# CSE251: Electronic Devices and Circuits

Lecture 5:

Closed Loop Op-amp configurations

Prepared By:

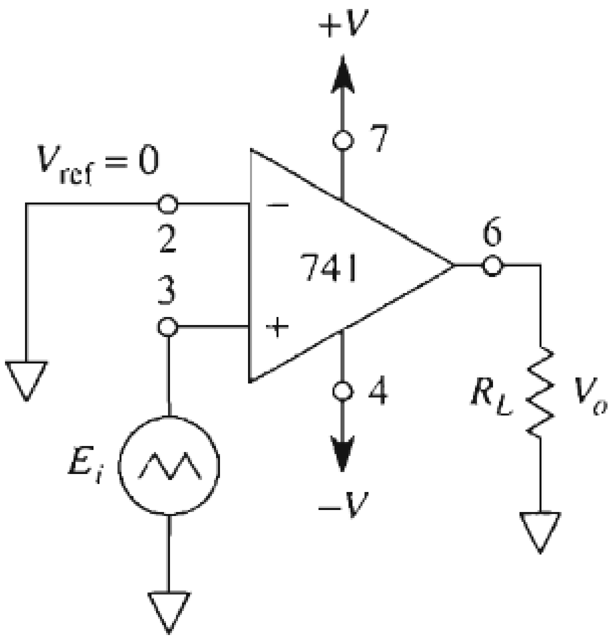
**Shadman Shahid (SHD)**

Lecturer, Department of Computer Science and Engineering, School of Data and Sciences, BRAC University

*Email: shadman9085@gmail.com*

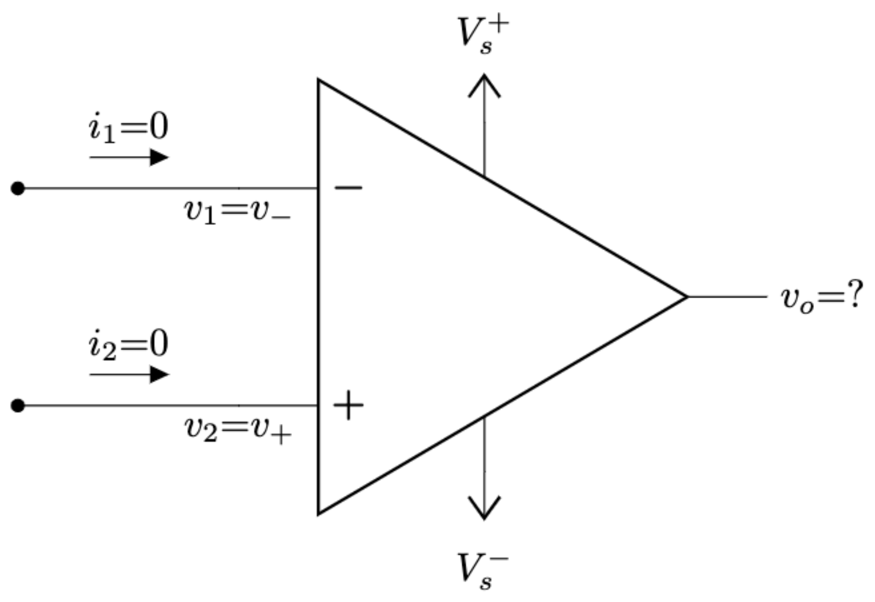
# Basic Op-Amp Configurations

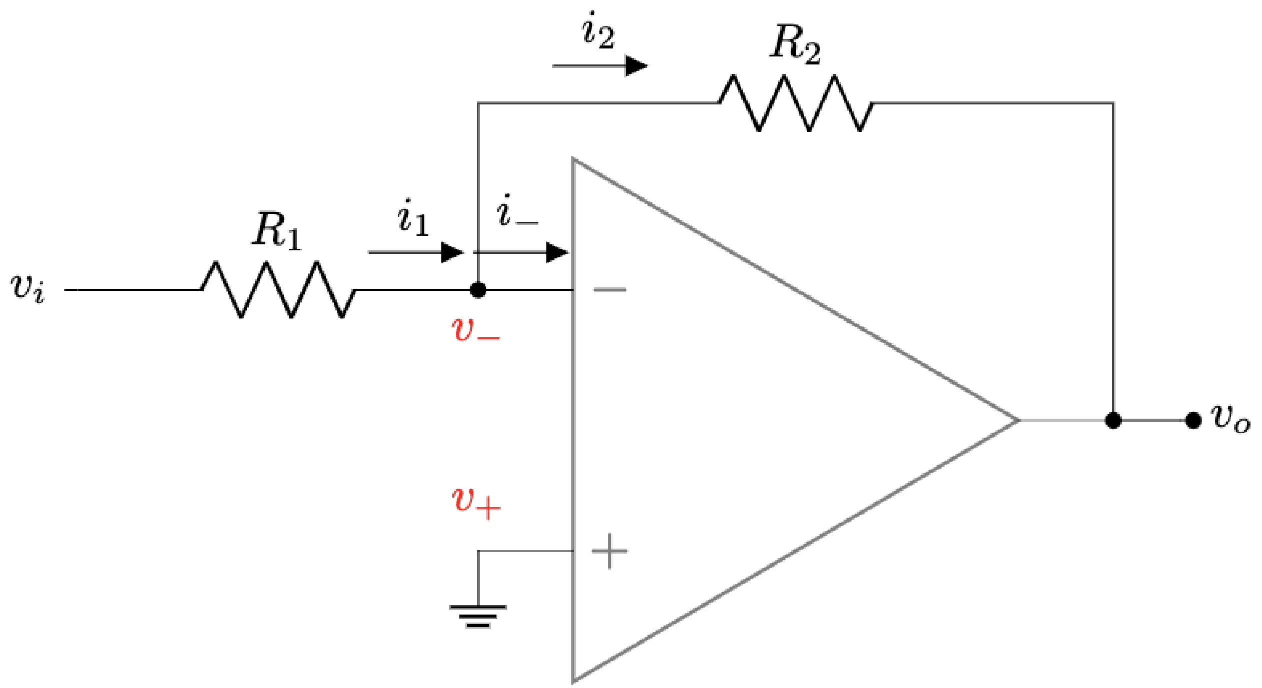
- **Open-loop Configurations**
  1. Comparator / Voltage Level Detectors




- **Closed Loop Configurations**
  1. Voltage Follower
  2. Inverting Amplifier
  3. Inverting Summer
  4. Non-Inverting Amplifier
  5. Weighted Subtractor
  6. Integrator
  7. Differentiator
  8. Exponential Converter
  9. Logarithmic Converter
  10. Multiplier
  11. Divider

# Solving Closed Loop Op-Amp Circuit

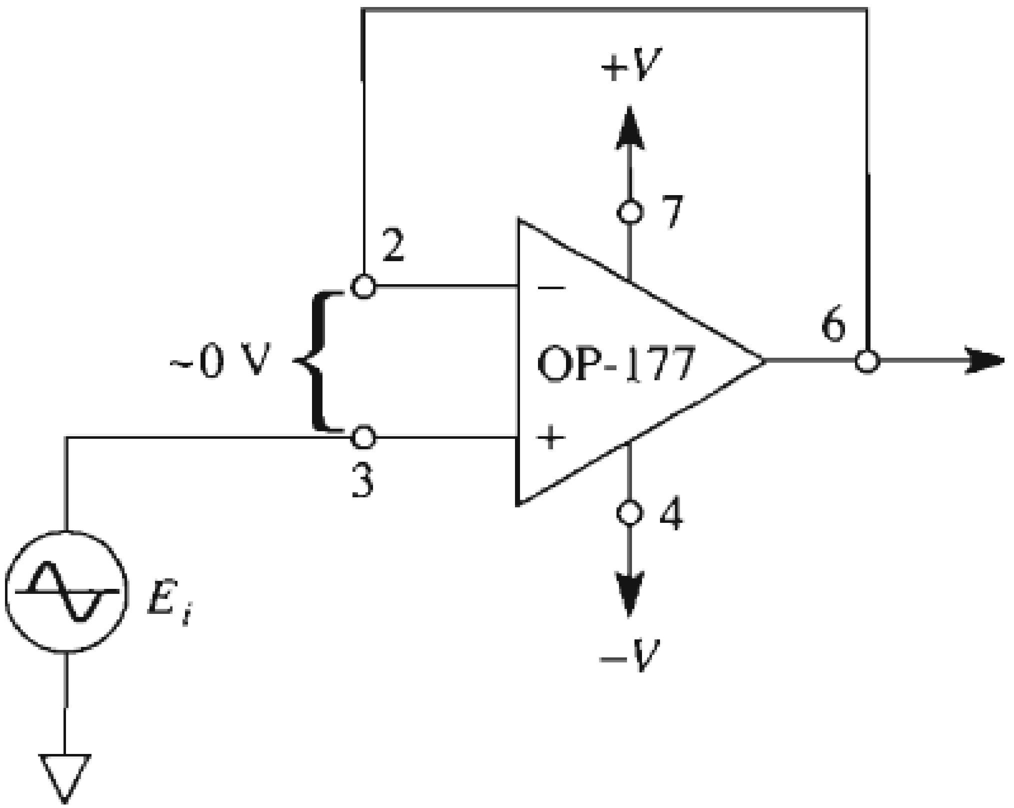



**Two Rules:**

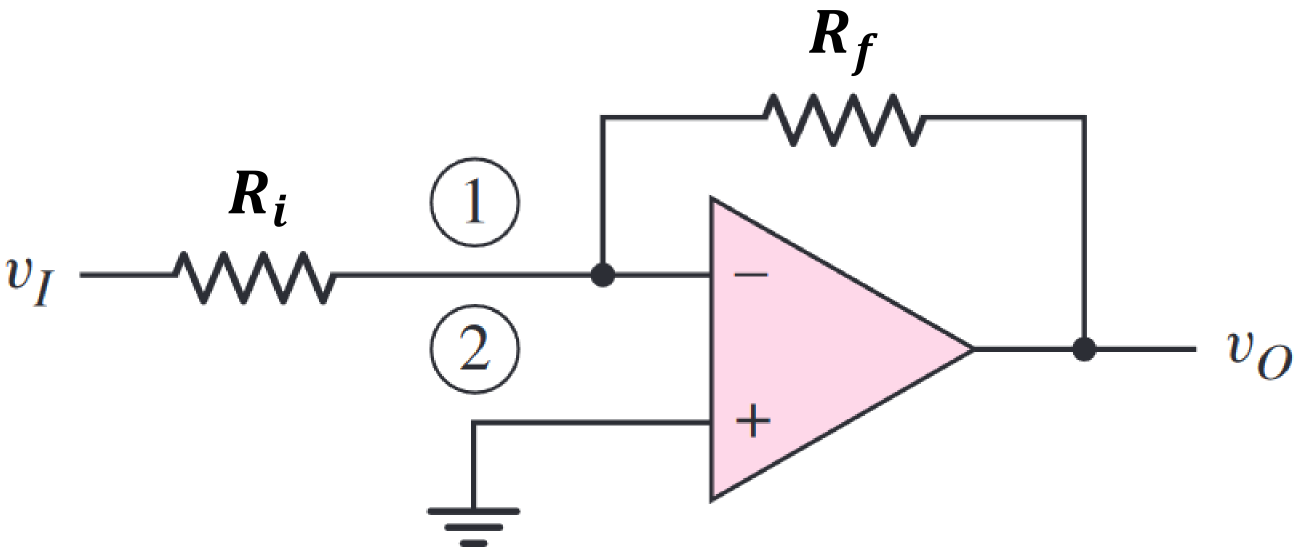
1. Virtual Shorting: $\boldsymbol{v_+ = v_-}$
2. Zero input bias current: $\boldsymbol{i_- = i_+ = 0}$

# Voltage Follower / Buffer:



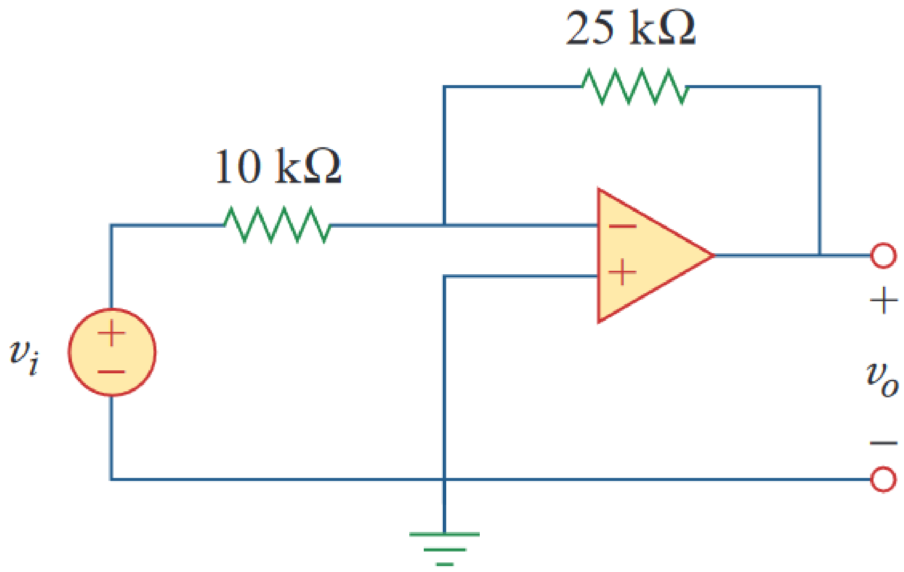

$$V_O = E_i$$

# Inverting Amplifier




$$= -\frac{R_f}{R_i} \cdot v_I$$

# Example - 1




If $\boldsymbol{v_i} = \mathbf{0.5}$ V, calculate:

(a) Output voltage $\boldsymbol{v_o}$.

(b) Current in the $\mathbf{10\ k\Omega}$ resistor.

(a)

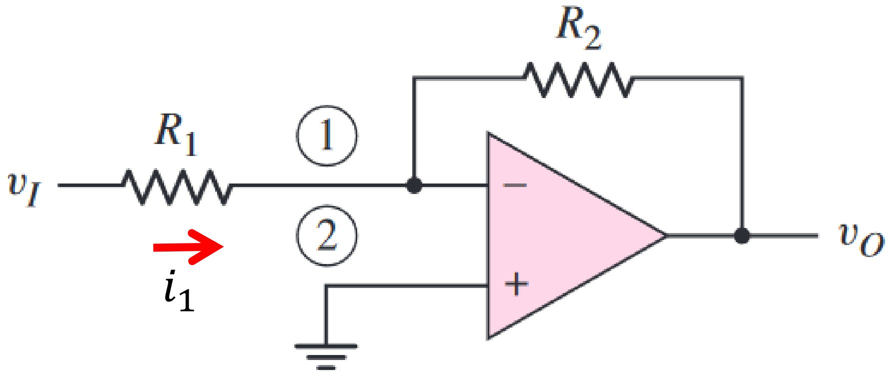
$$\boldsymbol{v_o = -\frac{R_f}{R_i} \cdot v_i = -2.5 v_i = -1.25\ \mathrm{V}}$$

(b) Current through the $\mathbf{10\ k\Omega}$ resistor is

$$i = \frac{v_i}{R_i} = \frac{0.5}{10}\ \mathrm{mA} = \mathbf{50\ \mu A}$$

# Example - 2

**Design** the circuit such that the closed loop voltage gain is $\boldsymbol{A_{\mathrm{CL}}} = -\mathbf{5}$. Assume the op-amp is driven by an ideal sinusoidal source, $\boldsymbol{v_I} = \mathbf{0.1\ sin}\ (\boldsymbol{\omega t})\ (\boldsymbol{V})$, that can supply a maximum current of $\mathbf{5\ \mu A}$.



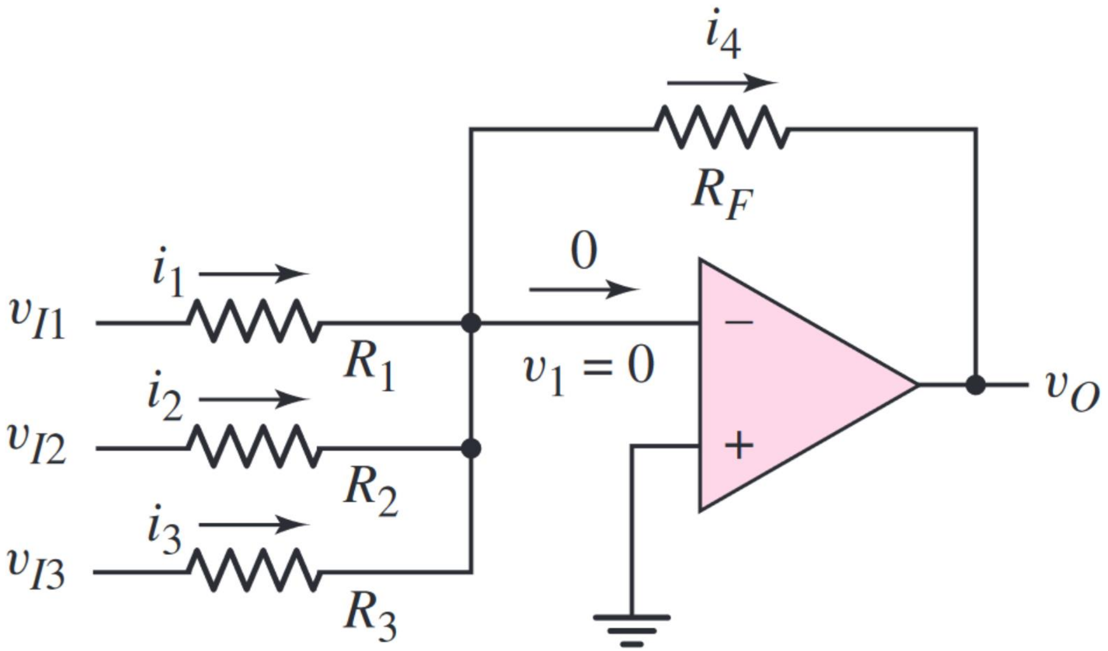

$$\boldsymbol{i_1} = \frac{\boldsymbol{v_I}}{\boldsymbol{R_1}}$$

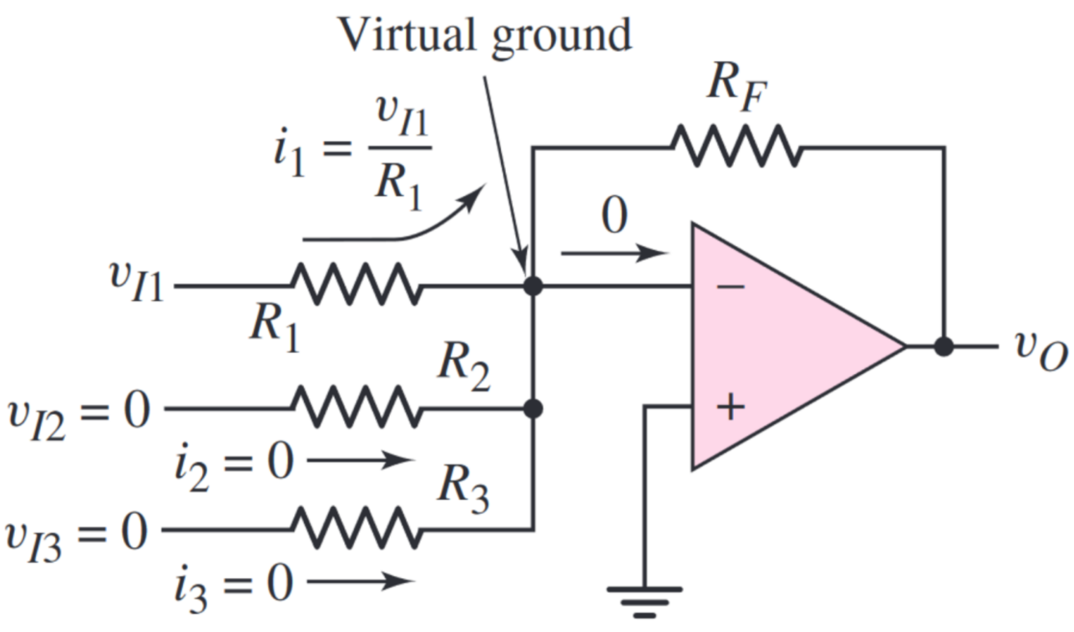
$$\boldsymbol{R_1} = \frac{v_I(\max)}{i_1(\max)} = \frac{0.1}{5 \times 10^{-3}} = \mathbf{20\ k\Omega}$$

$$\boldsymbol{R_2} = -A_{\mathrm{CL}} \cdot R_1 = 5 \times 20 = \mathbf{100\ k\Omega}$$

# Inverting Summer

- Multichannel Amplifier

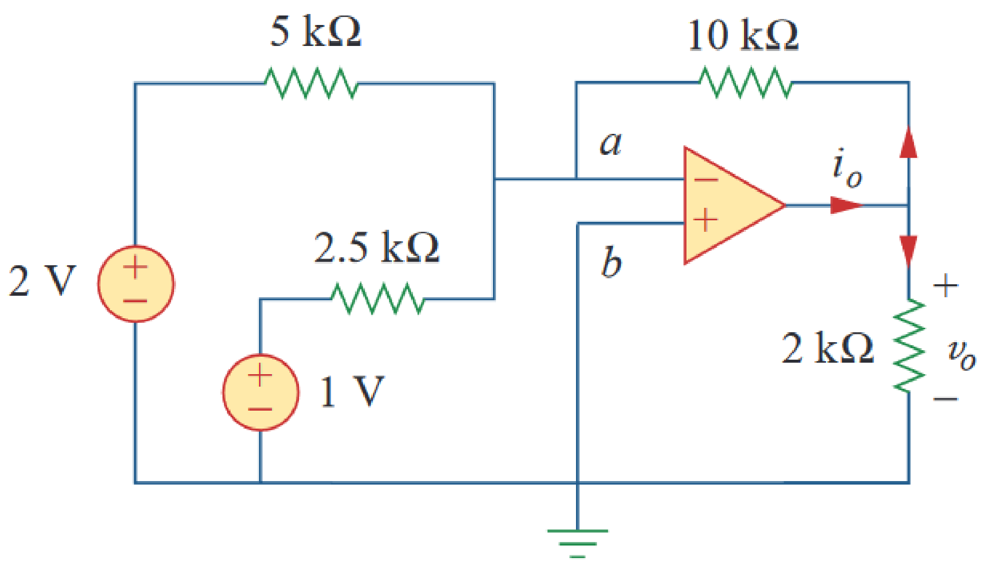



$$v_O(v_{I1}) = -i_1 R_F = -\left(\frac{R_F}{R_1}\right) v_{I1}$$

$$v_O = -\left(\frac{R_F}{R_1} v_{I1} + \frac{R_F}{R_2} v_{I2} + \frac{R_F}{R_3} v_{I3}\right)$$

# Example - 3




Calculate:

(a) Output voltage $\boldsymbol{v_o}$.

(b) Output current $\boldsymbol{i_o}$.

(a)

$$\boldsymbol{v_o = -\left(\frac{10}{5}\cdot 2 + \frac{10}{2.5}\cdot 1\right) = -8\ \mathrm{V}}$$

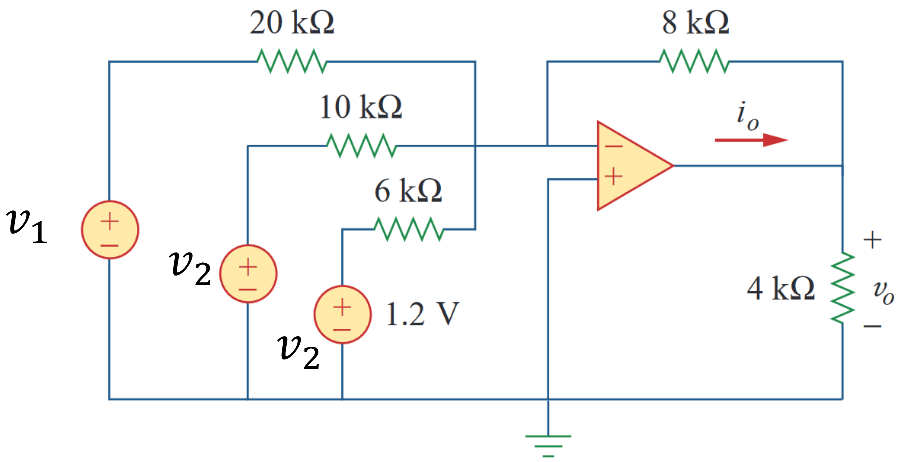
(b)

$$i = \frac{v_o}{10} + \frac{v_o}{2} = (-0.8 - 4\ )\ \mathrm{mA} = \boldsymbol{-4.8\ \mathrm{mA}}$$

# Example 4

Design an op-amp circuit with inputs $\boldsymbol{v_1}$, $\boldsymbol{v_2}$ and $\boldsymbol{v_3}$ such that, output voltage $\boldsymbol{v_o}$:

$$\boldsymbol{v_o = -\frac{2}{5}v_1 - \frac{4}{5}v_2 - \frac{4}{3}v_3}$$




## Solution:

The given function can be achieved by an **inverting summing amplifier**. Having the voltage transfer formula as:

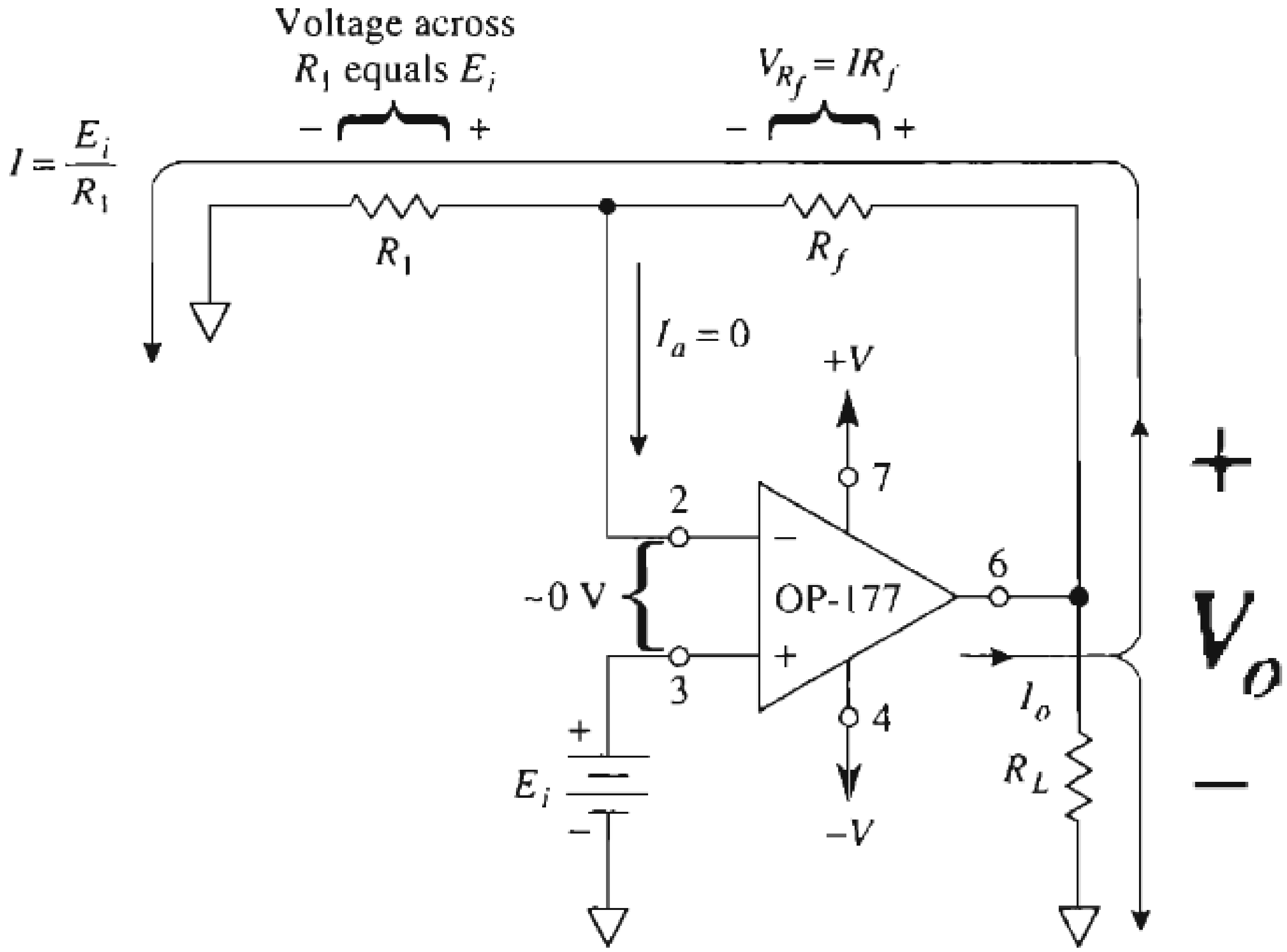
$$v_o = \left(-\frac{R_f}{R_1}v_1 - \frac{R_f}{R_2}v_2 - \cdots \frac{R_f}{R_n}v_n\right)$$

Here, the numerators of all the coefficients of input voltages are same ($\boldsymbol{R_f}$). As per the given problem, this can be achieved by setting the numerator to the LCM of 2 and 4 (i.e., to **8**).

$$\boldsymbol{v_o = -\frac{2}{5}v_1 - \frac{4}{5}v_2 - \frac{4}{3}v_3}$$

$$\boldsymbol{= -\frac{8}{20}v_1 - \frac{8}{10}v_2 - \frac{8}{6}v_3}$$

# Non-Inverting Amplifier



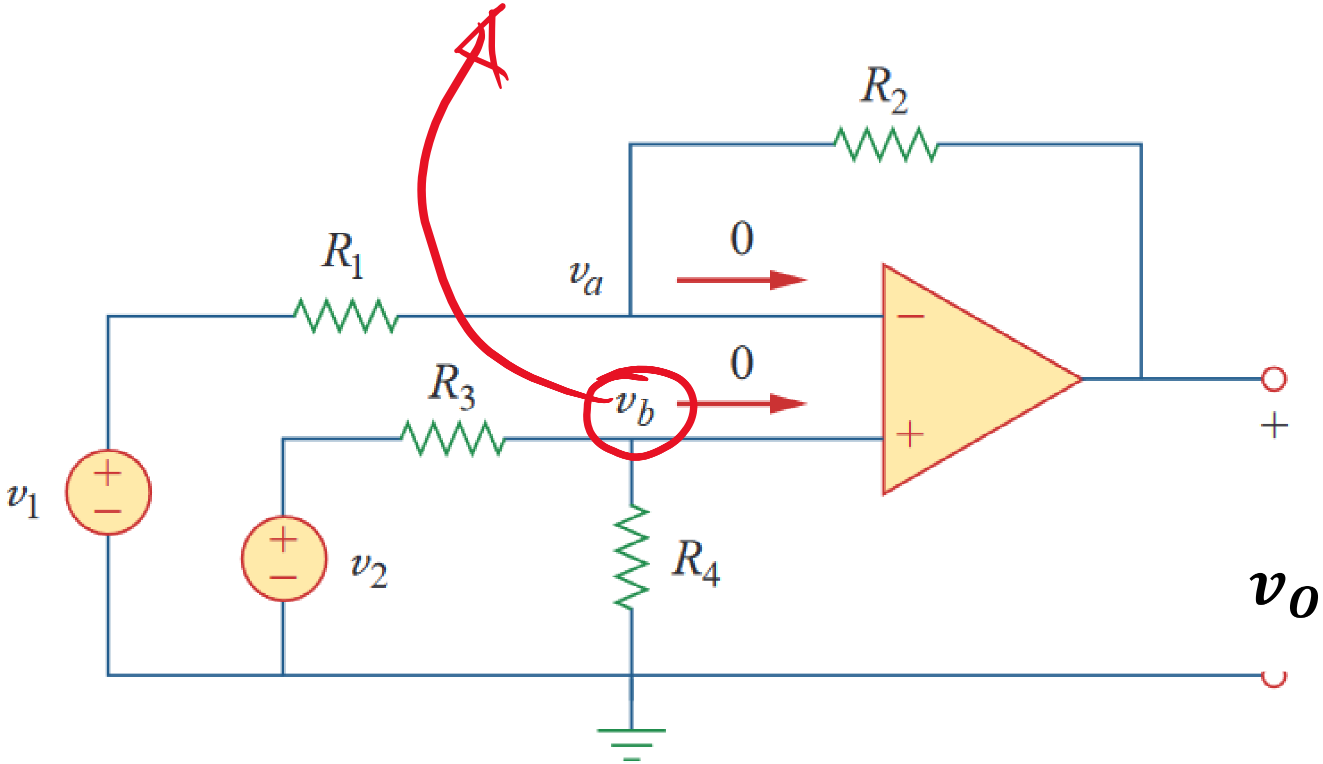

$$V_O > E_i$$

$$V_o = \left(1 + \frac{R_f}{R_1}\right)E_i$$

# Difference Amplifier

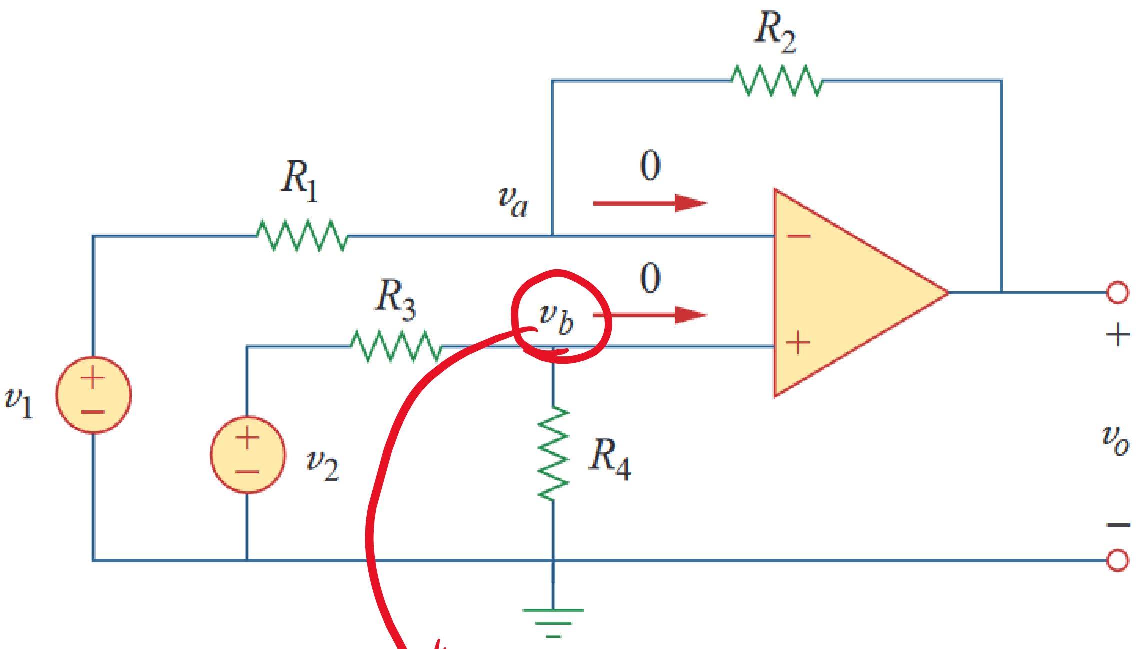
$$v_b = v_a = \frac{R_4}{R_3 + R_4} v_2$$

$$v_O = \left(1 + \frac{R_2}{R_1}\right) v_a - \frac{R_2}{R_1} \cdot v_1$$

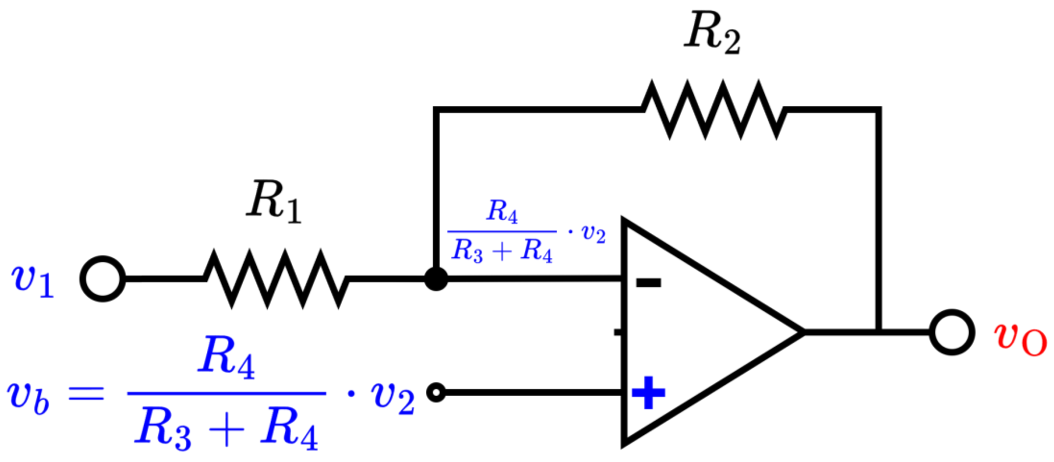



$$v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} \cdot v_1$$

# Difference Amplifier



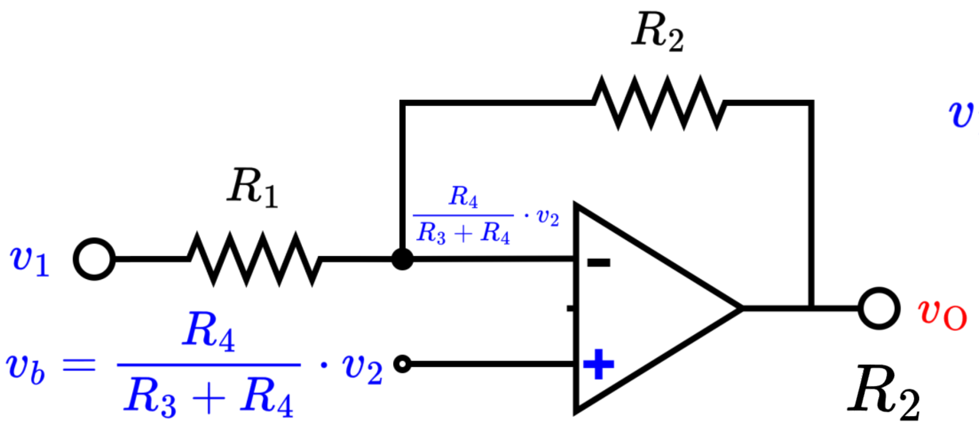

$$v_b = v_a = \frac{R_4}{R_3 + R_4} v_2$$

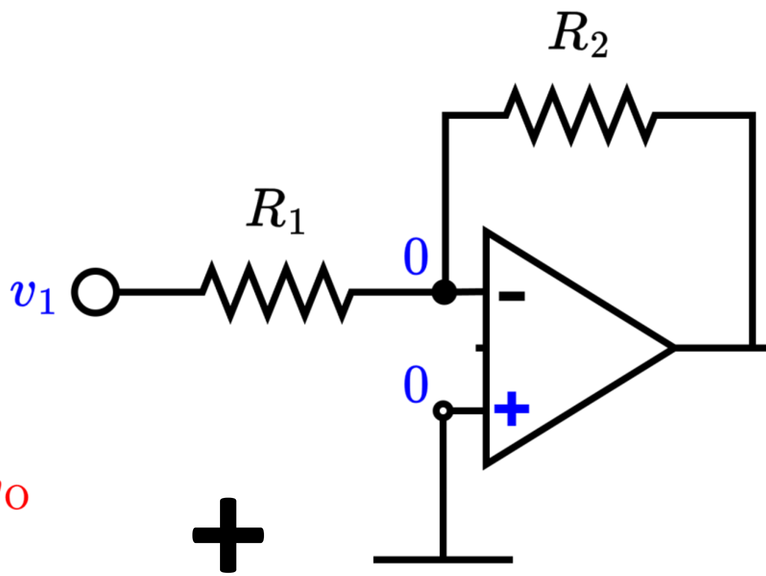



Simplified Circuit

# Difference Amplifier

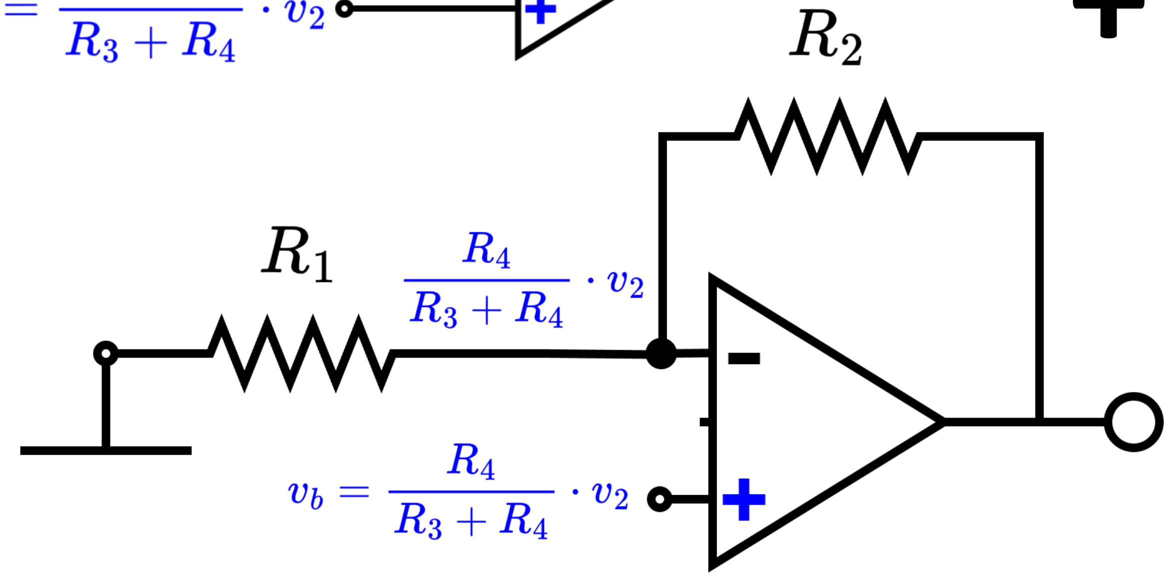
Apply superposition principle:




$$v_O' = -\frac{R_2}{R_1}\cdot v_1$$

+



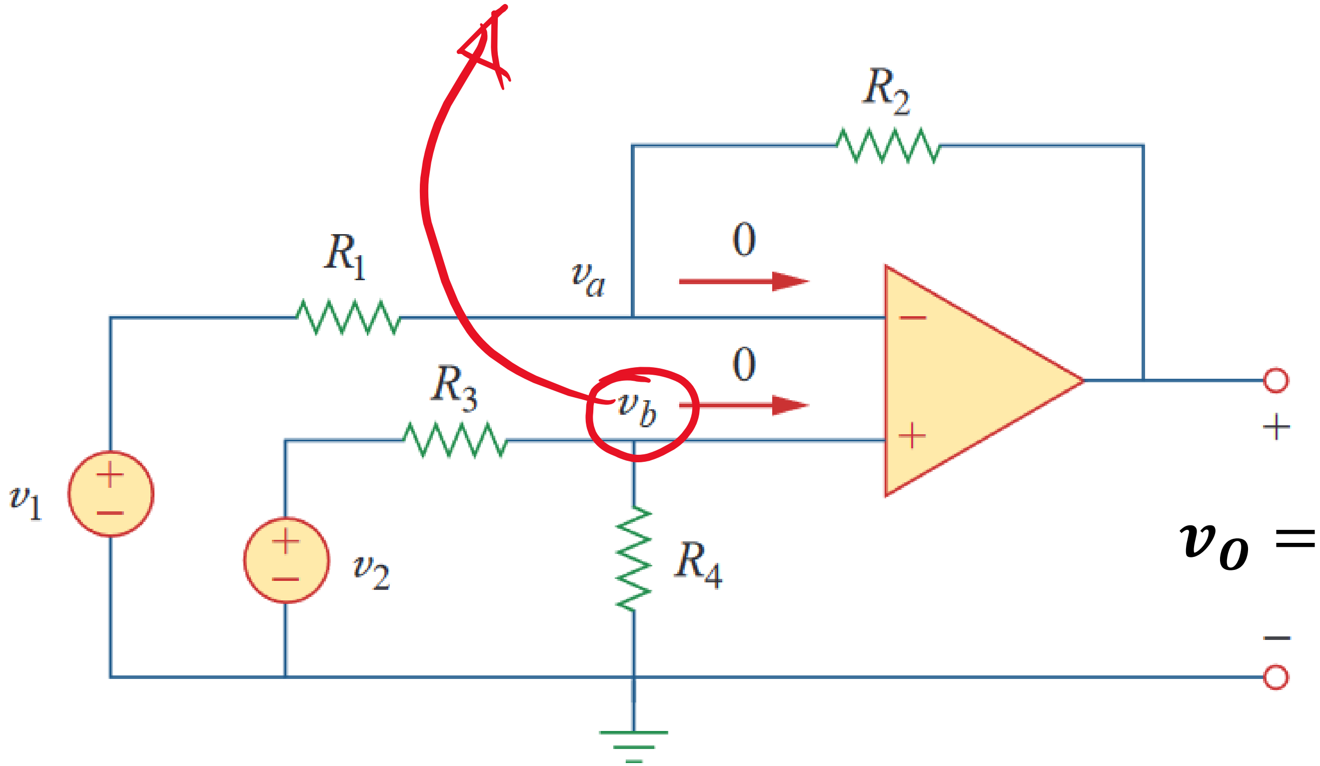

$$v_O'' = \left(1+\frac{R_2}{R_1}\right)\cdot\frac{R_4}{R_3+R_4}v_2$$

# Difference Amplifier

$$v_b = v_a = \frac{R_4}{R_3 + R_4} v_2$$

$$v_O = v_O'' + v_O'$$

$$v_O = \left(1 + \frac{R_2}{R_1}\right) v_b - \frac{R_2}{R_1} \cdot v_1$$

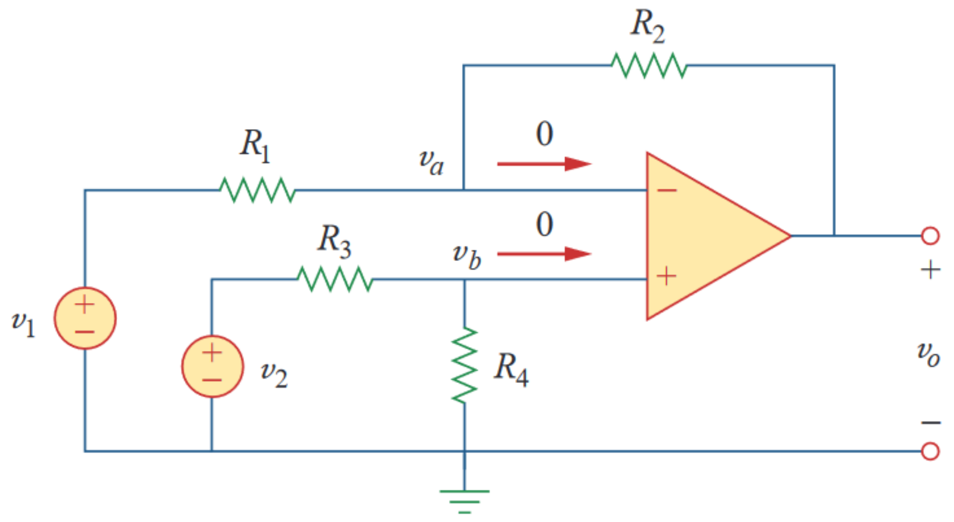



$$v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} \cdot v_1$$

# Difference Amplifier – Example 5

Design an op amp circuit with inputs $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$ such that

$$\boldsymbol{v_o = -5v_1 + 3v_2}.$$




**Solution: Method 1**

$$\boldsymbol{v_O = -\frac{R_2}{R_1}\cdot v_1 + \left(1+\frac{R_2}{R_1}\right)\cdot\frac{R_4}{R_3+R_4}v_2}$$

$$\boldsymbol{\therefore \frac{R_2}{R_1} = 5}$$

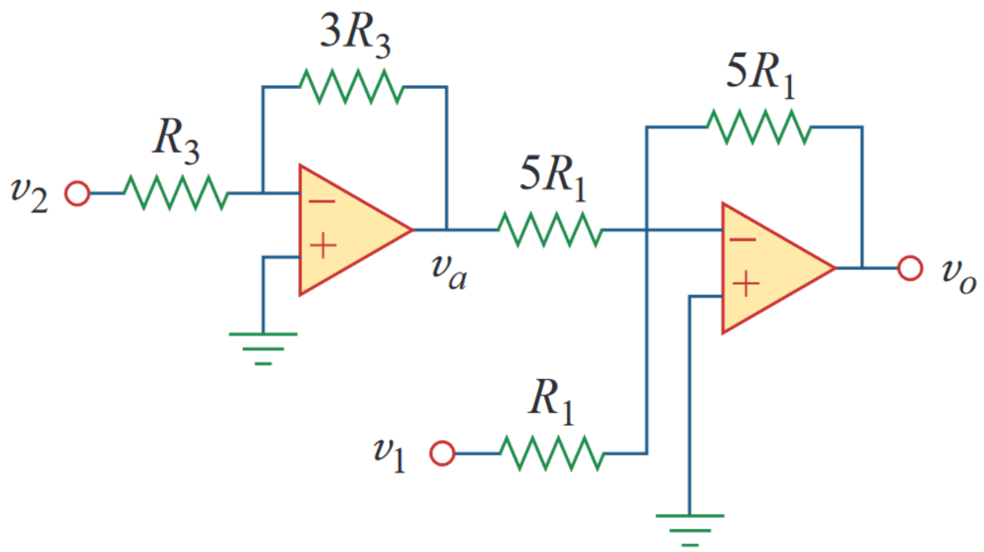
$$\boldsymbol{\therefore (1+5)\cdot\frac{R_4}{R_3+R_4} = 3}$$

$$\boldsymbol{\Rightarrow\ R_3 = R_4}$$

# Difference Amplifier – Example 6

Design an op amp circuit with inputs $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$ such that

$$\boldsymbol{v_o = -5v_1 + 3v_2.}$$




**Solution: Method 2**
Using two stages, we can implement this function.

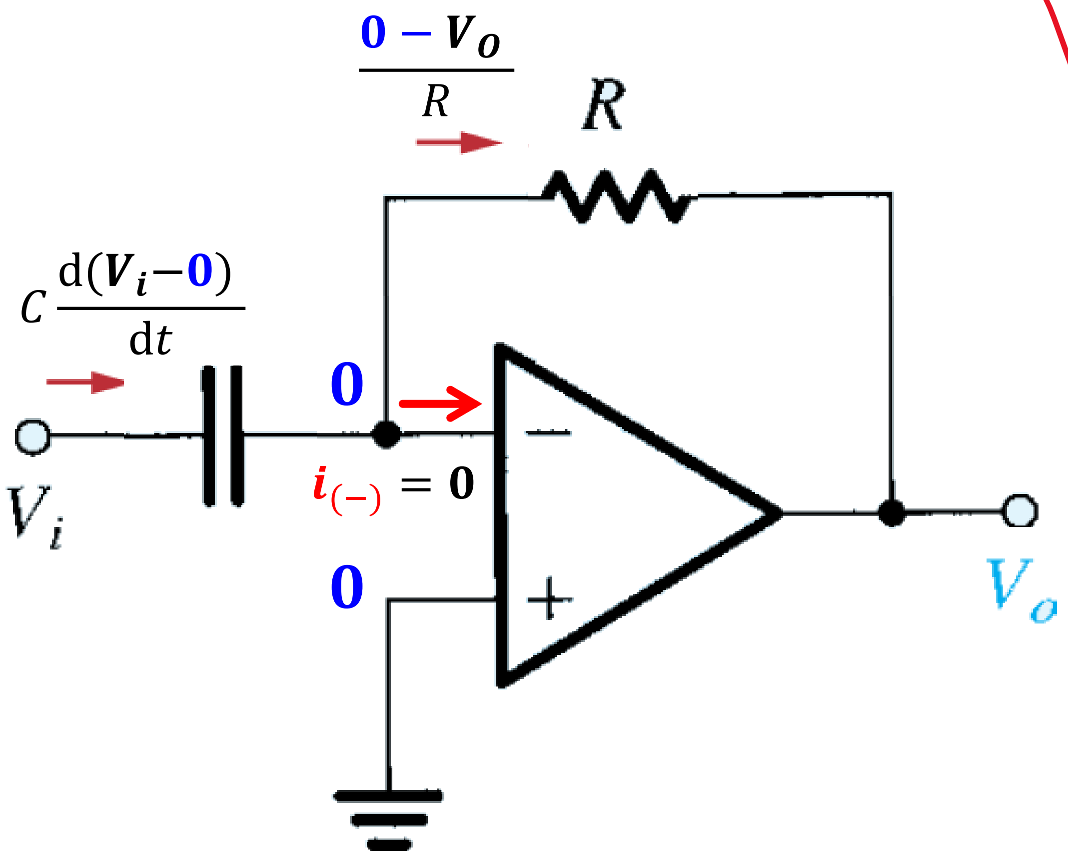
$\boldsymbol{-5v_1}$: Can be achieved with one stage inverting amplifier

$\boldsymbol{+3v_2}$: Can be achieved by cascading two inverting amplifiers → $(-\ \times\ -\ =+)$

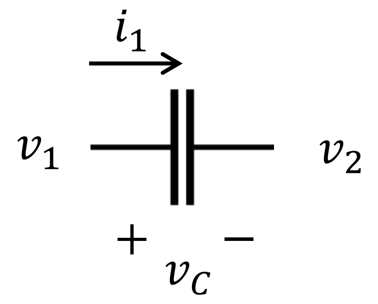
# Subtractor $(E_1 - E_2)$

# Op Amp as Differentiator

Since ideal op-amp, $i_{-} = i_{+} = 0$, so $i_1 = i_2$




Review – Capacitor



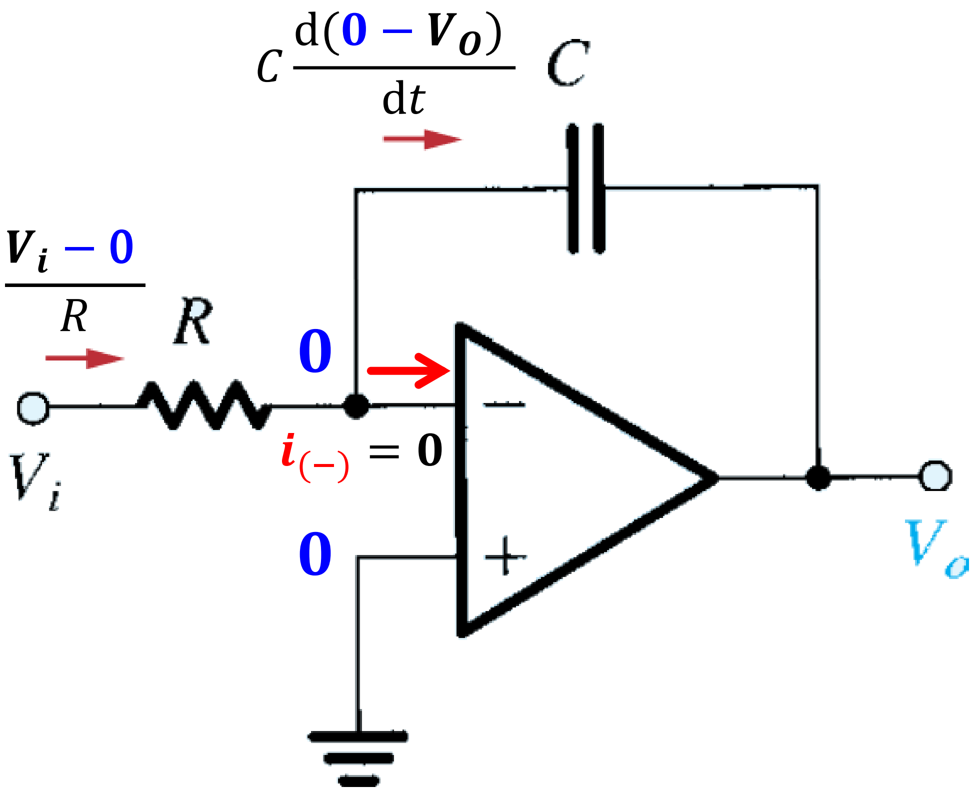

$$i_1 = C\frac{dv_C}{dt} = C\frac{d(v_1 - v_2)}{dt}$$

$$\Rightarrow -\frac{V_o}{R} = C\frac{dV_i}{dt}$$

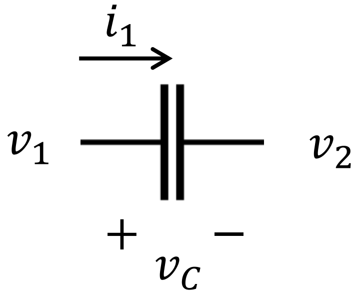
$$\boxed{\Rightarrow V_O = -RC\frac{dv_i}{dt}}$$

# Op Amp as Integrator

Since ideal op-amp, $i_- = i_+ = 0$, so $i_1 = i_2$




Review – Capacitor



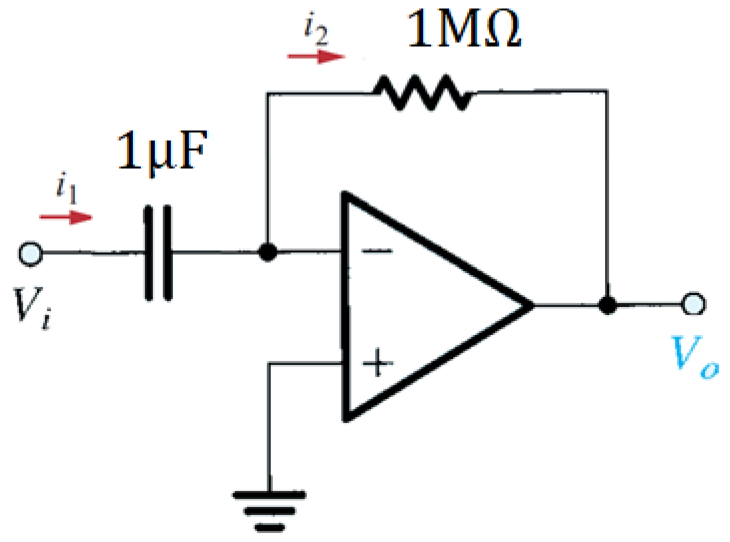

$$i_1 = C\frac{dv_C}{dt} = C\frac{d(v_1 - v_2)}{dt}$$

$$\Rightarrow \frac{V_i}{R} = -C\frac{dV_o}{dt}$$

$$\boxed{\Rightarrow V_o = -\frac{1}{RC}\int V_i(t)dt}$$

# Example 8

**Observe** the following Figure. If $V_i = 5 \cdot \sin(6t)$, Find the value of $\boldsymbol{V_0}$



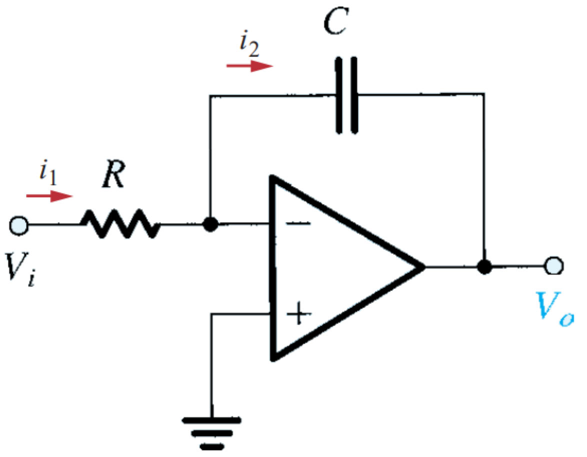

**Solution:**

This is a **differentiator**.

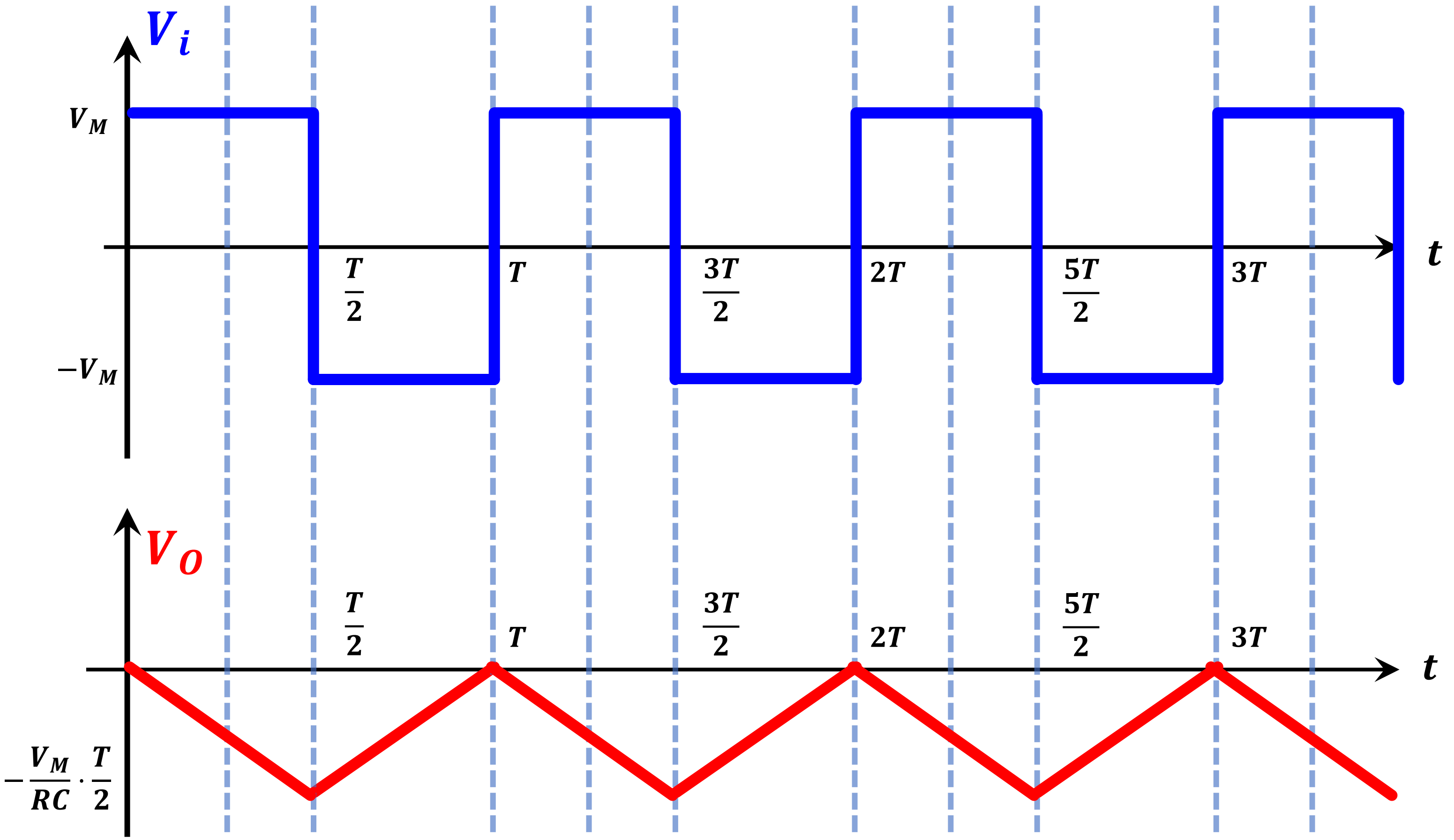
So, $v_o = -RC\frac{\mathrm{d}V_i}{\mathrm{d}t} = -1 \times 10^6 \times 1 \times 10^{-6} \times \frac{\mathrm{d}(5 \cdot \sin(6t))}{\mathrm{d}t}$

$\Rightarrow v_o = -1 \times (5 \times 6\cos(6t)) = \boldsymbol{-30\cos(6t)}$ [Ans.]

# Example 9

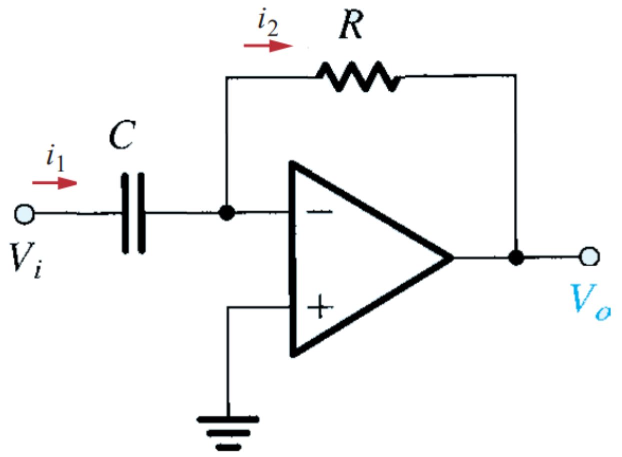


$C$
$i_2$
$i_1$
$R$
$V_i$
$V_o$

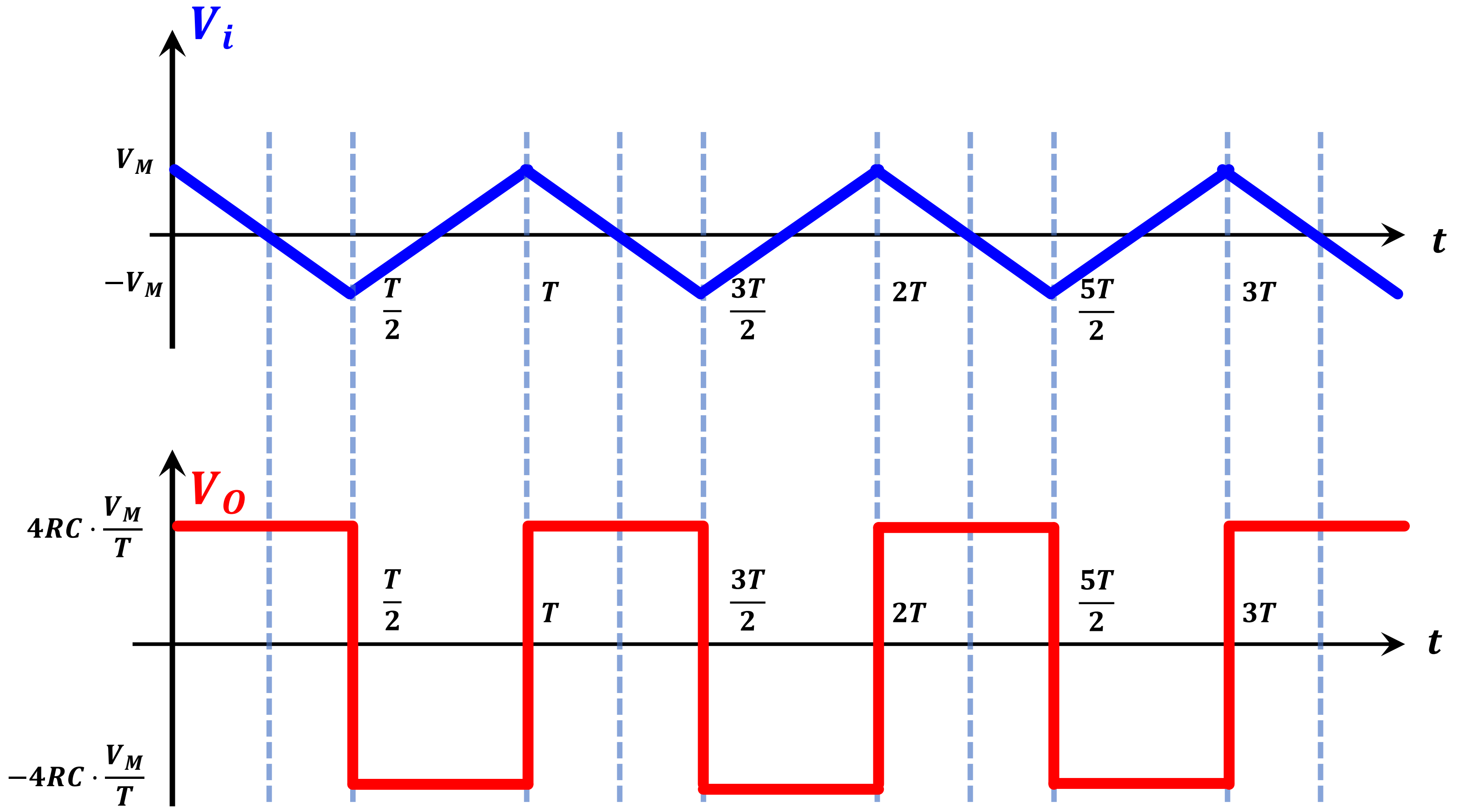



$V_i$
$V_M$
$-V_M$
$t$
$\frac{T}{2}$
$T$
$\frac{3T}{2}$
$2T$
$\frac{5T}{2}$
$3T$
$V_O$
$-\frac{V_M}{RC}\cdot\frac{T}{2}$

# Example 9




Slope: $\left|\frac{dv}{dt}\right| = \frac{V_M-(-V_M)}{T/2} = \frac{4V_M}{T}$



# APPLICATIONS:

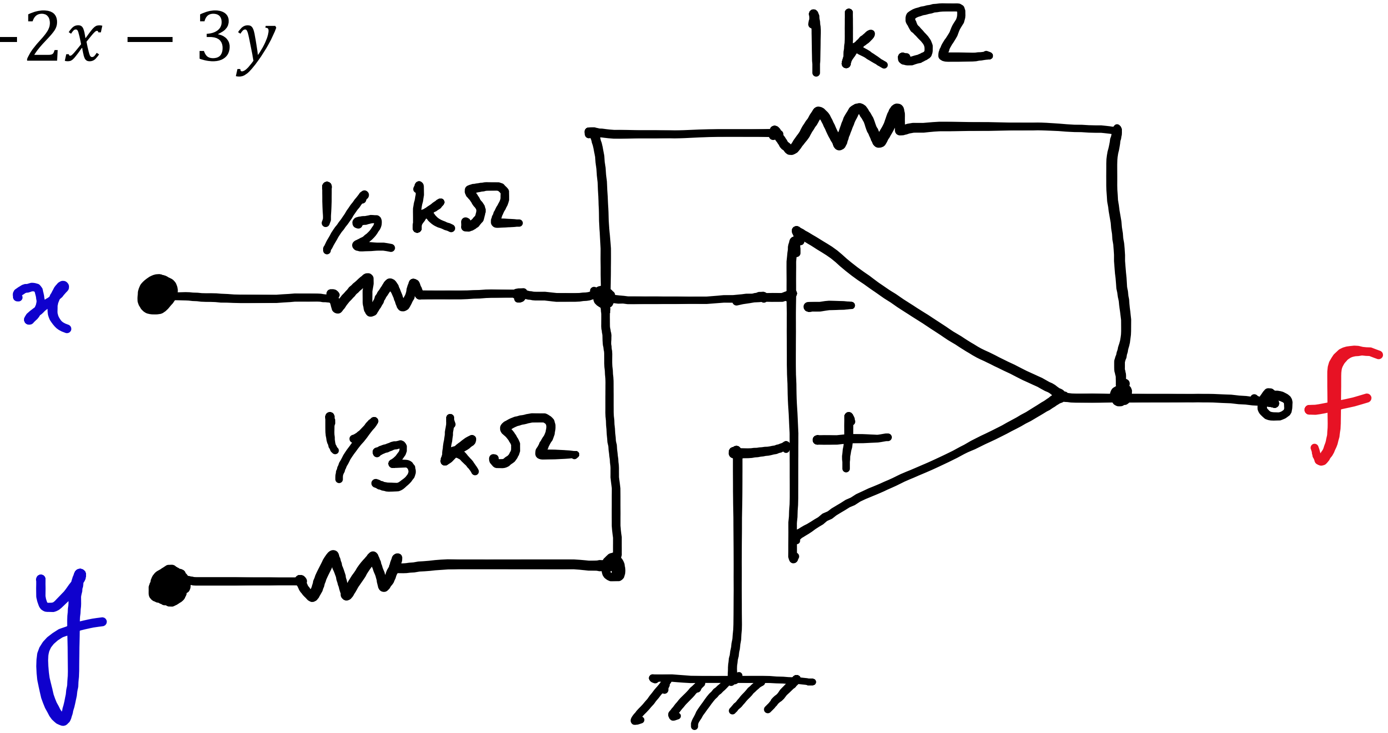
## Implementing operational functions

- $f = -2x - 3y$
- $f = -4x + 5y$
- $f = -7x + \frac{d}{dt}y$
- $f = -\frac{1}{3}\int x \cdot dt + 2\ln y + 4z$
- $f = -3\frac{dx}{dt} + 2\exp(y) + 4z$
- $f = xy/z$

# APPLICATIONS:

## Implementing operational functions

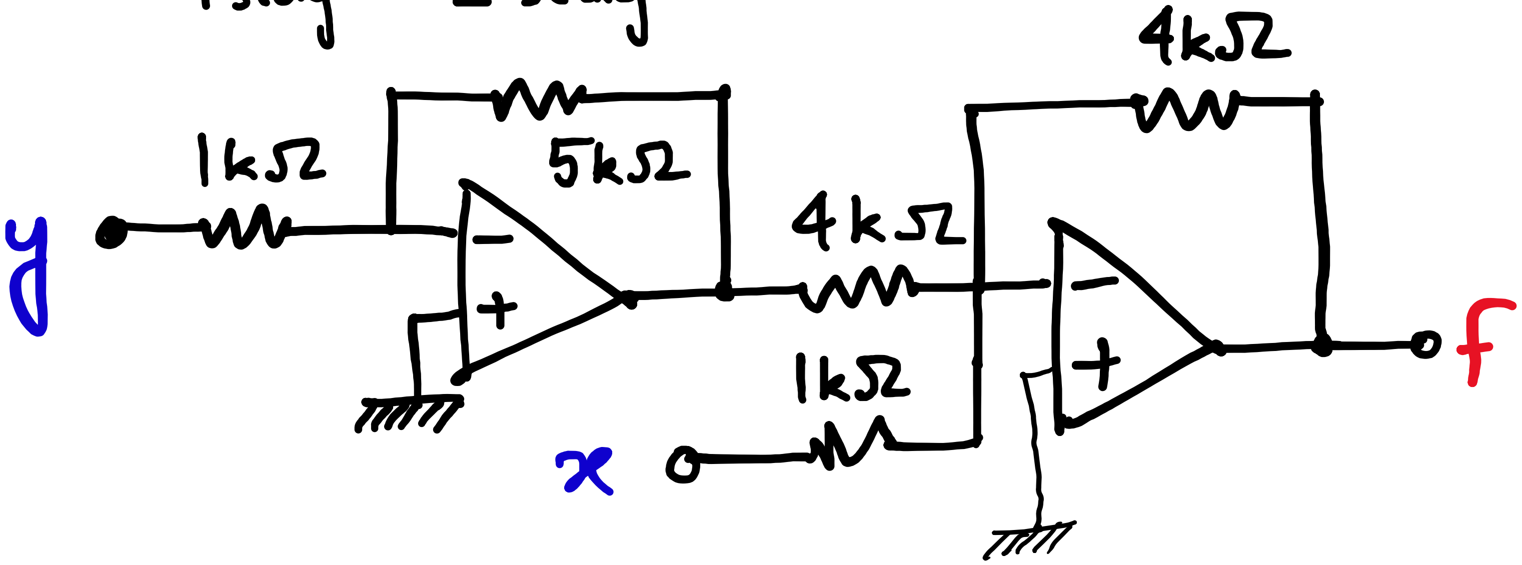
- $f = -2x - 3y$

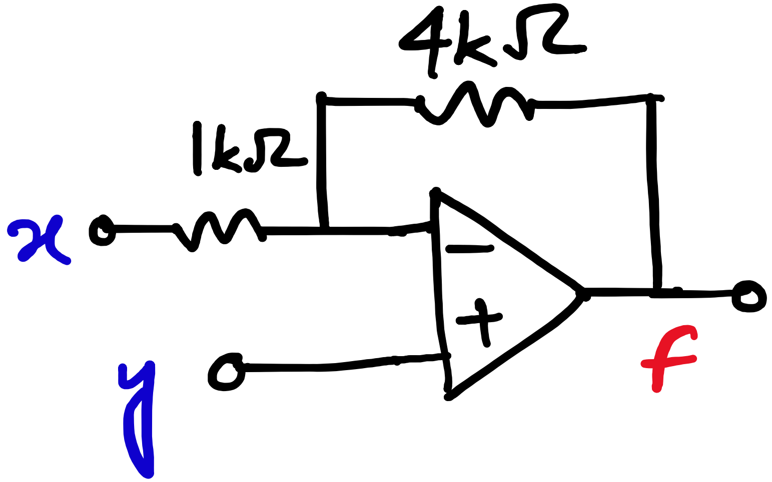


# APPLICATIONS:

## Implementing operational functions

- $f = \underbrace{-4x}_{\text{1 stage}} + \underbrace{5y}_{\text{2 stage}}$

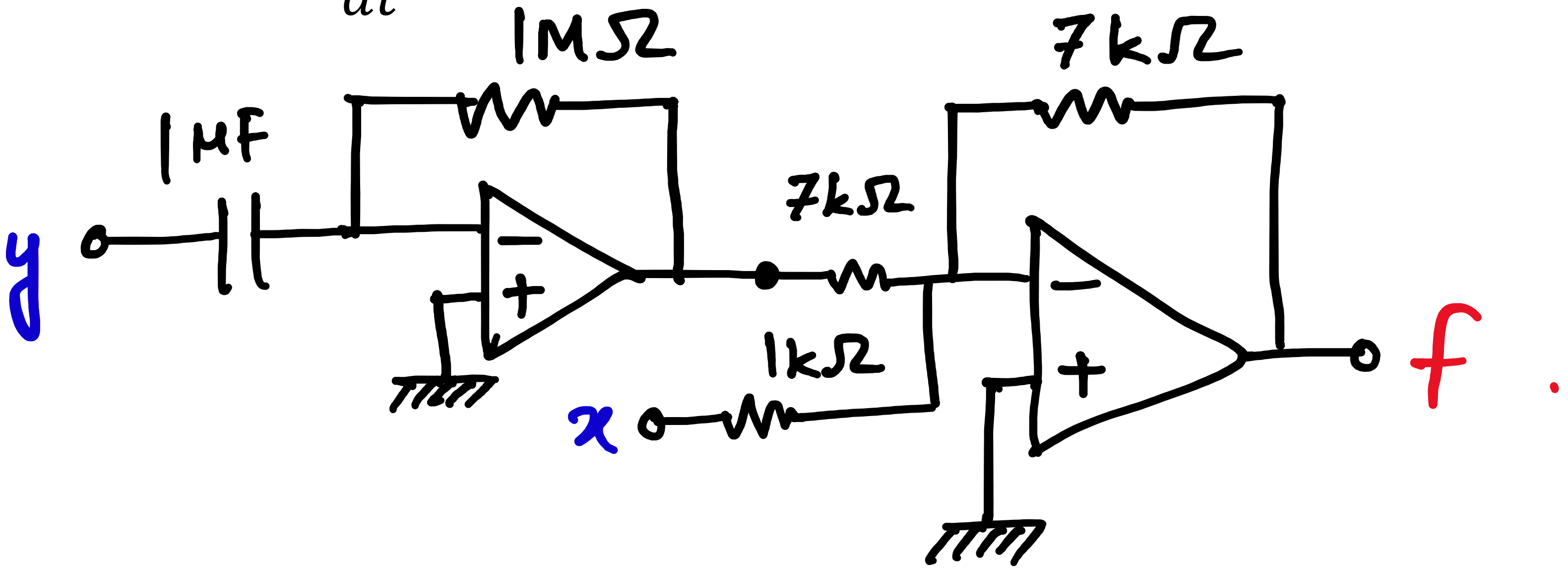


# APPLICATIONS:

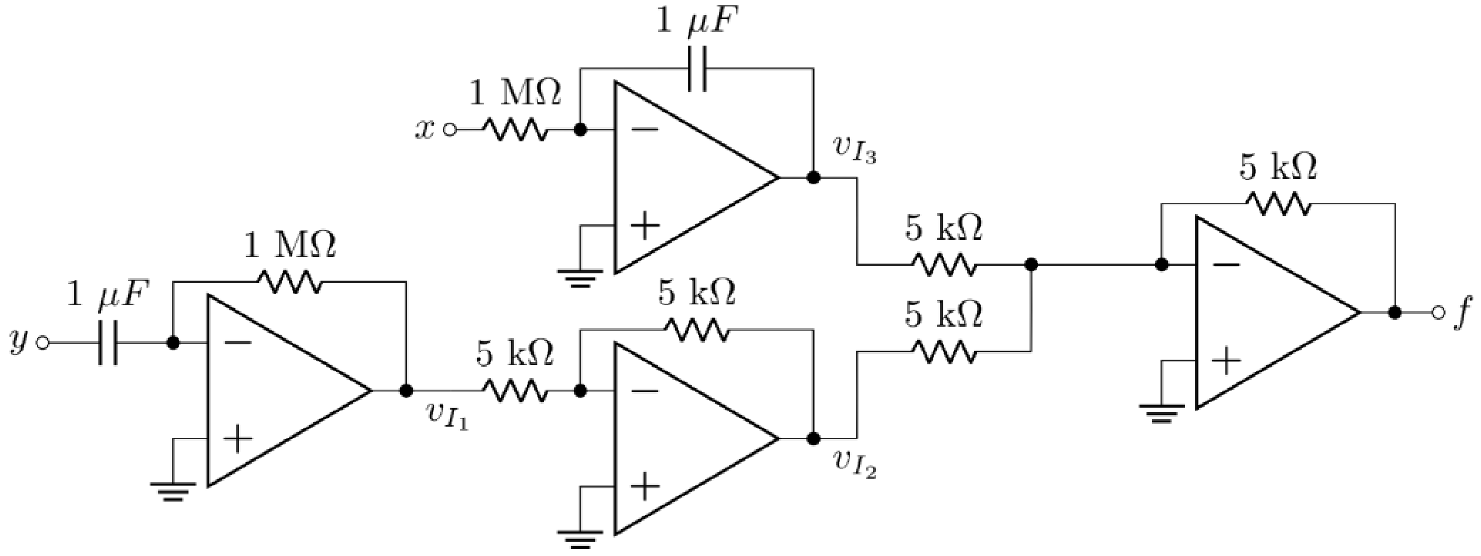
## Implementing operational functions

- $f = -7x + \frac{d}{dt} y$



# Example

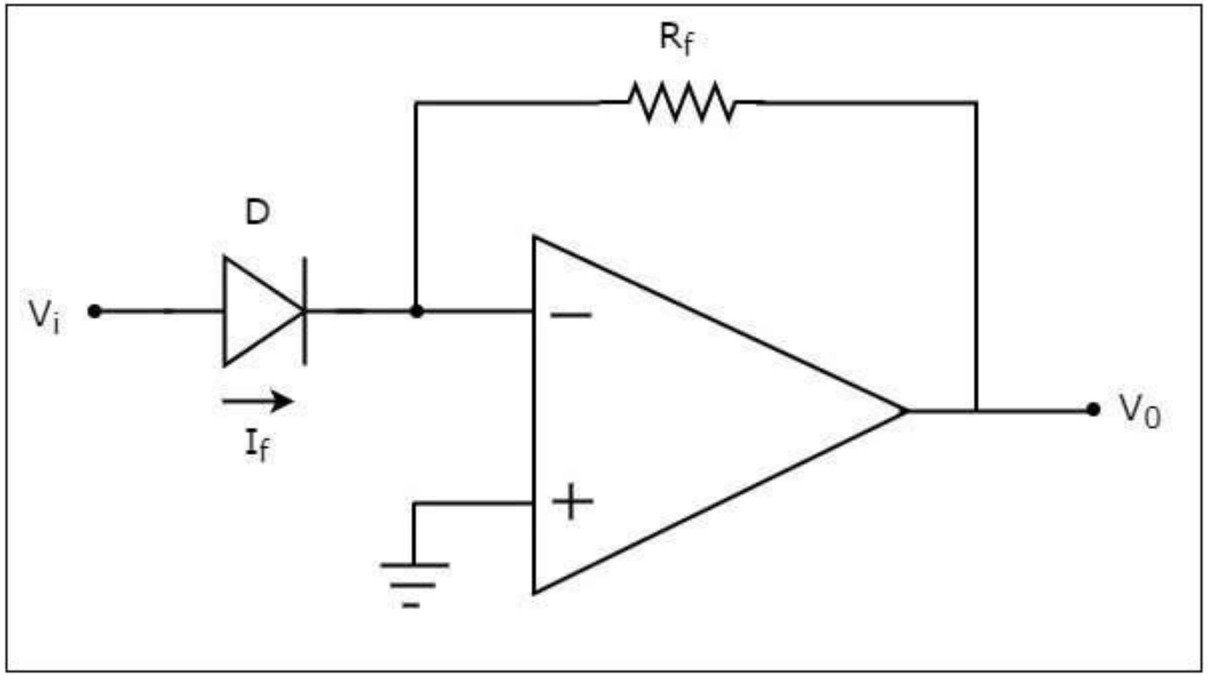
**Analyze** the circuit below to **find** an expression of f in terms of inputs x and y.




**Solution:**

$$v_{f1} = -\frac{dy}{dt}; v_{f2} = -\frac{1}{RC}\int x\, dt; v_{f3} = -v_{f1} = \frac{dy}{dt};\ v_o = -(v_{f1}+v_{f2}+v_{f3})$$

# Exponential (Anti-log) Converter

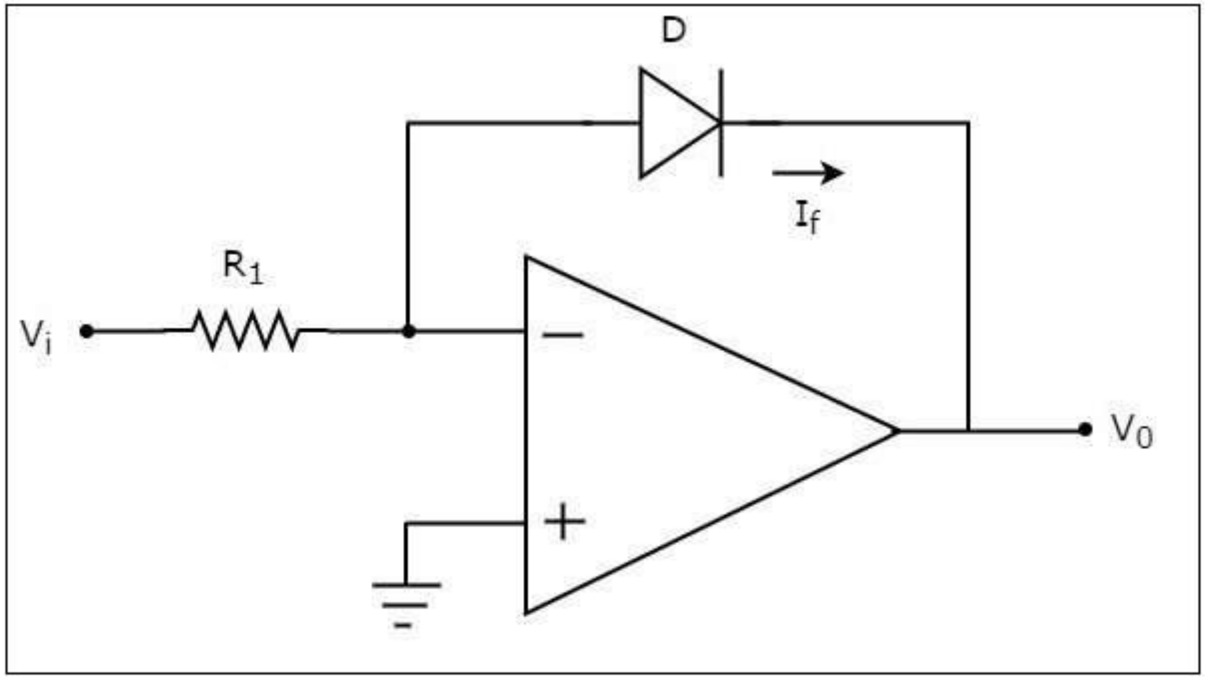



$$I_f = I_S \exp\left(\frac{V_i - 0}{V_T}\right)$$

$$\frac{0 - V_O}{R_f} = I_S \exp(\frac{V_i}{V_T})$$

$$\boldsymbol{V_O = I_s R_f \cdot \exp(\frac{V_i}{V_T})}$$

# Logarithmic Amplifier




$$I_f = I_S \exp\left(-\frac{V_O}{V_T}\right)$$

$$\frac{V_i}{R_1} = I_S \exp(-\frac{V_O}{V_T})$$

$$\frac{V_i}{I_S R_1} = \exp(-\frac{V_O}{V_T})$$

$$\boldsymbol{V_O = -V_T \cdot \ln\left(\frac{V_i}{I_S R_1}\right)}$$

# APPLICATIONS:

## Implementing operational functions

- $f = -\frac{1}{3}\int x \cdot dt + 2\ln y + 4z$

# APPLICATIONS:

## Implementing operational functions

- $f = -3\frac{dx}{dt} + 2\exp(y) + 4z$

# Multiplier

$$f = xy$$

$$\ln(f) = \ln(xy) = \ln(x) + \ln(y)$$

$$f = \exp(\ln(x) + \ln(y))$$

So,

$f = \exp(z)$ where $z = \ln(x) + \ln(y)$

# Divider

$$f = xy/z$$

$$\ln(f) = \ln(xy/z) = \ln(x) + \ln(y) - \ln(z)$$

$$f = \exp(\ln(x) + \ln(y) - \ln(z))$$

So,

$f = \exp(z)$ where $z = \ln(x) + \ln(y) - \ln(z)$

# APPLICATIONS:

## Implementing operational functions

- $f = xy/z$