CSE 251
Electronic Devices and Circuits

Lecture 4

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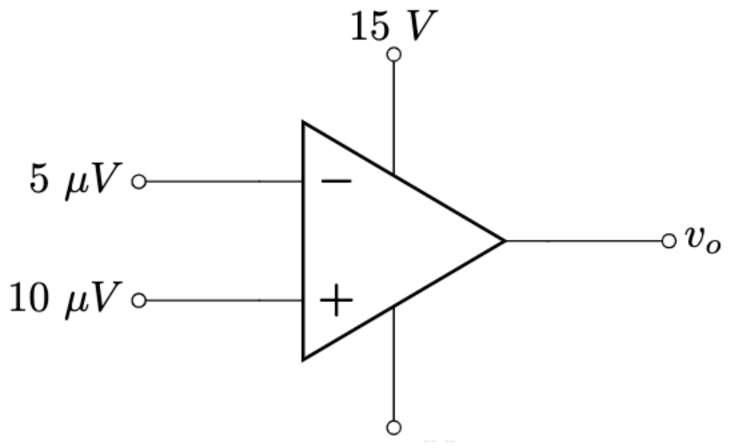
Outline

- Feedback in Op-Amp circuit
- Negative Feedback
- Open Loop VS Closed Loop Gain
- Closed Loop Configuration

Types of Op-Amp configuration

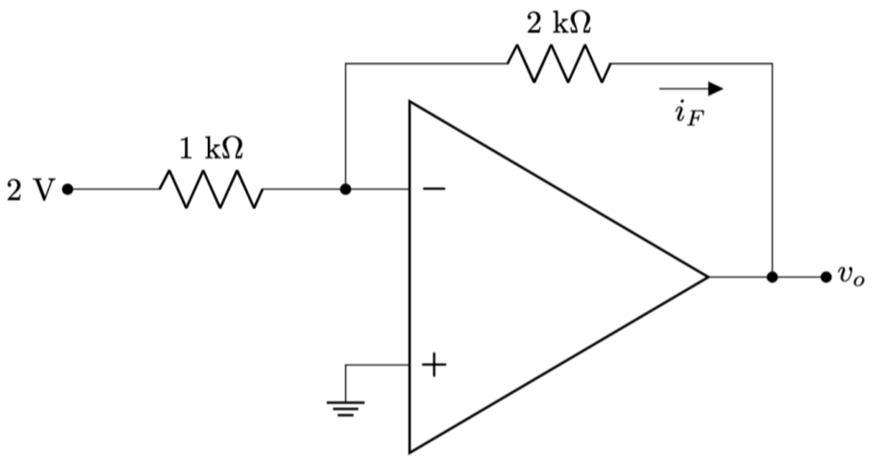
1. Open loop configuration:

   No physical connection between input and output



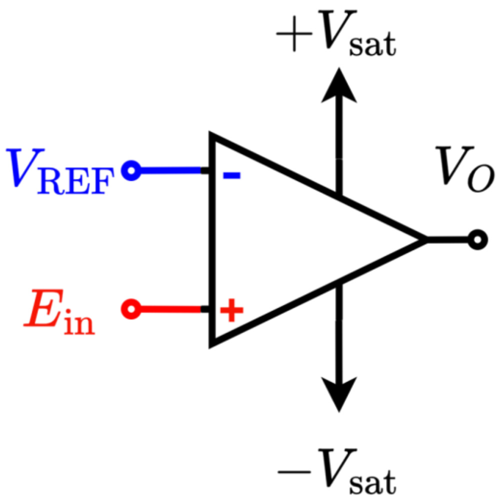
2. Closed loop configuration:

   Feedback from output terminal



Basic Op-Amp Configurations

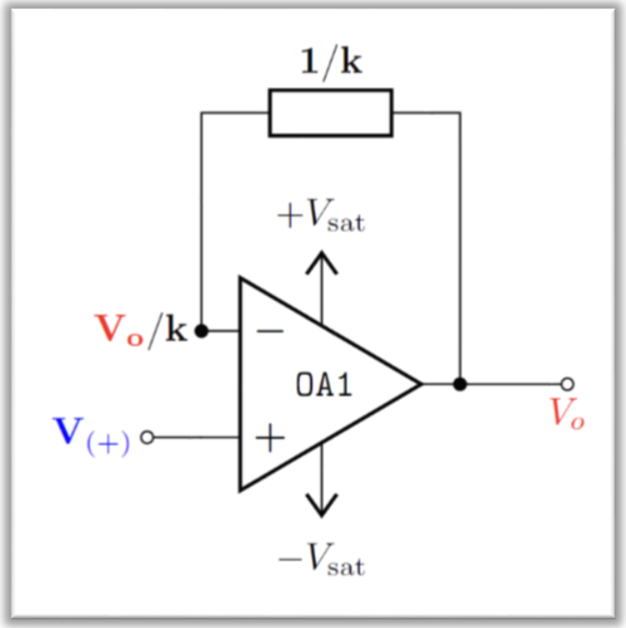
- **Open-loop Configurations**
  1. Comparator / Voltage Level Detectors



- **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

Closed Loop Configuration

Feedback



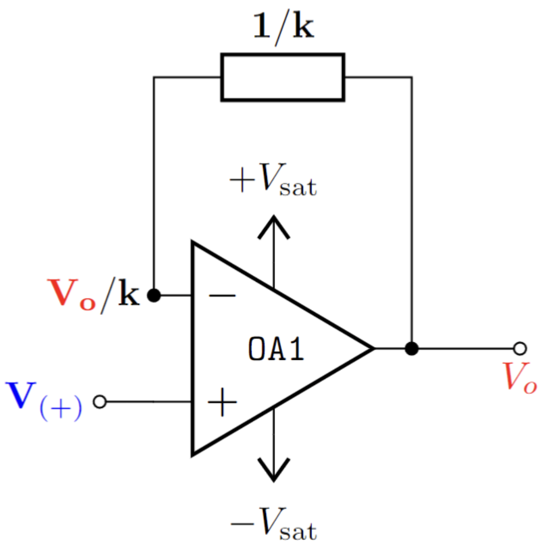
Feedback in Op-Amp circuit

Two types of feedback

1. Negative Feedback:

   Output voltage is fed to the inputs **negatively**

   The output voltage is connected to the **inverting** terminal

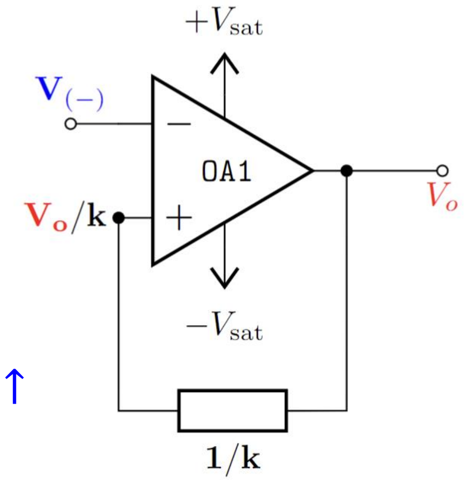


$$V_o \uparrow \quad \Rightarrow \frac{V_o}{k} \uparrow \quad \Rightarrow V_{(-)} \uparrow \quad \boxed{\Rightarrow V_d \downarrow = V_{(+)} - V_{(-)} \uparrow} \quad \Rightarrow V_o \propto V_d \downarrow$$

2. Positive Feedback:

   Output voltage is fed to the inputs **positively**

   The output voltage is connected to the **non-inverting** terminal



$$V_o \uparrow \quad \Rightarrow \frac{V_o}{k} \uparrow \quad \Rightarrow V_{(+)} \uparrow \quad \boxed{\Rightarrow V_d \uparrow \; = \; V_{(+)} \uparrow - V_{(-)}} \quad \Rightarrow V_o \propto V_d \uparrow$$

Feedback in Op-Amp circuit

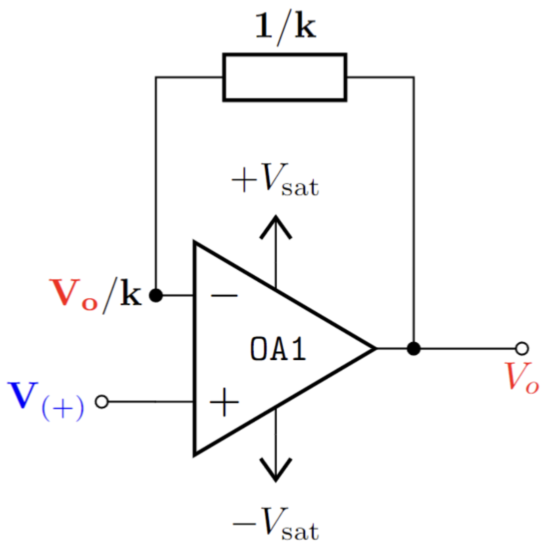
Two types of feedback

1. Negative Feedback:

   Output voltage is fed to the inputs **negatively**

   The output voltage is connected to the **inverting** terminal

$$V_o \uparrow \;\Rightarrow V_o \propto V_d \downarrow$$

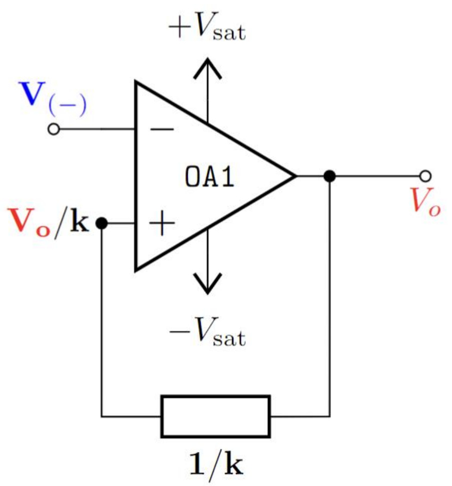


2. Positive Feedback:

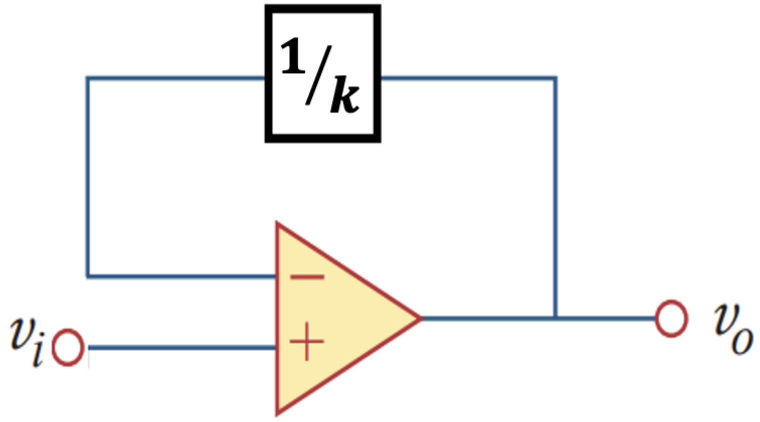
   Output voltage is fed to the inputs **positively**

   The output voltage is connected to the **non-inverting** terminal

$$V_o \uparrow \;\Rightarrow V_o \propto V_d \uparrow$$



Negative Feedback – Derivation of Gain



Here, $v_- = \frac{v_0}{k}$

We know, $v_o = Av_d$

or, $v_o = A(v_+ - v_-)$

$= A(v_i - \frac{v_0}{k})$

$= Av_i - \frac{A}{k} v_0$

or, $v_o(1 + \frac{A}{k}) = Av_i$

So, $v_o = \frac{Av_i}{1+\frac{A}{k}}$

or, $v_o = \frac{v_i}{\frac{1}{A}+\frac{1}{k}}$

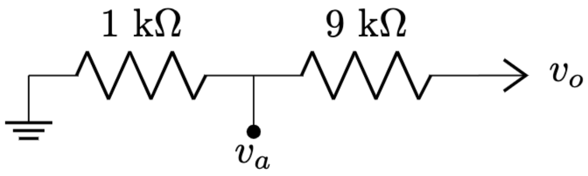
A is extremely large,

so, $\frac{1}{A} \approx 0$

$$v_o = \frac{v_i}{\frac{1}{k}} = kv_i$$

If k = 10 (meaning we feed back one tenth of the output to negative input), we will get v_o=10*v_i. that is 10 fold gain.

How to get 1/k of output to input? Voltage dividers!

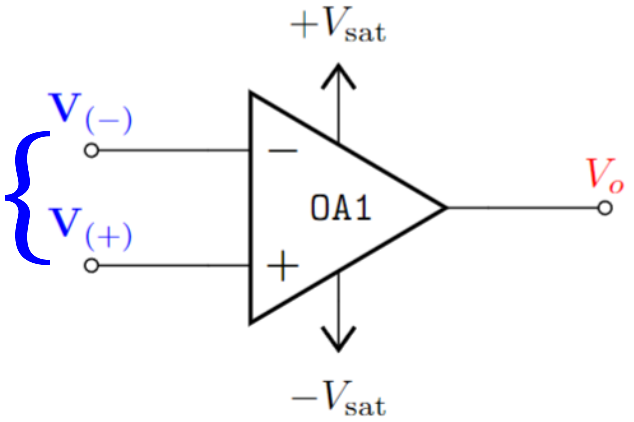


$$v_a = \frac{1\ k\Omega}{1\ k\Omega + 9\ k\Omega} \times v_o = \frac{v_o}{10}$$

Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration

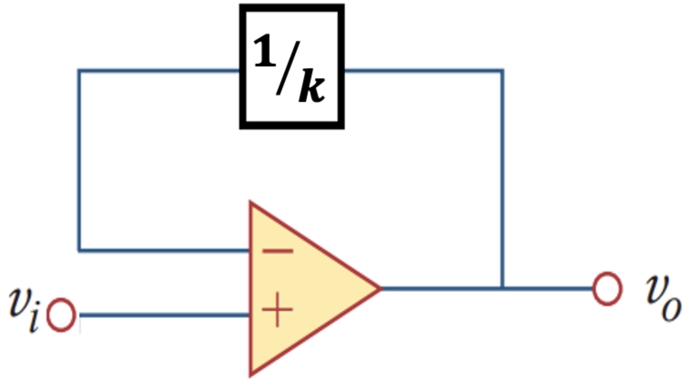
$$V_d = V_{(+)} - V_{(-)}$$



Input Voltage: V_d
Output Voltage: V_o

$\therefore$ Voltage Gain: $\dfrac{V_o}{V_d} = A \text{ or } K$

With "**Negative Feedback**":
Closed Loop (CL) Configuration



Input Voltage: V_i
Output Voltage: V_o

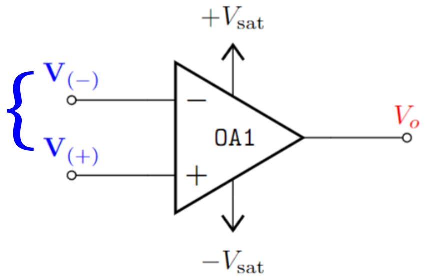
$\therefore$ Voltage Gain: $\dfrac{V_o}{V_i} = k$

OL Gain	CL Gain
A or $K \sim 10^5$	$k \ll A$ $k < 100$

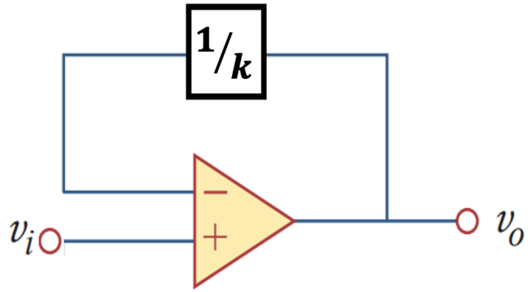
Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration

$\boldsymbol{V_d} = \boldsymbol{V}_{(+)} - \boldsymbol{V}_{(-)}$



Closed Loop (CL) Configuration



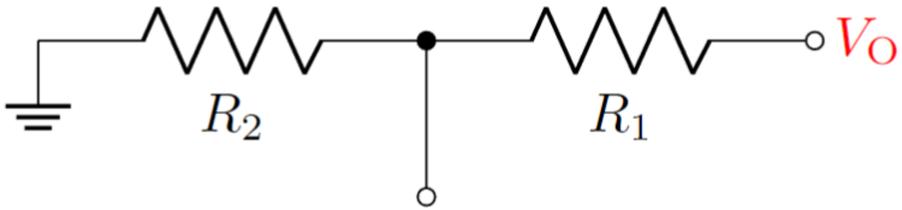
OL Gain	CL Gain
$\frac{\boldsymbol{V_o}}{\boldsymbol{V_d}} = A \text{ or } \boldsymbol{K} \sim 10^5$	$\frac{\boldsymbol{V_o}}{\boldsymbol{V_i}} = k \ll A$ $k < 100$
Can’t be controlled	Can be controlled by the feedback element
*Used as “**Comparator**”*	*Used as “**Linear Amplifier**”*

Negative Feedback in Op-Amp circuit

The **output voltage** is transformed in the following way:

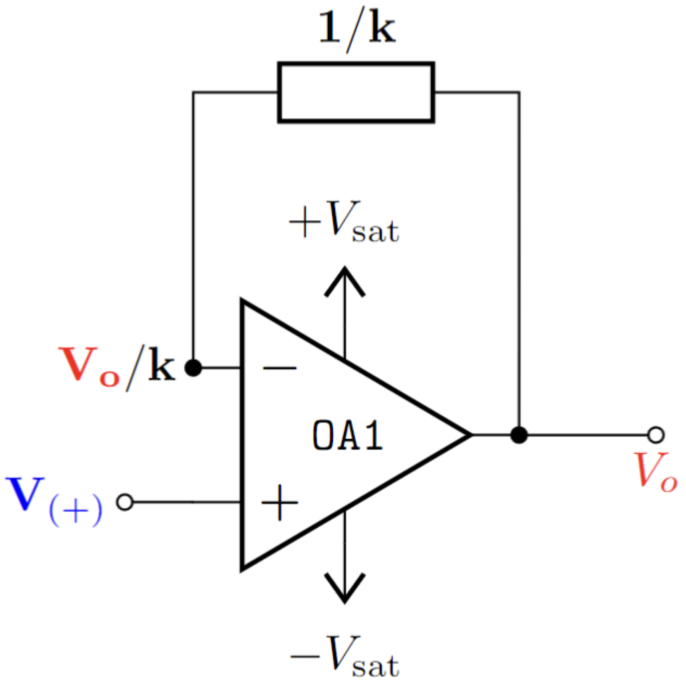
$$V_{(-)} = \frac{\mathbf{1}}{\boldsymbol{k}} \cdot V_O$$

This factor of $\mathbf{1}/\boldsymbol{k}$ can be achieved with a voltage divider network.



$$V_{(-)} = \frac{R_2}{R_2+R_1} \cdot \mathrm{V_O}$$

$$\boxed{\frac{\mathbf{1}}{\boldsymbol{k}} = \frac{\mathrm{R}_2}{R_1 + R_2}}$$

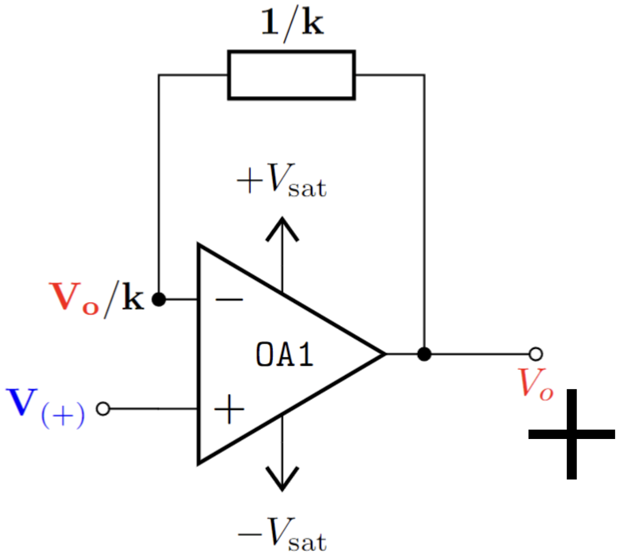


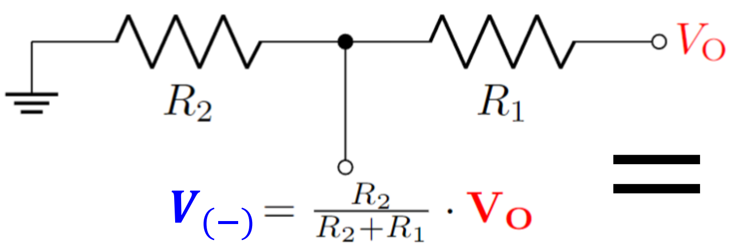
A voltage divider can act as a **multiplier/factor** in the feedback branch

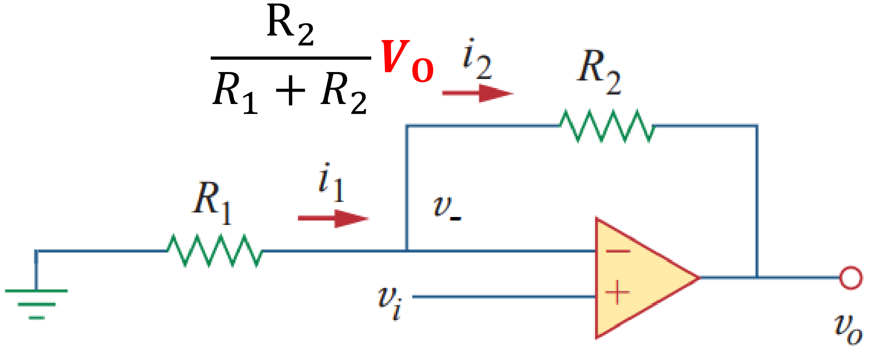
Negative Feedback in Op-Amp circuit

A voltage divider can act as a **multiplier/factor** in the **feedback** branch

$$\frac{R_2}{R_1 + R_2} = \frac{\mathbf{1}}{\boldsymbol{k}}$$



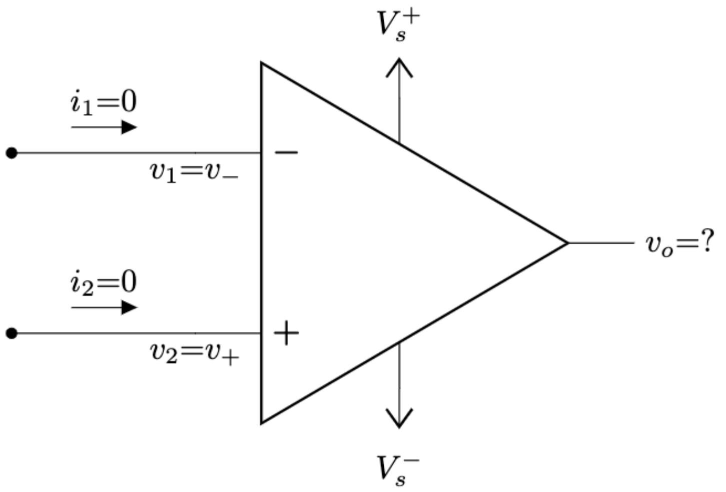




If $\boldsymbol{k}$ = 10 (meaning we feed back one tenth of the output to negative input), we will get $\boldsymbol{v_o}$=10*$\boldsymbol{v_i}$. that is 10-fold gain.

Solving Closed Loop Op-Amp Circuit

- For "**ideal**" op-amp
  - **Infinite** input resistance, $\boldsymbol{R_i} = \infty = \text{open circuit}$
  - **Zero** output resistance, $\boldsymbol{R_o} = \mathbf{0} = \text{short circuit}$
  - $\boldsymbol{i_i} = \mathbf{0}$ and $\boldsymbol{i_+} = \mathbf{0}$

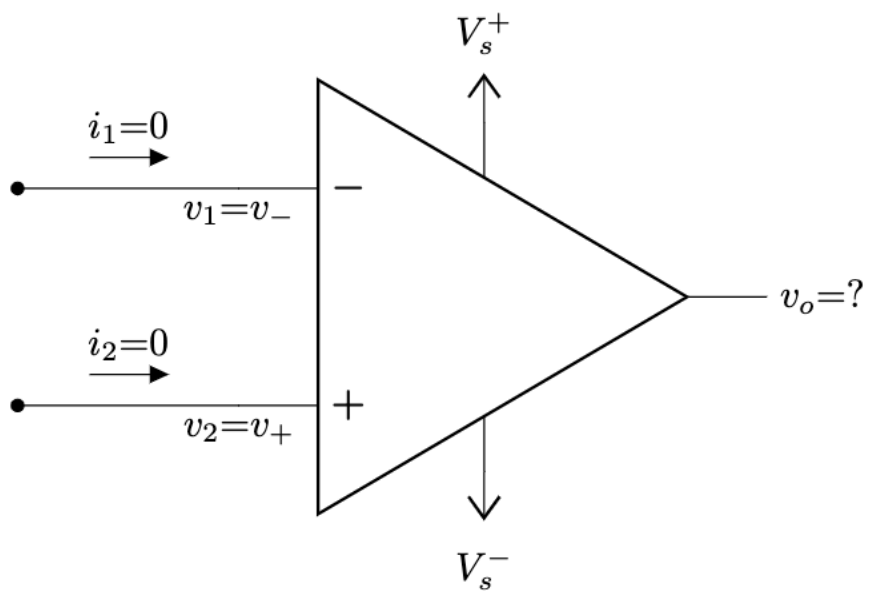


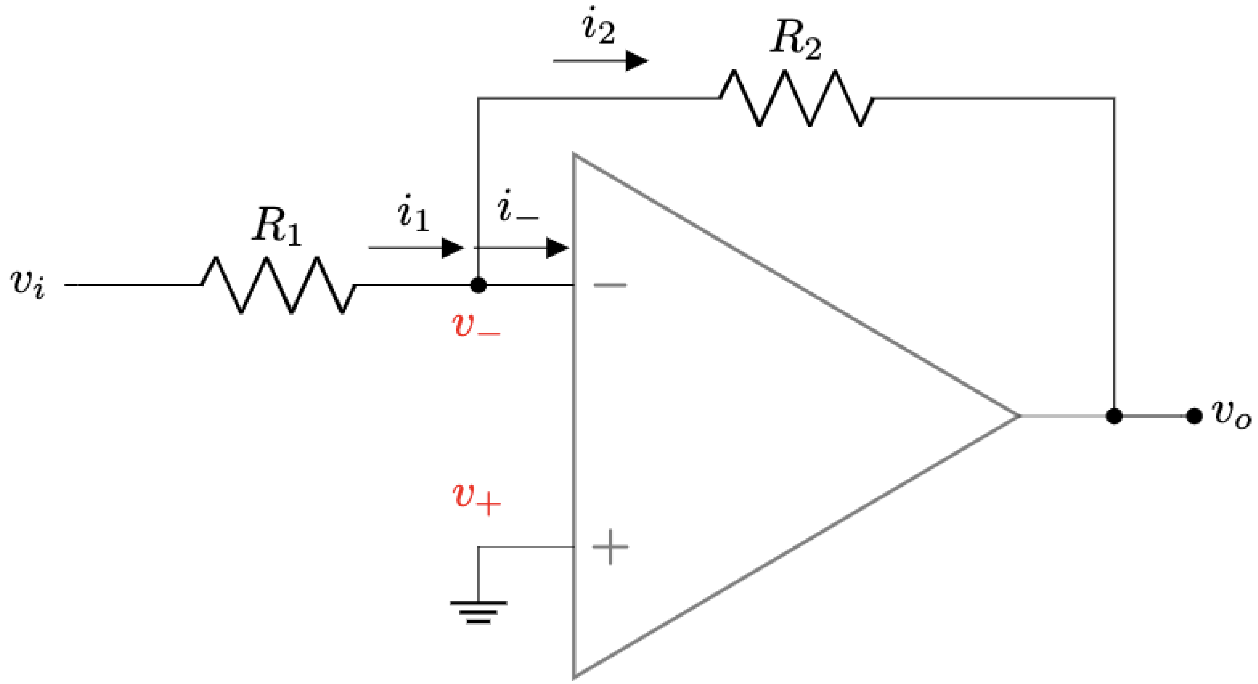
- ***<u>When there is negative feedback</u>***,
  - In an ideal op-amp, "$\boldsymbol{A}$" (or $\boldsymbol{K}$) is **infinitely high**. Thus, for a finite output voltage $\boldsymbol{v_o}$:

$$\frac{v_o}{A} = v_d \to 0 \Rightarrow v_+ = v_-.$$

  - This is called **virtual short circuit**

Solving Closed Loop Op-Amp Circuit

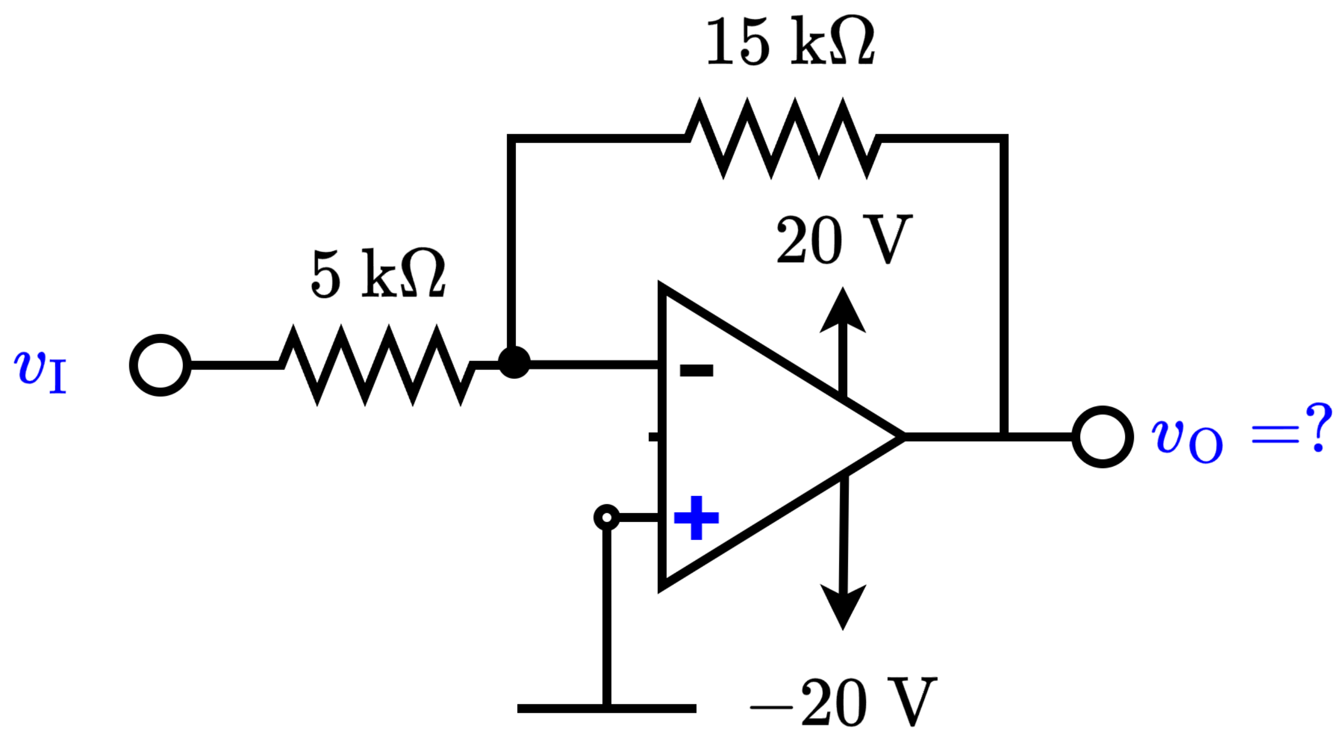




Two Rules:

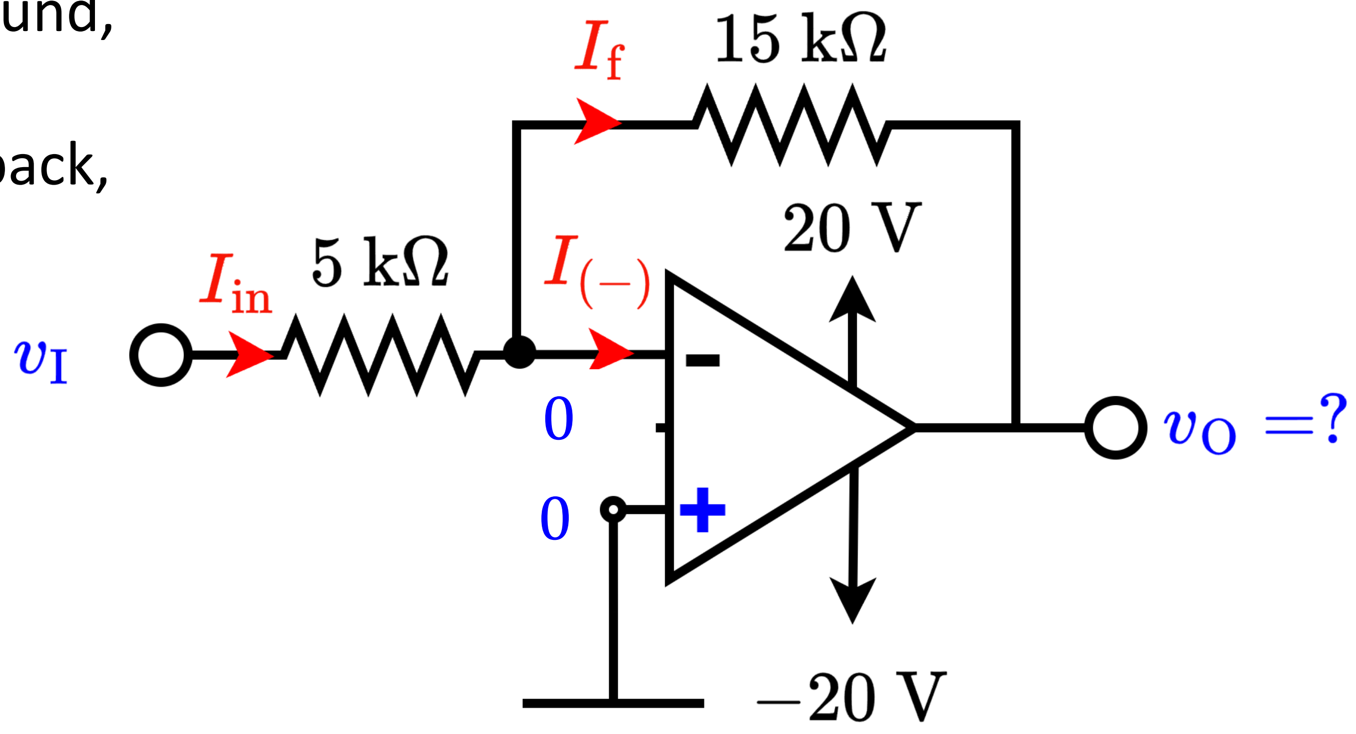
1. Virtual Shorting: $\boldsymbol{v_+ = v_-}$
2. Zero input bias current: $\boldsymbol{i_- = i_+ = 0}$

Solving Closed Loop Op-Amp Circuit



Solving Closed Loop Op-Amp Circuit

1. Since $\boldsymbol{v}_+$ is connected to ground,
$$\boldsymbol{v}_+ = \mathbf{0\ V}$$
2. Since there is negative feedback, from virtual short,
$$\boldsymbol{v}_- = \boldsymbol{v}_+ = \mathbf{0\ V}$$
3. Ohm's law for $\mathbf{5\ k\Omega}$:
$$I_{\text{in}} = \frac{v_{\text{I}} - 0}{5} = \frac{v_{\text{I}}}{5}$$
4. Ohm's law for $\mathbf{15\ k\Omega}$:
$$I_{\text{f}} = \frac{0 - v_O}{15} = -\frac{v_{\text{O}}}{15}$$



Solving Closed Loop Op-Amp Circuit

3. Ohm's law for **5 kΩ**:

$$I_{\text{in}} = \frac{v_I - 0}{5} = \frac{v_I}{5}$$

4. Ohm's law for **15 kΩ**:

$$I_f = \frac{0 - v_O}{15} = -\frac{v_O}{15}$$

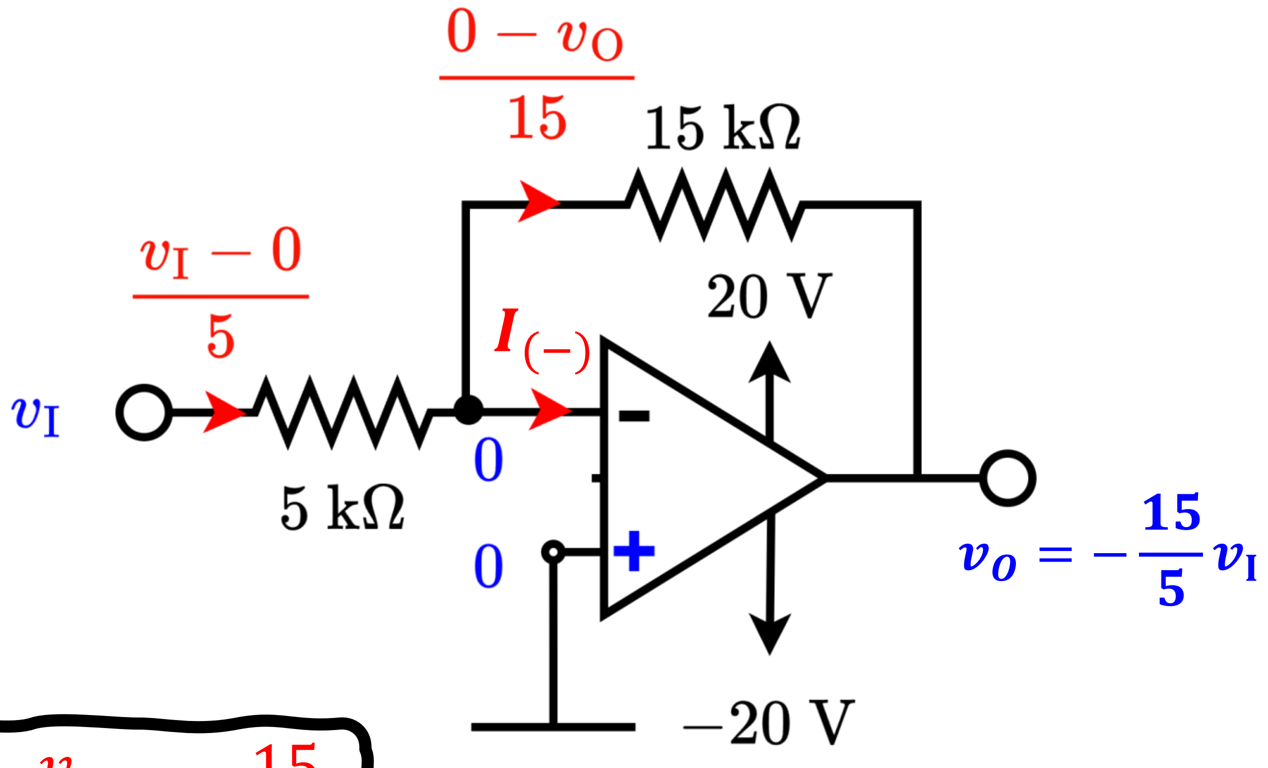
5. For "**ideal**" op-amp,

$$\boldsymbol{I}_{(-)} = \boldsymbol{I}_{(+)} = 0$$

6. So, $\boldsymbol{I}_{\mathbf{in}} = \boldsymbol{I}_{\mathbf{f}}$

$$-\frac{v_O}{15} = \frac{v_I}{5}$$

$$\boxed{\Rightarrow \frac{v_O}{v_I} = -\frac{15}{5}}$$



Solving Closed Loop Op-Amp Circuit

3. Ohm's law for **5 kΩ**:

$$I_{\text{in}} = \frac{v_{\text{I}} - 0}{R_{\text{I}}} = \frac{v_{\text{I}}}{R_{\text{I}}}$$

4. Ohm's law for **15 kΩ**:

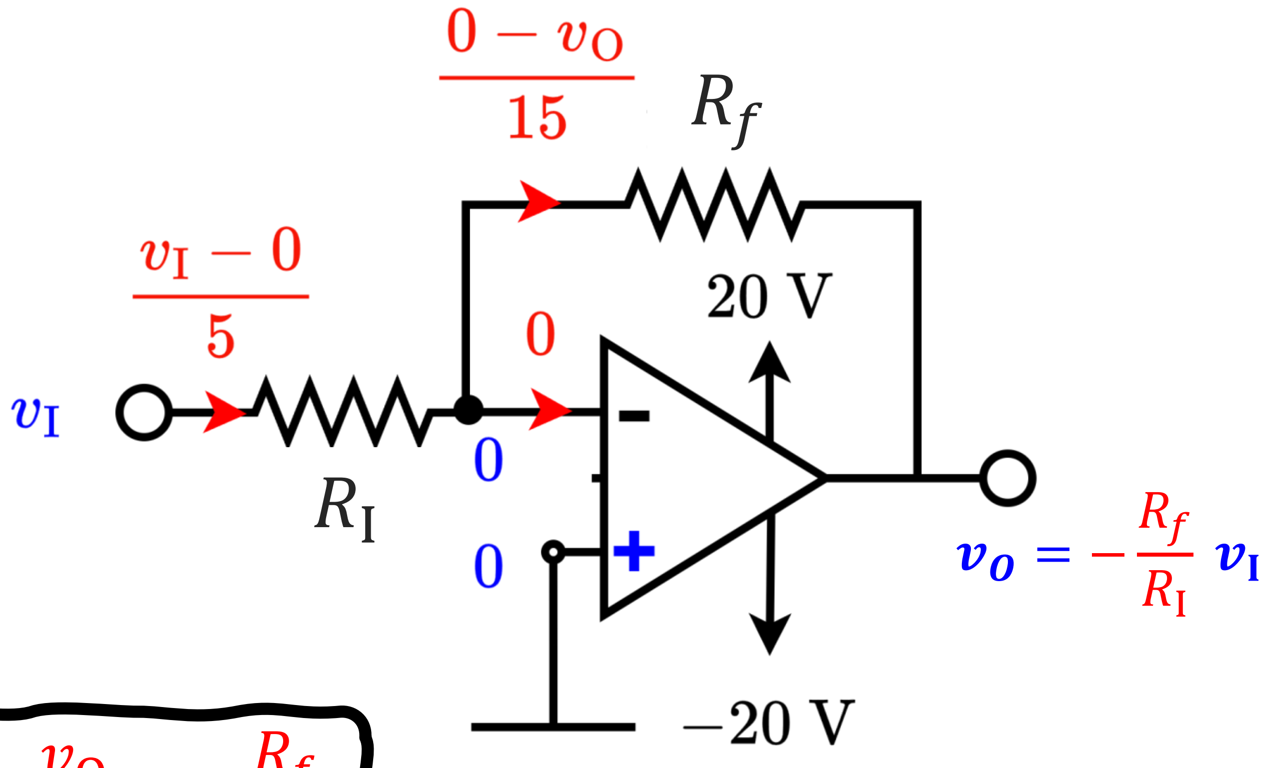
$$I_{\text{f}} = \frac{0 - v_O}{R_f} = -\frac{v_O}{R_f}$$

5. For "**ideal**" op-amp,

$$\boldsymbol{I}_{(-)} = \boldsymbol{I}_{(+)} = 0$$

6. So, $\boldsymbol{I}_{\text{in}} = \boldsymbol{I}_{\text{f}}$

$$-\frac{v_{\text{O}}}{R_f} = \frac{v_{\text{I}}}{R_{\text{I}}}$$



$$\Rightarrow \boxed{\frac{v_{\text{O}}}{v_{\text{I}}} = -\frac{R_f}{R_{\text{I}}}}$$

Solving Closed Loop Op-Amp Circuit

7. Check whether the amplified voltage exceeds **saturation limit**.

$$-\frac{R_f}{R_I}v_I = -\frac{15}{5}v_I = -3v_I$$

If $v_I = 3\text{ V}$:

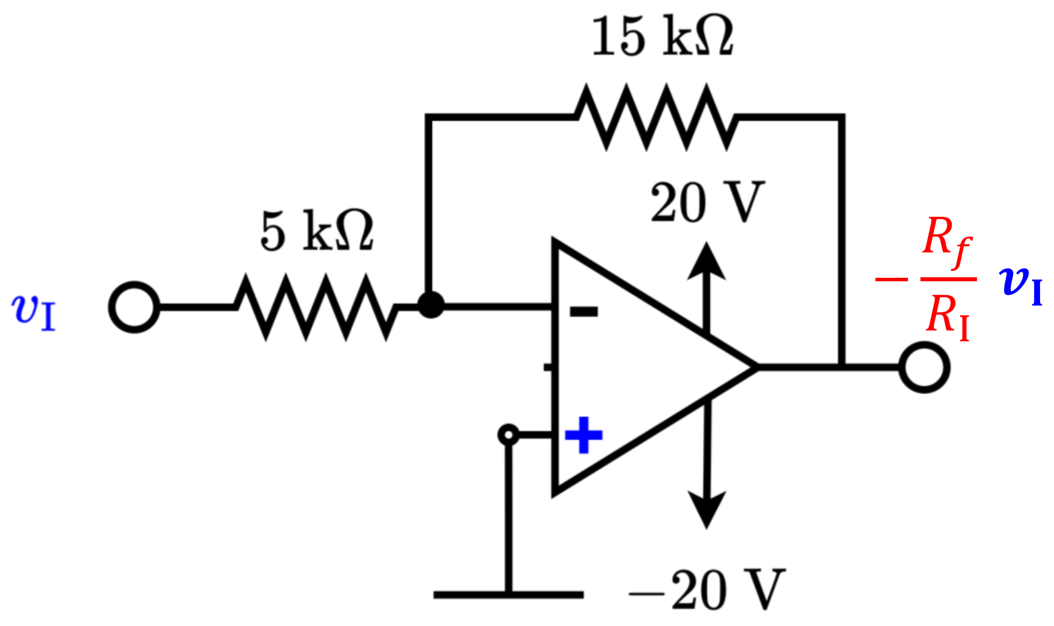
$$-3v_I = -3 \times 3 > -20\text{ V}$$

$$\therefore\ v_O = -9\text{ V}$$

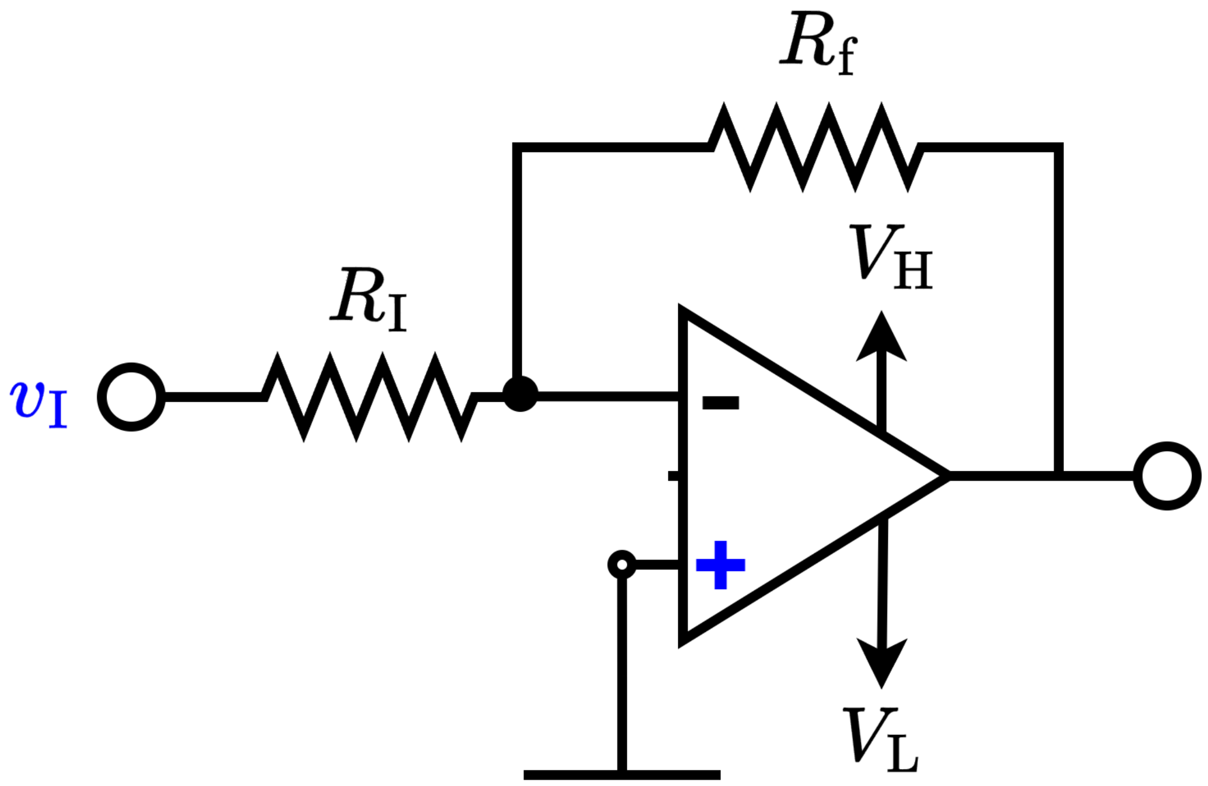
If $|v_I| > 6.67\text{ V}$:

Op-amp goes into saturation as $-3v_I = -3 \times 6.67 < -20$

$$\therefore\ v_O = -20\text{ V}$$

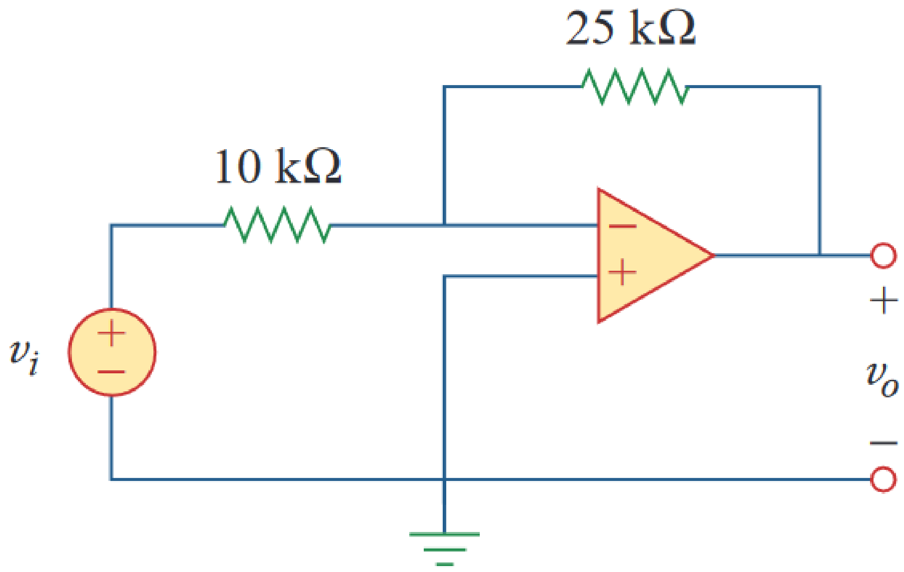


Inverting Amplifier



$$v_{\mathrm{O}} = \begin{cases} V_{\mathrm{H}}, & \text{if } v_O \geq V_{\mathrm{H}} \\ -v_I \cdot \frac{R_f}{R_i}, & \text{if } V_{\mathrm{L}} \leq v_O \leq V_{\mathrm{H}} \\ V_{\mathrm{L}}, & \text{if } v_O \leq V_{\mathrm{L}} \end{cases}$$

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.

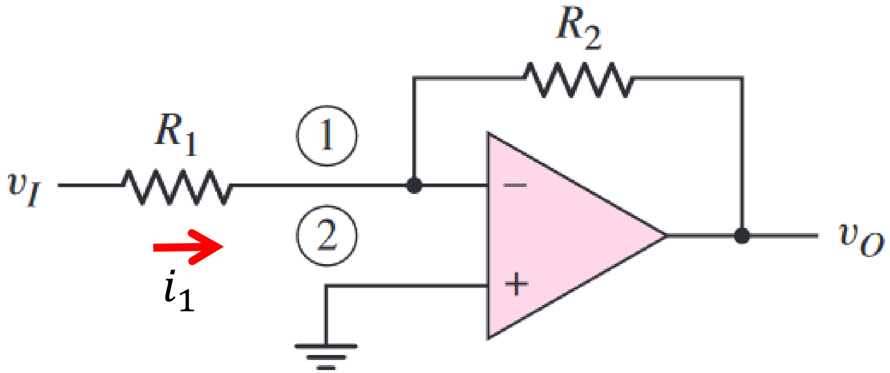
(a)

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

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

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

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 $\mathbf{5\ \mu A}$.

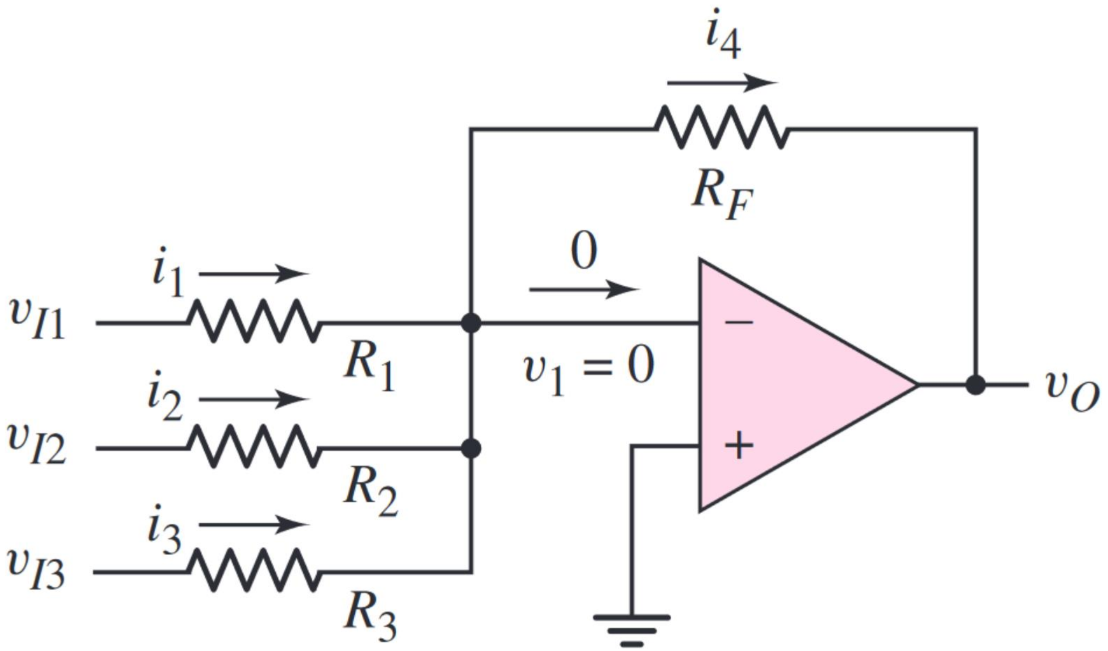
$$\boldsymbol{i_1} = \frac{\boldsymbol{v_I}}{\boldsymbol{R_1}}$$

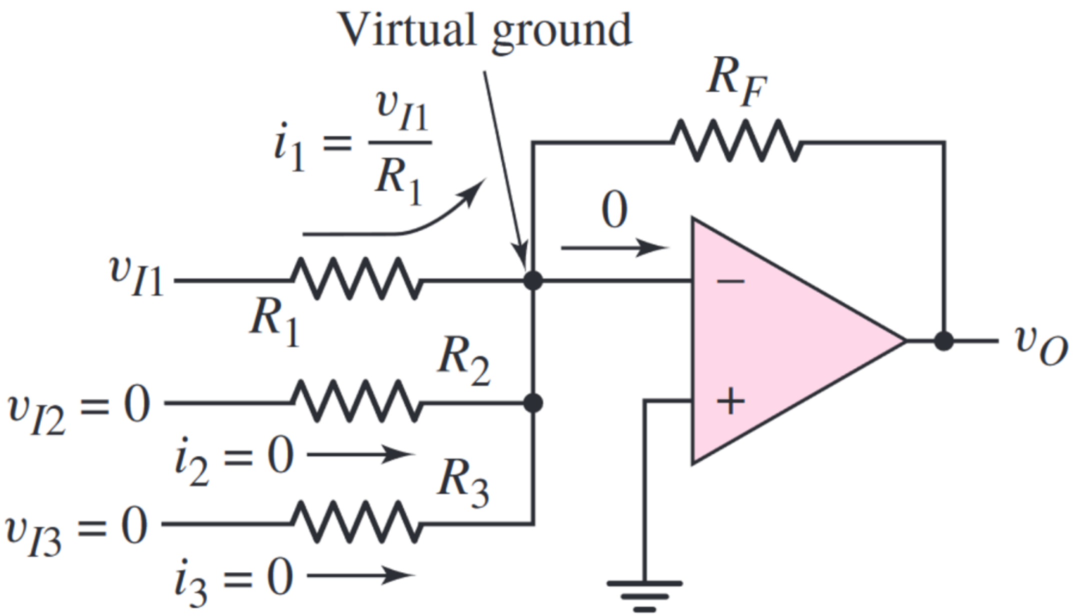
$$\boldsymbol{R_1} = \frac{v_I(\max)}{i_1(\max)} = \frac{0.1}{5 \times 10^{-3}} = \mathbf{20\ k\Omega}$$

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

Inverting Summer

- Multichannel Amplifier

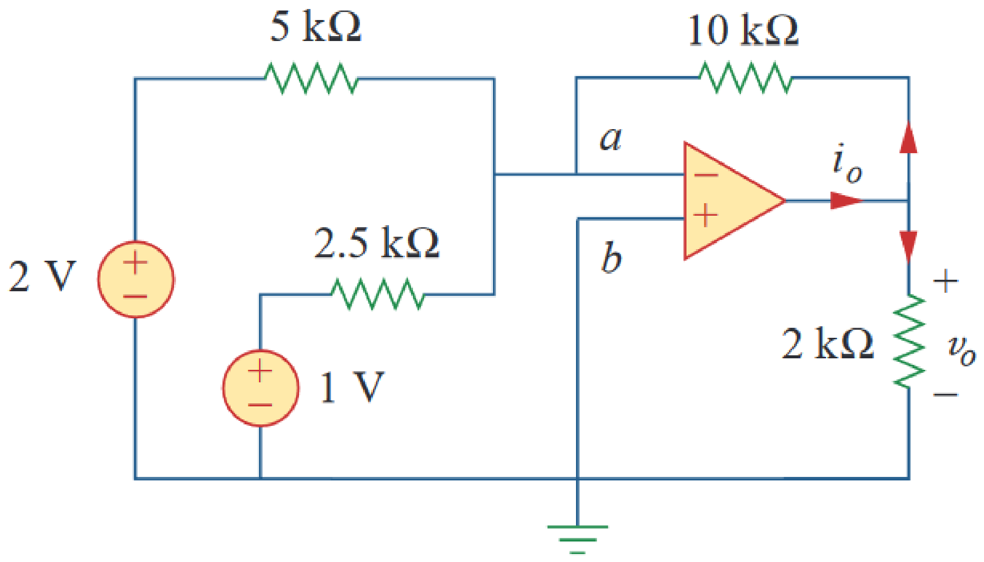




$$v_O(v_{I1}) = -i_1 R_F = -\left(\frac{R_F}{R_1}\right) v_{I1}$$

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

Example - 3



Calculate:

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

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

(a)

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

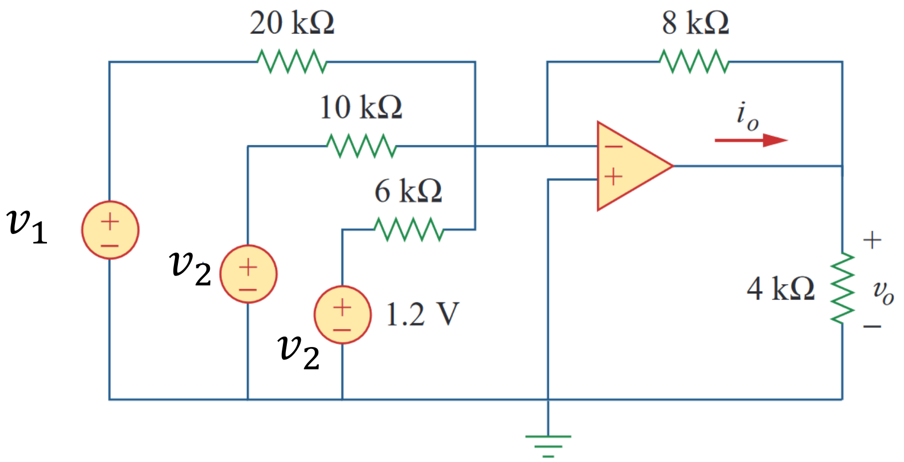
(b)

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

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**).

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

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

Example 4

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

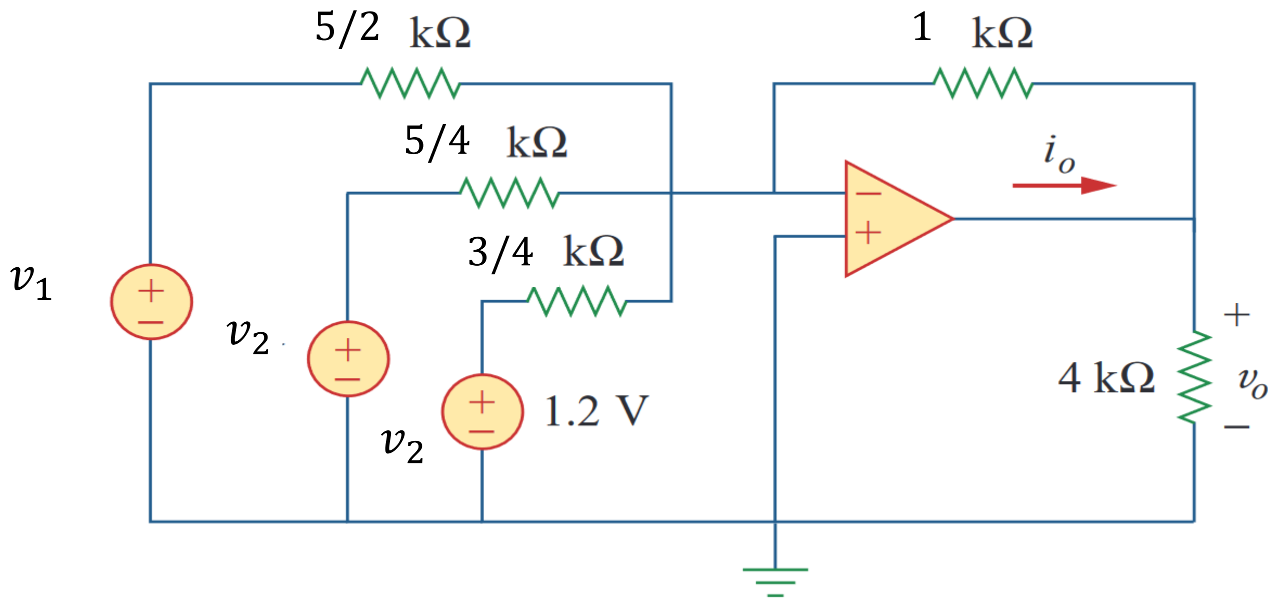
$$v_o = -\frac{2}{5}v_1 - \frac{4}{5}v_2 - \frac{4}{3}v_3$$

Easier Solution:

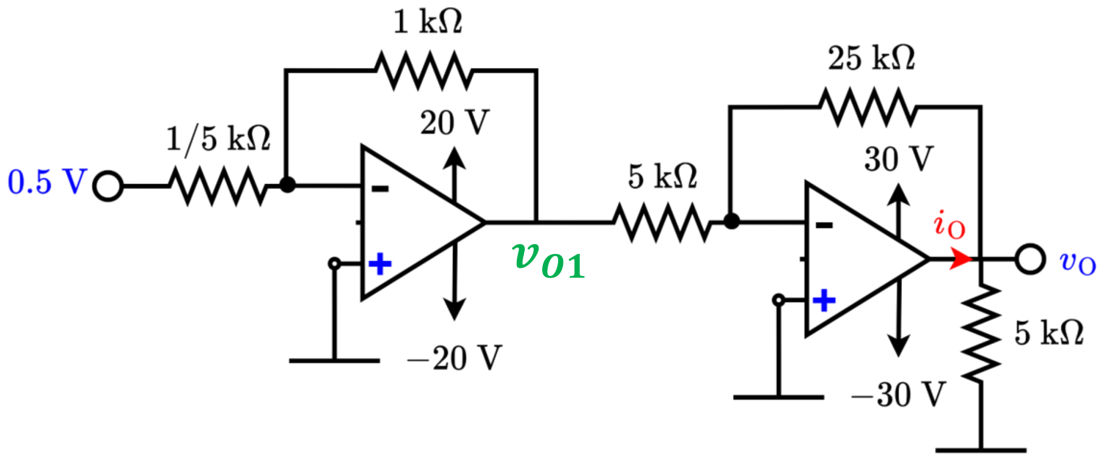
$$v_o = -\frac{2}{5}v_1 - \frac{4}{5}v_2 - \frac{4}{3}v_3$$

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

$$= -\frac{1}{5/2}v_1 - \frac{1}{5/4}v_2 - \frac{1}{3/4}v_3$$



Example - 5



$v_I = 0.5$ V. Calculate:

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

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

(a)

$$\boldsymbol{v_{O1} = -\frac{1}{1/5} \times 0.5\ \mathrm{V} = -2.5\ \mathrm{V}}$$

$$\boldsymbol{v_o = -\frac{25}{5} \cdot v_{O1} = 12.5\ \mathrm{V}}$$

$$\boldsymbol{v_o = \left(-\frac{1}{1/5}\right) \cdot \left(-\frac{25}{5}\right) \cdot 0.5 = 12.5\ \mathrm{V}}$$

(b)

$$i = \frac{v_O}{5} + \frac{v_O}{25} = (2.5 + 0.5\ )\ \mathrm{mA} = \mathbf{3\ mA}$$

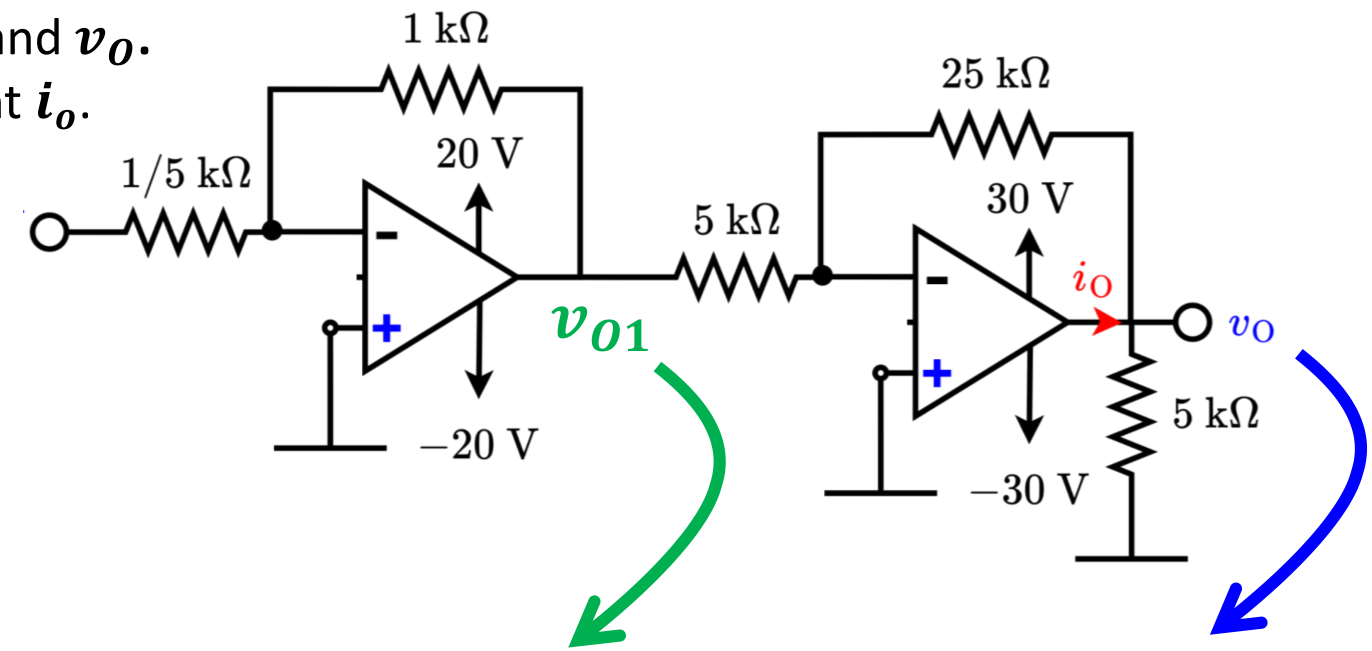
Example - 6

Calculate:

(a) Voltages $\boldsymbol{v_{o1}}$ and $\boldsymbol{v_O}$.

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

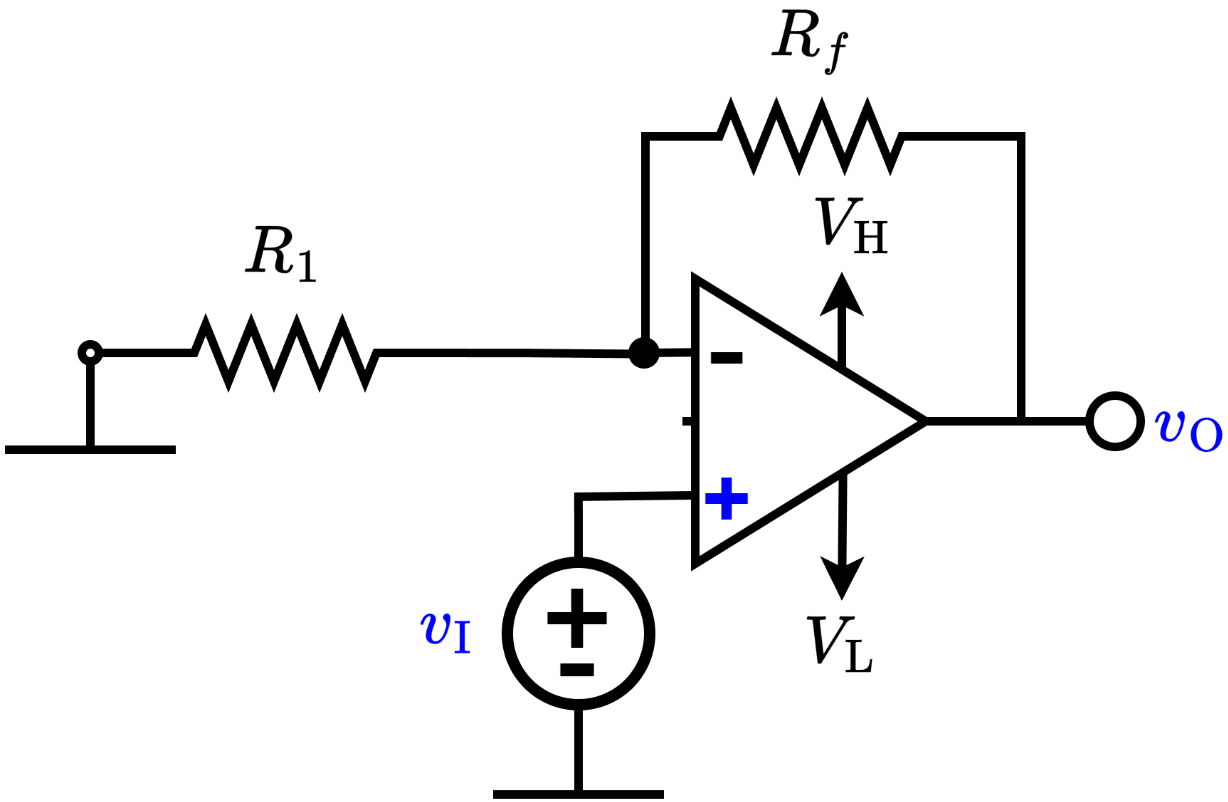
$\boldsymbol{v_{\mathrm{I}} = 0.5\sin(120\pi t)}$



$\boldsymbol{v_{O1} = 2.5\sin(120\pi t)}$

$\boldsymbol{v_O = 12.5\sin(120\pi t)}$

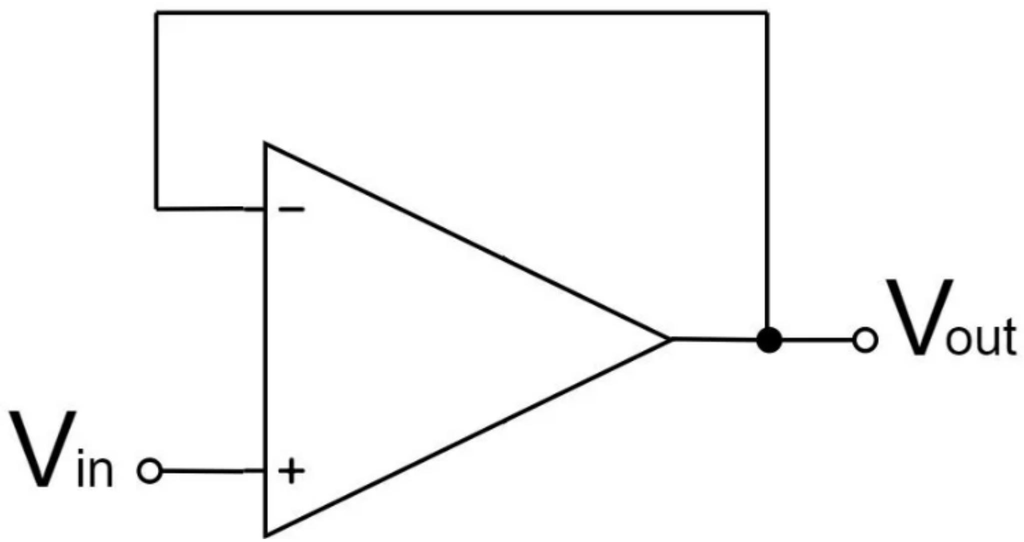
Non-Inverting Amplifier



$$v_O = \begin{cases} V_H, & \text{if } v_O \geq V_H \\ v_I \cdot (1 + \frac{R_f}{R_I}), & \text{if } V_L \leq v_O \leq V_H \\ V_L, & \text{if } v_O \leq V_L \end{cases}$$

$$v_O > v_I$$

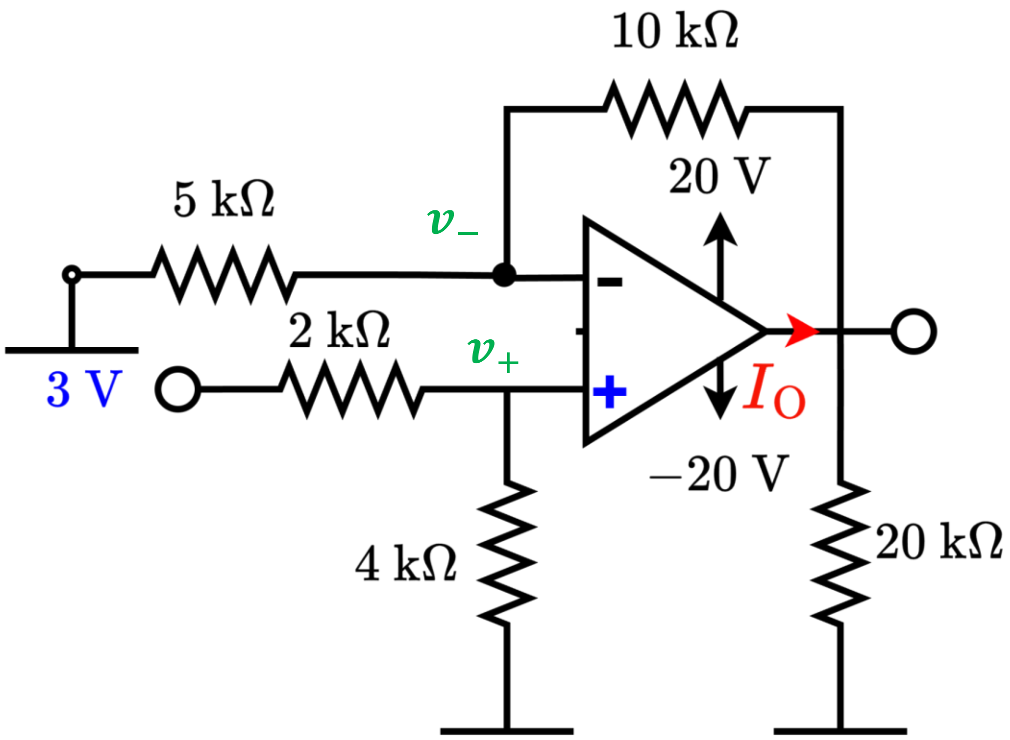
Voltage Follower / Buffer:



$$\boldsymbol{v_{Out} = v_{in}}$$

Regardless of the value of $\boldsymbol{R_f}$

Non-Inverting Amplifier: Example 7



Calculate:

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

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

(a)

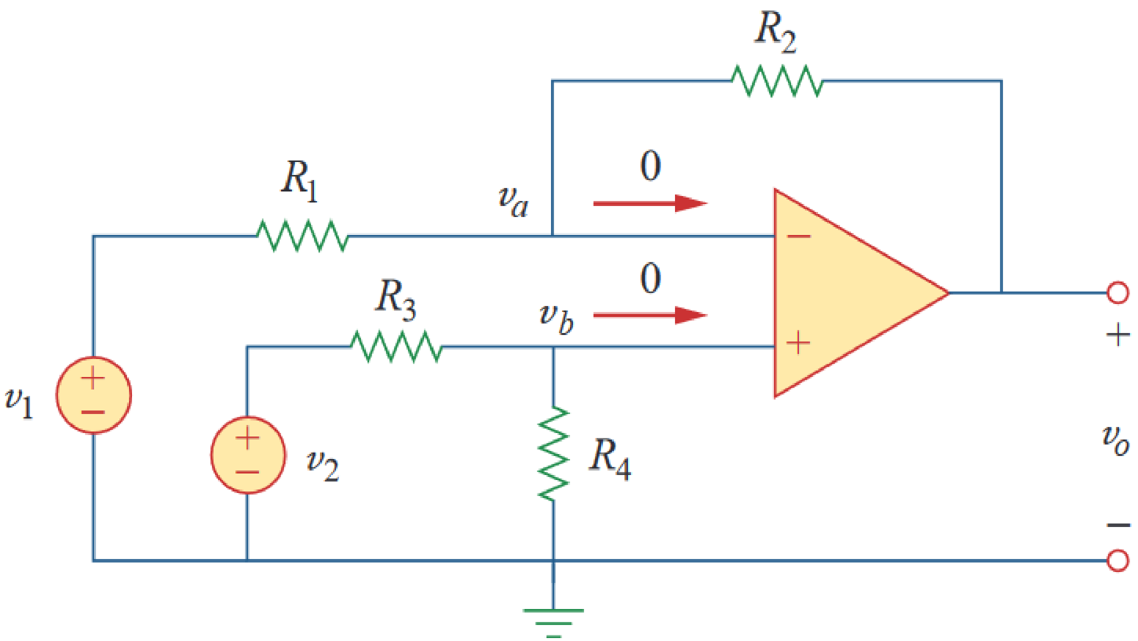
$$v_+ = \frac{4}{2+4} \times 3\ \mathrm{V} = 2\ \mathrm{V}$$

$$v_o = \left(1 + \frac{10}{5}\right) \cdot v_+ = 6\ \mathrm{V}$$

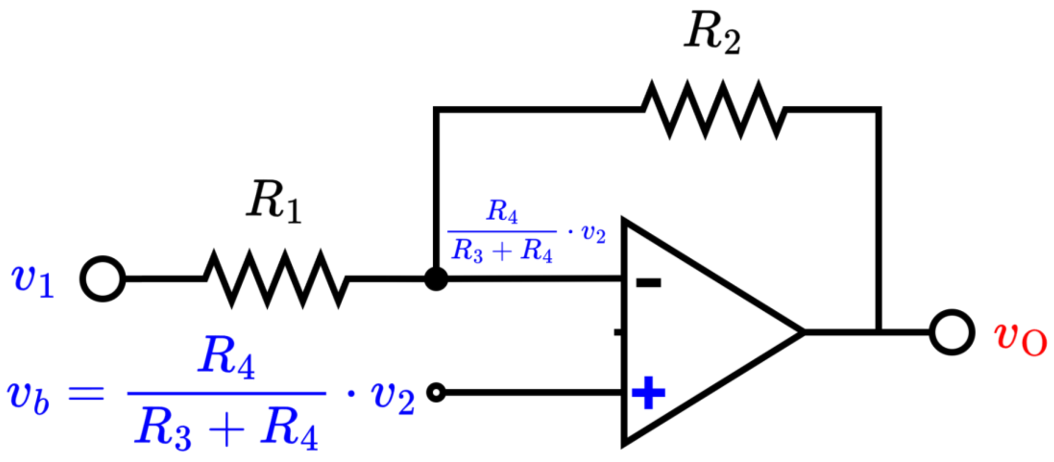
(b)

$$i = \frac{v_o}{20} + \frac{v_o}{10} = (0.3 + 0.6\,)\ \mathrm{mA} = 0.9\ \mathbf{mA}$$

Difference Amplifier



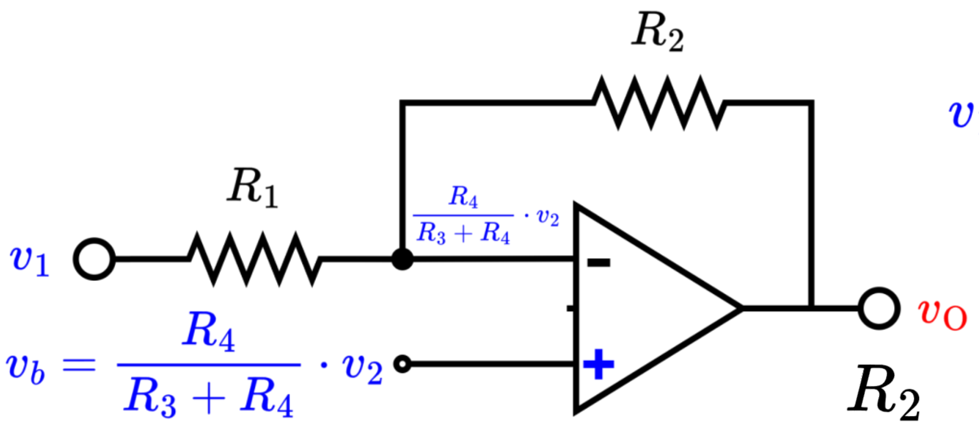
$$v_b = v_a = \frac{R_4}{R_3 + R_4} v_2$$

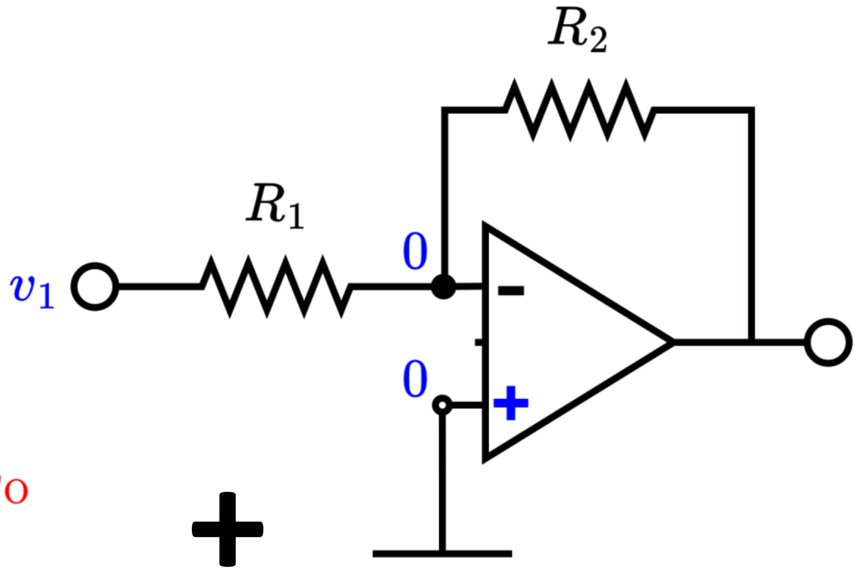


Simplified Circuit

Difference Amplifier

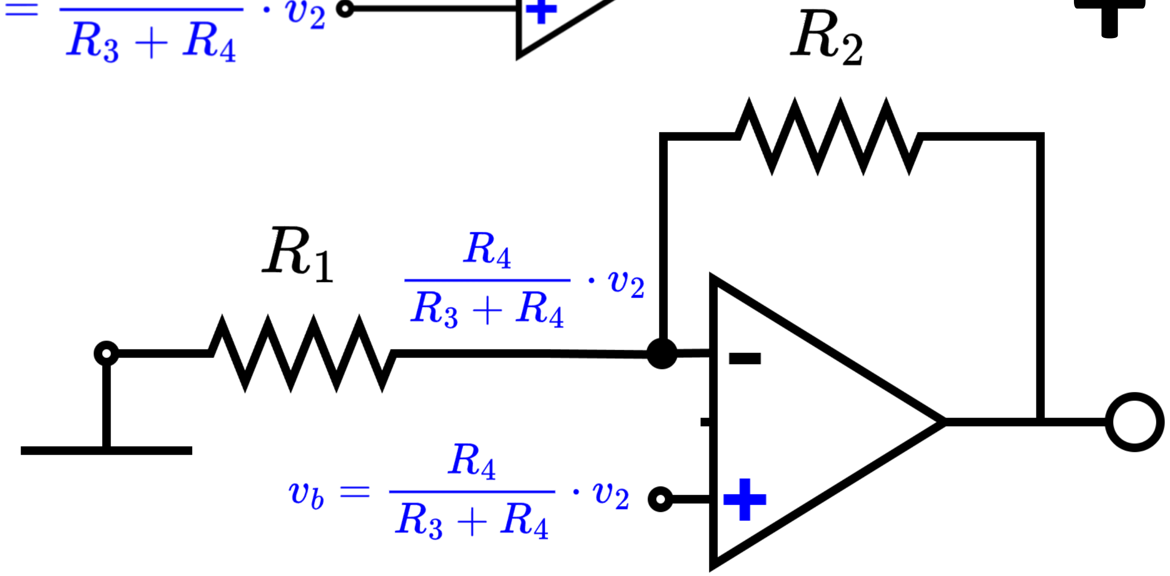
Apply superposition principle:





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

+



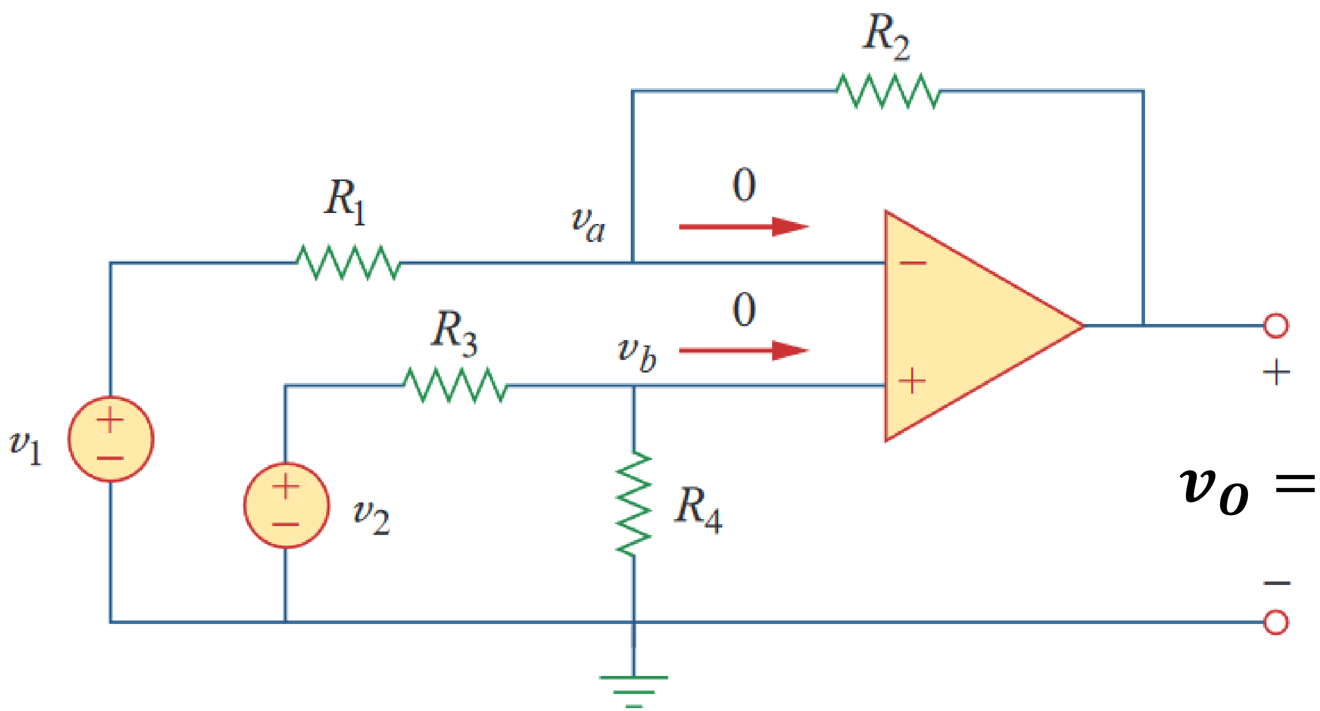
$$v''_O = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_4}{R_3+R_4} v_2$$

Difference Amplifier

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

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

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

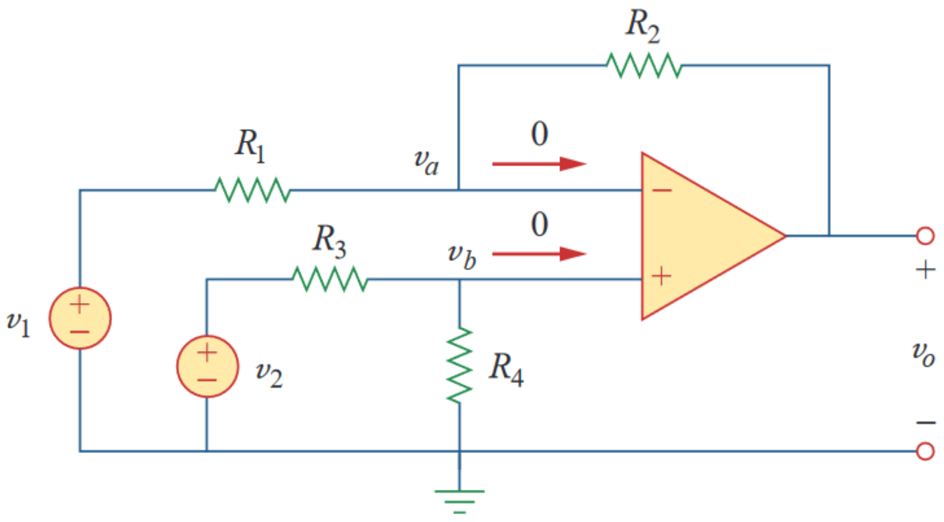


$$v_O = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} \cdot v_1$$

Difference Amplifier – Example 8

Design an op amp circuit with inputs v_1 and v_2 such that

$$v_o = -5v_1 + 3v_2.$$



Solution: Method 1

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

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

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

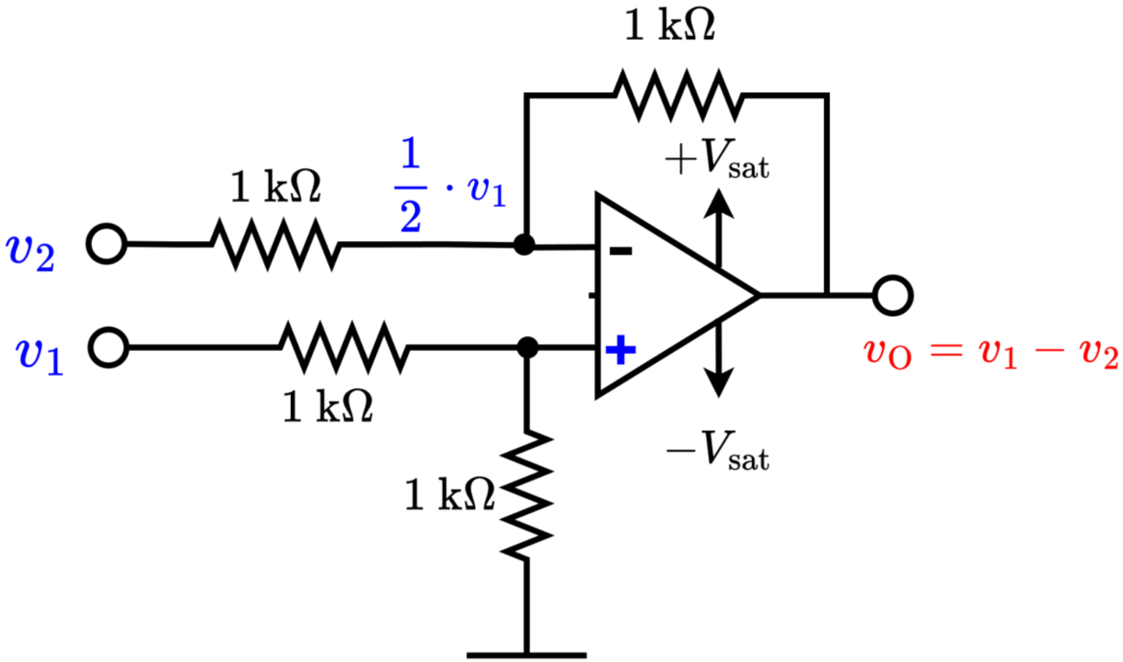
$$\Rightarrow \; R_3 = R_4$$

* To implement functions of the form $v_O = -Av_1 + Bv_2$, with difference amplifiers, **B must be less than $A + 1$**

Subtractor $(v_1 - v_2)$

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

$$\boldsymbol{v_o = v_1 - v_2}.$$



Solution: Method 1

Inverting ratio = 1

Non-inverting ratio = 1

So, $\frac{\boldsymbol{R_2}}{\boldsymbol{R_1}} = \mathbf{1}$ and $\left(\mathbf{1} + \frac{\boldsymbol{R_2}}{\boldsymbol{R_1}}\right) = \mathbf{2}$.

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

So, to get $\left(\mathbf{1} + \frac{\boldsymbol{R_2}}{\boldsymbol{R_1}}\right) \cdot \frac{\boldsymbol{R_4}}{\boldsymbol{R_3 + R_4}} = \mathbf{1}$,

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