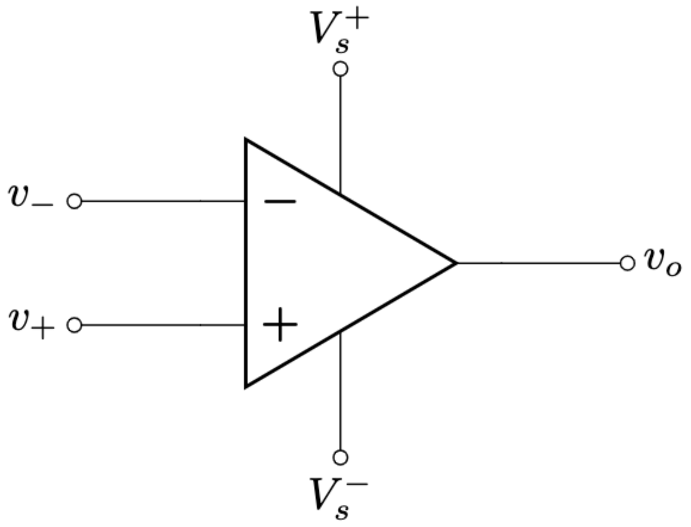
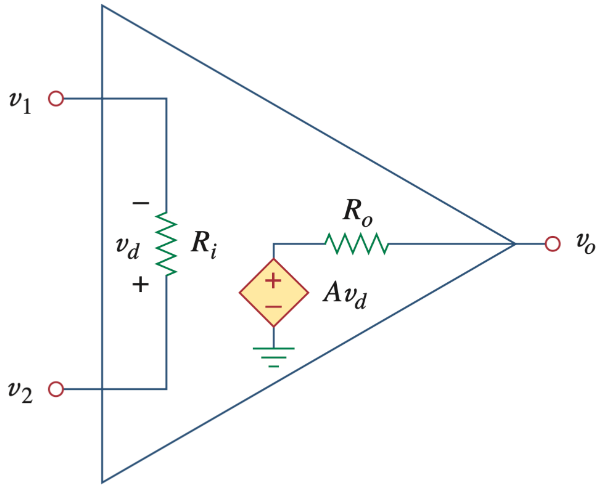
Lecture 4

Op Amp – Part 2

Review – Operational Amplifier





$v_1 = v_- =$ voltage of inverting terminal

$v_2 = v_+ =$ voltage of noninverting terminal

$v_d = v_+ - v_- = v_2 - v_1$
$= \text{differential input voltage for VCVS}$

$A =$ Open loop gain

$R_i =$ Input resistance

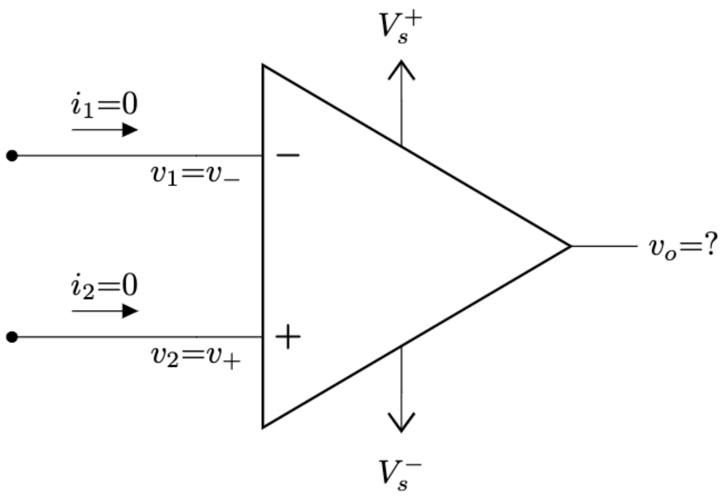
$R_o =$ Output resistance

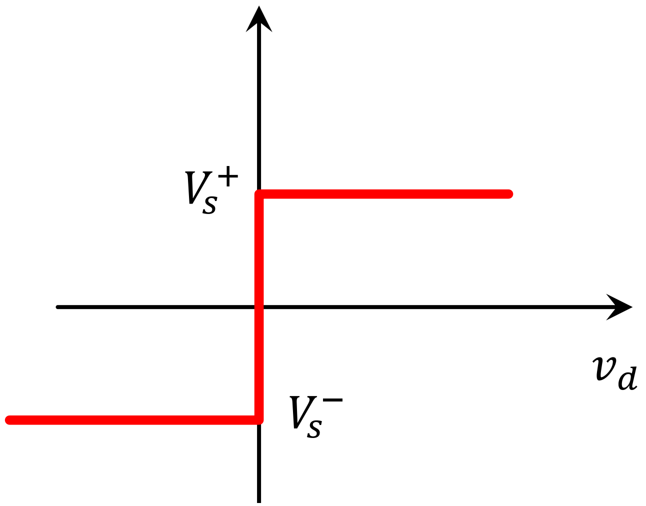
Differential amplifier ⇒ amplifies the difference

$$v_o = Av_d = A(v_2 - v_1) = A(v_+ - v_-)$$

Review – Ideal Op Amp

- Infinite open-loop gain, $A = \infty$
- Infinite input resistance, $R_i = \infty = \text{open circuit}$
- Zero output resistance, $R_o = 0 = \text{short circuit}$
- As $R_i = \infty$ (open circuit), $i_1 = i_2 = 0$. **Therefore, <u>circuit solving become much simpler</u>**





VTC of ideal op amp

$$v_o = \begin{cases} V_s^+ \; if \; v_d > 0 \Rightarrow v_2 > v_1 \\ V_s^- \; if \; v_d < 0 \Rightarrow v_2 < v_1 \end{cases}$$

Application of Ideal Op Amp - Comparator

- A comparator compares two voltages to determine which is larger.
- The comparator is essentially an op-amp operated in an open-loop configuration
- Two types –
  - (1) **Non-inverting**: outputs a positive voltage ($V_H = V_S^+$) when input is greater than reference
  - (2) **Inverting**: outputs a negative voltage ($V_L = V_S^-$) when input is greater than reference
- Application – smoke detector, turning AC on/off automatically, etc

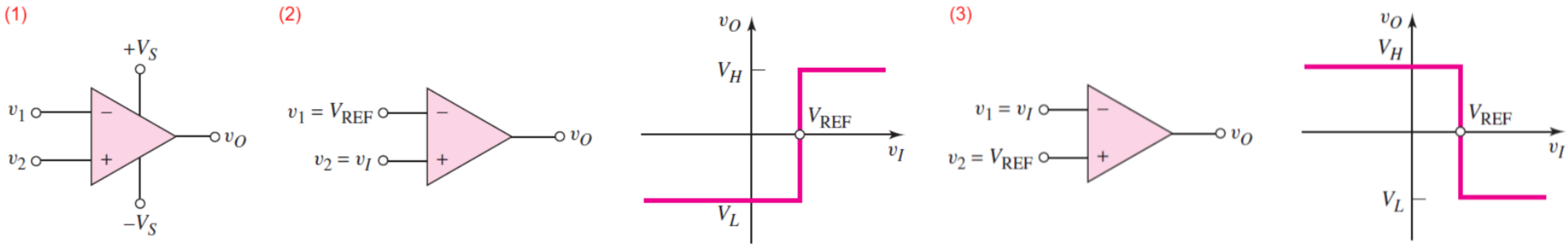
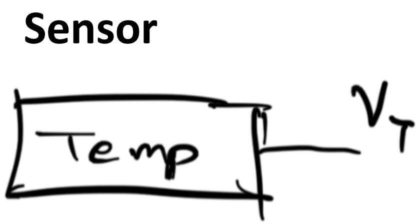


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

Comparator Application – Automatic AC

Auto AC ON/OFF



$V_T \propto T$

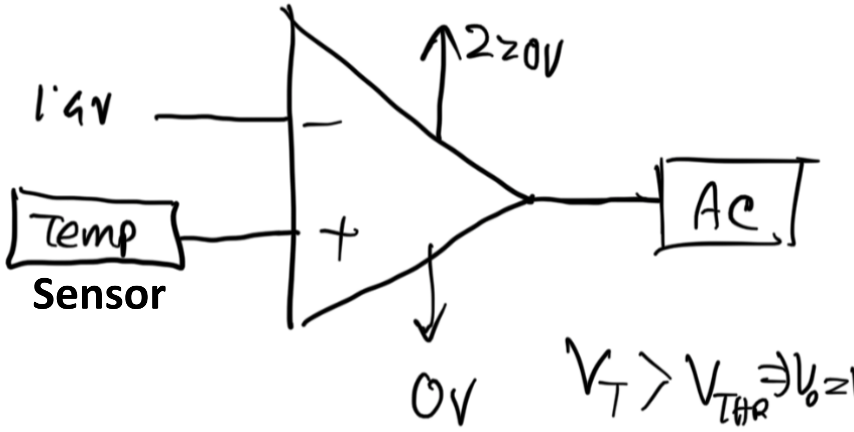
23°, $V_T = 1.2V$

$\boxed{24°, \quad V_T = 1.4V}$

25°, $V_T = 1.6V$

AC should be on if

$T > 24°C$



$V_T > V_{THR} \Rightarrow V_0 = V_S^+$

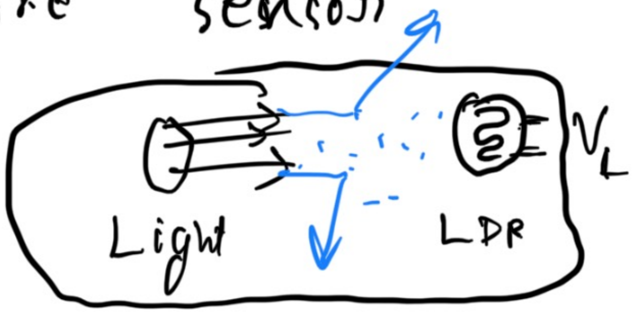
$V_T < V_{THR} \Rightarrow V_S^-$

$V_{THR} = 1.4V$

Smoke Detector

(3) Smoke Detector

Smoke sensor



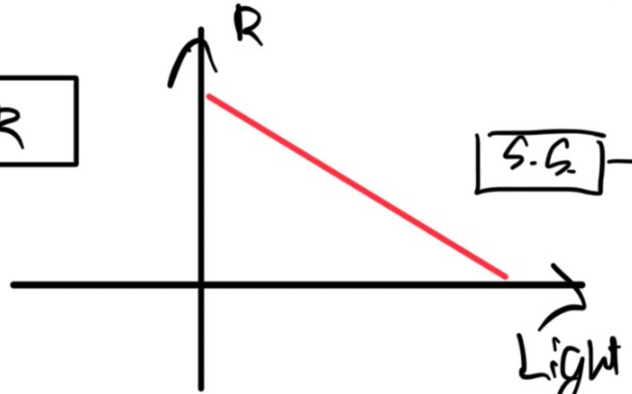
No smoke, V_L = small = 2V

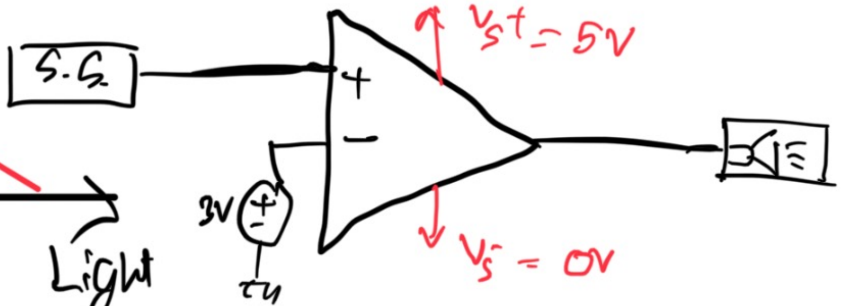
Smoke, V_L = high = 4V

$V_L > 3V \Rightarrow$ Alarm ON

$V_L < 3V \Rightarrow$ " OFF

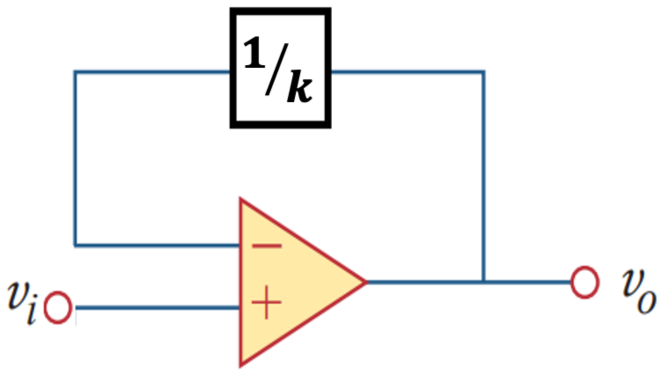
$\boxed{V_L \propto R}$





Introducing Negative Feedback

- The gain (A) of an ideal op amp is infinity, practically extremely large.
- The power supply (+Vs and –Vs) limits the op amp's output.
- We require a method to have a finite gain. That is what negative feedback does.
- Negative feedback: feeding back **a portion** of ***output*** to inverting ***input***
- Idea – the output will become stable due to a self-correcting mechanism

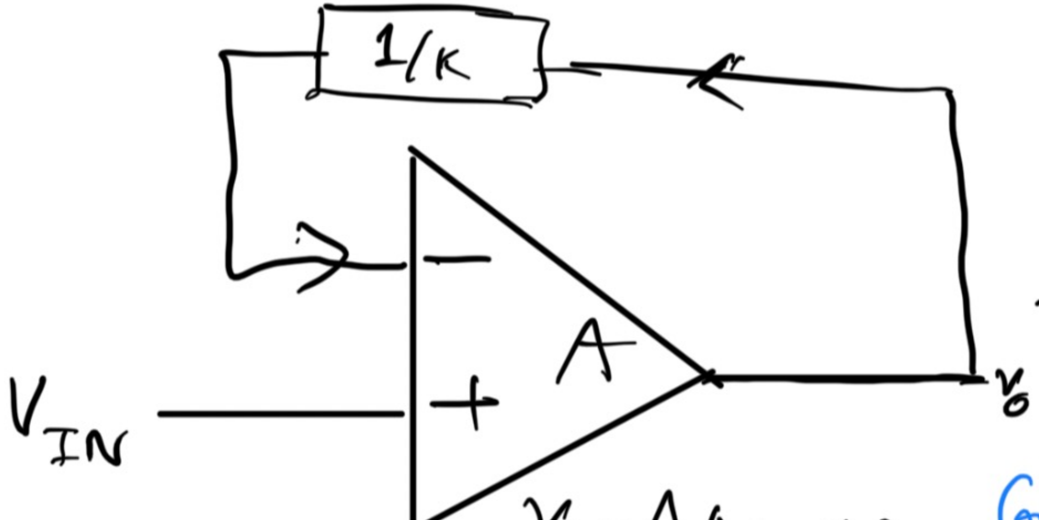


For example, her, $v_- = \text{one k}'\text{th part of ouput} = \frac{1}{k}$

If v_o increases, v_- will increase, hence v_d will decrease, eventtually v_o decreases

If v_o decreases, v_- will decrease, hence v_d will increase, eventtually v_o increase

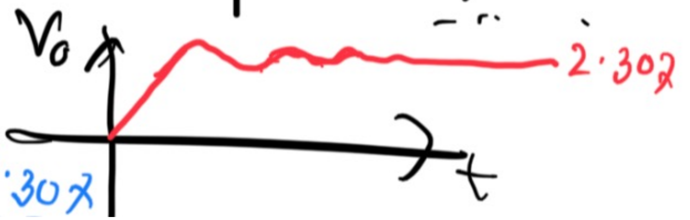
Negative Feedback – Numerical Example



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

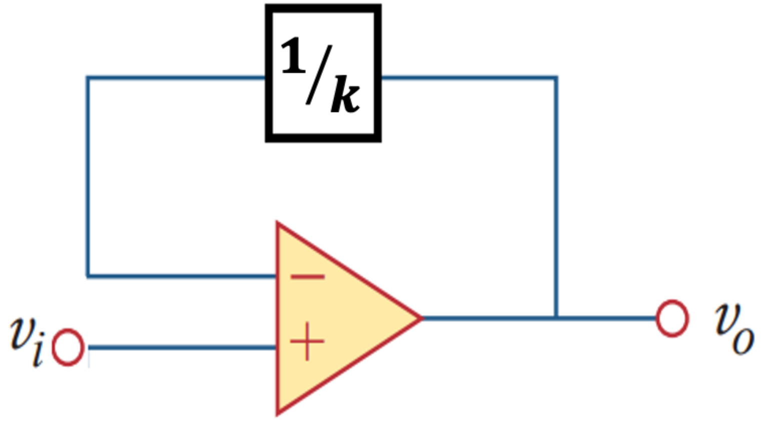
$V_{IN} = 1V$, $K = 10$, $A = 3$

$V_o = 0V$	$V_o = 3V$	$V_o = 2.1V$	$V_o = 2.307$
$V_- = 0V$	$V_- = 0.3V$	$V_- = 0.21V$	$V_- = 0.2307$
$V_d = 1V$	$V_d = 0.7$	$V_d = 0.79$	$V_d = 0.7693$
$\therefore V_o = 3V$	$V_o = 2.1V$	$V_o = 2.37$	$V_o = 2.307$



$\text{Gain} = \frac{\text{OUT}}{\text{IN}} = 2.307$

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

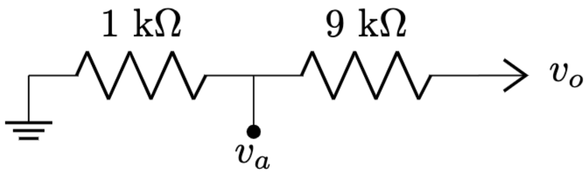
A is extremely large,

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

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

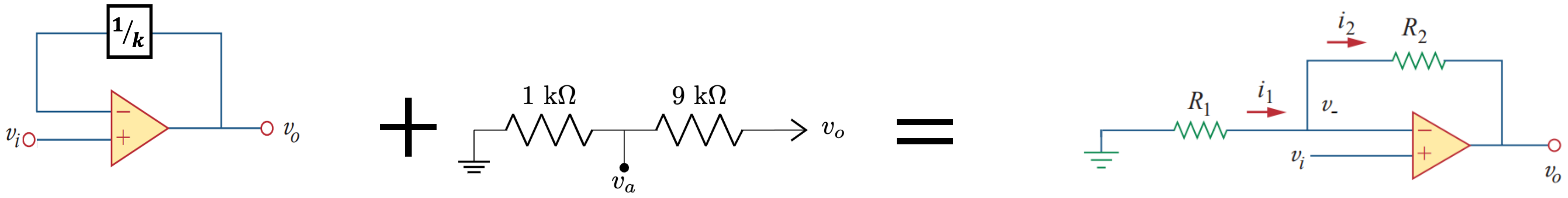
If $\boldsymbol{k}$ = 10 (meaning we feed back one tenth of the output to negative input), we will get $\boldsymbol{v_o}$=10*$\boldsymbol{v_i}$. that is 10 fold gain.

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



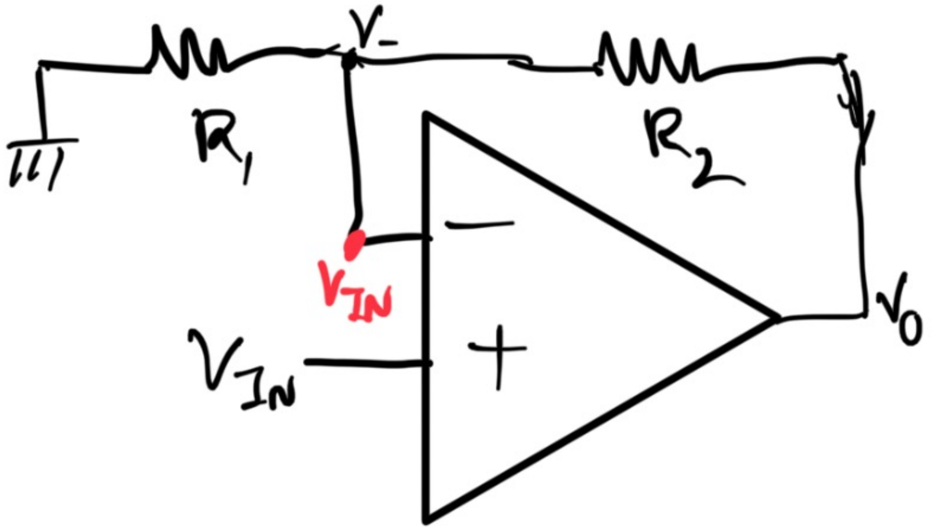
$$v_a = \frac{1\ k\Omega}{1\ k\Omega + 9\ k\Omega} \times v_o = \frac{v_o}{10}$$

Inverting Amplifier



Inverting Amplifier

Gain > 1

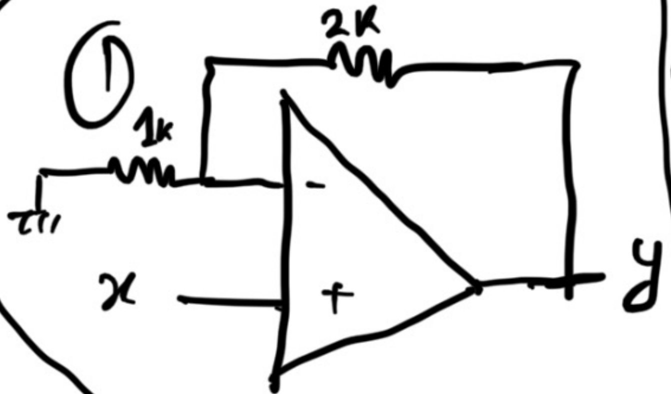


$$V_- = \frac{R_1}{R_1 + R_2} V_0 = \frac{1}{1 + \frac{R_2}{R_1}} V_0$$

K

$$\boxed{\therefore V_0 = \left(1 + \frac{R_2}{R_1}\right) V_{IN}}$$

①

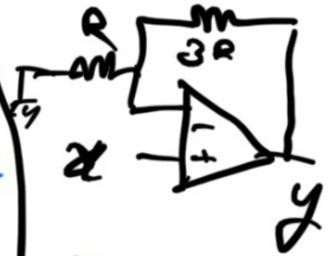


$$y = \left(1 + \frac{2}{1}\right) x$$

$$\Rightarrow y = 3x$$

② Design $y = 4x$

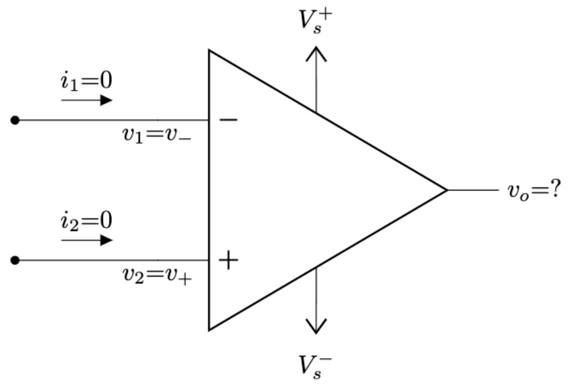
$$1 + \frac{R_2}{R_1} = 4 \Rightarrow \frac{R_2}{R_1} = 3$$



$y = 4x$

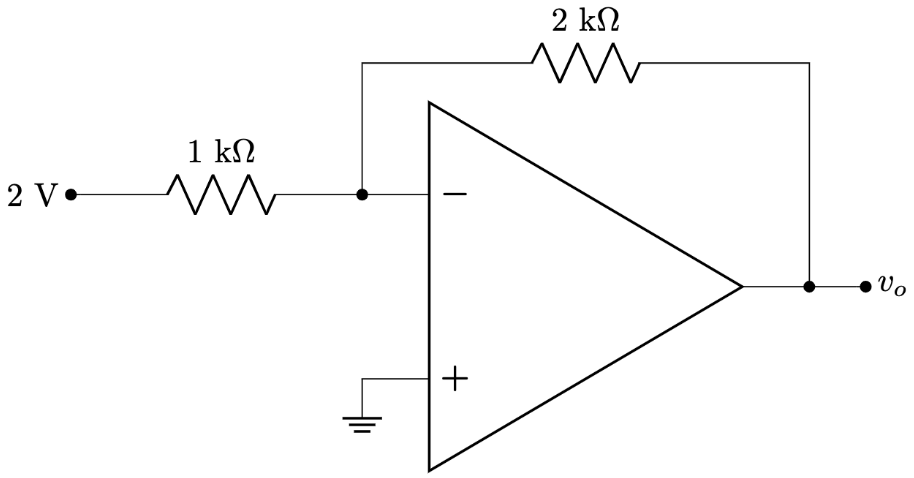
Solving Circuit with Ideal Op Amp + NF

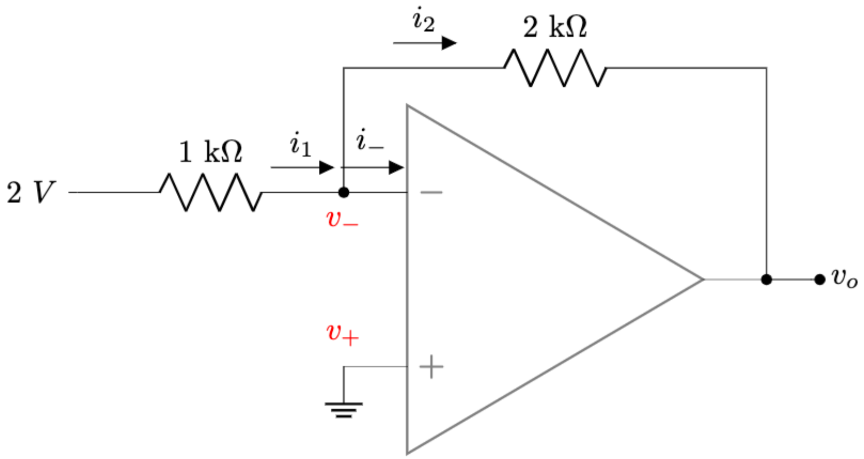
- For ideal op-amp
  - Infinite input resistance, $R_i = \infty = \text{open circuit}$
  - Zero output resistance, $R_o = 0 = \text{short circuit}$
  - $i_i = 0$ and $i_+ = 0$
- ***<u>When there is negative feedback</u>***, For ideal A as is infinitely high, for a finite output voltage v_o, $\frac{v_o}{A} = v_d = 0 \Rightarrow v_+ = v_-$. This is called **virtual short circuit**
- Because of these, solving ideal op-amp circuit with negative feedback is very simple



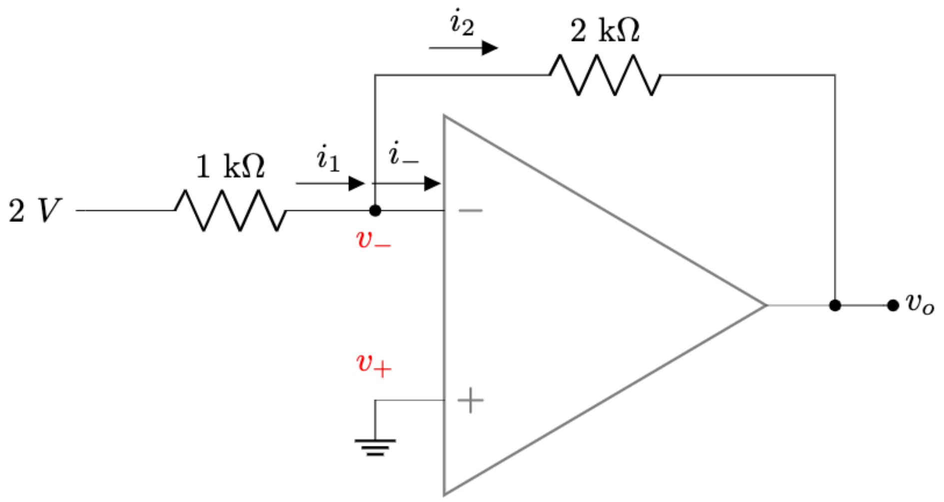
Example – Inverting Amplifier

Solve the ciruit to find v_o





Example – Inverting Amplifier



Since v_+ is connected to ground, $v_+ = 0V$

Since there is negative feedback, from virtual short, $v_- = v_+ = 0V$

From Ohm's law for $1\ k\Omega \Rightarrow i_1 = \frac{2V - 0V}{1\ k\Omega} = 2mA$

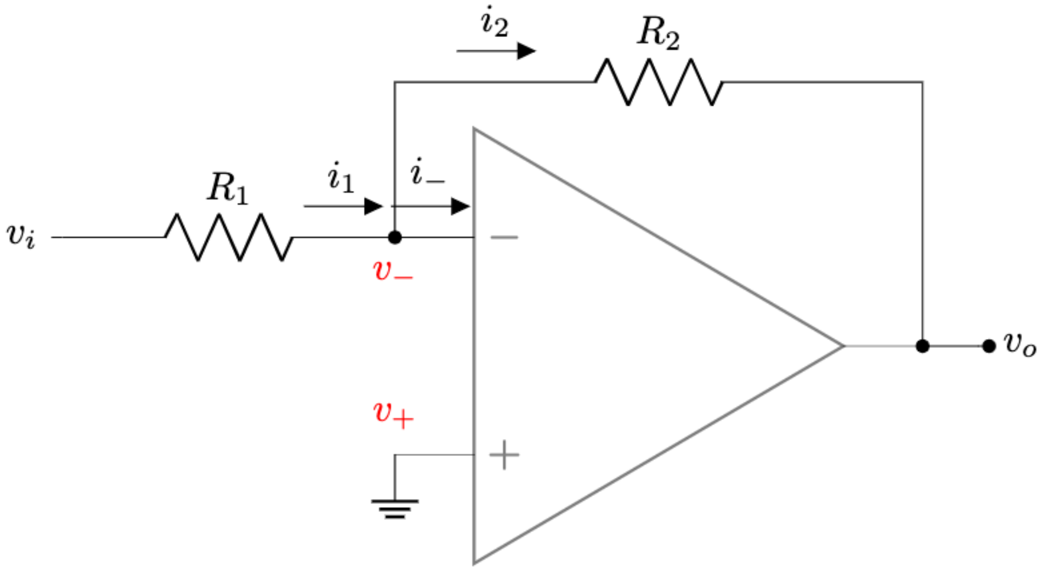
Since ideal op-amp, $i_- = i_+ = 0$

From KCL at v_-, $i_1 = i_- + i_2 \Rightarrow i_1 = i_2 = 2\ mA$

From Ohm's law for $2\ k\Omega \Rightarrow i_2 = \frac{v_- - v_0}{2\ k\Omega} = 2mA \Rightarrow v_o = -i_2 \times 2 = -4V$ [ANS]

Gain = $-\frac{4V}{2V} = -2$ (hence **inverting**)

General



Since v_+ is connected to ground, $v_+ = 0V$

Since there is negative feedback, from virtual short, $v_- = v_+ = 0V$

From Ohm's law for R$_1$ $\Rightarrow i_1 = \frac{v_i - 0V}{R_1} = v_i/R_1$

Since ideal op-amp, $i_- = i_+ = 0$

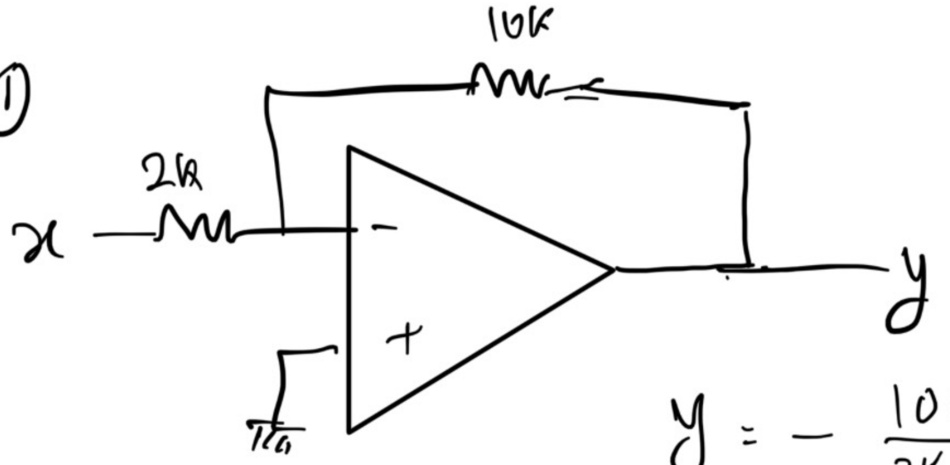
From KCL at v_-, $i_1 = i_- + i_2 \Rightarrow i_1 = i_2 = v_i/R_1$

From Ohm's law for $R_2 \Rightarrow i_2 = \frac{v_- - v_0}{R_2} = \frac{v_i}{R_1} \Rightarrow v_o = -i_2 \times R_2 \Rightarrow v_o = -\frac{R_2}{R_1} v_i$ [ANS]

Gain = $-\frac{R_2}{R_1}$

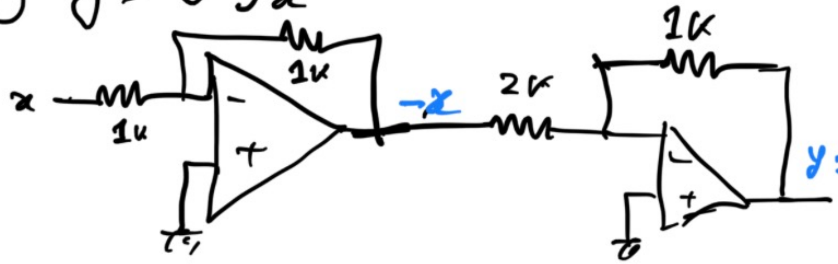
Example

1



$$y = -\frac{10K}{2K}x \Rightarrow \boxed{y = -5x}$$

2 $y = 0.5x$



$$y = \left(-\frac{1}{2}\right)(-x) = 0.5x$$