# In this topic, we’ll learn

- Wave shaping circuits
- Low pass and High pass Filter
- Operational Amplifiers (Op-amp)
- Different circuits of Op-amp

# WAVE SHAPING CIRCUITS

- A wave shaping circuit changes the shape of the input signal using Linear or Non-linear circuits
- A linear circuit uses R/L/C components
- A non-linear circuit uses diode/BJT etc.

Linear Wave Shaping

Linear elements such as resistors, capacitors and inductors are employed to shape a signal in this linear wave shaping.

A Sine wave input has a sine wave output and hence the non-sinusoidal inputs are more prominently used to understand the linear wave shaping.

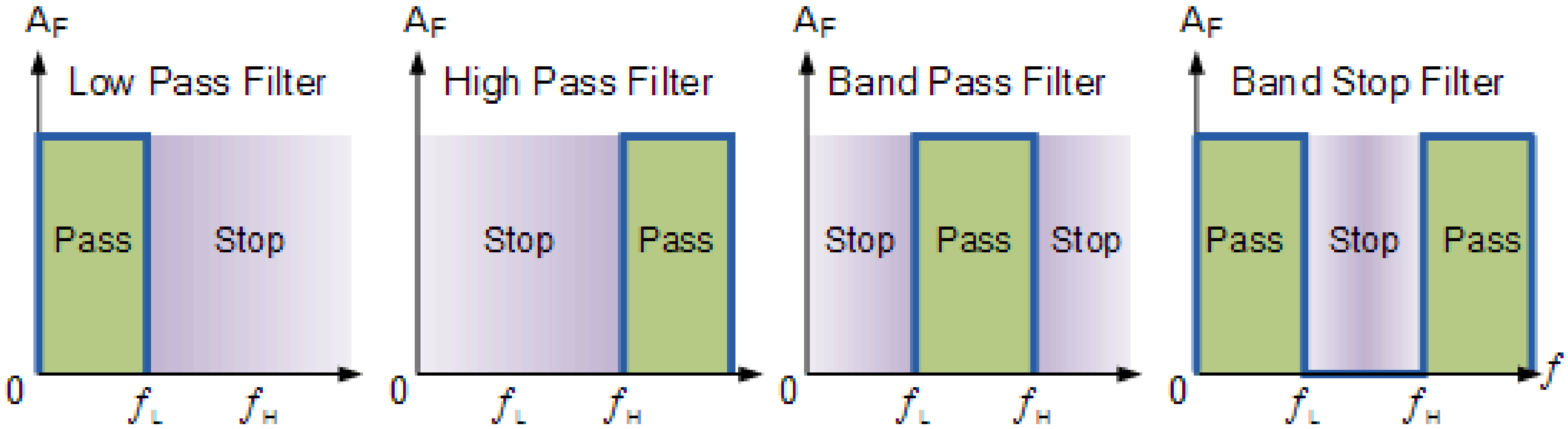
In the process of shaping a signal, if some portions of the signal are felt unwanted, they can be cut off using a Filter Circuit.

A **Filter** is a circuit that can remove unwanted portions of a signal at its input.

- A **Capacitor** has the property to **allow AC** and to **block DC**
- An **Inductor** has the property to **allow DC** but **blocks AC**.

We have four main types of filters –

- Low pass filter
- High pass filter
- Band pass filter
- Band stop filter

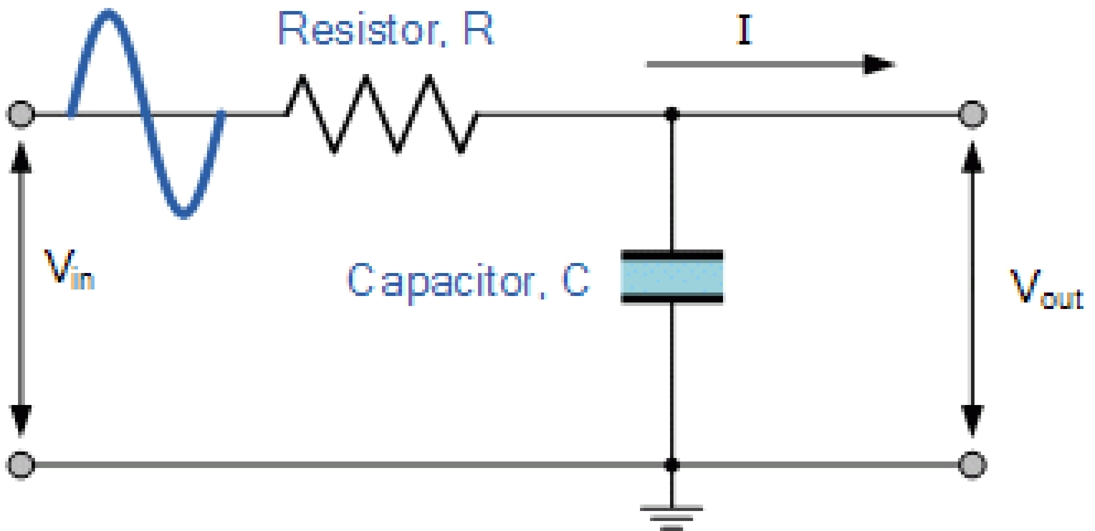


# RC Low Pass Filter Circuit

At low frequencies the capacitive reactance, ( $X_C$ ) of the capacitor will be very large compared to the resistive value of the resistor, R.

This means that the voltage potential, $V_C$ across the capacitor will be much larger than the voltage drop, $V_R$ developed across the resistor.

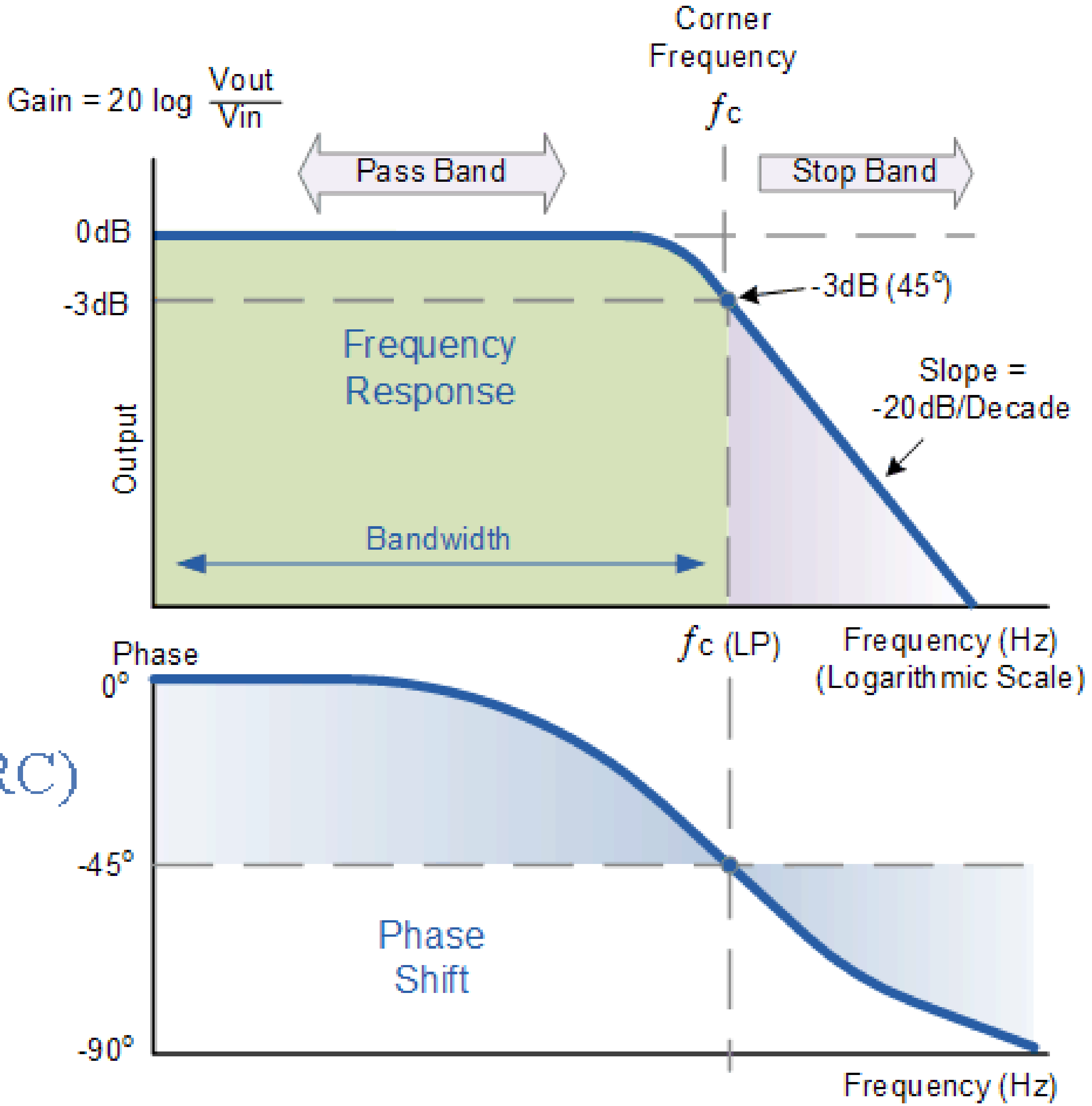
At high frequencies the function reverses.



$$X_C = \frac{1}{2\pi f C} \text{ in Ohm's}$$

$$f_c = \frac{1}{2\pi RC}$$

$$\text{Phase Shift } \varphi = -\arctan(2\pi f RC)$$




**Frequency Response of a 1st-order Low Pass Filter**

A **Low Pass Filter** circuit consisting of a resistor of 4k7Ω in series with a capacitor of 47nF is connected across a 10 V sinusoidal supply. Calculate the output voltage ( $V_{OUT}$ ) at a frequency of 100 Hz and again at frequency of 10,000 Hz or 10 kHz.

**Voltage Output at a Frequency of 100Hz**

$$Xc = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 100 \times 47 \times 10^{-9}} = 33{,}863\Omega$$

$$V_{OUT} = V_{IN} \times \frac{Xc}{\sqrt{R^2 + X_C^2}} = 10 \times \frac{33863}{\sqrt{4700^2 + 33863^2}} = 9.9v$$

**Voltage Output at a Frequency of 10,000Hz (10kHz)**

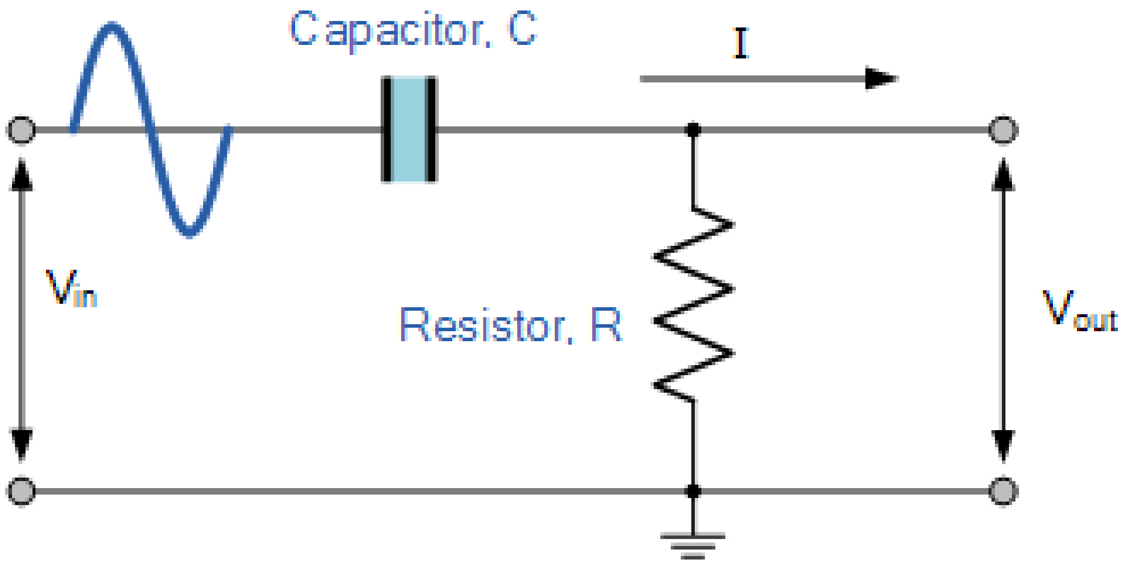
$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 10{,}000 \times 47 \times 10^{-9}} = 338.6\Omega$$

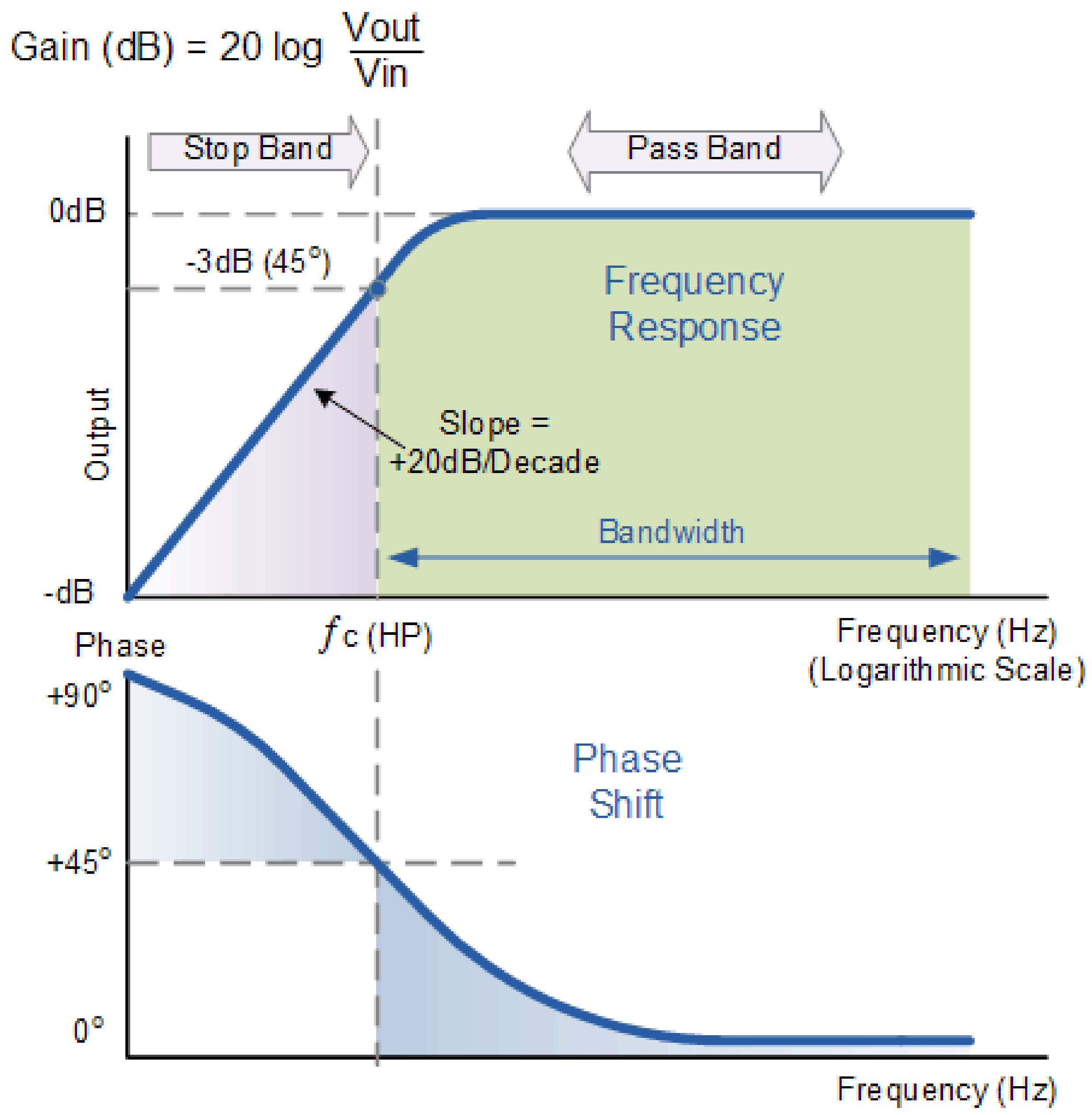
$$V_{OUT} = V_{IN} \times \frac{X_C}{\sqrt{R^2 + X_C^2}} = 10 \times \frac{338.6}{\sqrt{4700^2 + 338.6^2}} = 0.718v$$

## RC High Pass Filter Circuit

In this circuit arrangement, the reactance of the capacitor is very high at low frequencies so the capacitor acts like an open circuit and blocks any input signals at $V_{IN}$ until the cut-off frequency point ( $f_C$ ) is reached.

Above this cut-off frequency point the reactance of the capacitor has reduced sufficiently as to now act more like a short circuit allowing all of the input signal to pass directly to the output as shown in the filter's response curve.






**Frequency Response of a 1st Order High Pass Filter**

$$fc = \frac{1}{2\pi RC}$$

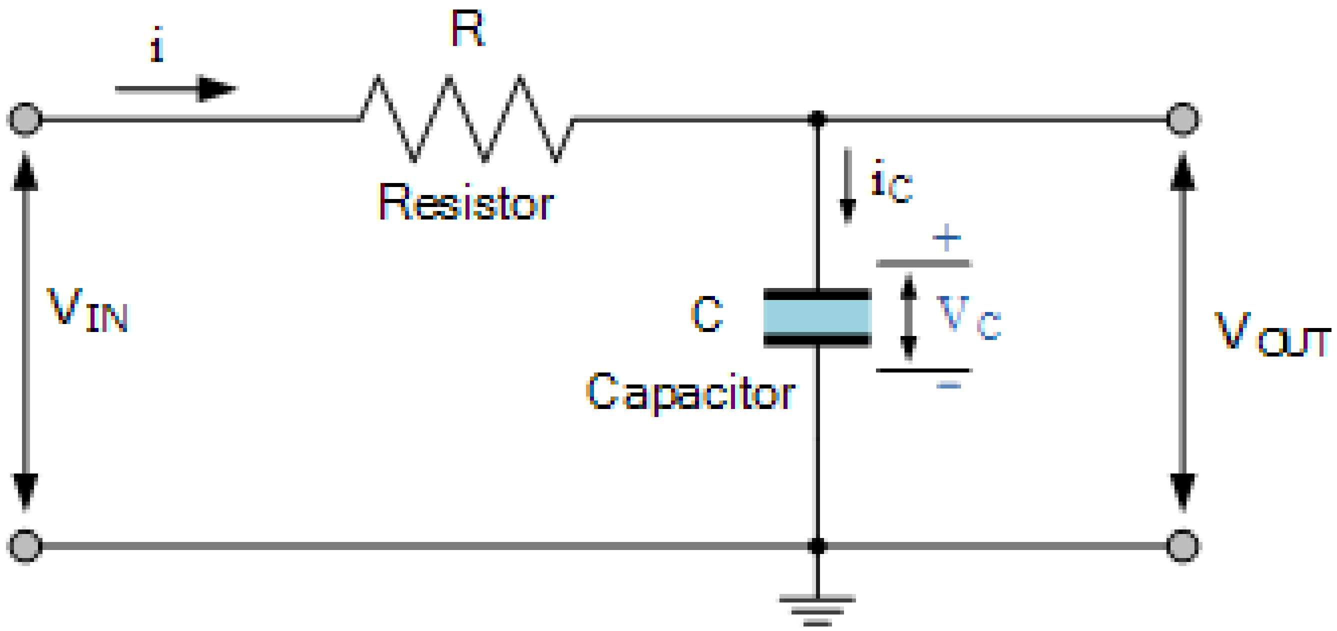
$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{R}{\sqrt{R^2 + Xc^2}} = \frac{R}{Z}$$

$$Phase\ Shift\ \phi = arctan \frac{1}{2\pi fRC}$$

$$\text{at low } f: \ Xc \to \infty, \ Vout = 0$$
$$\text{at high } f: \ Xc \to 0, \ Vout = Vin$$

Calculate the cut-off or “breakpoint” frequency ( ƒc ) for a simple passive high pass filter consisting of an 82pF capacitor connected in series with a 240kΩ resistor. Also find the Vout

# RC Integrator




The capacitor charging current can be written as:

$$i_{C(t)} = C\frac{dV_{C(t)}}{dt}$$

The time constant of a RC integrator circuit is the time interval that equals the product of R and C. **Here RC >> T**

We know that

$i$ = dQ/dt

Hence Q = ∫idt

$$RC = R\frac{Q}{V} = R\frac{i\times T}{i\times R} = \cancel{R}\frac{\cancel{i}\times T}{\cancel{i}\times \cancel{R}} = T$$

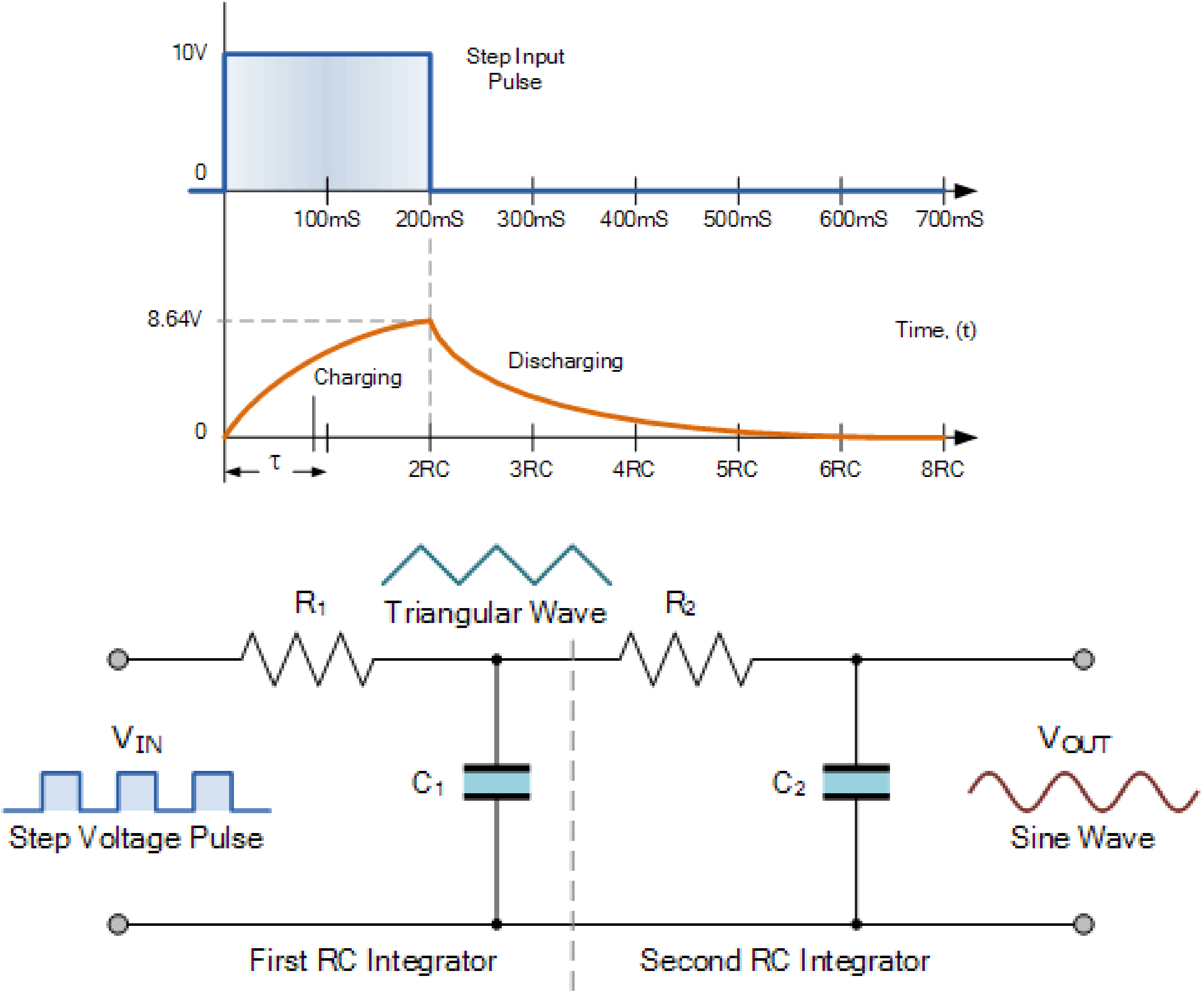
$$\therefore T = RC$$

Since the input is connected to the resistor, the same current, *i* must pass through both the resistor and the capacitor ($i_R = i_C$) producing a $V_R$ voltage drop across the resistor so the current, (*i*) flowing through this series RC network is given as:

$$i(t) = \frac{V_{IN}}{R} = \frac{V_R}{R} = C\frac{dV}{dt}$$

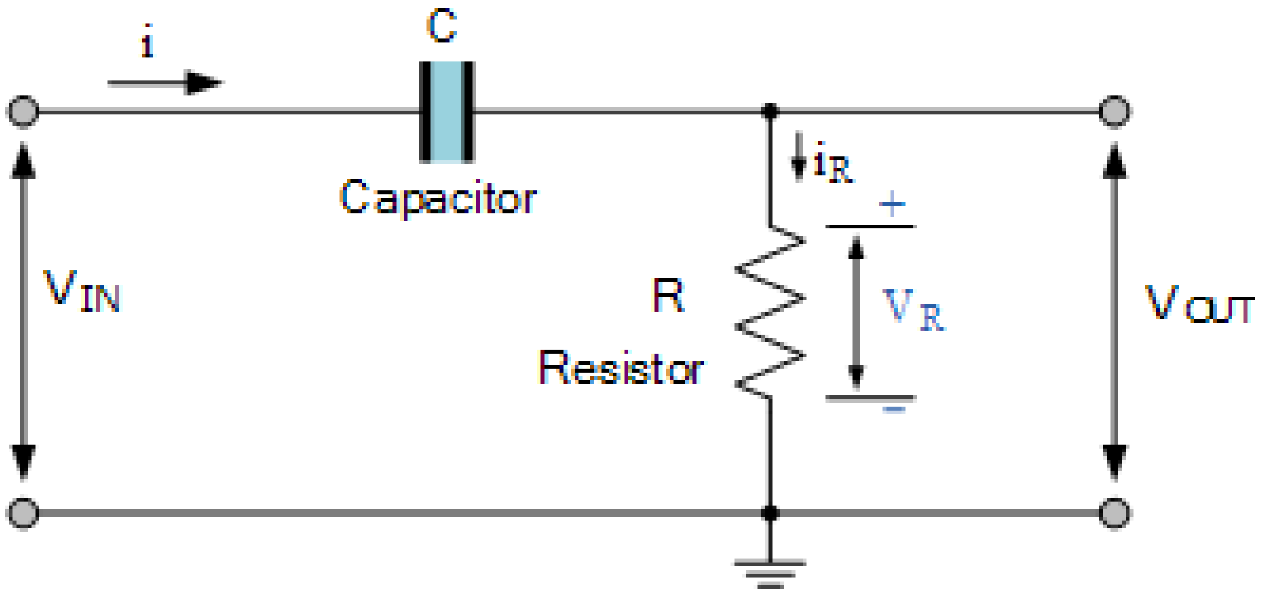
$$V_{OUT} = V_C = \frac{Q}{C} = \frac{\int i dt}{C} = \frac{1}{C}\int i(t)dt$$

$$V_{OUT} = \frac{1}{C}\int\left(\frac{V_{IN}}{R}\right)dt = \frac{1}{RC}\int V_{IN}dt$$



10V
0
Step Input Pulse
100mS
200mS
300mS
400mS
500mS
600mS
700mS
8.64V
Time, (t)
Charging
Discharging
τ
2RC
3RC
4RC
5RC
6RC
8RC
Triangular Wave
R1
R2
VIN
C1
C2
VOUT
Step Voltage Pulse
Sine Wave
First RC Integrator
Second RC Integrator

## RC Differentiator Circuit

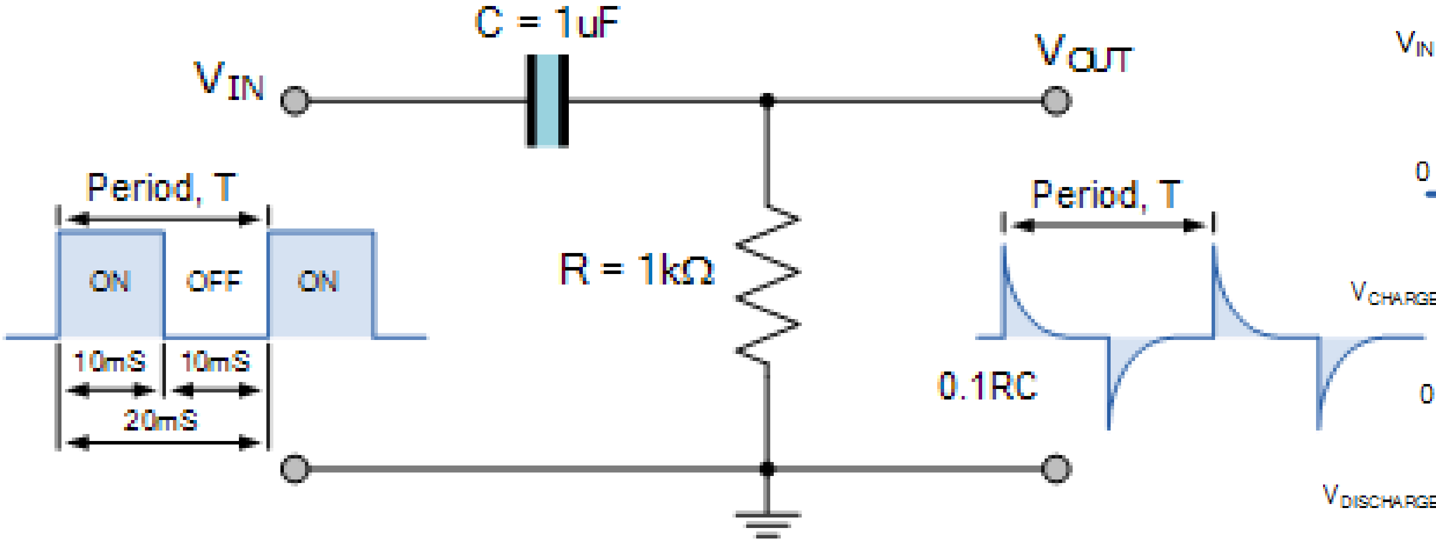


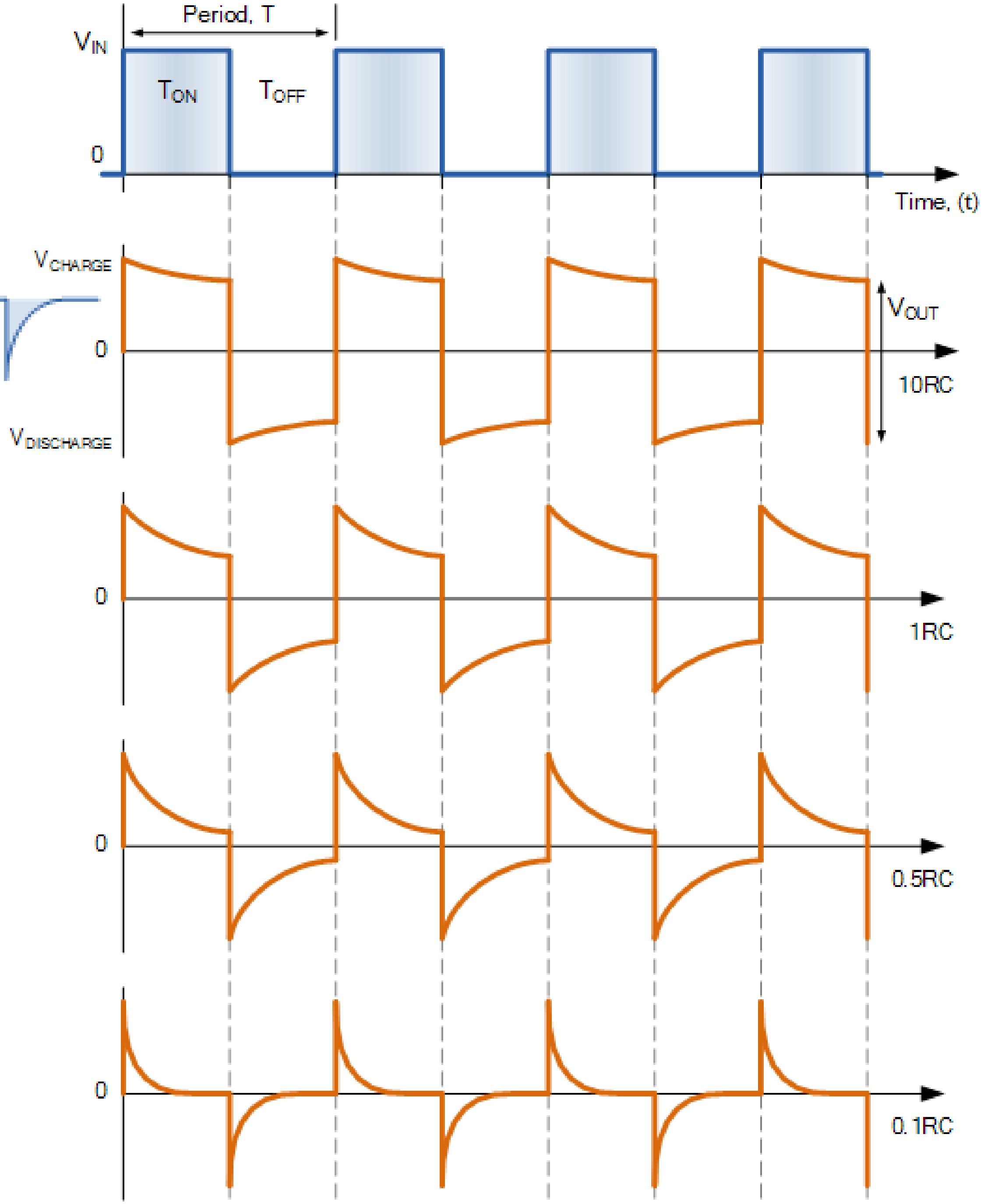

**Here RC << T**

$$i_{(t)} = \frac{dQ}{dt} = \frac{d(C \times dV_C)}{dt} = C\frac{dV_C}{dt} = C\frac{dV_{IN}}{dt}$$

## RC Differentiator Formula

$$i_{C(t)} = C\frac{dV_{IN(t)}}{dt}$$




It is the time required to charge the capacitor, through the resistor, from an initial charge voltage of zero to approximately 63.2% of the value of an applied DC voltage, or to discharge the capacitor through the same resistor to approximately 36.8% of its initial charge voltage. These values are derived from the mathematical constant *e*, 63.2% is approx. 1-e^{-1}} and 36.8 % e^{-1}}

RC INTEGRATOR:

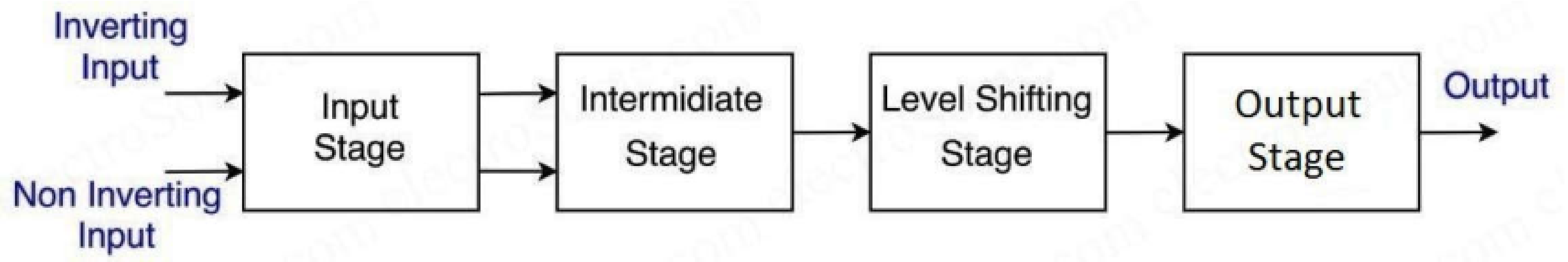
Sine → Cosine
Triangular → Sine
Rectangular → Triangular

RC DIFFERENTIATOR:

Sine → Cosine
Triangular → Square
Rectangular → Spikes

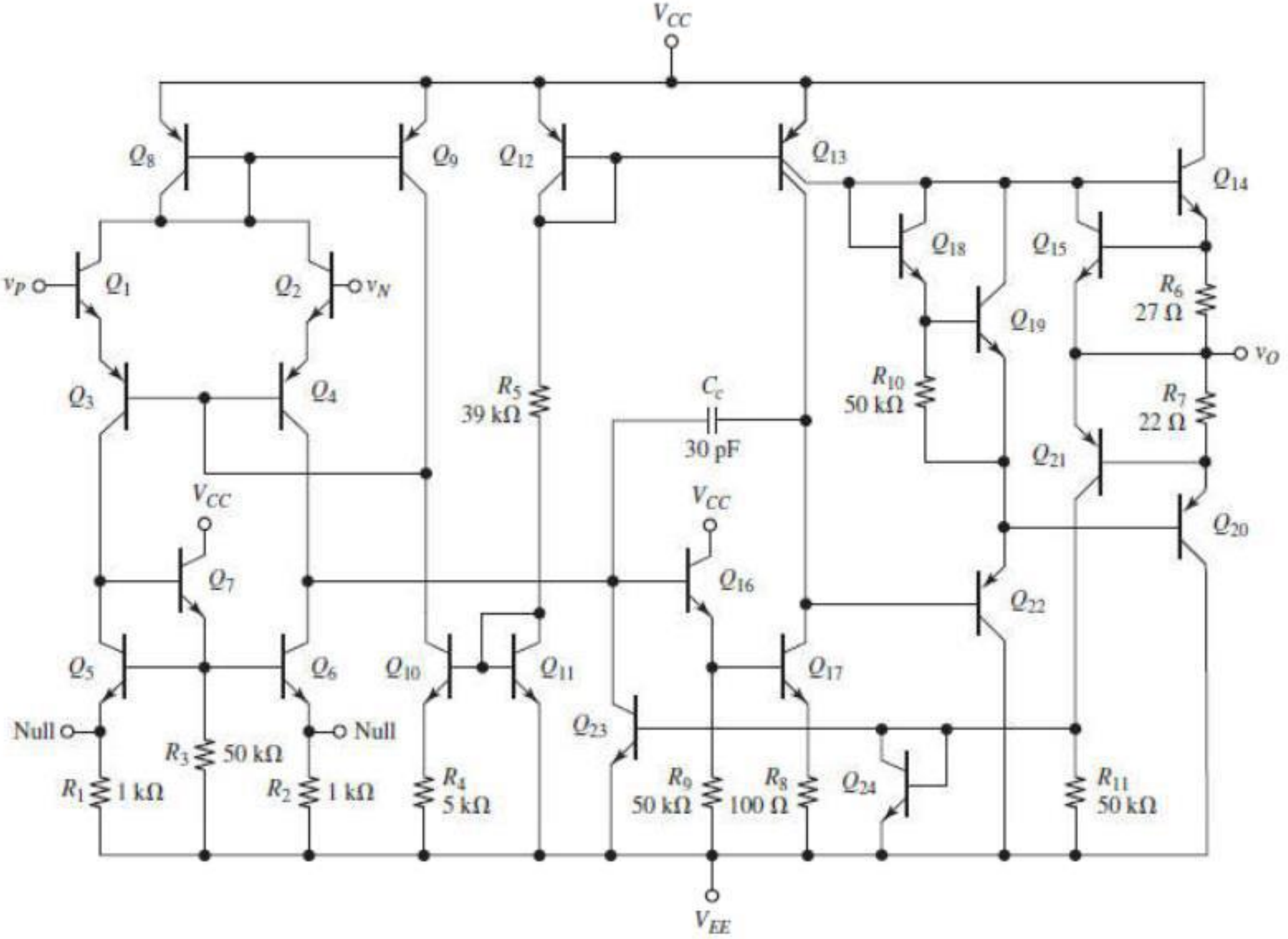
# OPERATIONAL AMPLIFIER

An operational amplifier (*OP*Amp) is an active circuit element designed to perform such mathematical operations as addition, subtraction, integration and differentiation. Hence, the name operational amplifier.

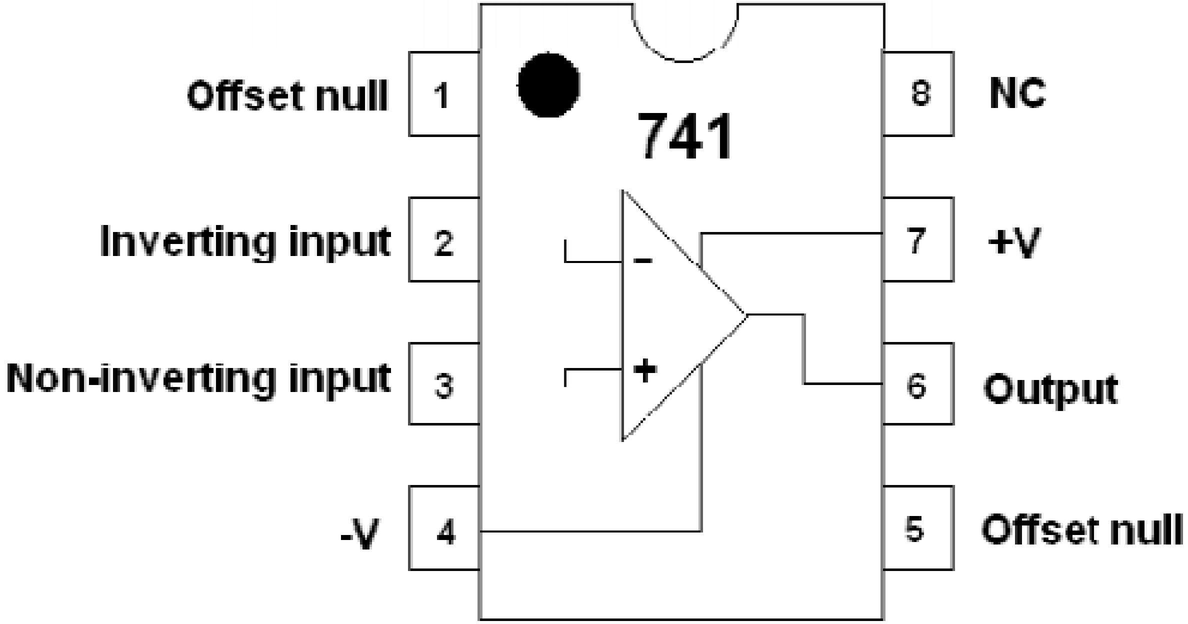


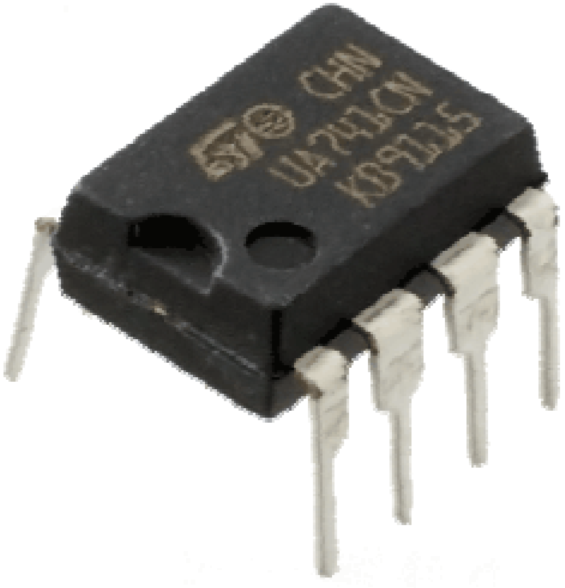

*The key electronic circuit in an OP-Amp is the* ***differential amplifier.*** A differential amplifier (*DA*) can accept two input signals and amplifies the difference between these two input signals.

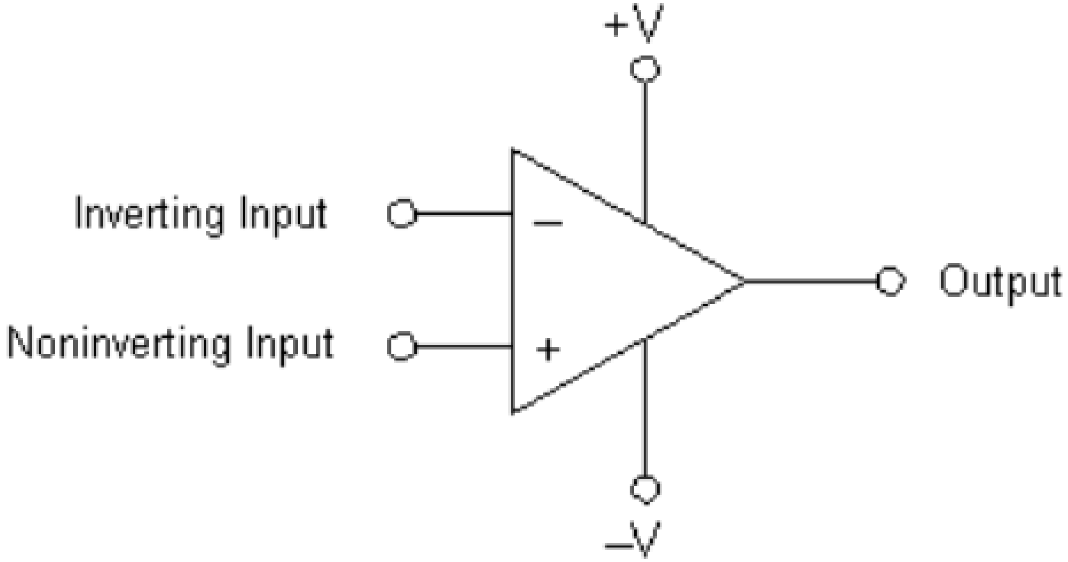
# INTERNAL CIRCUIT OF AN OP-AMP



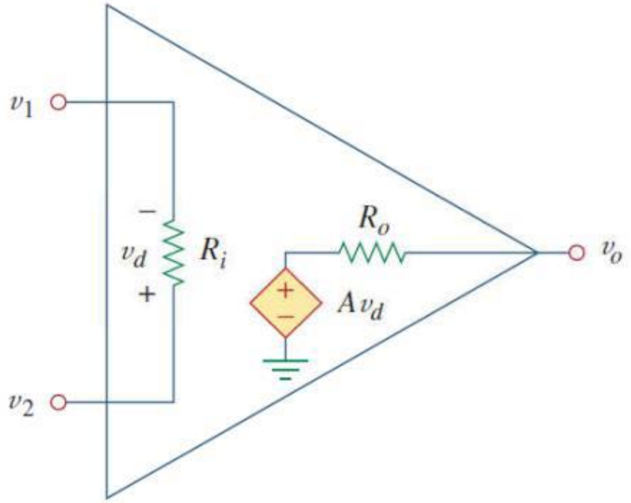
# 741 PACKAGE AND PINS DETAILS






| Parameter | Ideal Op-Amp | Real Op-Amp |
|---|---|---|
| Differential Voltage Gain | ∞ | $10^5$ - $10^9$ |
| Gain Bandwidth Product (Hz) | ∞ | 1-20 MHz |
| Input Resistance (R) | ∞ | $10^6$ - $10^{12}$ Ω |
| Output Resistance (R) | 0 | 100 - 1000 Ω |

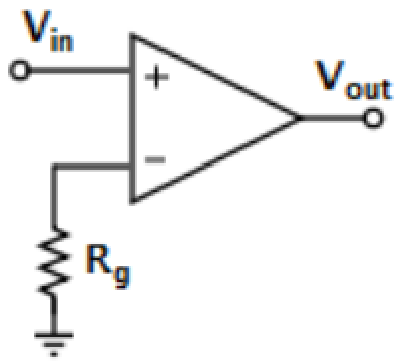



- An op-amp amplifies the difference of the inputs $V_+$ and $V_-$ (known as the differential input voltage)
- This is the equation for an *open loop* gain amplifier:

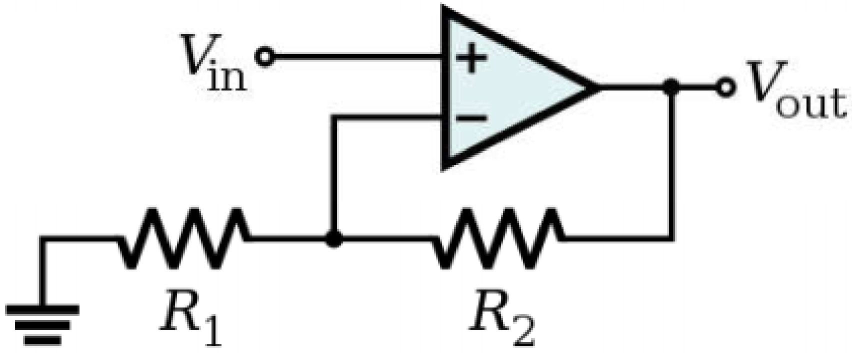
$$\boxed{V_{out}=A(V_+-V_-)}$$

- K is typically very large – at around 10,000 or more for IC Op-Amps
- This equation is the basis for all the types of amps we will be discussing

- A closed loop op-amp has feedback from the output to the input, an open loop op-amp does not




Open Loop




Closed Loop

- **Ideal Opamp**
  - Opamp does not accepts any input current
  - Voltage at inverting Terminal = Voltage at non-inverting terminal.

**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.

**2. OP-Amp Input/Output Polarity Relationship.** The polarity relationship between $v_1$ and $v_2$ will determine whether the *OP*-amp output voltage polarity is positive or negative. There is an easy method for it. 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.*

**3. Supply Voltages.** The supply voltages for an *OP*-amp are normally equal in magnitude and opposite in sign *e.g.*, $\pm 15$V, $\pm 12$V, $\pm 18V$. 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.

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

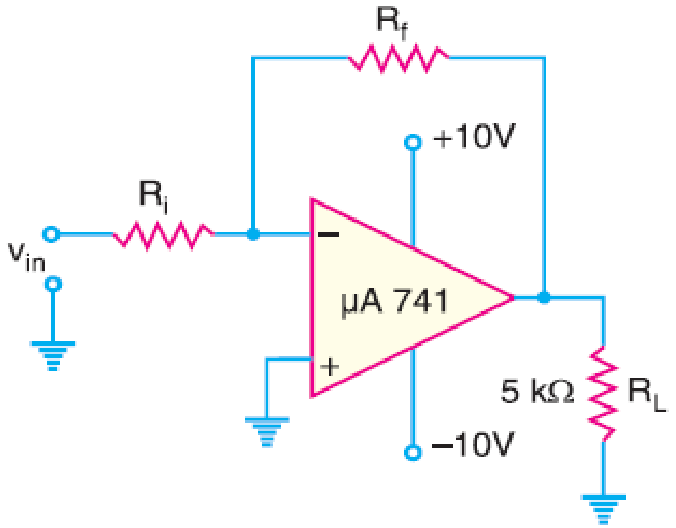
$$\therefore \qquad V_{in} = \frac{V_{sat}}{A_{OL}} = \frac{13V}{20{,}000} = 650\ \mu\text{V}$$

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 slew rate of an *OP*-amp is 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.




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

**Solution.** The maximum peak output voltage($V_{pk}$) is approximately 8*V*. Therefore, maximum operating frequency ($f_{max}$) is given by;

$$f_{max} = \frac{\text{Slew rate}}{2\pi\, V_{pk}} = \frac{0.5\ V/\mu s}{2\pi \times 8}$$

$$= \frac{500\ \text{kHz}}{2\pi \times 8} \quad (\because\ 0.5\ \text{V}/\mu\text{s} = 500\ \text{kHz})$$

$$= \mathbf{9.95\ kHz}$$

# OP-Amp with Negative Feedback

**(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 stabilizes 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)** The inverting amplifier provides constant voltage gain.

One important parameter is **gain-bandwidth product (GBW).** It is defined as under :

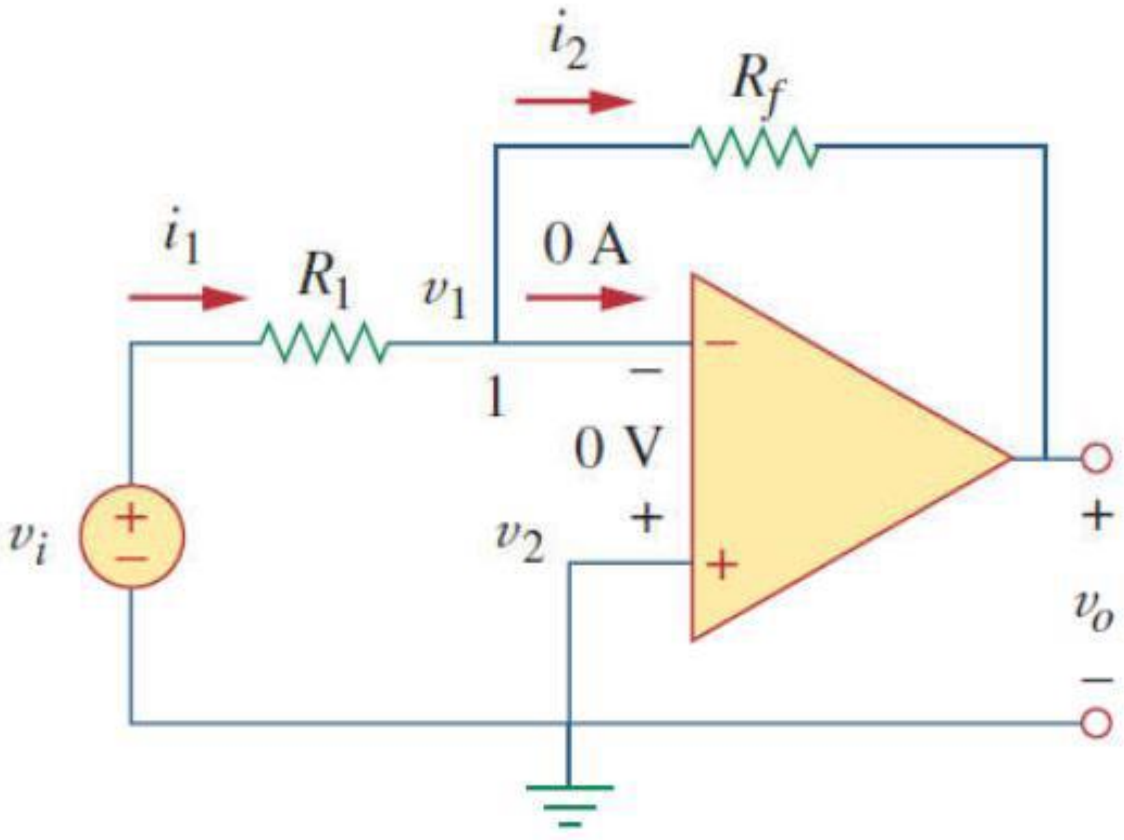
$$A_{CL} \times f_2 = f_{unity} = \text{GBW}$$

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

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

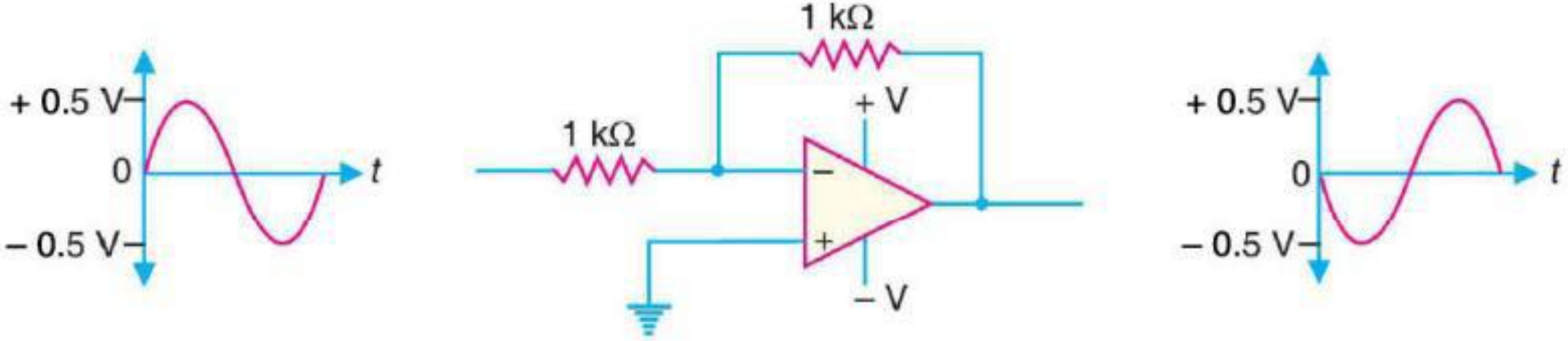
$$\text{Bandwidth, } BW = \frac{GBW}{A_{CL}}$$

# Inverting Amplifier

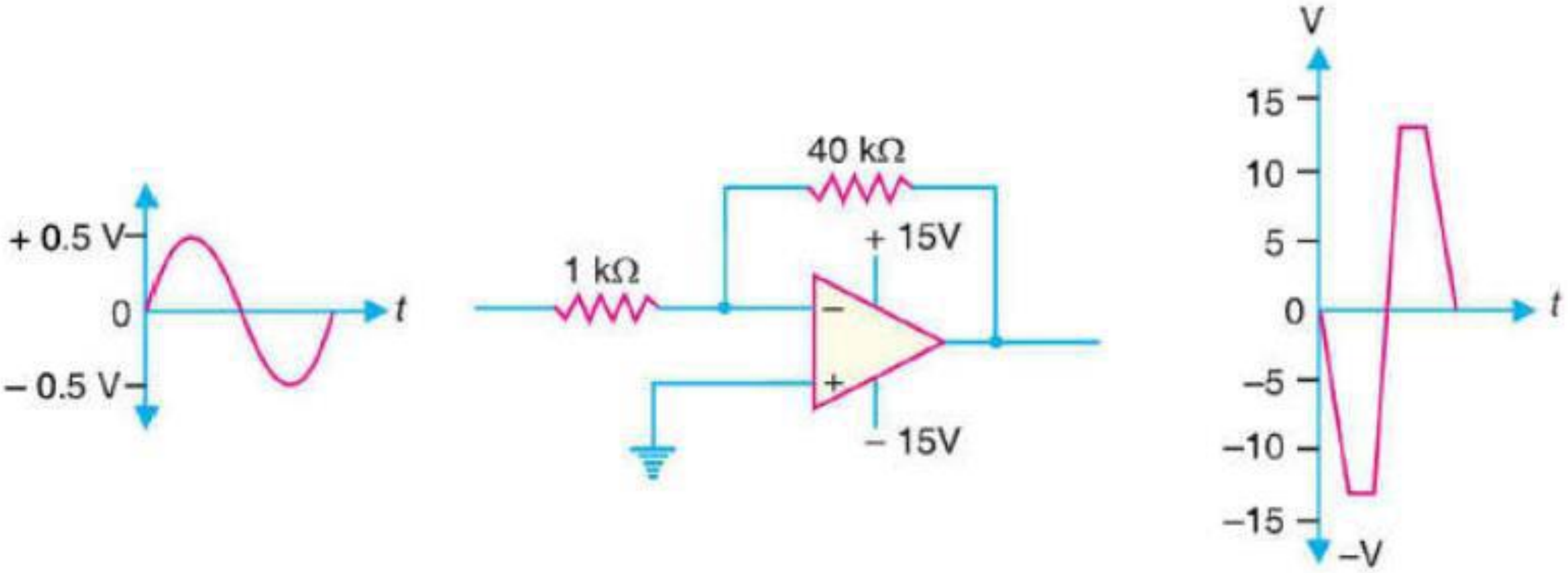



$$i_1 = i_2 \quad \Rightarrow \quad \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

$$v_o = -\frac{R_f}{R_1} v_i$$



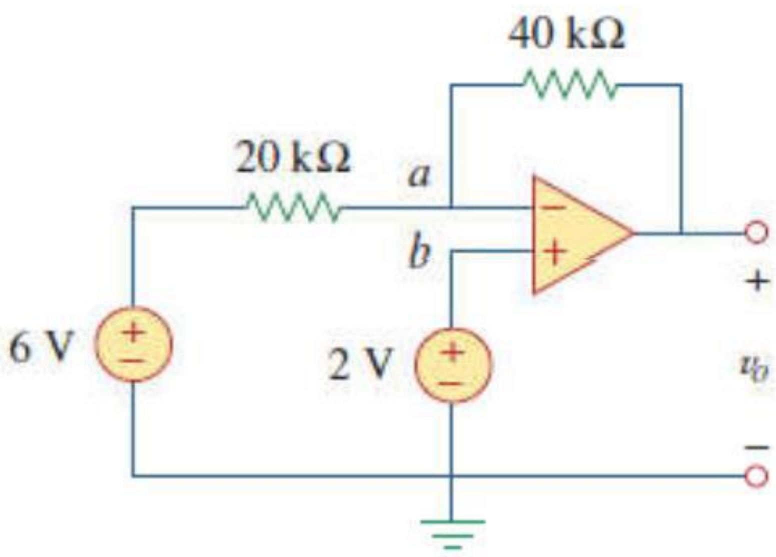

$$\text{Voltage gain, } A_{CL} = -\frac{R_f}{R_i} = -\frac{1\ \text{k}\Omega}{1\ \text{k}\Omega} = -1$$

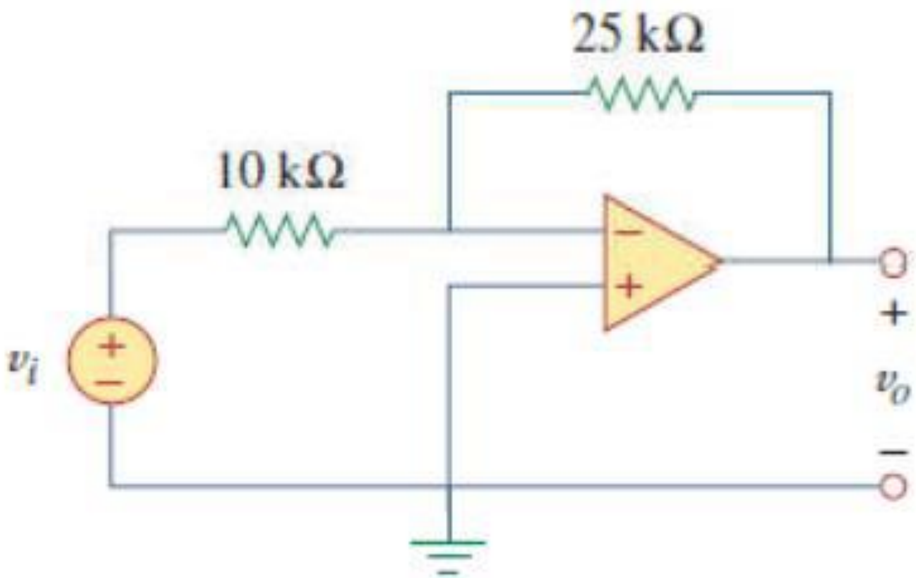



$$\text{Voltage gain, } A_{CL} = -\frac{R_f}{R_i} = -\frac{40\ \text{k}\Omega}{1\ \text{k}\Omega} = -40$$

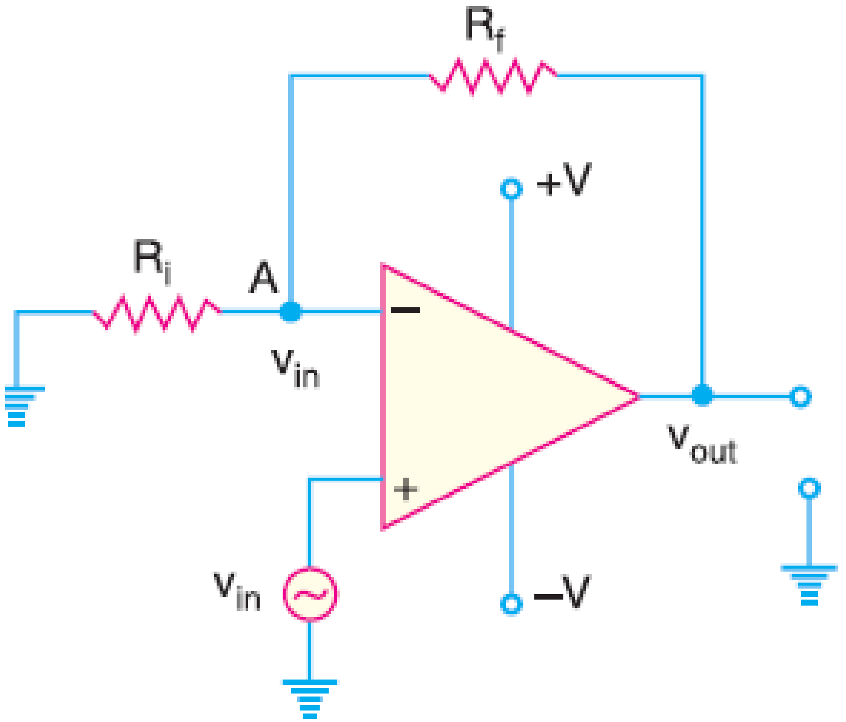
| | **Voltage gain** | **Input Z** | **Output Z** | **Bandwidth** |
|---|---|---|---|---|
| Without negative feedback | $A_{OL}$ is too high for linear amplifier applications | Relatively high | Relatively low | Relatively narrow |
| With negative feedback | $A_{CL}$ is set by the feedback circuit to 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 |

- For the opamp in figure below. If vi is 0.5 V, calculate: (a) the output voltage vo, and (b) the current in the 10-k resistor.



# Non-Inverting Amplifier



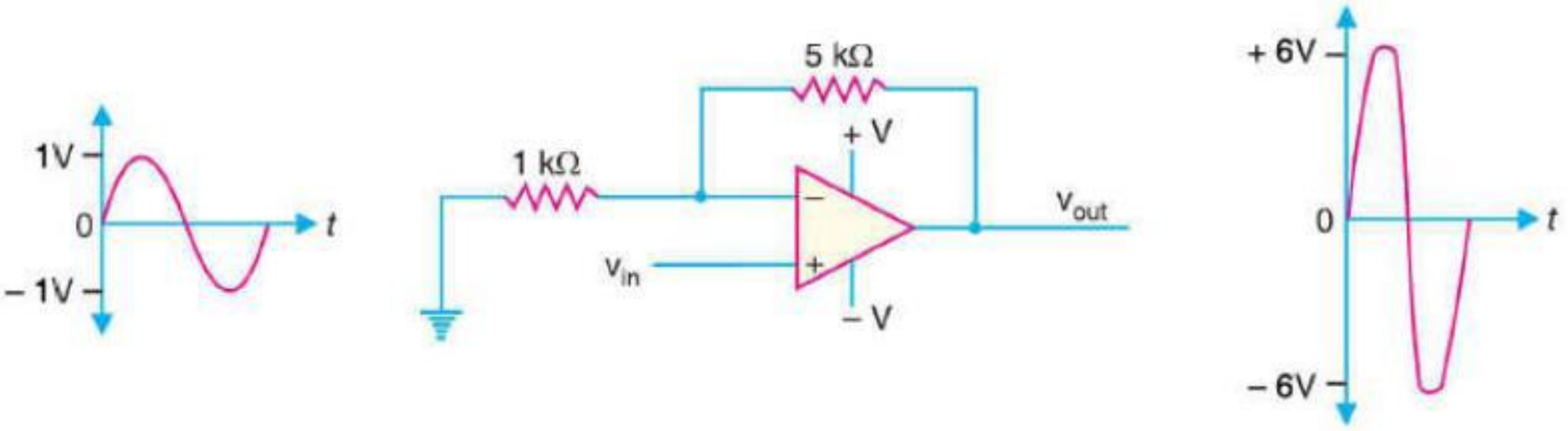

$$i_1 = i_2 \Rightarrow \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

But $v_1 = v_2 = v_i$. Equation (5.10) becomes

$$\frac{-v_i}{R_1} = \frac{v_i - v_o}{R_f}$$

or

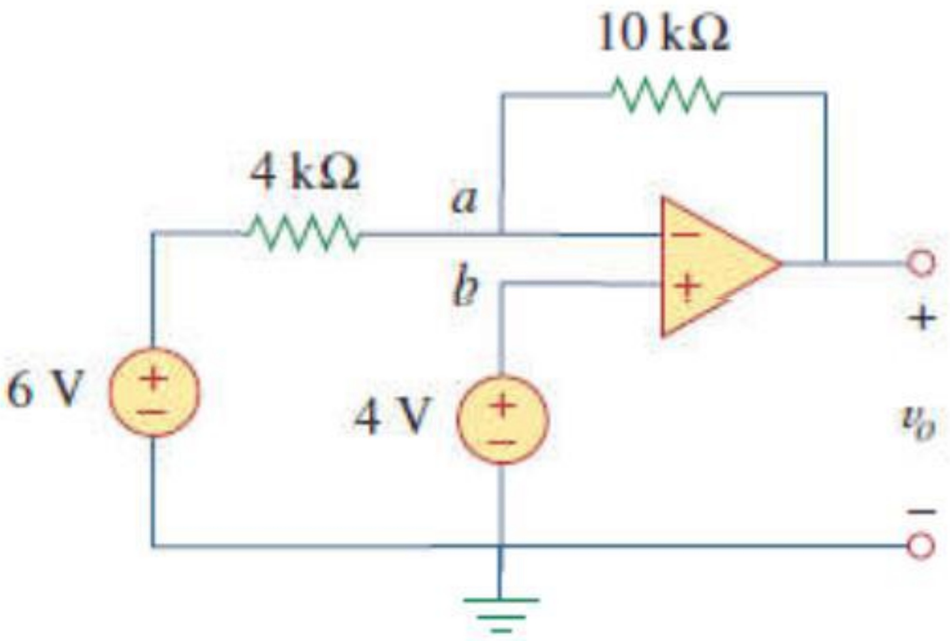
$$\boxed{v_o = \left(1 + \frac{R_f}{R_1}\right)v_i}$$




The input signal is 2 V peak-to-peak.

$$\text{Voltage gain, } A_{CL} = 1 + \frac{R_f}{R_i} = 1 + \frac{5\,\text{k}\Omega}{1\,\text{k}\Omega} = 1 + 5 = 6$$

$\therefore$ Peak-to-peak output voltage $= A_{CL} \times v_{inpp} = 6 \times 2 =$ **12 V**




Determine *V*o

Applying KCL at node $a$,

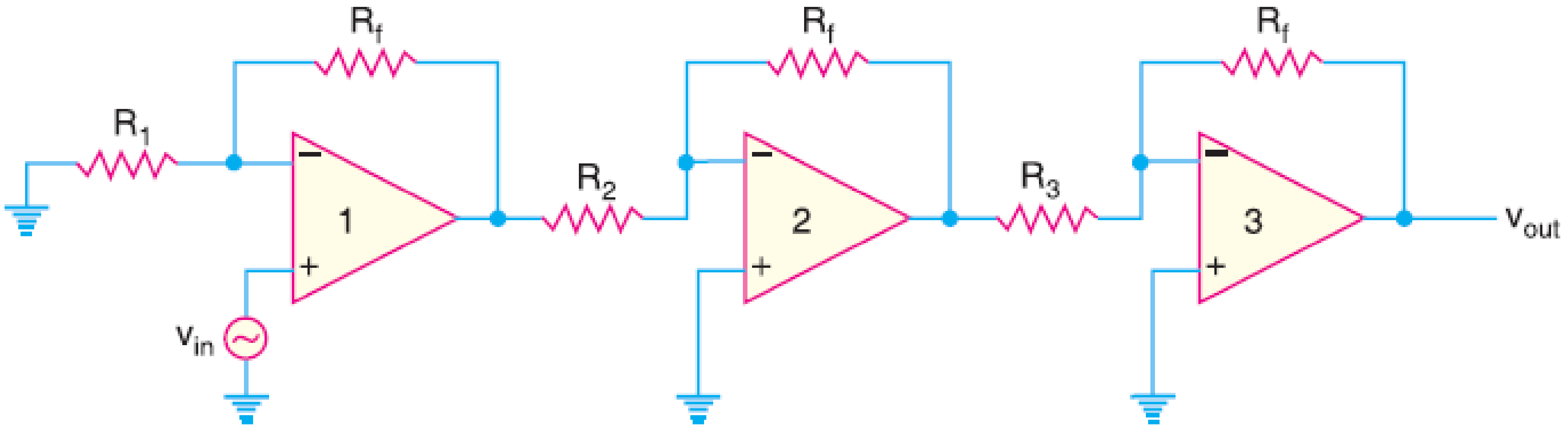
$$\frac{6 - v_a}{4} = \frac{v_a - v_o}{10}$$

But $v_a = v_b = 4$, and so

$$\frac{6-4}{4} = \frac{4 - v_o}{10} \quad \Rightarrow \quad 5 = 4 - v_o$$

or $v_o = -1$ V, as before.

# Multi-stage OP-Amp Circuits




The overall voltage gain $A$ of this circuit is given by;

$$A = A_1 A_2 A_3$$

where $A_1$ = Voltage gain of first stage = $1 + (R_f/R_1)$

$A_2$ = Voltage gain of second stage = $-R_f/R_2$

$A_3$ = Voltage gain of third stage = $-R_f/R_3$

Since the overall voltage gain is positive, the circuit behaves as a noninverting amplifier.

*For the Fig. shown, the resistor values are : $R_f$ = 470 kΩ ; $R_1$ = 4.3 kΩ ; $R_2$ = 33 kΩ and $R_3$ = 33 kΩ. Find the output voltage for an input of 80 µV.*

**Solution.** Voltage gain of first stage, $A_1 = 1 + (R_f/R_1) = 1 + (470\ \text{k}\Omega/4.3\ \text{k}\Omega) = 110.3$

Voltage gain of second stage, $A_2 = -R_f/R_2 = -470\ \text{k}\Omega/33\ \text{k}\Omega = -14.2$

Voltage gain of third stage, $A_3 = -R_f/R_3 = -470\ \text{k}\Omega/33\ \text{k}\Omega = -14.2$

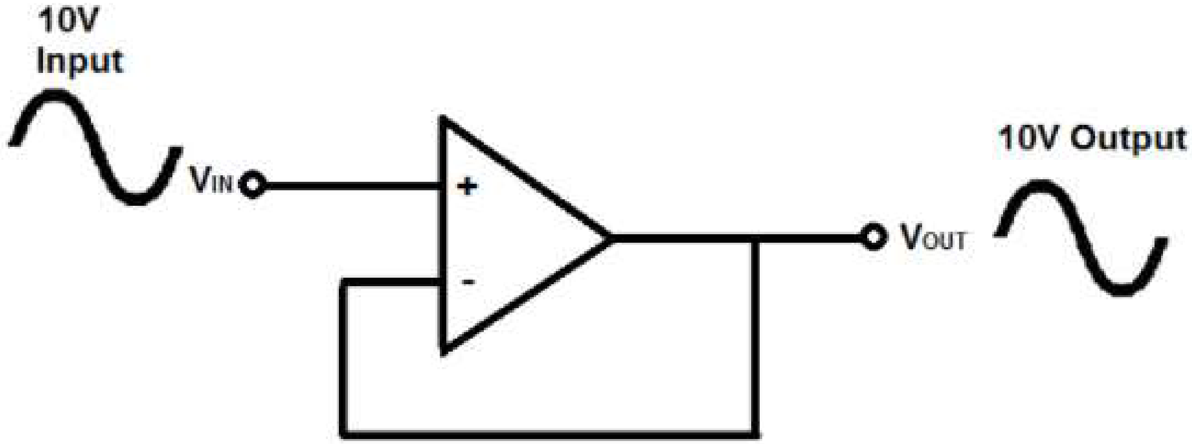
$\therefore$ Overall voltage gain, $A = A_1A_2A_3 = (110.3) \times (-14.2) \times (-14.2) = 22.2 \times 10^3$

Output voltage, $v_{out} = A \times v_{in} = 22.2 \times 10^3 \times (80\ \mu\text{V}) =$ **1.78V**

# OP AMP AS A BUFFER

A voltage follower is also known as a buffer amplifier, unity gain amplifier, or isolation amplifier

It is an Op-Amp circuit whose output voltage is equal to the input voltage , so the output voltage follows the input voltage ($V_{out}=V_{in}$)



A voltage follower Op Amp does not amplify the input signal and has a voltage gain of 1

Gain with feedback or closed loop gain of this circuit is 1

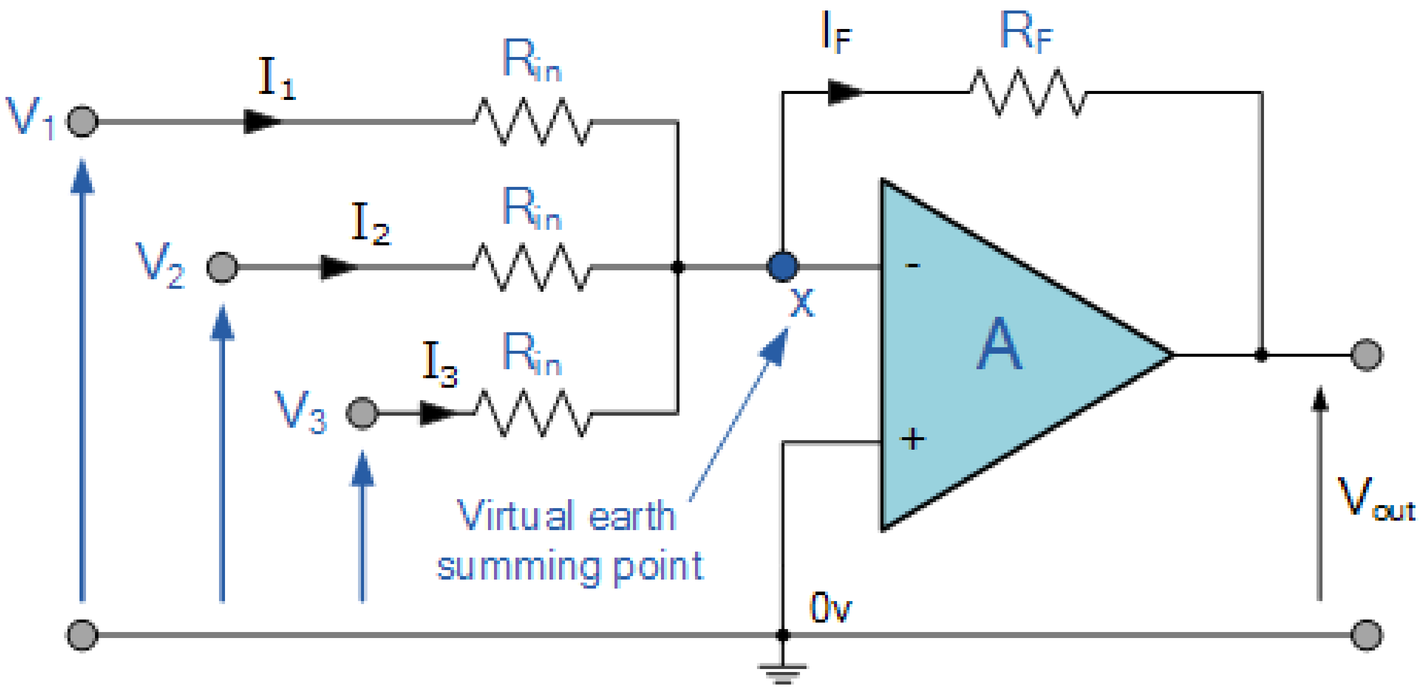
The voltage follower provides no attenuation or amplification only buffering.

It is a special case of non-inverting Op-Amp, therefore, in this circuit the output signal is in phase with the input signal

The feedback resistance $R_f = 0$ and the input resistance $R_i = \infty$

# Summing Amplifier Circuit

## Inverting Summing Amplifier




$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin}\right]$$

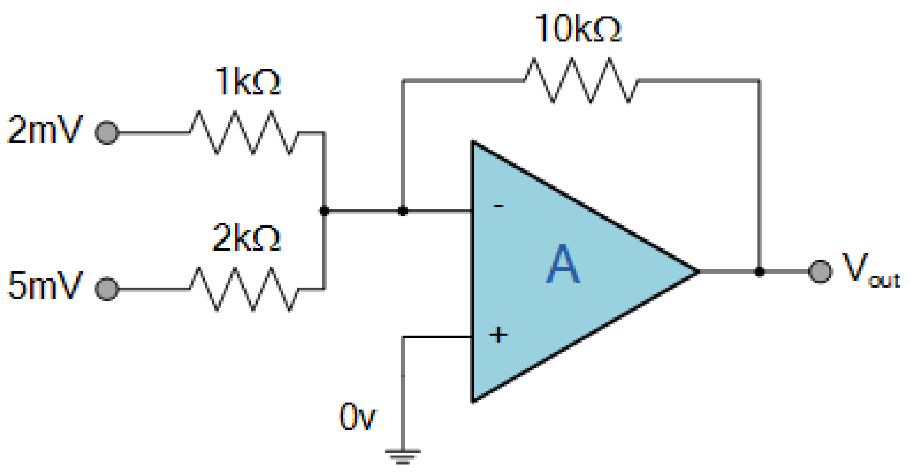
Inverting Equation: $Vout = -\frac{Rf}{Rin} \times Vin$

$$-Vout = \frac{R_F}{R_{IN}}\left(V1 + V2 + V3 \ldots .etc\right)$$

then, $-Vout = \left[\frac{R_F}{Rin}V1 + \frac{R_F}{Rin}V2 + \frac{R_F}{Rin}V3\right]$

A **Scaling Summing Amplifier** can be made if the individual input resistors are “NOT” equal. Then the equation would have to be modified to:

$$-V_{OUT} = V_1\left(\frac{R_f}{R_1}\right) + V_2\left(\frac{R_f}{R_2}\right) + V_3\left(\frac{R_f}{R_3}\right) \text{....etc}$$

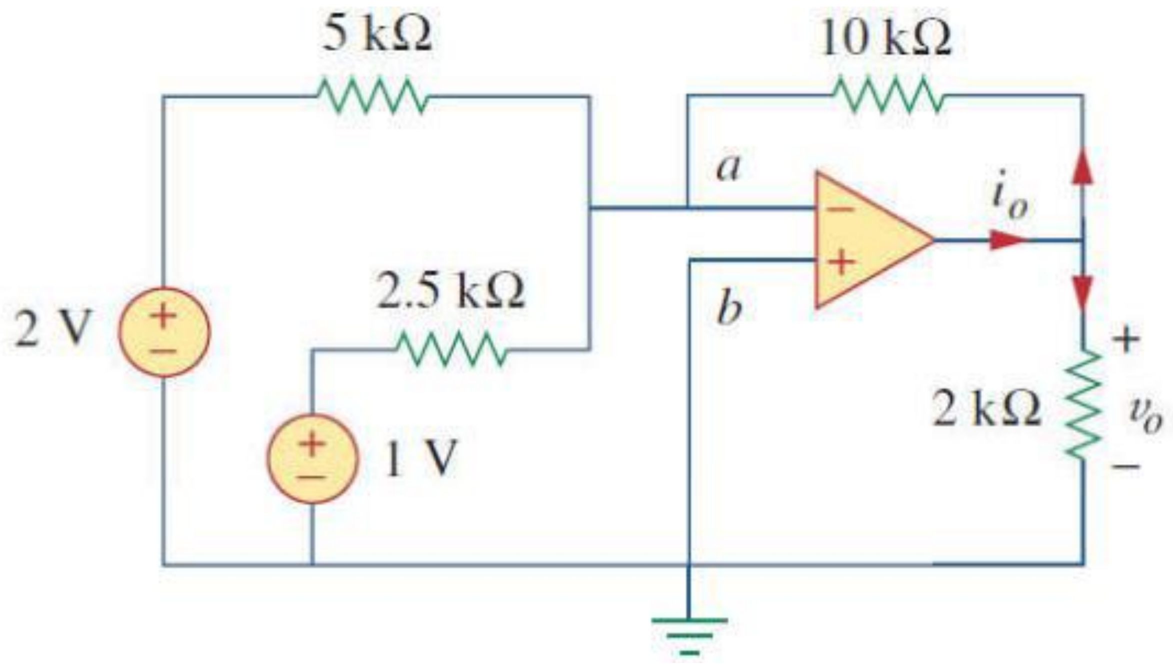



$$A_1 = \frac{10k\Omega}{1k\Omega} = -10$$

$$A_2 = \frac{10k\Omega}{2k\Omega} = -5$$

$$Vout = (A_1 \times V_1) + (A_2 \times V_2)$$

$$Vout = (-10(2mV)) + (-5(5mV)) = -45mV$$



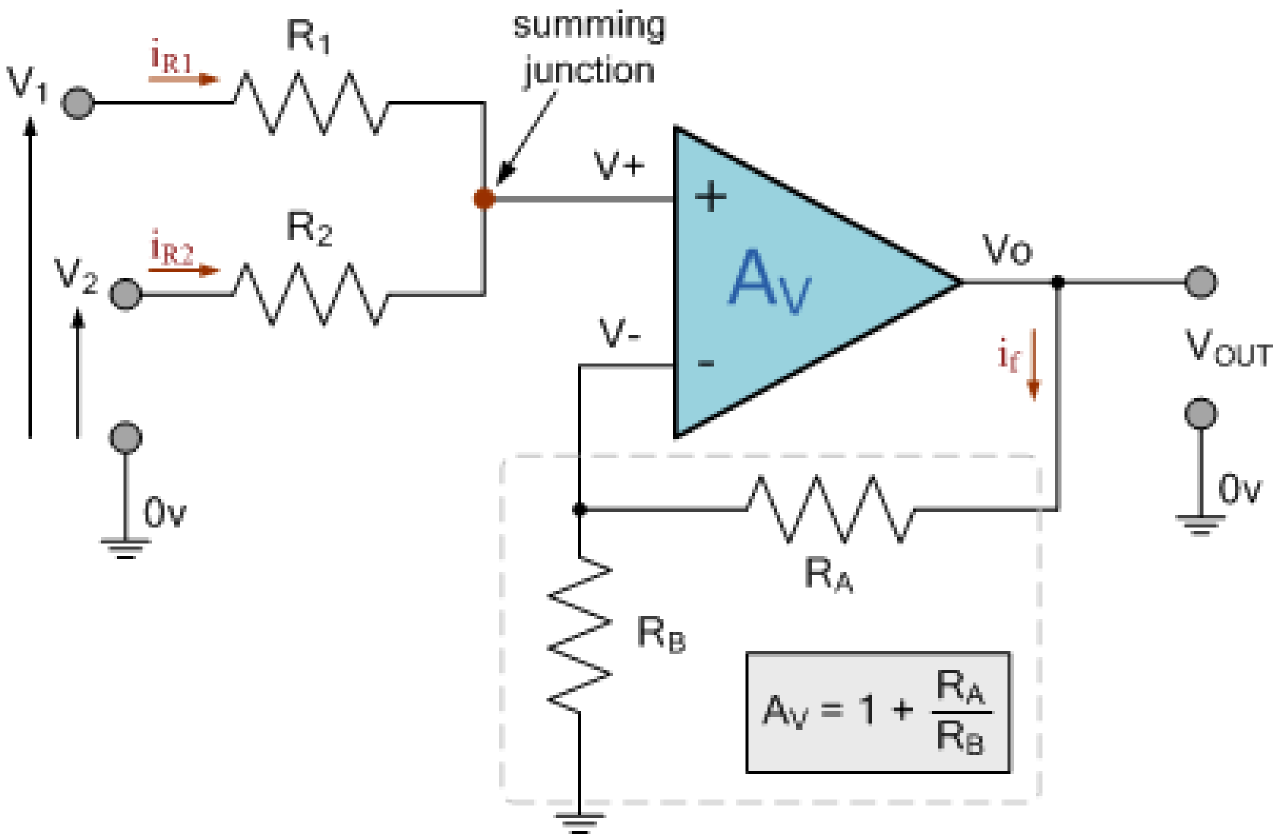

This is a summer with two inputs.

$$v_o = -\left[\frac{10}{5}(2) + \frac{10}{2.5}(1)\right] = -(4 + 4) = -8 \text{ V}$$

The current $i_o$ is the sum of the currents through the 10-kΩ and 2-kΩ resistors. Both of these resistors have voltage $v_o = -8$ V across them, since $v_a = v_b = 0$. Hence,

$$i_o = \frac{v_o - 0}{10} + \frac{v_o - 0}{2} \text{ mA} = -0.8 - 4 = -4.8 \text{ mA}$$

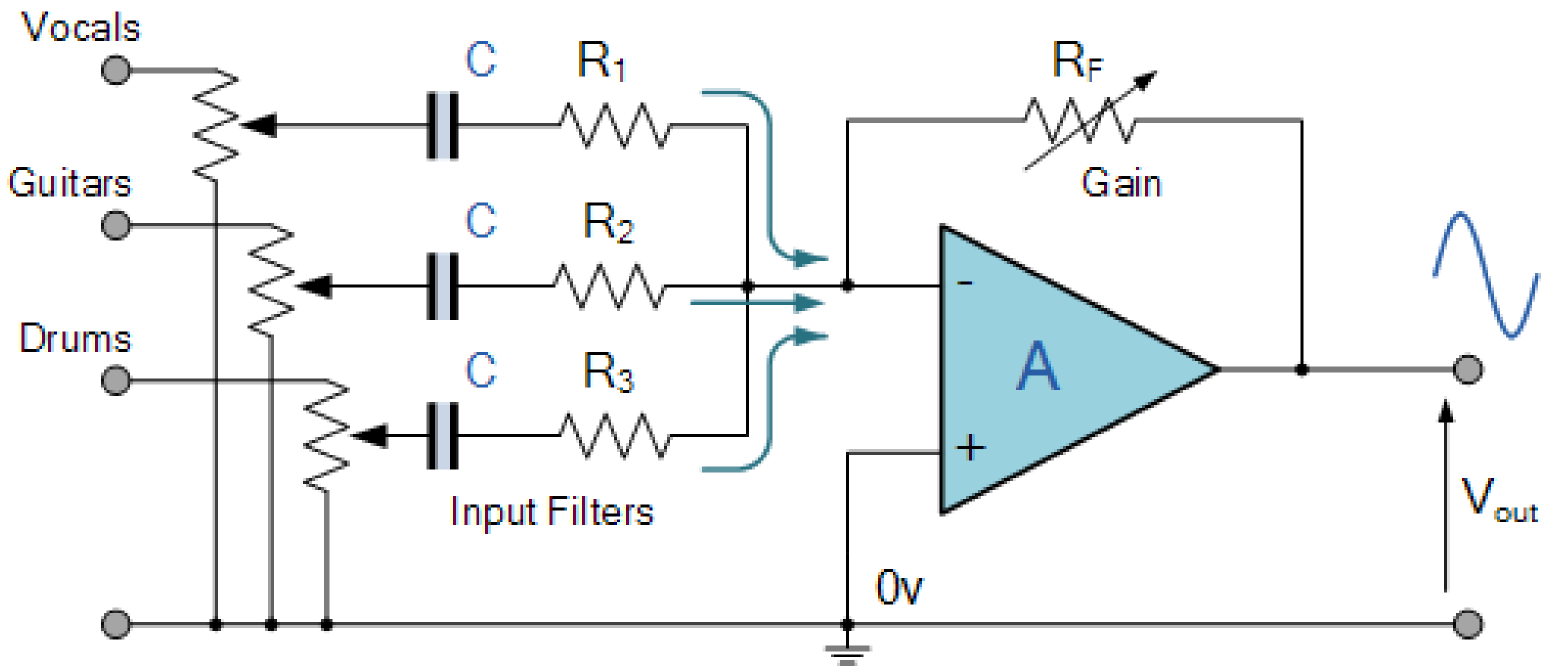
# Non-Inverting Summing Amplifier




$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT}}{V+} = 1 + \frac{R_A}{R_B}$$

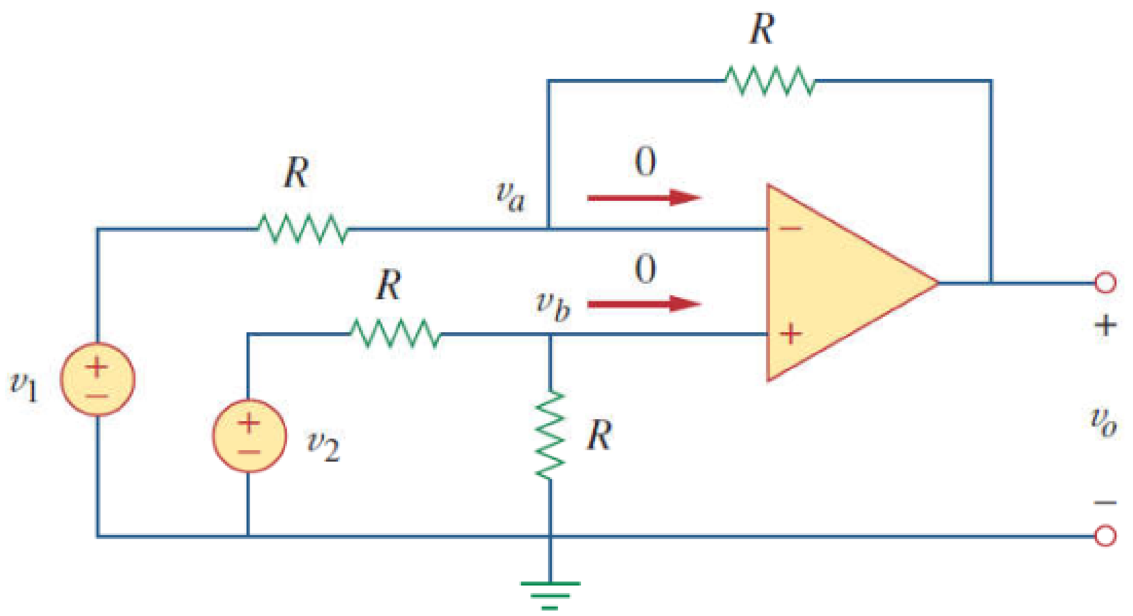
$$\therefore \quad V_{OUT} = \left[1 + \frac{R_A}{R_B}\right] V+$$

$$\text{Thus:} \quad V_{OUT} = \left[1 + \frac{R_A}{R_B}\right] \frac{V_1 + V_2}{2}$$




Application: Mixing together individual waveforms (sounds) from different source channels (vocals, instruments, etc) before sending them combined to an audio amplifier.

# Subtractor Amplifier Circuit

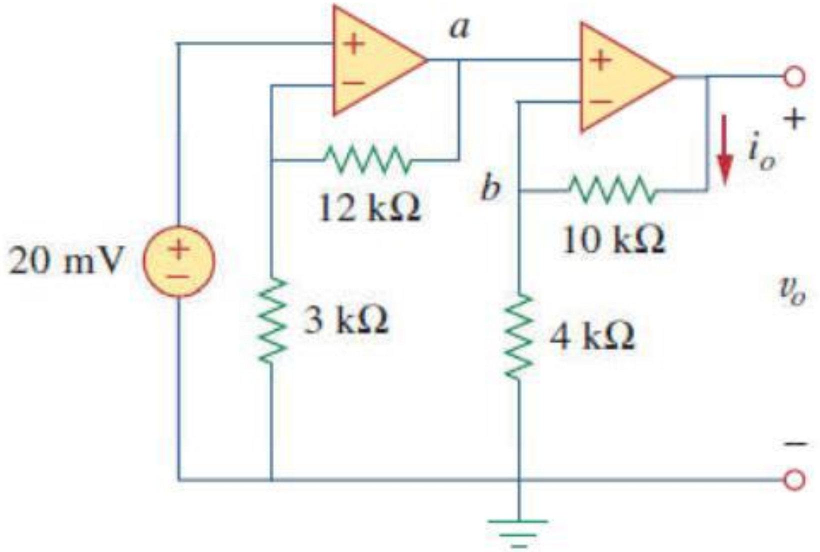



$$v_o = -\frac{R}{R}v_1 + \left(1 + \frac{R}{R}\right)v_b$$

$$v_b = \frac{R}{R+R}v_2$$

$$\boxed{v_o = v_2 - v_1}$$

Find $v_o$ and $i_o$ in the circuit




This circuit consists of two noninverting amplifiers cascaded. At the output of the first op amp,

$$v_a = \left(1 + \frac{12}{3}\right)(20) = 100 \text{ mV}$$

At the output of the second op amp,

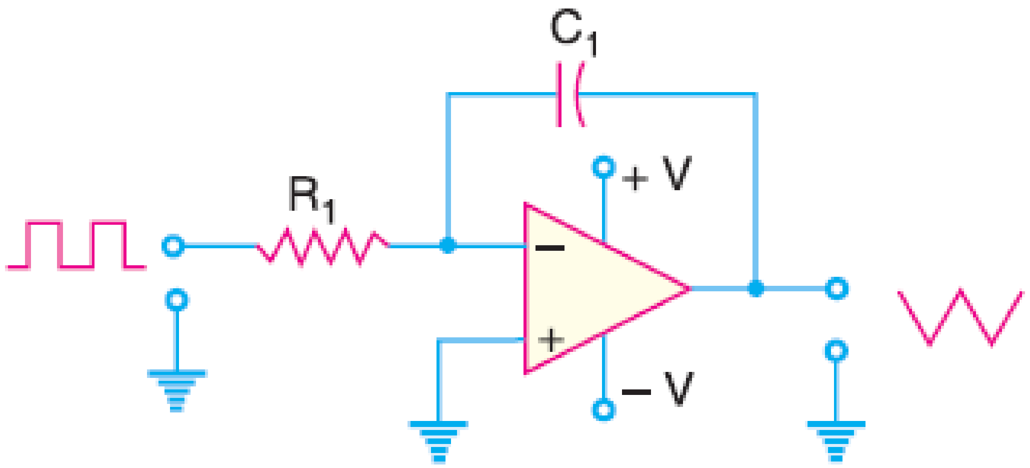
$$v_o = \left(1 + \frac{10}{4}\right)v_a = (1 + 2.5)100 = 350 \text{ mV}$$

The required current $i_o$ is the current through the 10-kΩ resistor.

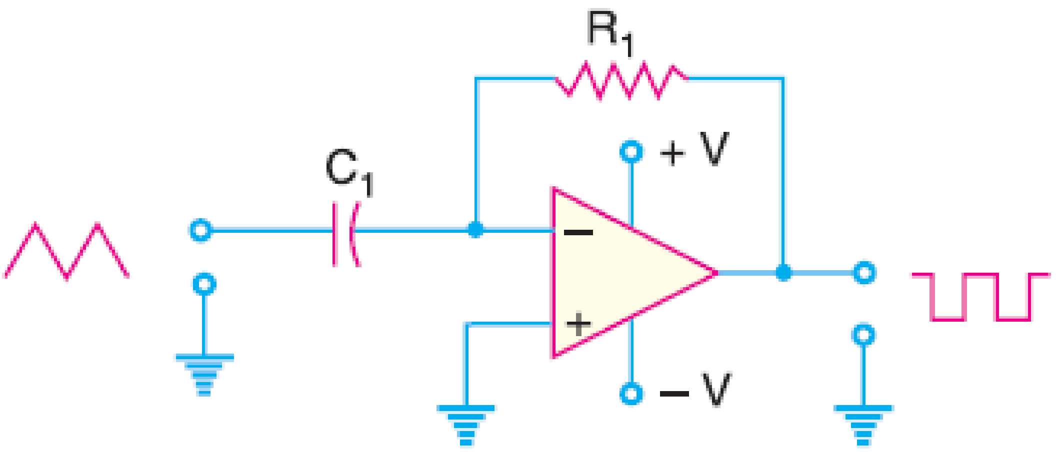
$$i_o = \frac{v_o - v_b}{10} \text{ mA}$$

But $v_b = v_a = 100$ mV. Hence,

$$i_o = \frac{(350 - 100) \times 10^{-3}}{10 \times 10^3} = 25 \ \mu\text{A}$$



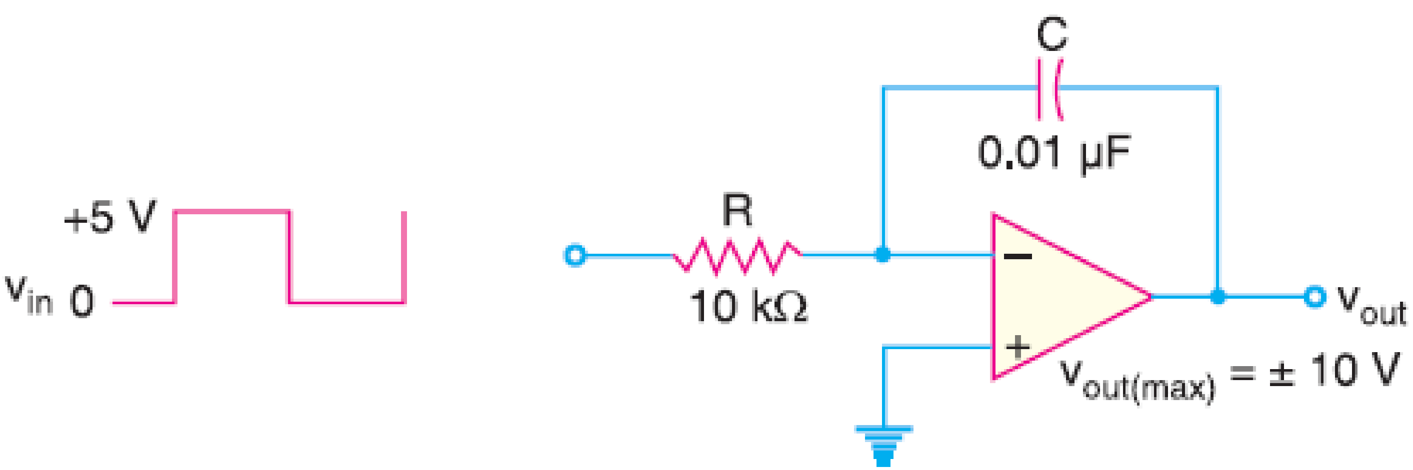

*OP*-amp Integrator

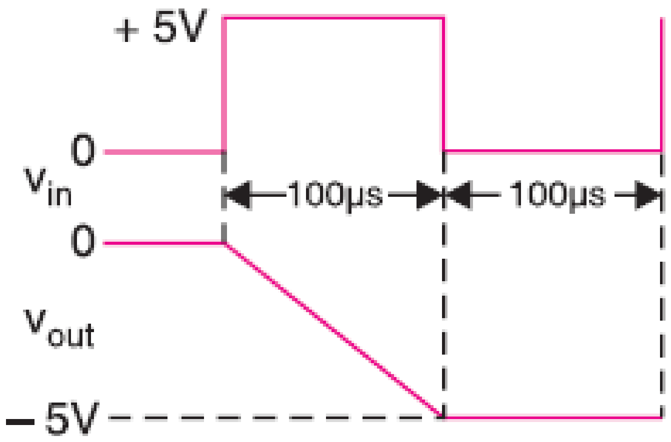



*OP*-amp differentiator

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

$$v_o = -RC\frac{dv_i}{dt}$$




(*i*) Output voltage, $v_{out}$

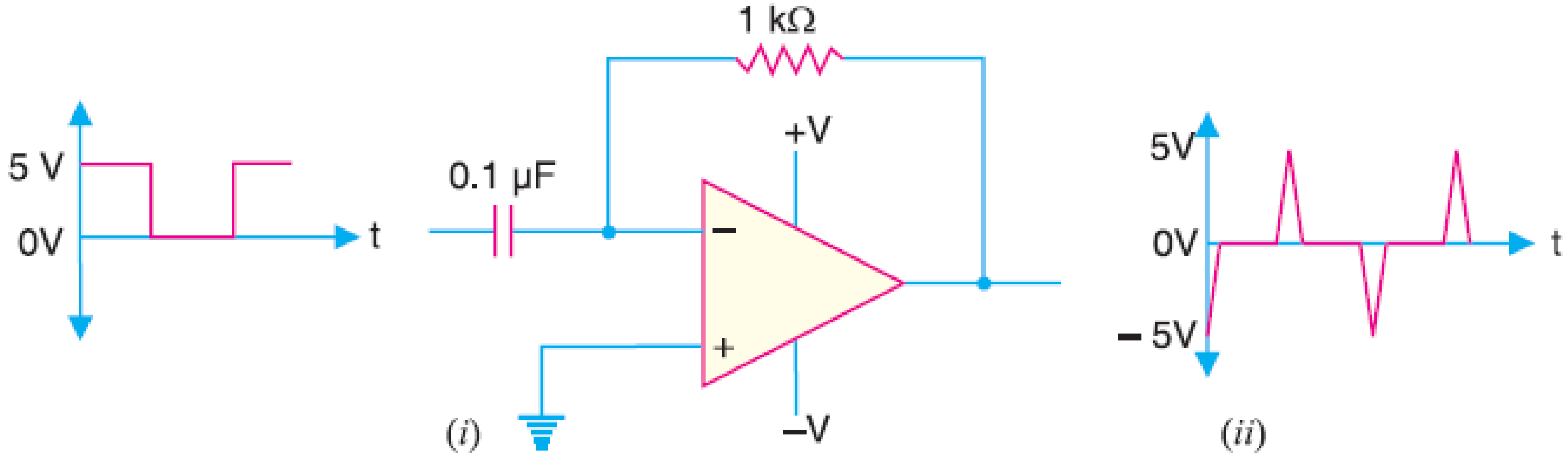
$$= -\frac{1}{RC}\int_0^t v_{in}\,dt$$

Therefore, the rate of change of output voltage is

$$\frac{\Delta v_{out}}{dt} = -\frac{v_{in}}{RC} = -\frac{5\text{ V}}{(10\text{ k}\Omega)\,(0.01\,\mu\text{F})} = -50\text{ kV/s} = \mathbf{-50\text{ mV}/\mu s}$$

(*ii*) The rate of change of output voltage is – 50 mV/μ*s*. When the input is at + 5 V, the output is a negative-going ramp. When the input is at 0 V, the output is a constant level. In 100 μ*s*, the output voltage decreases.

$$\therefore \quad \Delta v_{out} = \frac{\Delta v_{out}}{dt}\times dt = -\frac{50\text{ mV}}{\mu\text{s}}\times 100\,\mu\text{s} = -5\text{V}$$

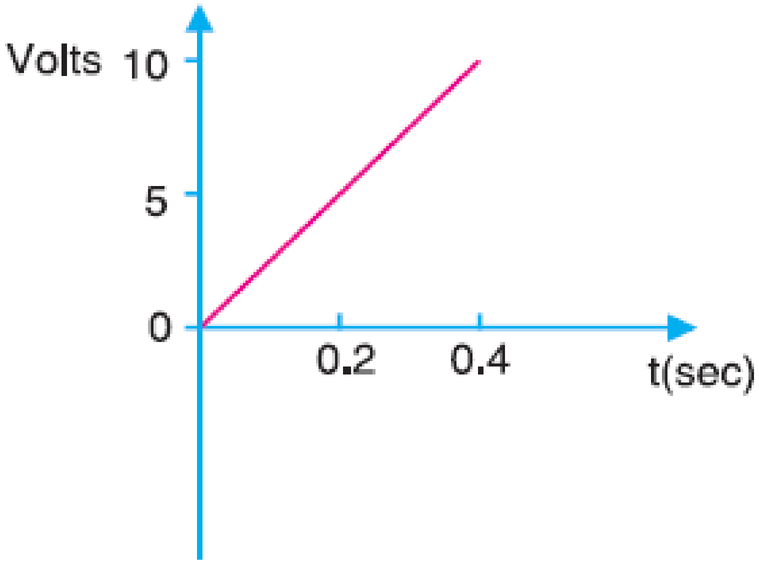


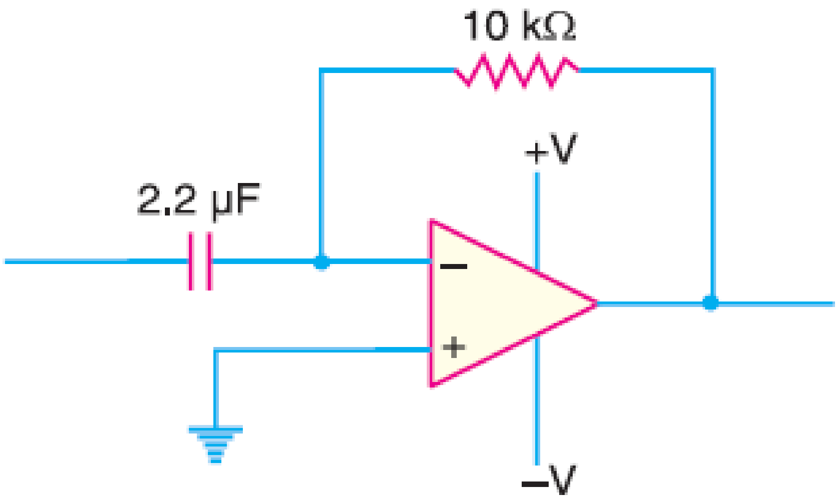

**Solution.** Output voltage, $v_o = -RC\dfrac{dv_i}{dt}$

Now, $RC = (1\,\text{k}\Omega) \times (0.1\,\mu\text{F}) = (10^3\,\Omega)\,(0.1 \times 10^{-6}\,\text{F}) = 0.1 \times 10^{-3}\,s$

Also, $\dfrac{dv_i}{dt} = \dfrac{5\text{V}}{0.1\,\text{ms}} = \dfrac{5 \times 10^4\,\text{V}}{s} = 5 \times 10^4\,\text{V/s}$

$\therefore \quad v_o = -(0.1 \times 10^{-3})\,(5 \times 10^4) = $ **−5V**




**Solution.** Output voltage, $v_o = -RC\dfrac{dv_i}{dt}$

Now, $RC = (10\ \text{k}\Omega) \times (2.2\ \mu\text{F}) = (10^4\ \Omega)\ (2.2 \times 10^{-6}\ \text{F}) = 2.2 \times 10^{-2}\ s$

Also, $\dfrac{dv_i}{dt} = \dfrac{(10-0)\ V}{0.4s} = \dfrac{10\text{V}}{0.4\text{s}} = 25\ \text{V/s}$

$\therefore \quad v_o = -(2.2 \times 10^{-2}) \times 25 = \mathbf{-0.55\ V}$

The output voltage stays constant at – 0.55 V.