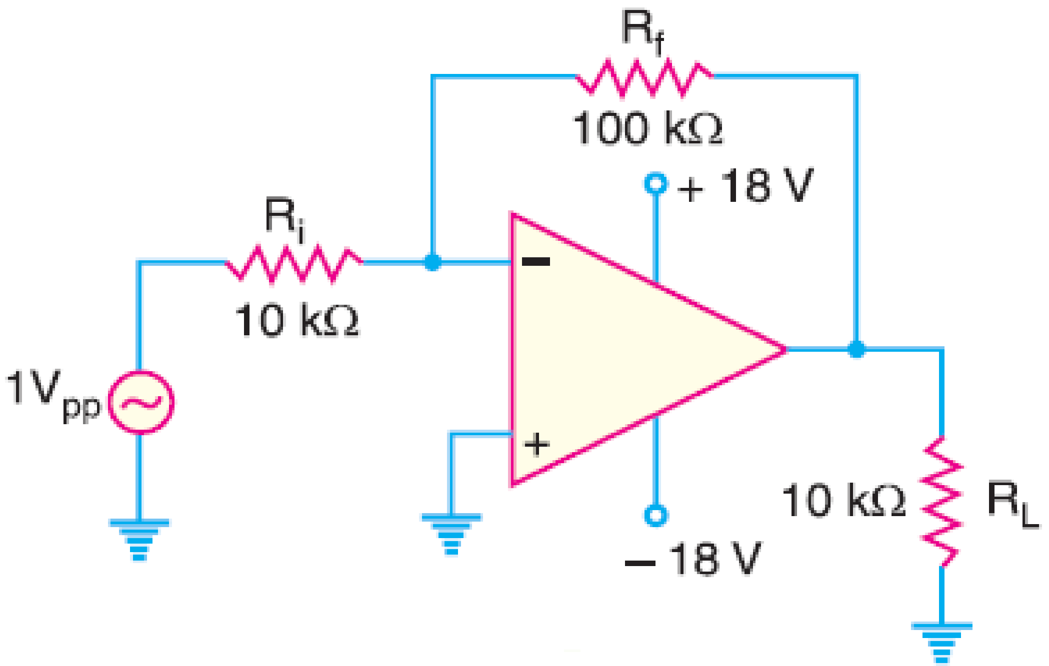
Example

For the circuit shown in Fig. 25.53, find

(i) closed-loop voltage gain

(ii) input impedance of the circuit

(iii) the maximum operating frequency. The slew rate is 0.5V/μs.



Ans.

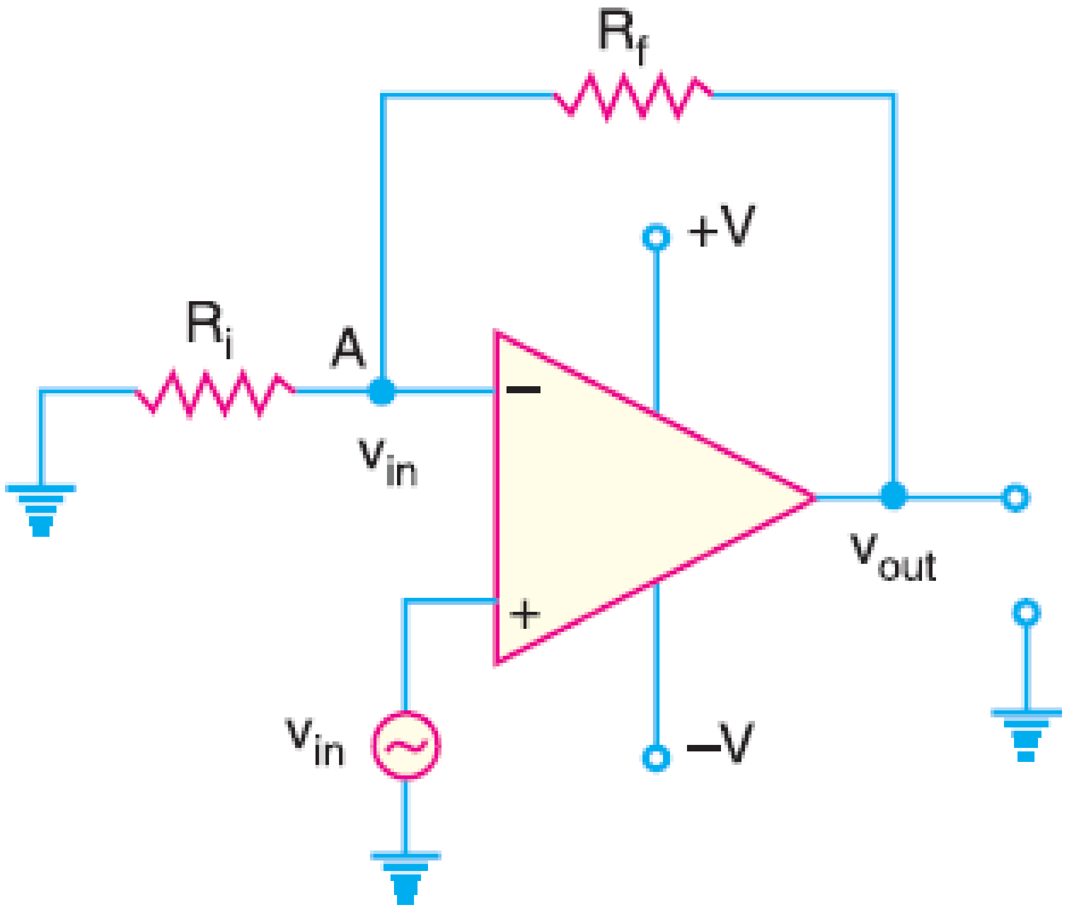
(i) -10

(ii) 10 kΩ

(iii) 15.9 kHz

Noninverting Amplifier

- The output is applied back to the input through the feedback circuit formed by feedback resistor *Rf* and input resistance *Ri*.
- Note that resistors *Rf* and *Ri* form a voltage divide at the inverting input (–).
- This produces **negative feedback* in the circuit.



Noninverting Amplifier

Voltage gain

$$\text{Voltage across } R_i = V_{in} - 0 \ ; \ \text{Voltage across } R_f = V_{out} - V_{in}$$

Now $\quad \text{Current through } R_i = \text{Current through } R_f$

or $$\frac{V_{in} - 0}{R_i} = \frac{V_{out} - V_{in}}{R_f}$$

or $$V_{in} R_f = V_{out} R_i - V_{in} R_i$$

or $$V_{in} (R_f + R_i) = V_{out} R_i$$

or $$\frac{V_{out}}{V_{in}} = \frac{R_f + R_i}{R_i} = 1 + \frac{R_f}{R_i}$$

$\therefore$ Closed-loop voltage gain, $A_{CL} = \dfrac{V_{out}}{V_{in}} = 1 + \dfrac{R_f}{R_i}$

Input and Output Impedance of Noninverting Amplifier

- Input Impedance (Z'_{in})

$$Z'_{in} \cong Z_{in}(1 + \beta A_{ol})$$

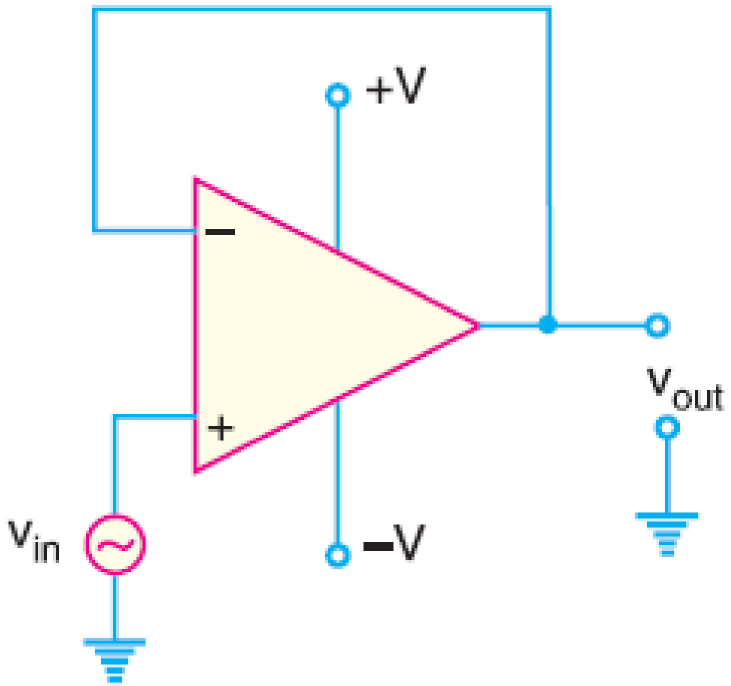
- Output Impedance (Z'_{out})

$$Z'_{out} = \frac{Z_{out}}{(1 + \beta A_{ol})}$$

Where: $\beta = \frac{R_{in}}{R_{in}+R_f}$

Voltage Follower

A special case of noninverting amplifier where all of the output voltage is fed back to the inverting input as shown in the figure.



- Closed-loop voltage gain (A_{CL}):

$$A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{0}{R_i} = 1$$

- The most important features of the voltage follower configuration are its *very high input impedance* and its *very low output impedance*.
- These features make it a nearly ideal buffer amplifier to be connected between high-impedance sources and low-impedance loads.

Input and Output Impedance of Voltage Follower

- Input Impedance (Z'_{in})

$$Z'_{in} = Z_{in}(1 + A_{ol})$$

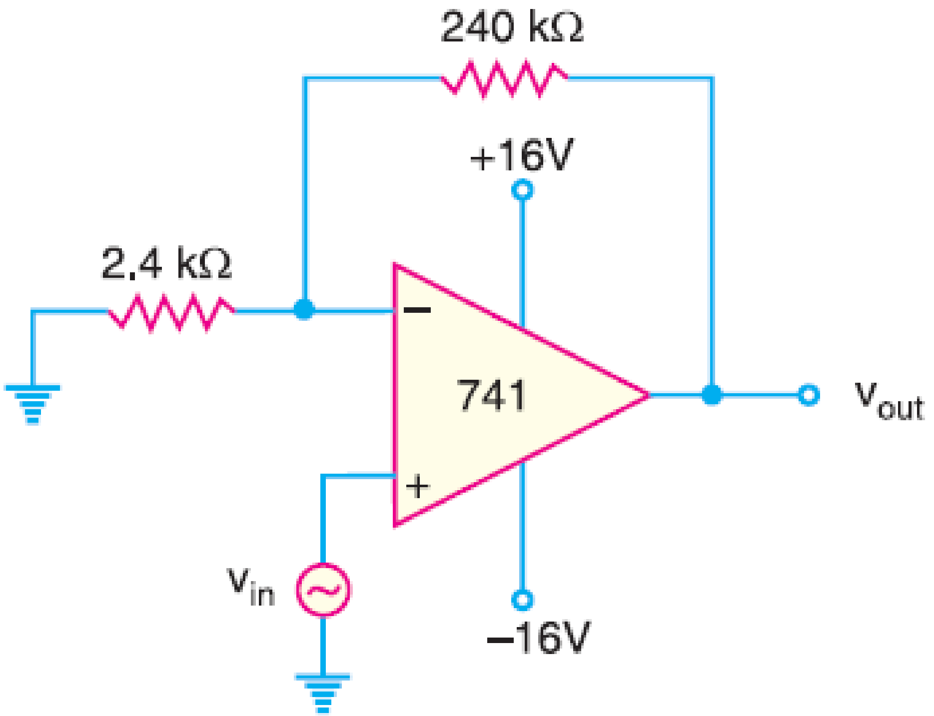
- Output Impedance (Z'_{out})

$$Z'_{out} = \frac{Z_{out}}{(1 + A_{ol})}$$

Where: $\beta = \frac{R_{in}}{R_{in}+R_f}$

Example

Calculate the output voltage from the noninverting amplifier circuit shown in the figure for an input of 120 µV.



Ans.

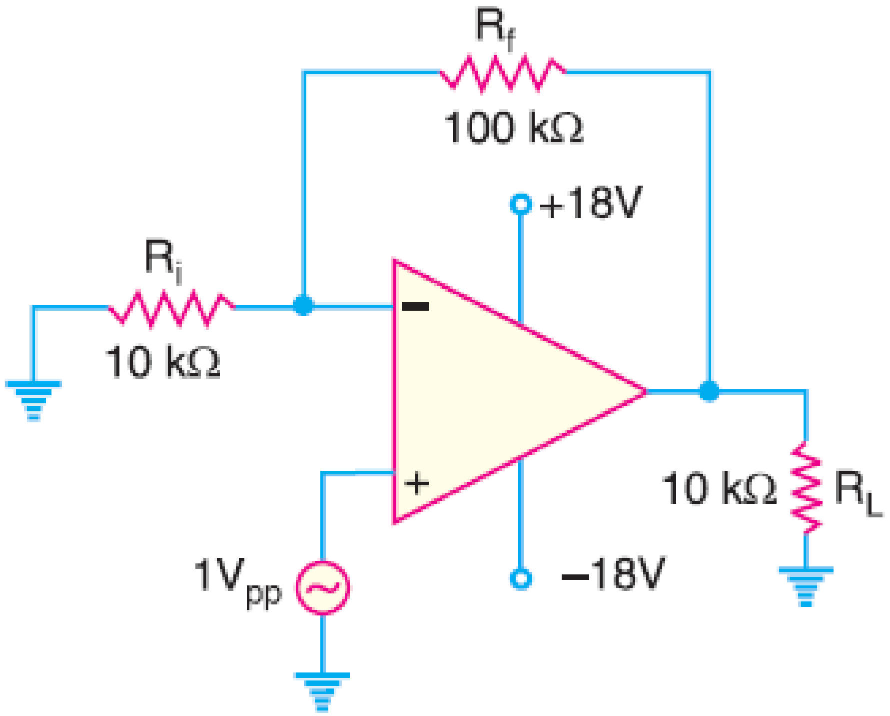
$$V_o = 12.12 \text{ mV}$$

Example

For the noninverting amplifier circuit shown in the figure, find

(i) Closedloop voltage gain

(ii) Maximum operating frequency if the slew rate is 0.5 V/µs.



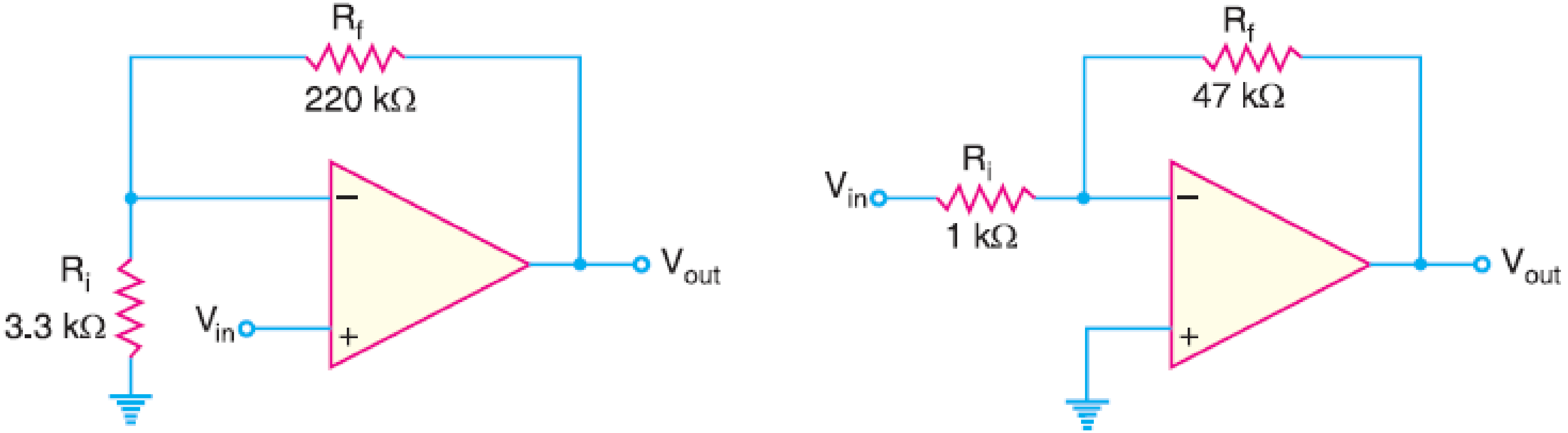
Ans.

(i) 11

(ii) 14.47 kHz

Example

Determine the bandwidth of each of the amplifiers in the figure. Both Op-amps have an open-loop voltage gain of 100 dB and a unity-gain bandwidth of 3MHz.



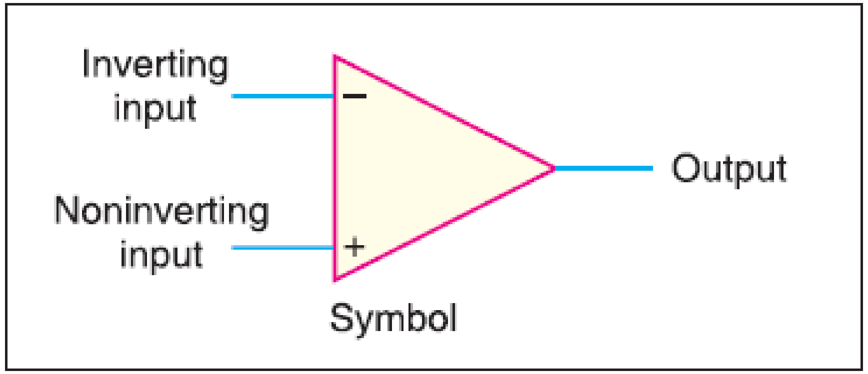
Ans.

a. 44.3 kHz

b. 63.8 kHz

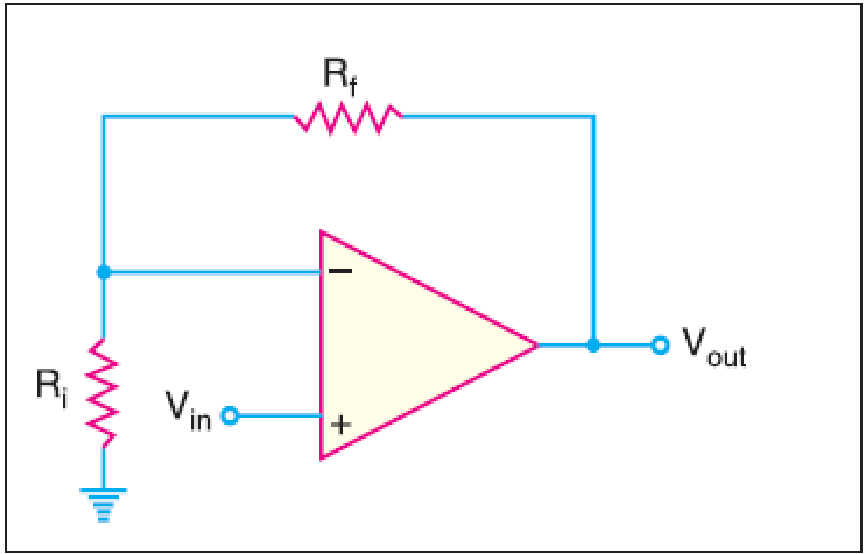
Summary

Basic OP-AMP



- Very high open-loop voltage gain
- Very high input impedance
- Very low output impedance

Noninverting Amplifier



- Voltage gain:

$$A_{CL(NI)} = 1 + \frac{R_f}{R_i}$$

- Input impedance:

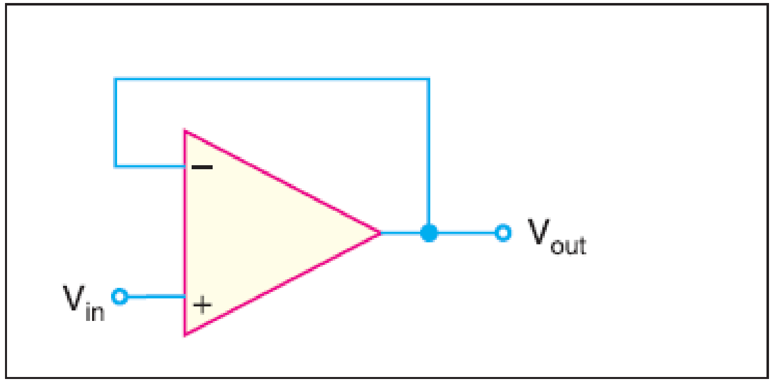
$$Z_{in(NI)} = (1 + A_{OL}m_v)\,Z_{in}$$

- Output impedance:

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{OL}m_v}$$

Summary

Voltage Follower



- Voltage gain:

$A_{CL(VF)} = 1$

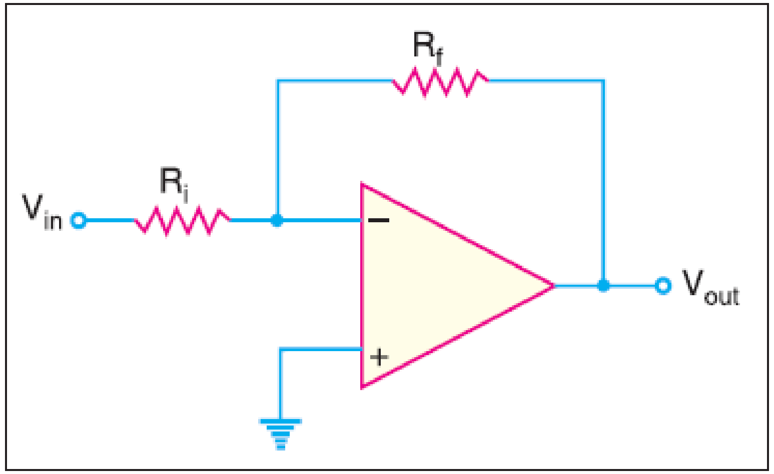
- Input impedance:

$Z_{in(VF)} = (1 + A_{OL})\,Z_{in}$

- Output impedance:

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{OL}}$$

Inverting Amplifier



- Voltage gain:

$$A_{CL} = -\frac{R_f}{R_i}$$

- Input impedance:

$Z_{in(I)} \simeq R_i$

- Output impedance:

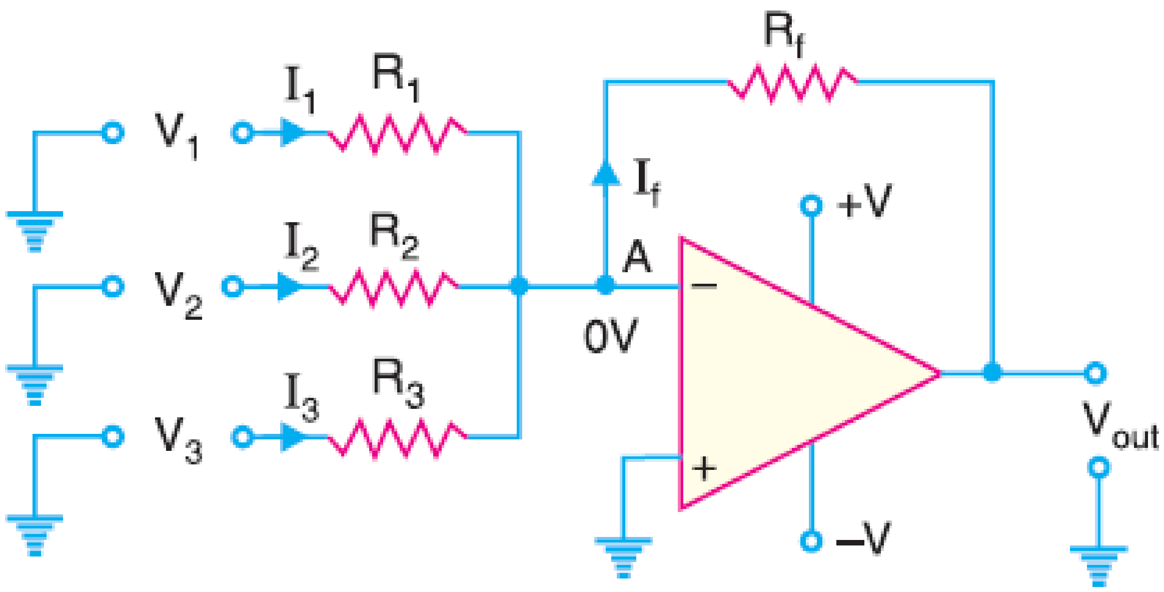
$Z_{out(I)} \simeq Z_{out}$

Summing Amplifier

A summing amplifier is an inverted *OP*-amp that can accept two or more inputs.

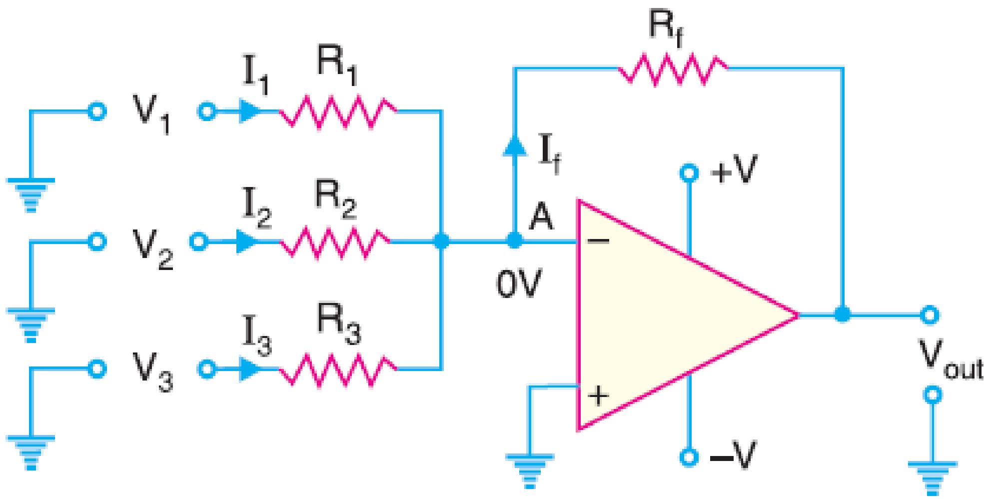
The output voltage of a summing amplifier is *proportional to the negative of the algebraic sum of its input voltages*.

$$I_f = I_1 + I_2 + I_3$$



Summing Amplifier

$$I_f = I_1 + I_2 + I_3$$



When all the three inputs are applied, the output voltage is

$$\text{Output voltage, } V_{out} = -I_f R_f = -R_f(I_1 + I_2 + I_3)$$

$$= -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

$$\therefore \quad V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

If $R_1 = R_2 = R_3 = R$, then, we have,

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 + V_3)$$

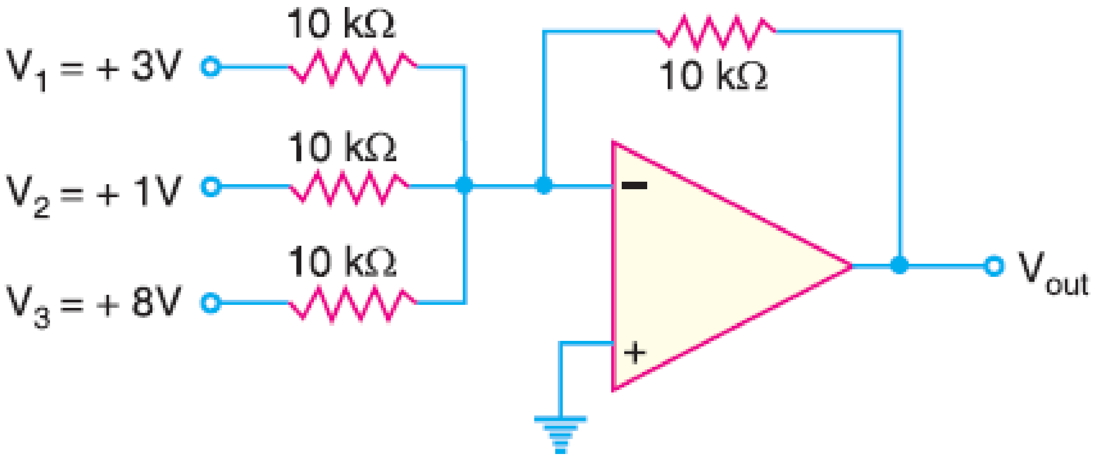
Thus the output voltage is proportional to the algebraic sum of the input voltages (of course neglecting negative sign). An interesting case results when the **gain of the amplifier is unity.** In that case, $R_f = R_1 = R_2 = R_3$ and output voltage is

$$V_{out} = -(V_1 + V_2 + V_3)$$

Thus, when the gain of summing amplifier is unity, the output voltage is the algebraic sum of the input voltages.

Example

Determine the output voltage for the summing amplifier in the figure.



Ans.

-12 V

Example

Two voltages of + 0.6V and – 1.4 V are applied to the two input resistors of a summing amplifier. The respective input resistors are 400 kΩ and 100 kΩ and feedback resistor is 200 kΩ. Determine the output voltage.

Ans.

$$V_0 = 2.5 \text{ V}$$

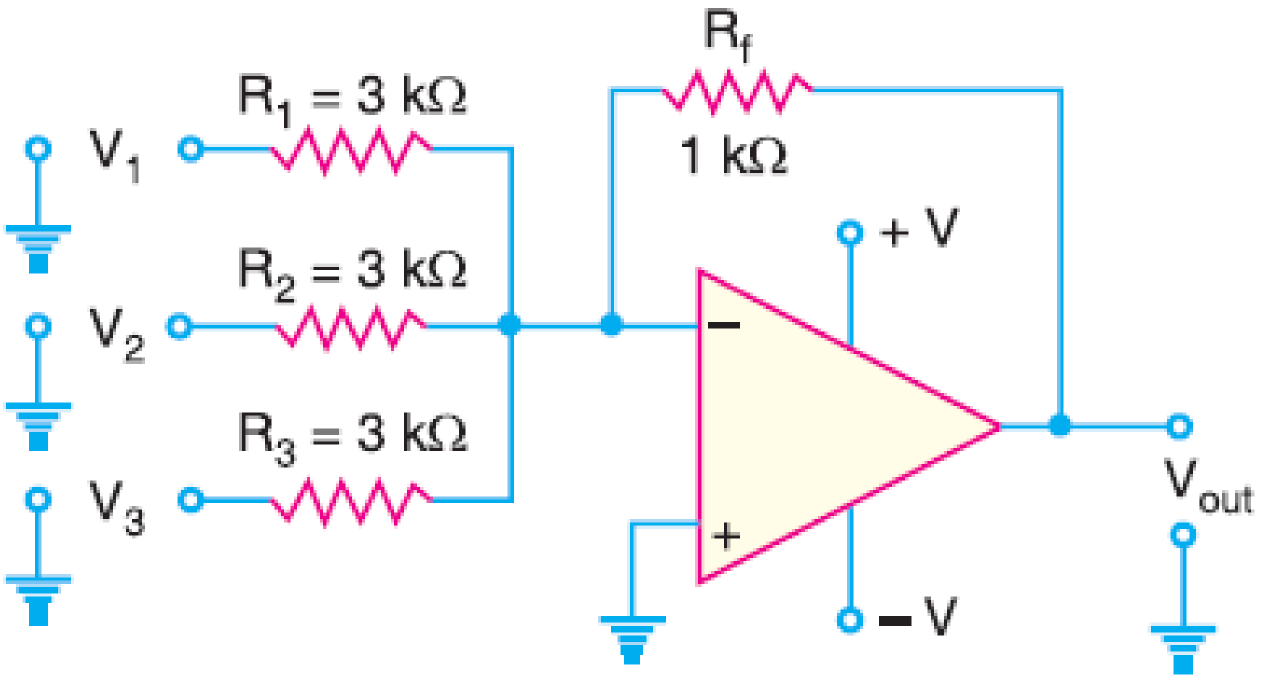
Applications of Summing Amplifiers

1) As averaging amplifier

Conditions:

i. All input resistors (*R*1, *R*2 and so on) are *equal in value.*

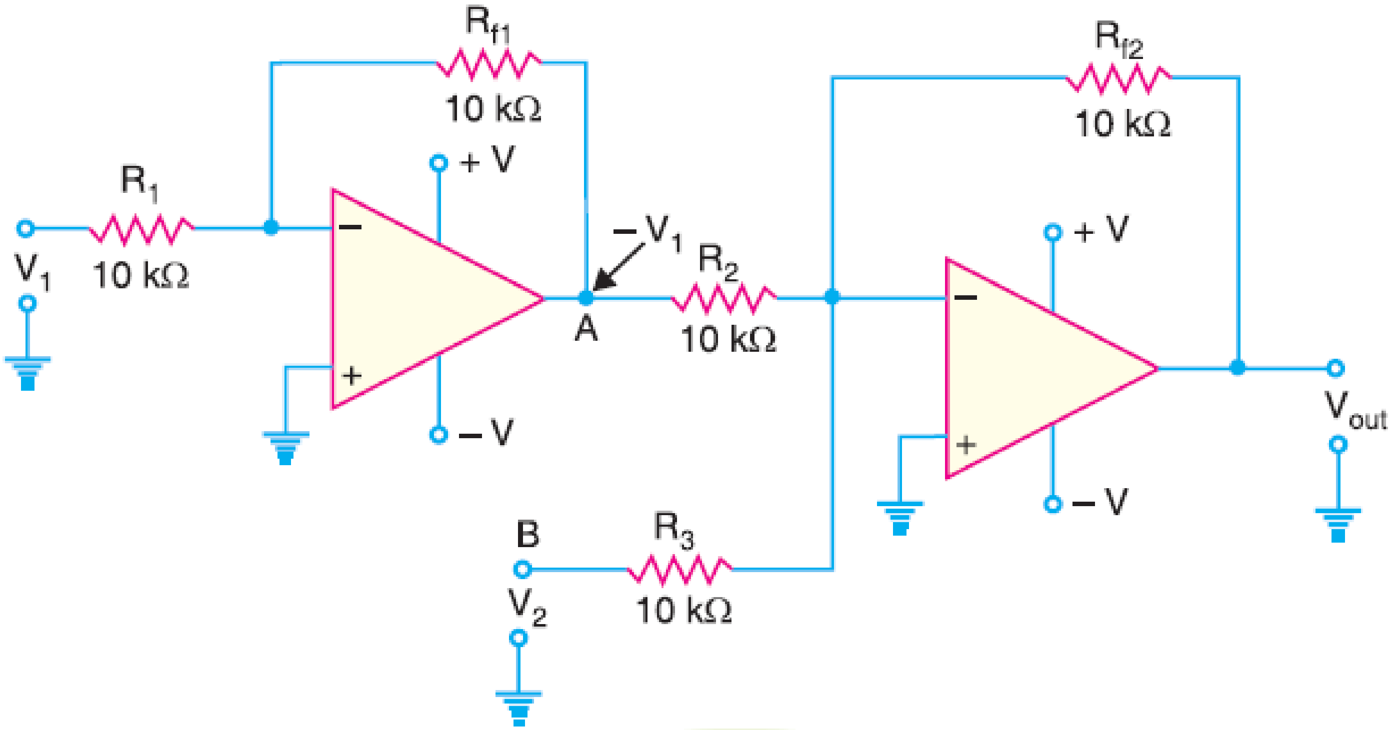
ii. The ratio of any input resistor to the feedback resistor is equal to the number of input circuits.



Applications of Summing Amplifiers

2) As subtractor

- A summing amplifier can be used to provide an output voltage that is equal to the difference of two voltages.
- Such a circuit is called a **subtractor** and is shown in the figure.



OP-Amp Integrators and Differentiators

- Integrator

  A circuit that performs the mathematical integration of input signal is called an *integrator.*

  The output of an integrator is proportional to the area of the input waveform over a period of time.

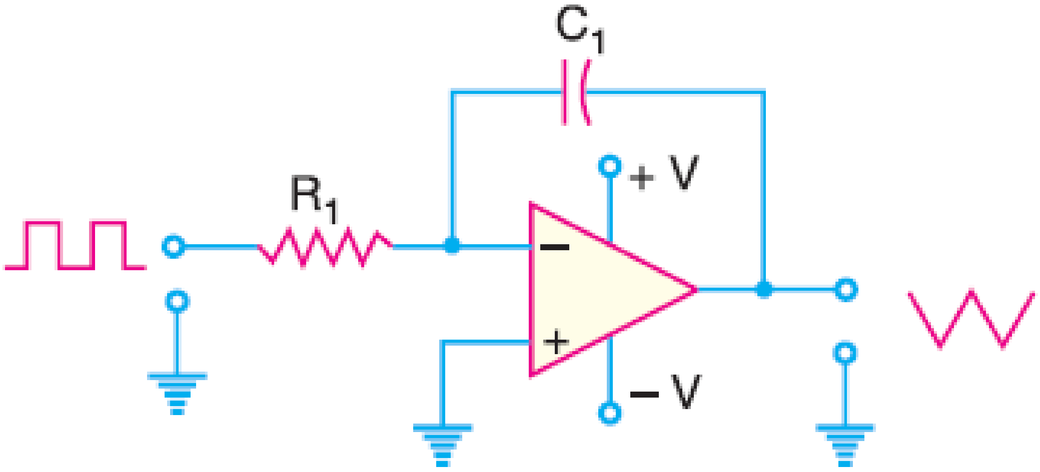
- Integrator

  A circuit that performs the mathematical differentiation of input signal is called a differentiator.

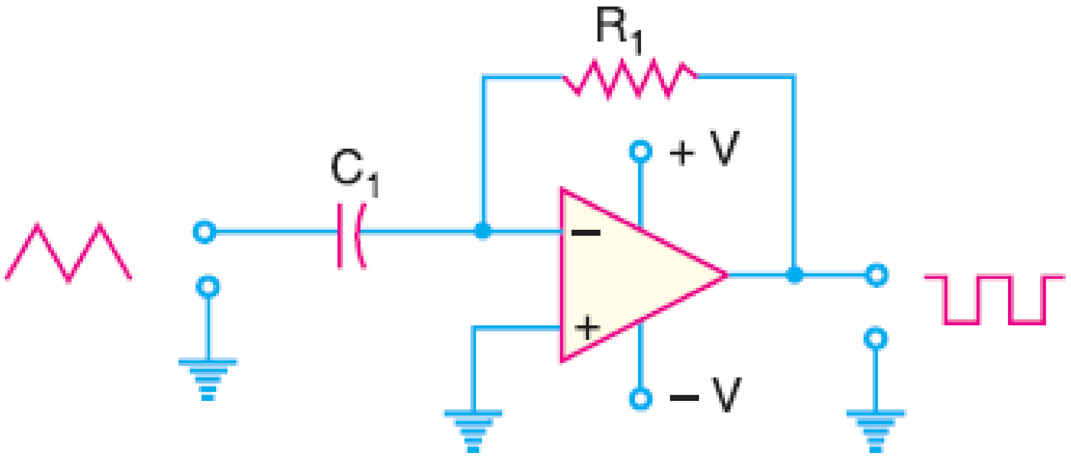
  The output of a differentiator is proportional to the rate of change of its input signal.

*Note that the two operations are opposite.

OP-Amp Integrators and Differentiators



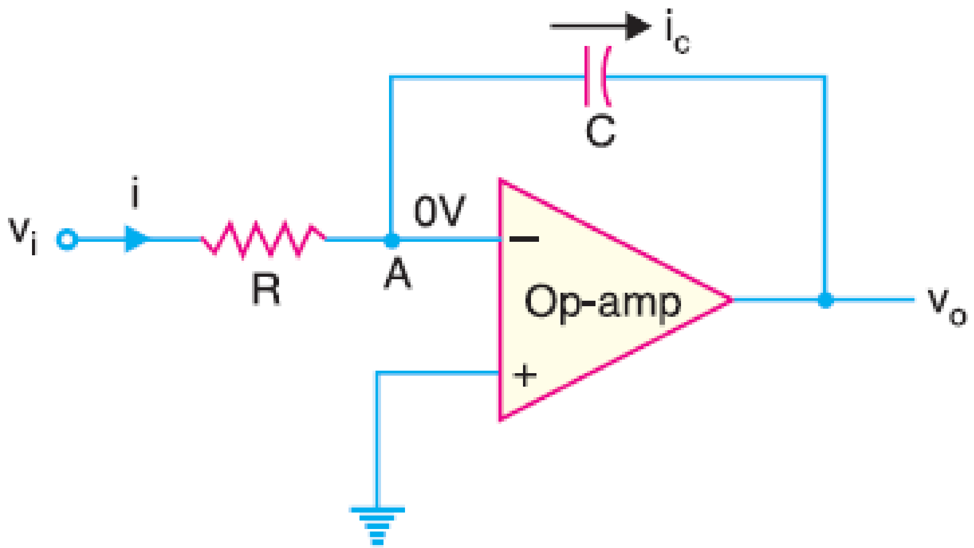
OP-amp Integrator

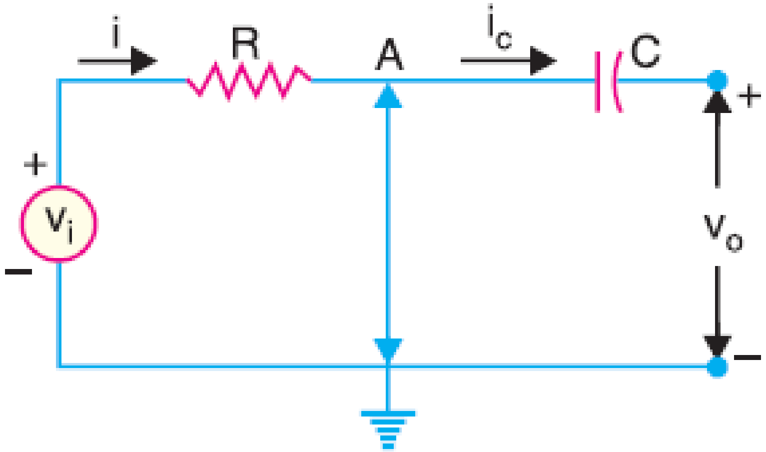


OP-amp differentiator

OP-Amp Integrator

The most popular application of an integrator is to produce a ramp output voltage.





Now $$i = \frac{v_i - 0}{R} = \frac{v_i}{R}$$

Also voltage across capacitor is $v_c = 0 - v_o = -v_o$

$$\therefore \quad i_c = \frac{C\,dv_c}{dt} = -C\frac{dv_o}{dt}$$

$$\frac{v_i}{R} = -C\frac{dv_o}{dt}$$

or $$\frac{dv_o}{dt} = -\frac{1}{RC}v_i$$

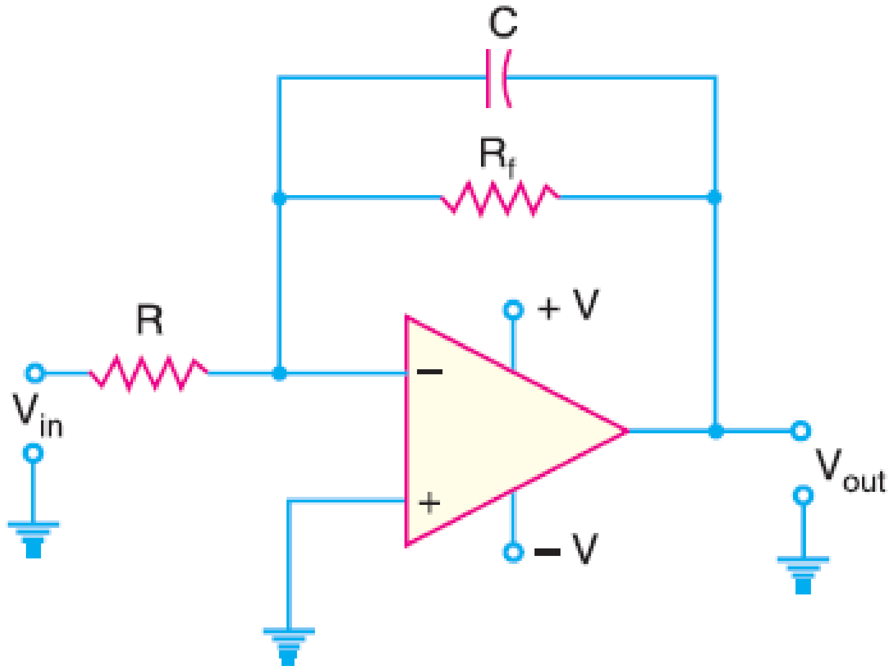
To find the output voltage, we integrate both sides of eq. (*iii*) to get,

$$v_o = -\frac{1}{RC}\int_0^t v_i\,dt$$

Critical Frequency of Integrators

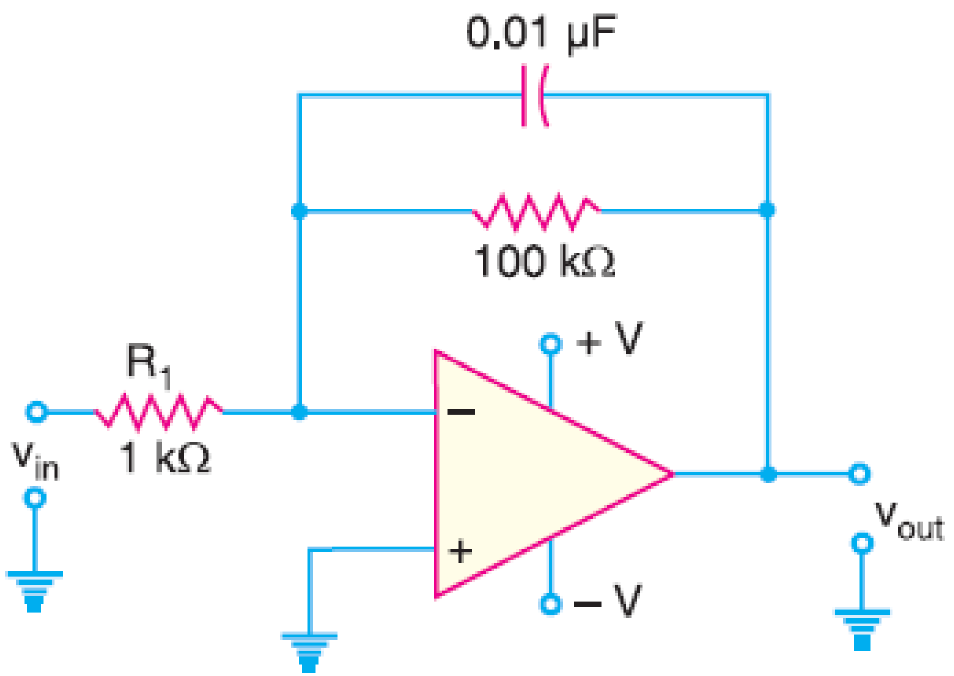
- The integrator shown in figure has no feedback at 0 Hz.
- This is a serious disadvantage in low-frequency applications.
- By connecting a feedback resistor *Rf* in parallel with the capacitor, precise closed-loop voltage gain is possible.
- The circuit shown in figure is an integrator with a feedback resistor *Rf* to provide increased stability.
- All integrators have a critical frequency *fc* below which they do not perform proper integration.
- If the input frequency is less than *fc*, the circuit behaves like a simple inverting amplifier and no integration occurs.
- The following equation is used to calculate
- the critical frequency of an integrator:

$$f_c = \frac{1}{2\pi R_f C}$$



Example

Determine the lower frequency limit (critical frequency) for the integrator circuit shown in the figure.

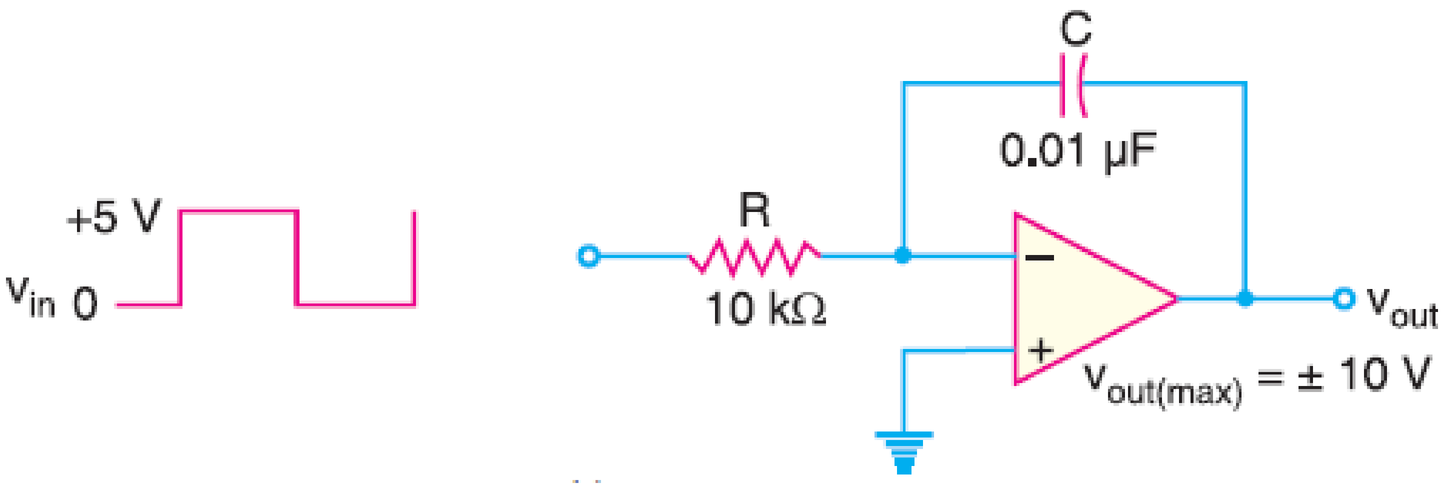


Ans.

159 Hz

Example

Determine the rate of change of the output voltage in response to a single pulse input to the integrator circuit shown in the figure.

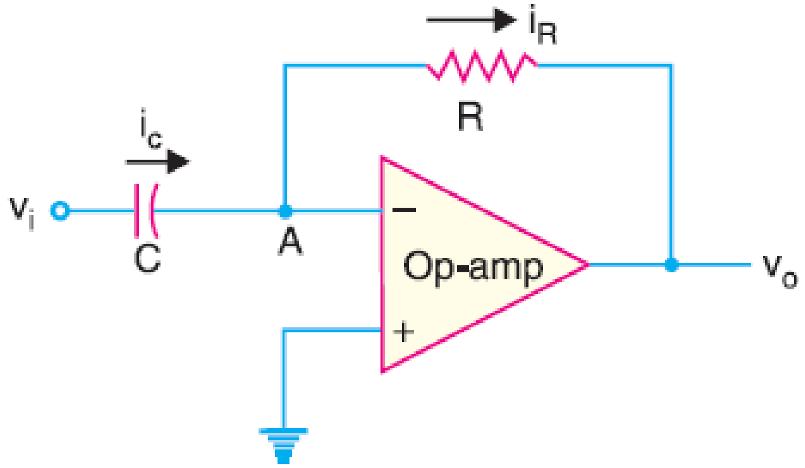


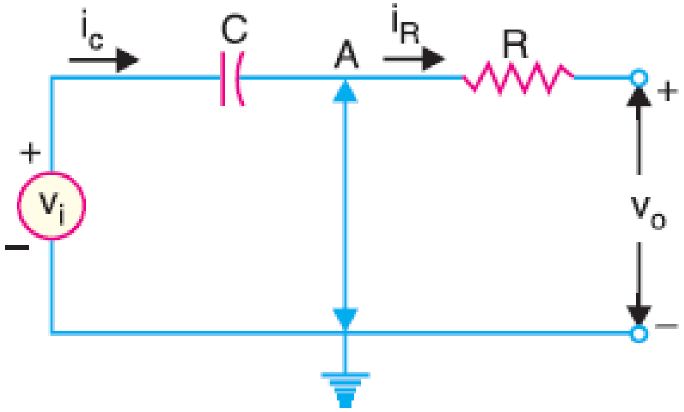
Ans.

$-\,50\ \mathrm{mV}/\mu\mathrm{s}$

OP-Amp Differentiator

Its important application is to produce a rectangular output from a ramp input.





$$\therefore \quad i_R = \frac{0 - v_o}{R} = -\frac{v_o}{R} \quad \text{and} \quad v_c = v_i - 0 = v_i$$

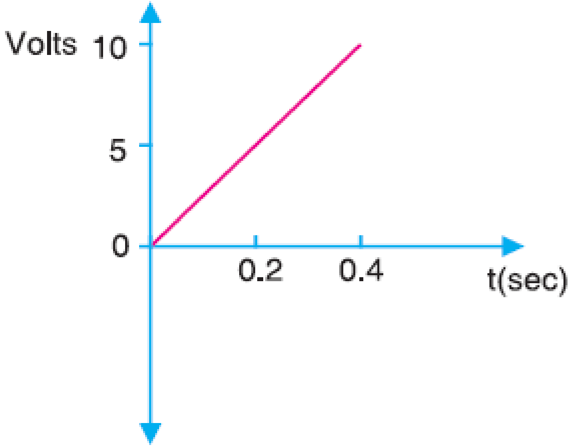
$$\text{Also} \quad i_c = C\frac{dv_c}{dt} = C\frac{dv_i}{dt}$$

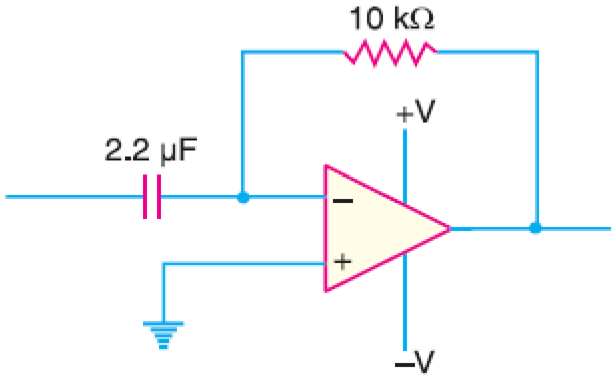
$$\therefore \quad -\frac{v_o}{R} = C\frac{dv_i}{dt}$$

$$\text{or} \quad v_o = -RC\frac{dv_i}{dt}$$

Example

For the differentiator circuit shown in the figure, determine the output voltage if the input goes from 0V to 10V in 0.4s. Assume the input voltage changes at constant rate.





Ans.

$$V_o = -0.55\ V$$

Comparator

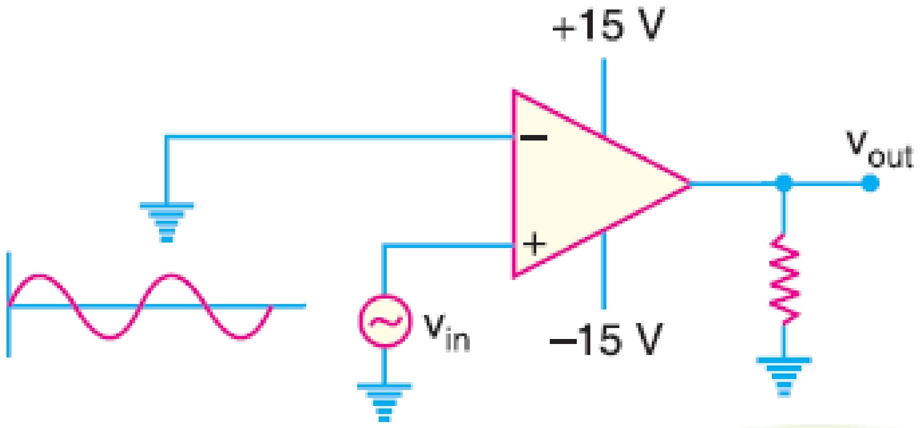
A comparator circuit has the following two characteristics :

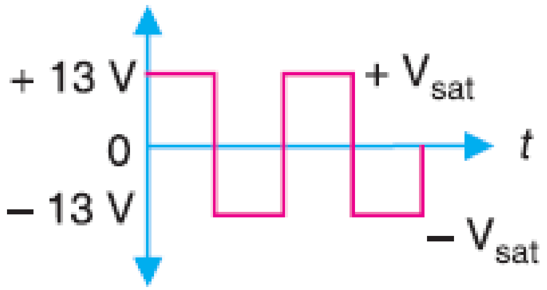
a) It uses no feedback so that the voltage gain is equal to the open-loop voltage gain (A_{OL}) of *OP*-amp.

b) It is operated in a non-linear mode.

Comparator

1) As a square wave generator

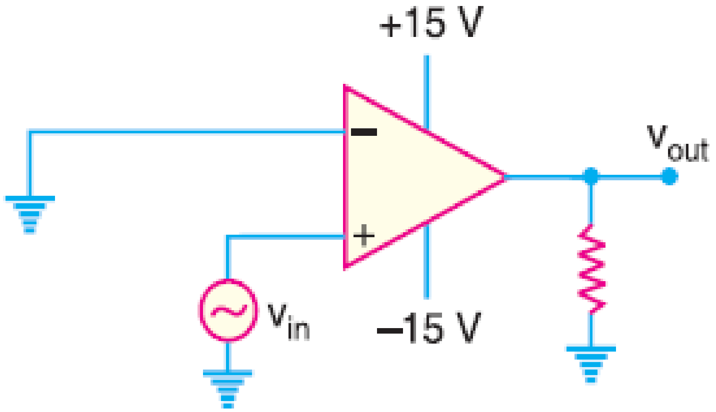


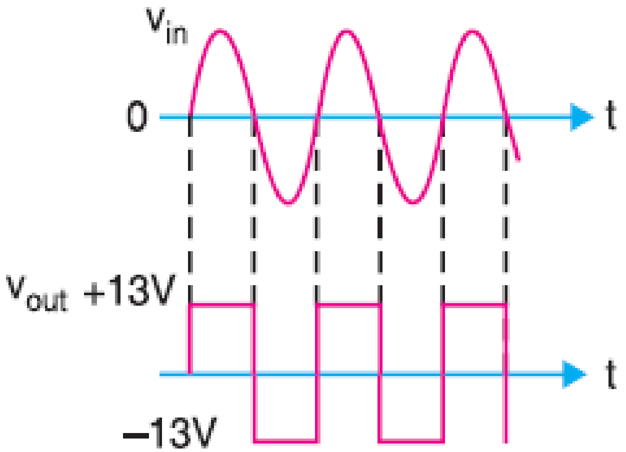


When the input signal goes positive, the output jumps to about + 13 V. When the input goes negative, the output jumps to about – 13 V. The output changes rapidly from – 13 V to + 13 V and *vice-versa*. This change is so rapid that we get a square wave output for a sine wave input.

Comparator

2) As a zero-crossing detector





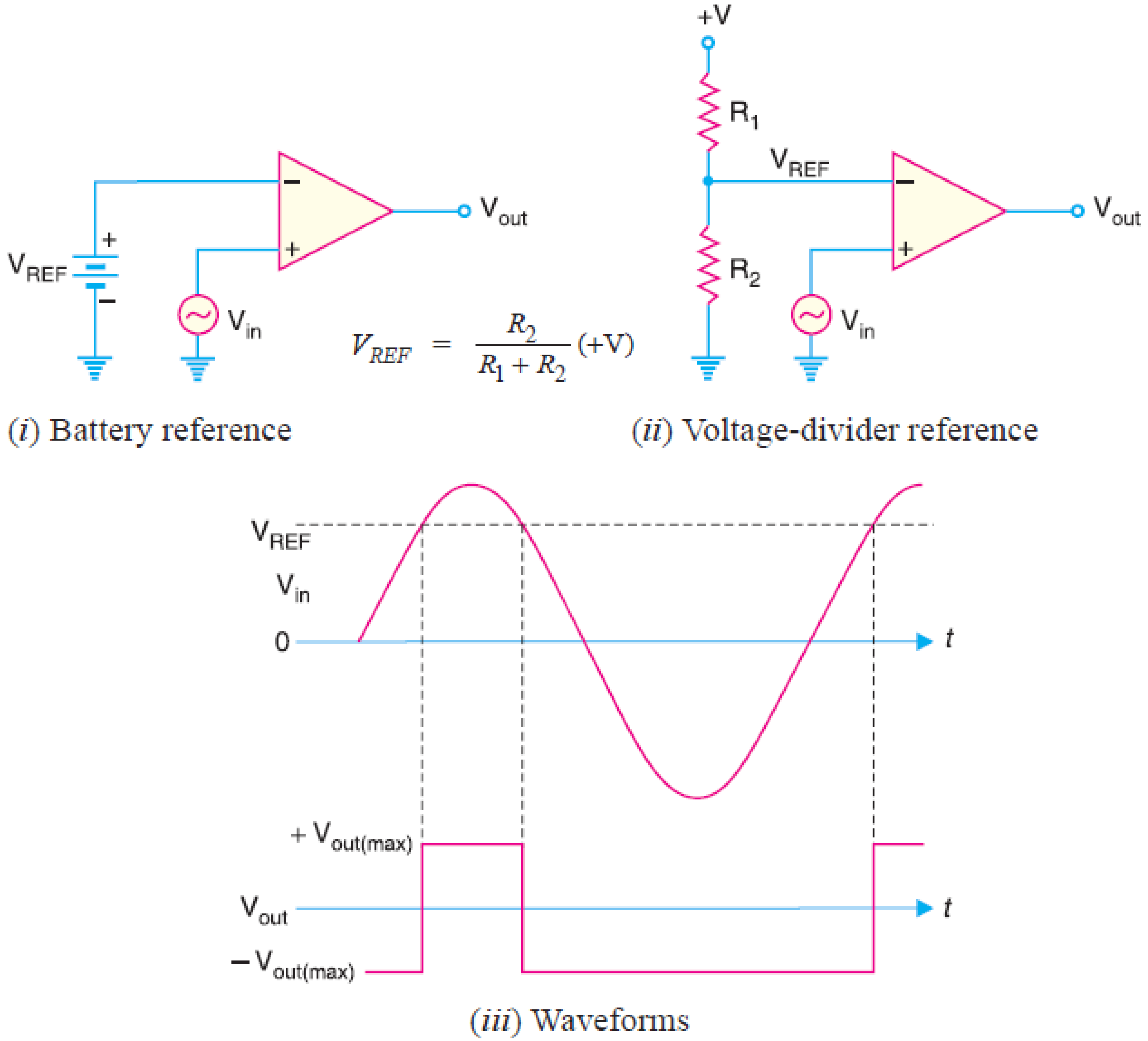
From the input/output waveforms, you can see that every time the input crosses 0 V going positive, the output jumps to + 13 V. Similarly, every time the input crosses 0 V going negative, the output jumps to – 13 V. Since the change (+ 13 V or – 13 V) occurs every time the input crosses 0 V, we can tell when the input signal has crossed 0 V. Hence the name zero-crossing detector.

Comparator

3) As a level detector

- When the input voltage is less than the reference voltage (*i.e.* $V_{in} < V_{REF}$), the output goes to maximum negative level.
- It remains here until V_{in} increases above V_{REF}.
- When the input voltage exceeds the reference voltage (*i.e.* $V_{in} > V_{REF}$), the output goes to its maximum positive state.
- It remains here until V_{in} decreases below V_{REF}.
- (*iii*) shows the input/output waveforms.

- (Note that this circuit is used for non zero-level detection.)



Feedback Systems, Oscillators, and Filters

Feedback Systems, Oscillators, and Filters

- Feedback
  - A portion of the output signal taken back to the input.
- Oscillators
  - A non-rotating electronic device which converts dc energy into ac energy.
- Filters
  - A circuit that passes certain frequencies and attenuates or rejects other frequencies.

Feedback

Feedback

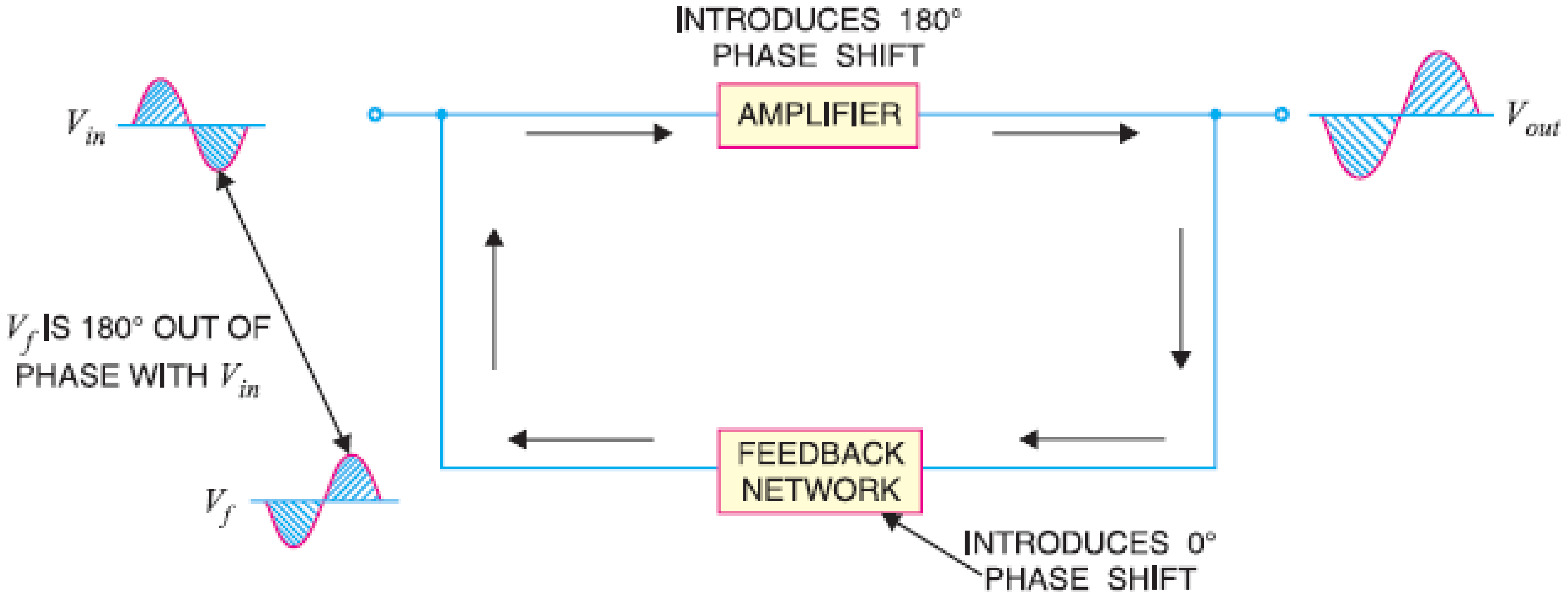
The process of injecting a fraction of output energy of some device back to the input is known as feedback.

Two Basic Types of Feedback:

a) Negative feedback
b) Positive feedback

Negative Feedback

- When the feedback energy (voltage or current) is out of phase with the input signal and thus opposes it, it is called negative feedback.



Negative Feedback

- Voltage Gain (with feedback):

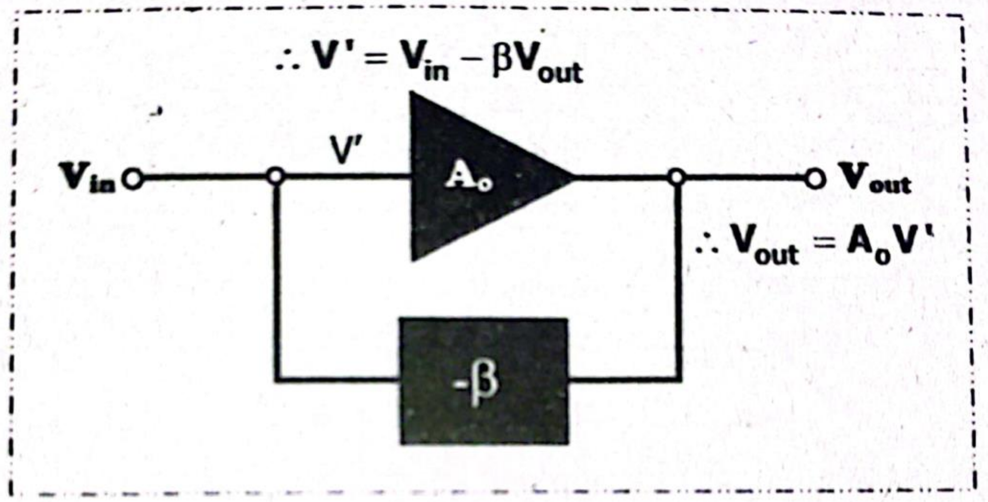
$$\mathrm{A_f} = \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}} = \frac{\mathbf{A_o}}{\mathbf{1 + \beta A_o}} \cong \frac{\mathbf{1}}{\boldsymbol{\beta}}$$

- Input Impedance:

$$\mathbf{Z_{in(f)}} = \mathbf{Z_{in(o)}}(\mathbf{1} + \boldsymbol{\beta}\mathbf{A_o})$$

- Output Impedance:

$$\mathbf{Z_{out(f)}} = \frac{\mathbf{Z_{out(o)}}}{(\mathbf{1} + \boldsymbol{\beta}\mathbf{A_o})}$$



Advantages of Negative Voltage Feedback

1) Gain stability

$$A_f \cong \frac{\mathbf{1}}{\boldsymbol{\beta}}$$

2) Reduces non-linear distortion

$$\mathbf{D}_{(\mathbf{f})} = \frac{\mathbf{D}_{(\mathbf{o})}}{(\mathbf{1} + \boldsymbol{\beta}\mathbf{A}_{\mathbf{o}})}$$

3) Improves frequency response
   - As feedback is usually obtained through a resistive network, therefore, voltage gain of the amplifier is *independent of signal frequency.

4) Increases circuit stability

5) Increases input impedance and decreases output impedance

Example

The overall gain of a multistage amplifier is 140. When negative voltage feedback is applied, the gain is reduced to 17.5. Find the fraction of the output that is fed back to the input.

Ans.

1/20

Example

With a negative voltage feedback, an amplifier gives an output of 10 V with an input of 0.5 V. When feedback is removed, it requires 0.25 V input for the same output.

Calculate (i) gain without feedback (ii) feedback fraction β.

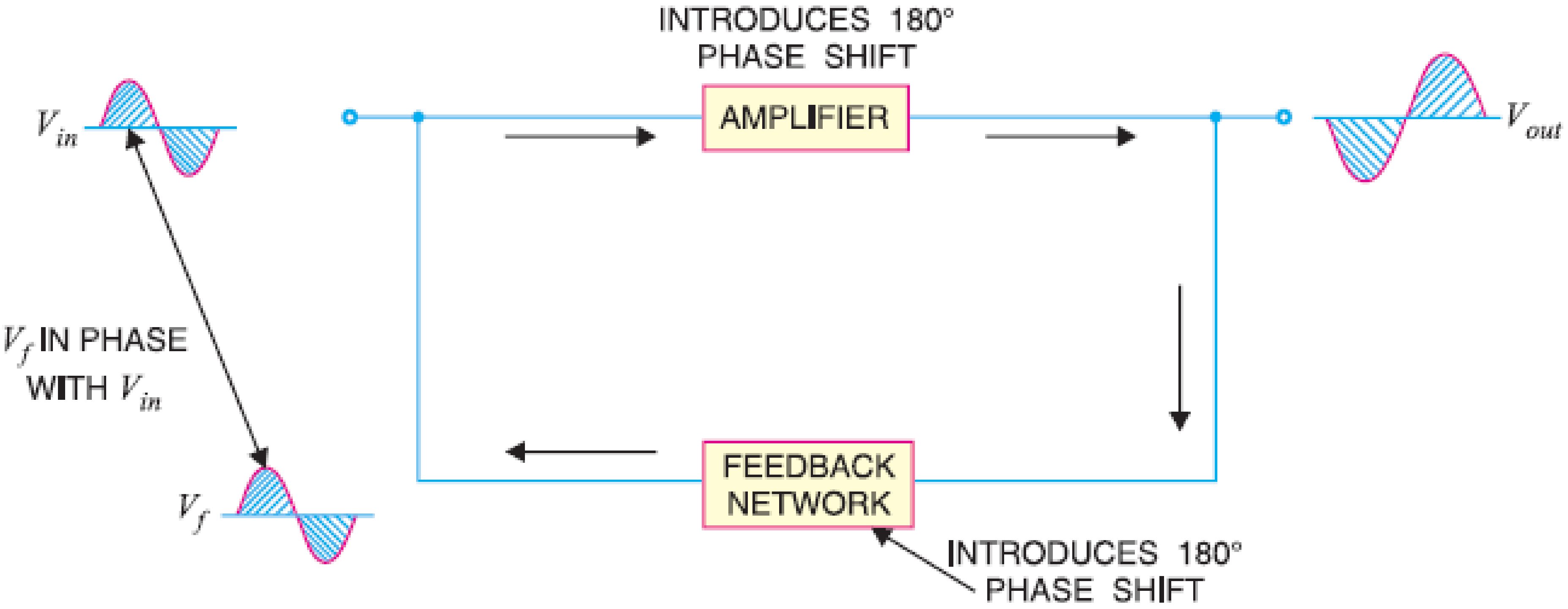
Ans.

i) 40

ii) 1/40

Positive Feedback

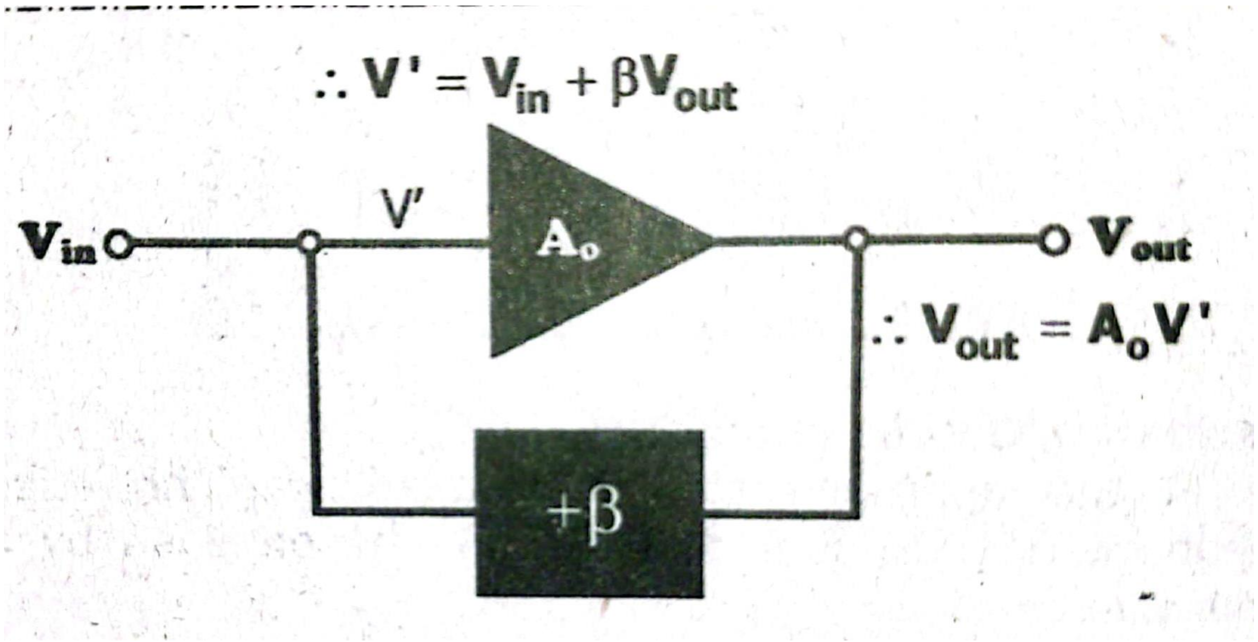
- The use of positive feedback is useful for producing oscillators.
- The portion of the output is combined in phase with the input.



Negative Feedback

- Voltage Gain (with feedback):

$$A_f = \frac{V_{out}}{V_{in}} = \frac{\mathbf{A_o}}{\mathbf{1-\beta A_o}} \cong -\frac{\mathbf{1}}{\boldsymbol{\beta}}$$



Oscillator

Oscillator

- A non-rotating electronic device which converts dc energy into ac.
- The function of an oscillator is just the reverse of a rectifier, therefore sometimes called an “inverter”.
- Oscillator differ from an amplifier in the sense that oscillator does not require an external signal either to start or maintain energy conversion process.

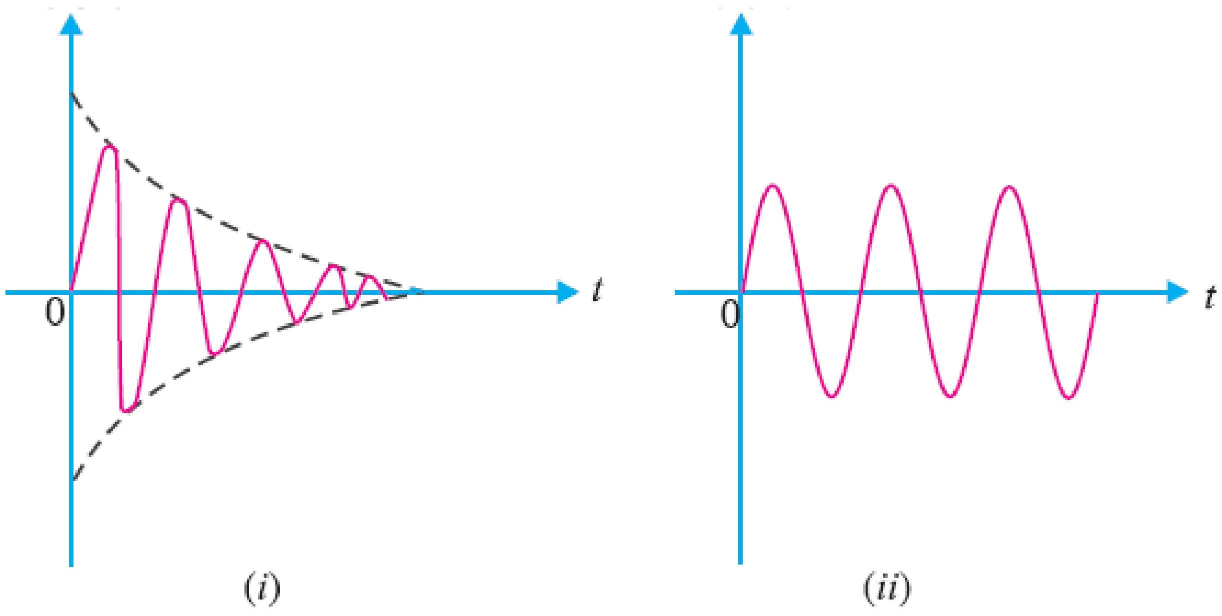
Type of Oscillations

i. Damped Oscillations

- The electrical oscillations whose amplitude goes on decreasing with time are called **damped oscillations**.

ii. Undamped Oscillations

- The electrical oscillations whose amplitude remains constant with time are called **undamped oscillations**.



Oscillatory Circuit

A circuit which produces electrical oscillations of any desired frequency is known as an oscillatory circuit or tank circuit.

The Frequency of Oscillations (f_r):

$$\mathbf{f_r = \frac{1}{2\pi\sqrt{LC}}}$$

Barkhausen Criterion

In order to produce continuous undamped oscillations at the output of an amplifier, the positive feedback should be such that :

$$\beta A_o = 1$$

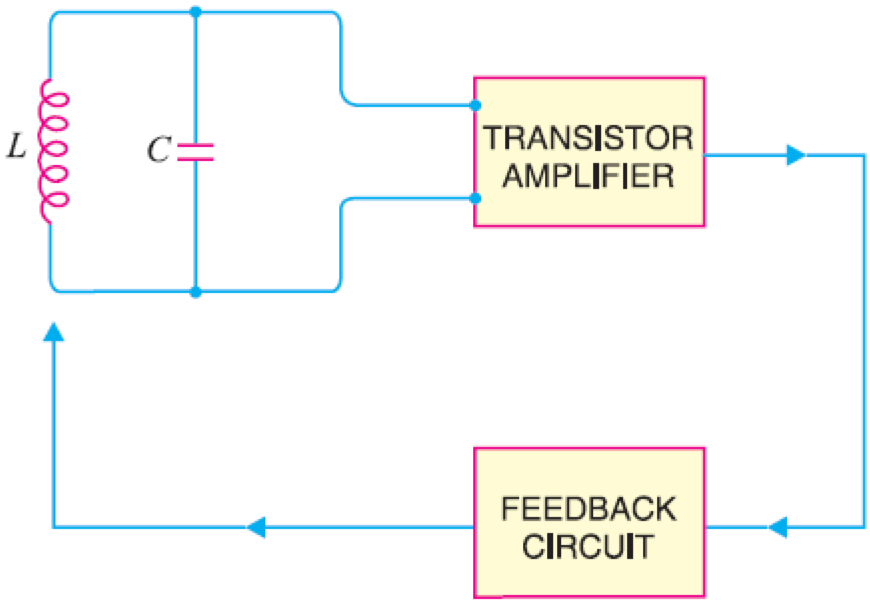
Mathematical explanation:

The voltage gain of a positive feedback amplifier is given by:

$$\mathrm{A_f} = \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}} = \frac{\mathbf{A_o}}{\mathbf{1 - \beta A_o}} \cong \frac{\mathbf{A_o}}{\mathbf{1 - 1}} = \infty$$

Transistor Oscillator

- ***Tank circuit*.**
  - It consists of inductance coil (*L*) connected in parallel with capacitor (*C*).
  - The frequency of oscillations in the circuit depends upon the values of inductance of the coil and capacitance of the capacitor.
- ***Transistor amplifier***
  - The oscillations occurring in the tank circuit are applied to the input of the transistor amplifier.
  - Because of the amplifying properties of the transistor, we get increased output of these oscillations.
- **Feedback circuit.**
  - The feedback circuit supplies a part of collector energy to the tank circuit in correct phase to aid the oscillations i.e. it provides positive feedback.



Different Types of Transistor Oscillators

The major difference between these oscillators lies in the method by which energy is supplied to the tank circuit to meet the losses.

The following are the transistor oscillators commonly used at various places in electronic circuits :

a) Tuned collector oscillator
b) Colpitt's oscillator
c) Hartley oscillator
d) Phase shift oscillator
e) Wien Bridge oscillator
f) Crystal oscillator

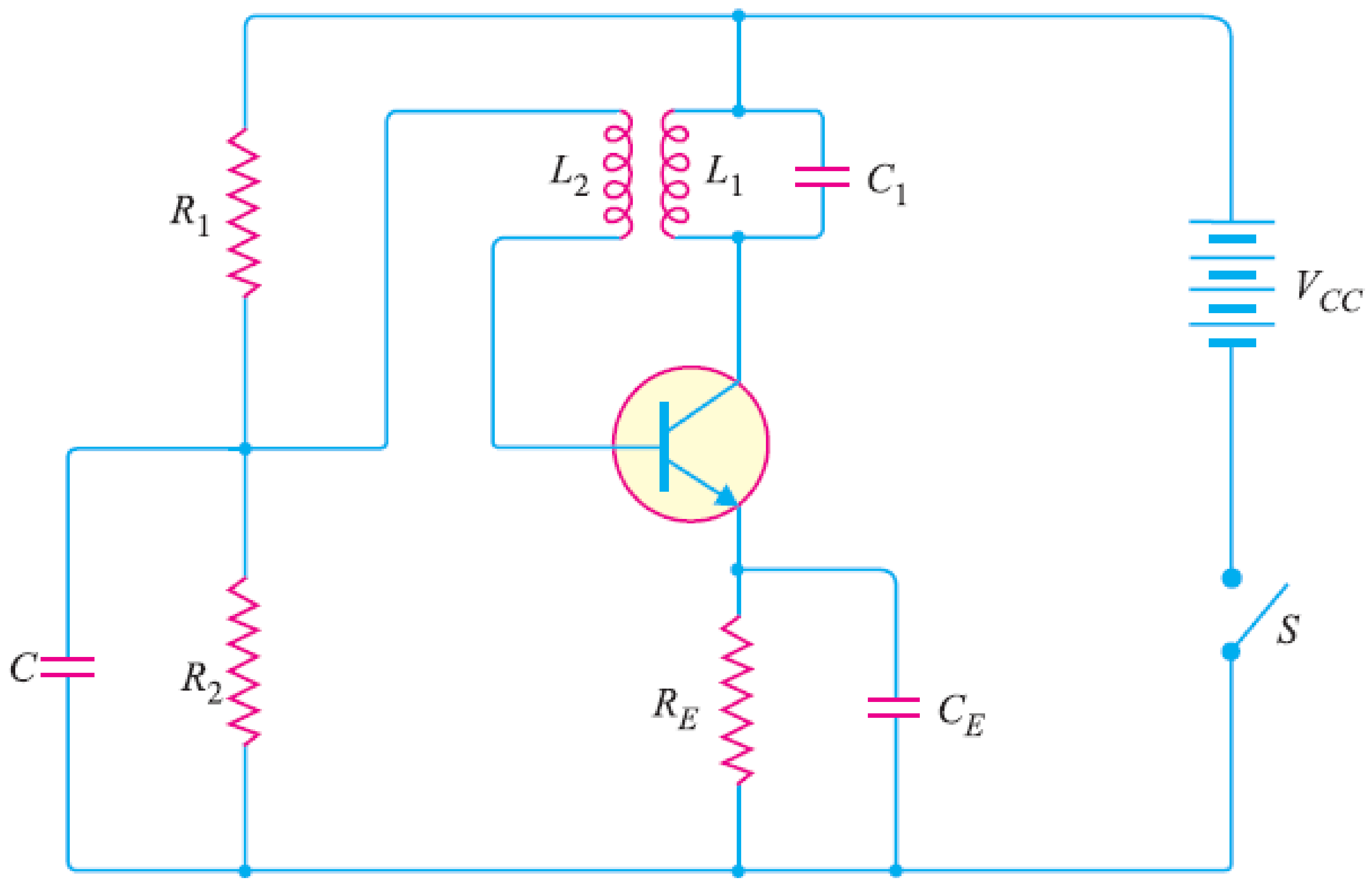
Tuned Collector Oscillator

It contains tuned circuit L1-C1 in the collector.

Frequency of Oscillations (f_r):

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

*The feedback coil L2 in the base circuit is magnetically coupled to the tank circuit coil L1.



Example

The tuned collector oscillator circuit used in the local oscillator of a radio receiver makes use of an LC tuned circuit with $L1 = 58.6\ \mu H$ and $C1 = 300\ pF$. Calculate the frequency of oscillations.

Ans.

1199 kHz

Example

Find the capacitance of the capacitor required to build an LC oscillator that uses an inductance of L1 = 1 mH to produce a sine wave of frequency 1000×10^9 Hz.

Ans.

2.53×10^{-11} pF

Colpitt's Oscillator

It uses two capacitors and placed across a common inductor *L* and the center of the two capacitors is tapped.

Frequency of Oscillations (f_r):

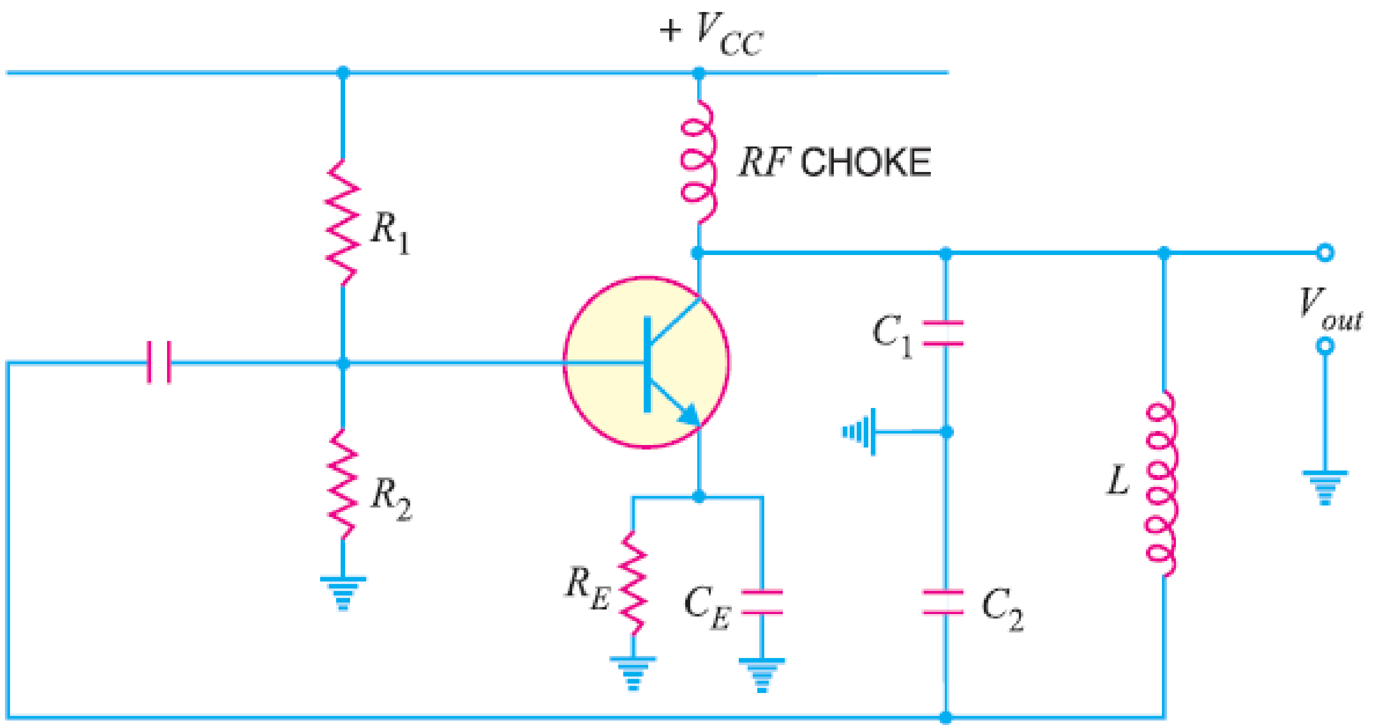
$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

Where:

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

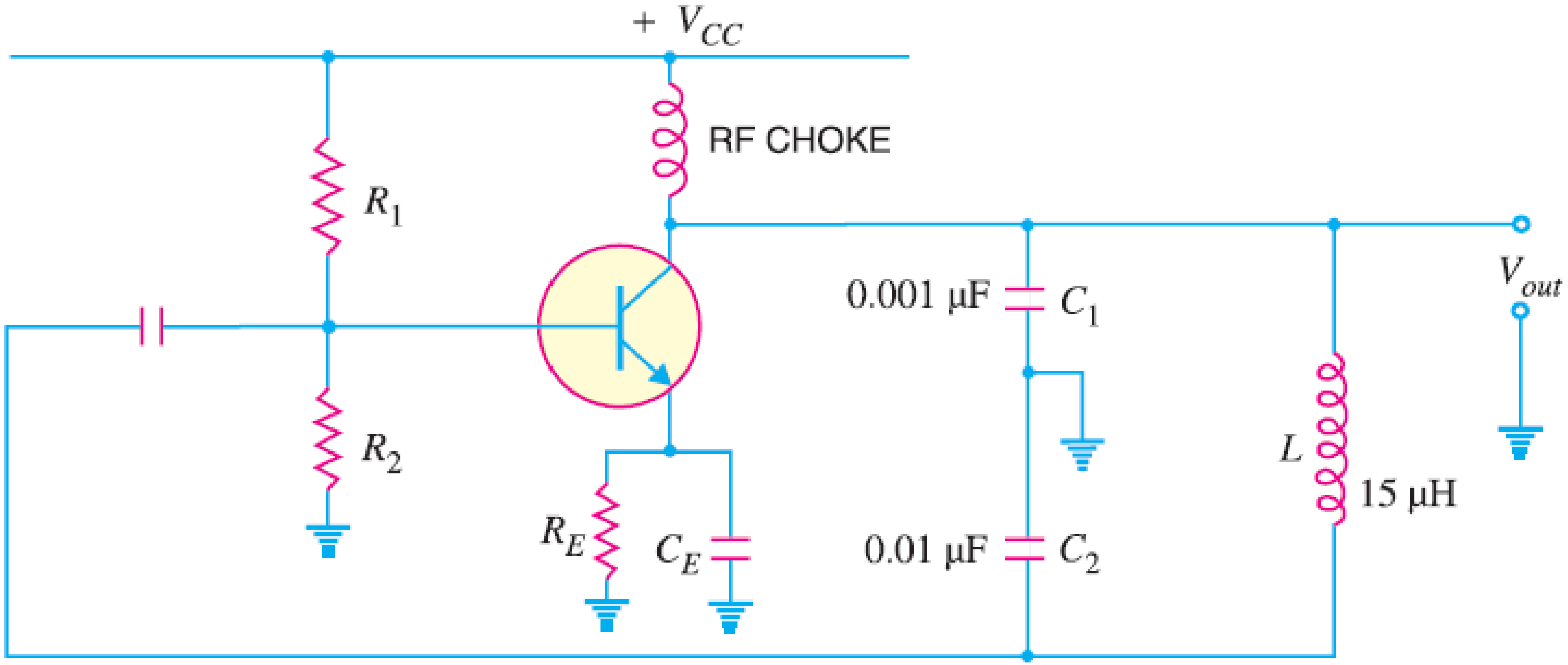
Feedback Fraction (β):

$$\beta = \frac{V_f}{V_0} = \frac{X_{c2}}{X_{c1}} = \frac{\boldsymbol{C_1}}{\boldsymbol{C_2}}$$



Example

Determine the (i) operating frequency and (ii) feedback fraction for Colpitt's oscillator shown.



Ans.

i. 1361 kHz

ii. 0.1

Example

A 1 mH inductor is available. Choose the capacitor values in a Colpitts oscillator so that f = 1 MHz and β = 0.25.

Ans.

C2 = 126.5 pF

C1 = 31.6 pF

Hartley Oscillator

It is similar to Colpitt's oscillator but instead of using tapped capacitors, two inductors L1 and L2 are placed across a common capacitor C and the center of the inductors is tapped.

Frequency of Oscillations (f_r):

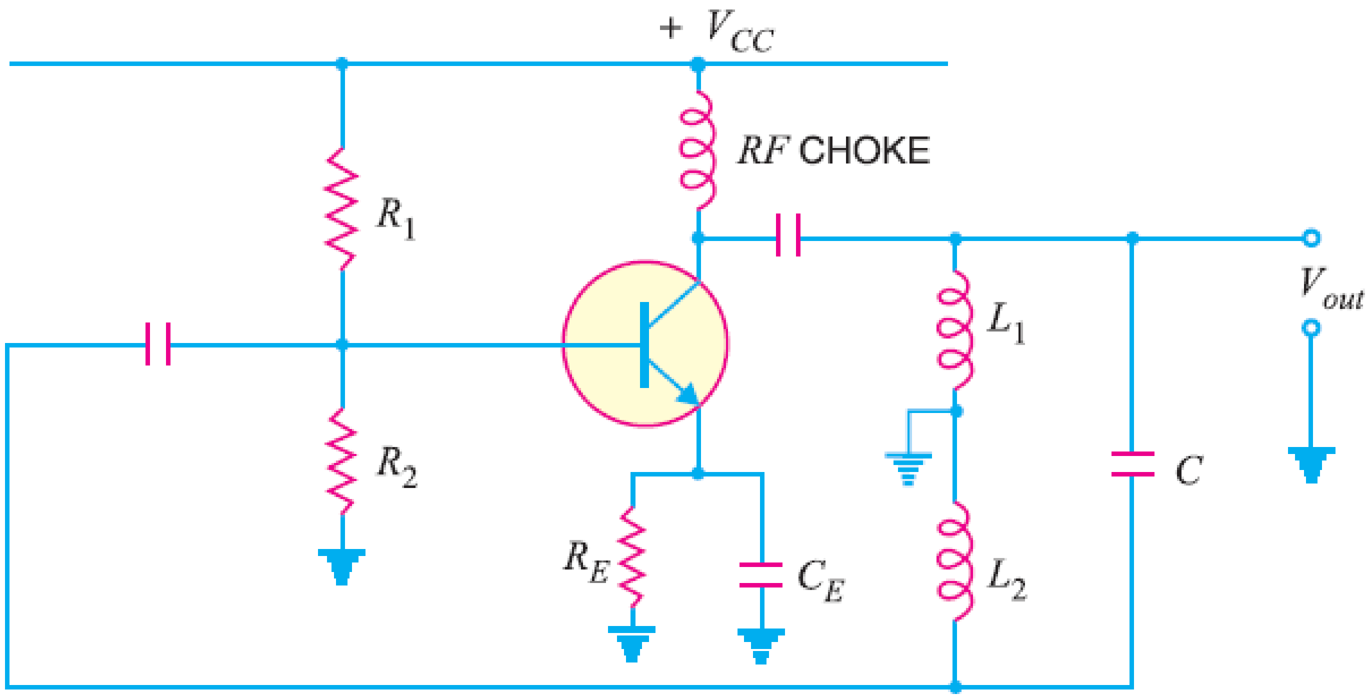
$$f_r = \frac{1}{2\pi\sqrt{CL_T}}$$

Where:

$$L_T = L_1 + L_2 \pm 2M$$

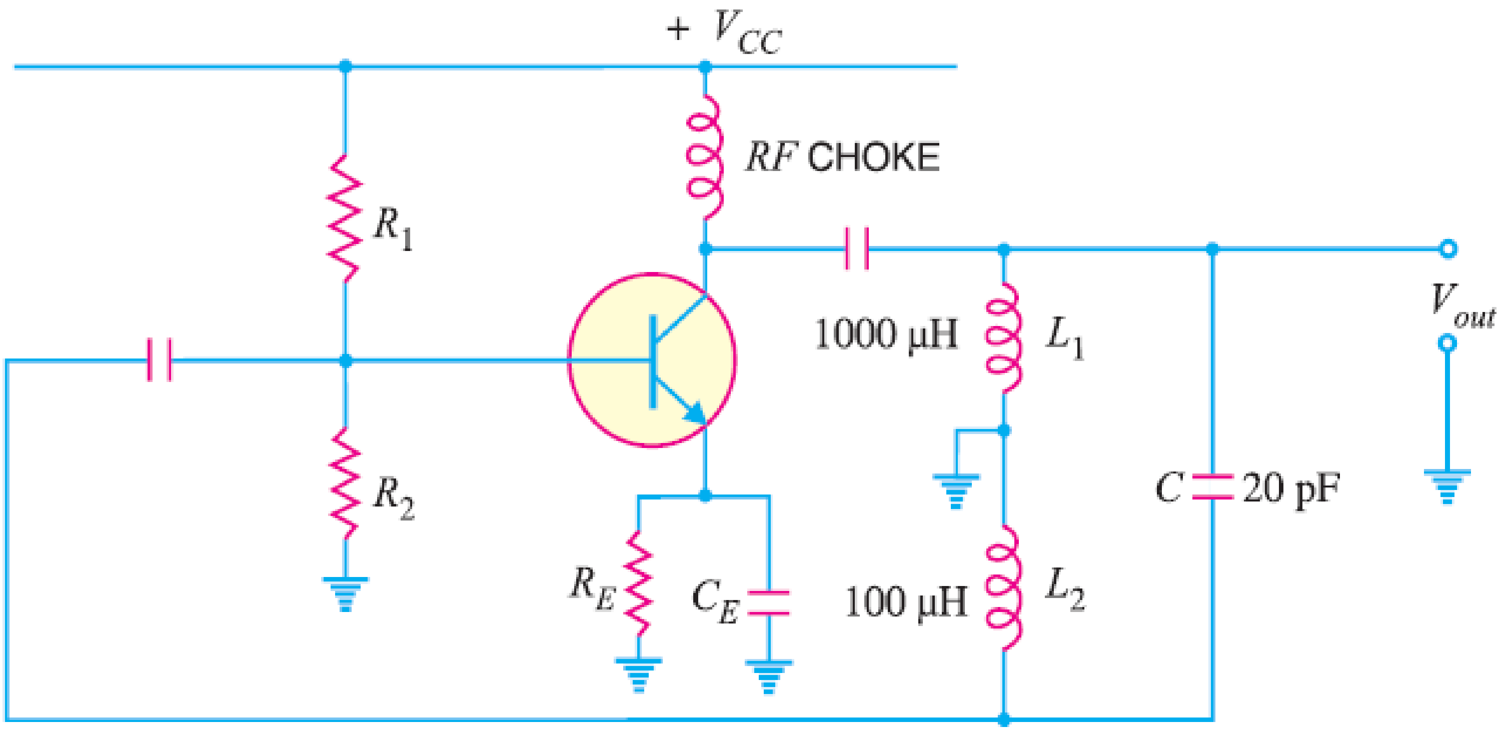
Feedback Fraction (β):

$$\beta = \frac{V_f}{V_0} = \frac{X_{L2}}{X_{L1}} = \frac{\boldsymbol{L_2}}{\boldsymbol{L_1}}$$



Example

Calculate the (i) operating frequency and (ii) feedback fraction for Hartley oscillator shown in Fig. 14.15. The mutual inductance between the coils, M = 20 μH.



Ans.

i) 1052 kHz

ii) 0.1

Example

A 1 pF capacitor is available. Choose the inductor values in a Hartley oscillator so that f = 1 MHz and β = 0.2.

Ans.

L2 = 4.22 mH

L1 = 21.1 mH

Phase Shift Oscillators

The phase shift network consists of three sections R1C1, R2C2 and R3C3. At some particular frequency f_r, the phase shift in each RC section is 60°, total of 180°.

Frequency of Oscillations (f_r):

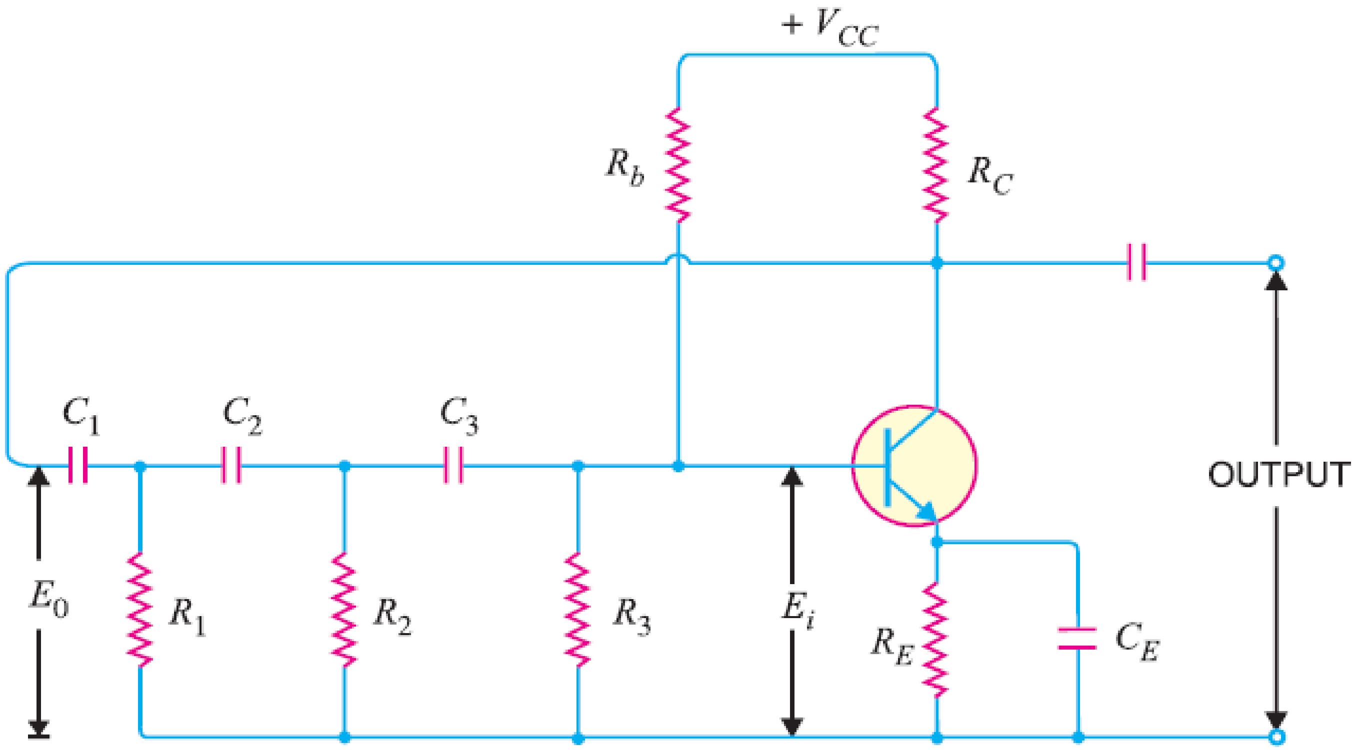
$$f_r = \frac{1}{2\pi RC\sqrt{6}}$$

Where:

$$R_1 = R_2 = R_3 = R\ ;\ C_1 = C_2 = C_3 = C$$

Feedback Fraction (β):

$$\beta = \frac{V_f}{V_0} = \frac{E_i}{E_0} = \frac{1}{29}$$



Phase Shift Oscillators

Advantages

- It does not require transformers or inductors.
- It can be used to produce very low frequencies.
- The circuit provides good frequency stability.

Disadvantages

- It is difficult for the circuit to start oscillations as the feedback is generally small.
- The circuit gives small output.

Example

In a phase shift oscillator, R1 = R2 = R3 = 1MΩ and C1 = C2 = C3 = 68 pF. At what frequency does the circuit oscillate ?

Ans.

954 Hz

Example

A phase shift oscillator uses 5 pF capacitors. Find the value of R to produce a frequency of 800 kHz.

Ans.

16.2 kΩ

Wien Bridge Oscillator

The standard oscillator circuit for all freq. in the range of 10 Hz to about 1 MHz.

It is the most frequently used type of audio oscillator as the output is free from circuit fluctuations and ambient temp.

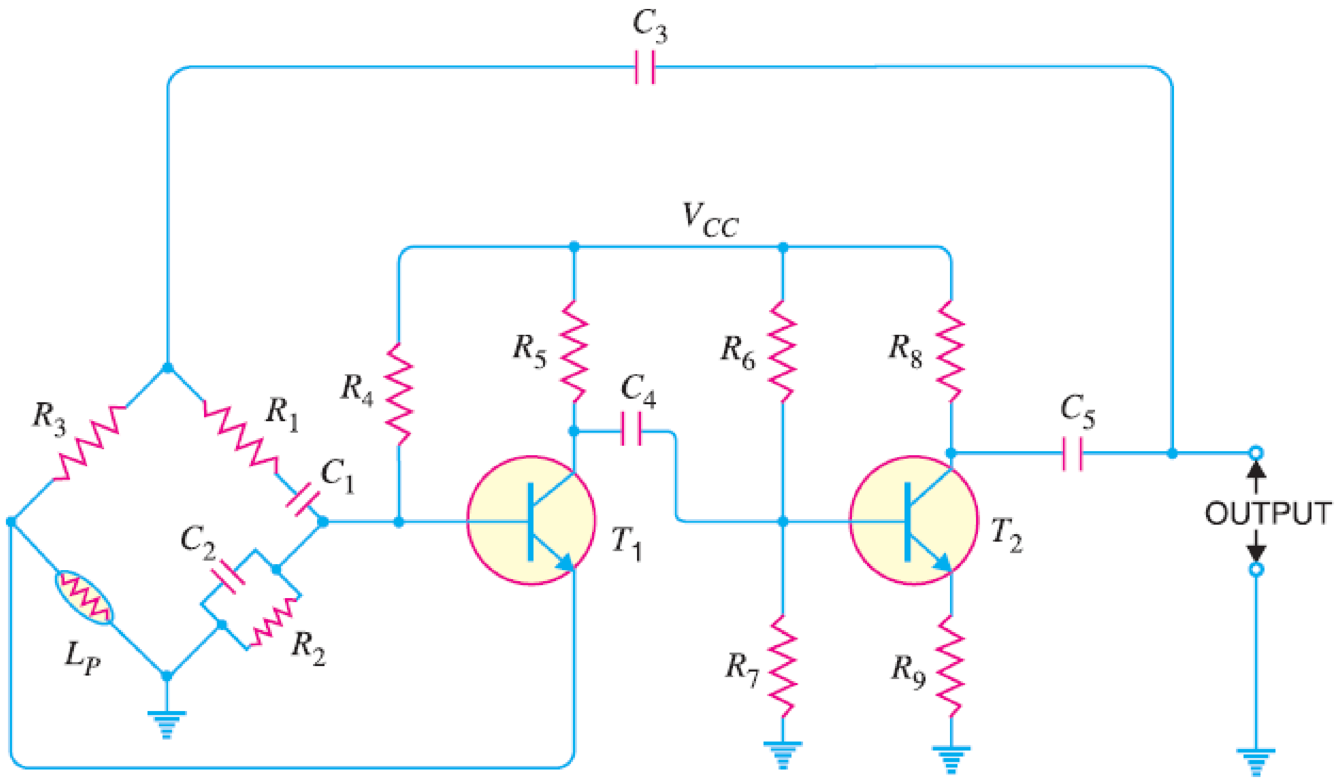
Frequency of Oscillations (f_r):

$$f_r = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$

Then,

$$\boldsymbol{f_r = \frac{1}{2\pi RC}}$$



Wien Bridge Oscillator

Advantages

- It gives constant output.
- The circuit works quite easily.
- The overall gain is high because of two transistors.
- The frequency of oscillations can be easily changed by using a potentiometer.

Disadvantages

- The circuit requires two transistors and a large number of components.
- It cannot generate very high frequencies.

Example

In the Wien bridge oscillator shown in Fig. 14.18, R1 = R2 = 220 kΩ and C1 = C2 = 250 pF. Determine the frequency of oscillations.

Ans.

2892 Hz

Piezoelectric Crystals

Certain crystalline materials, namely, Rochelle salt, quartz and tourmaline exhibit the piezoelectric effect i.e., when we apply an a.c. voltage across them, they vibrate at the frequency of the applied voltage.

Conversely, when they are compressed or placed under mechanical strain to vibrate, they produce an a.c. voltage. Such crystals which exhibit piezoelectric effect are called piezoelectric crystals.

Frequency of crystal

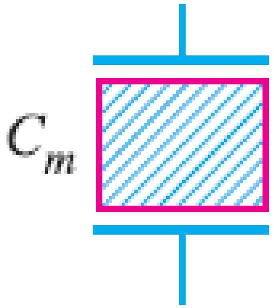
Frequency of crystal (f):

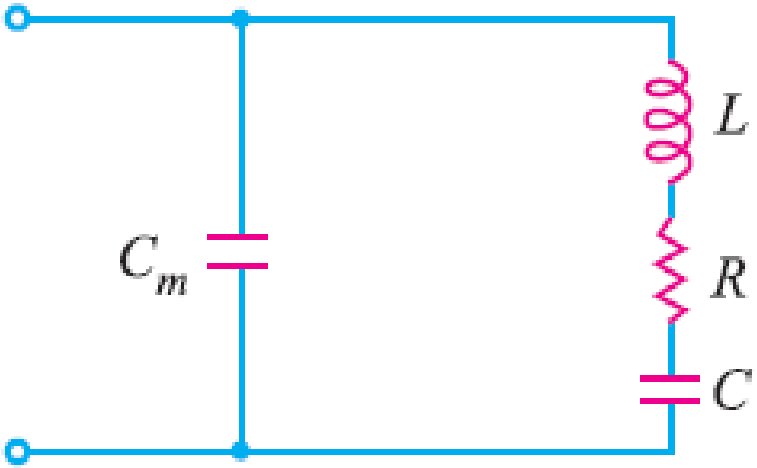
$$f = \frac{K}{t}$$

Where:

K is a constant that depends upon the cut and
t is the thickness of the crystal.

Equivalent Circuit of Crystal





Where:

$C_m = mounting\ capacitance$

L, R, C = electrical equivalent of vibrational characteristic of the crystal

Quality Factor (Q)

Quality Factor of Crystal (Q)

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

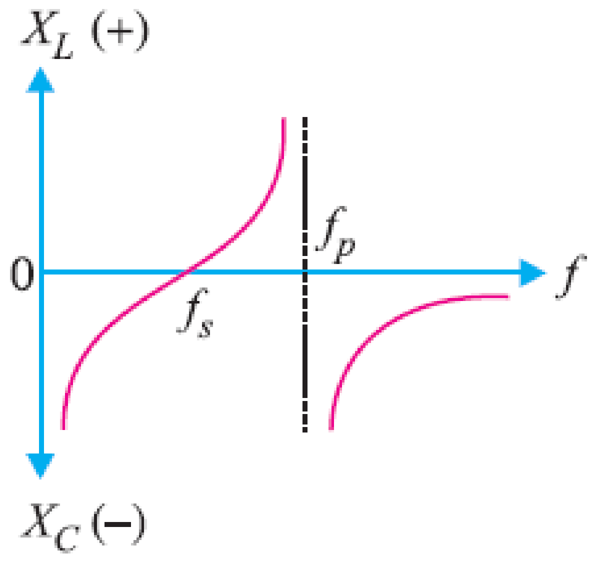
Frequency Response of Crystal

- The frequency at which the vibrating crystal behaves as a series-resonant circuit is called series-resonant frequency (fs).

$$f_s = \frac{1}{2\pi\sqrt{LC}}$$

- At a slightly higher frequency, the net reactance of branch R – L – C becomes inductive and equal to XCm.

The frequency at which the vibrating crystal behaves as a parallel-resonant circuit is called parallel-resonant frequency (fp).



$$f_p = \frac{1}{2\pi\sqrt{LC_T}}$$

where $$C_T = \frac{C \times C_m}{C + C_m}$$

Since C_T is less than C, f_p is always greater than f_s. Note that frequencies f_s and f_p are very close to each other.

Crystal Oscillator

Advantages

- They have a high order of frequency stability.
- The quality factor (Q) of the crystal is very high. The Q factor of the crystal may be as high as 10,000 compared to about 100 of L-C tank.

Disadvantages

- They are fragile and consequently can only be used in low power circuits.
- The frequency of oscillations cannot be changed appreciably.

Example

A crystal has a thickness of t mm. If the thickness is reduced by 1%, what happens to frequency of oscillations ?

Ans.

If the thickness of the crystal is reduced by 1%, the frequency of oscillations will increase by 1%.

Example

The ac equivalent circuit of a crystal has these values: L = 1H, C = 0.01 pF, R = 1000 Ω and Cm = 20 pF. Calculate fs and fp of the crystal.

Ans.

fs = 1589 kHz

fp = 1590 kHz