CSE251: Electronic Devices and Circuits

Lecture 3

Operational Amplifier I

Prepared By:

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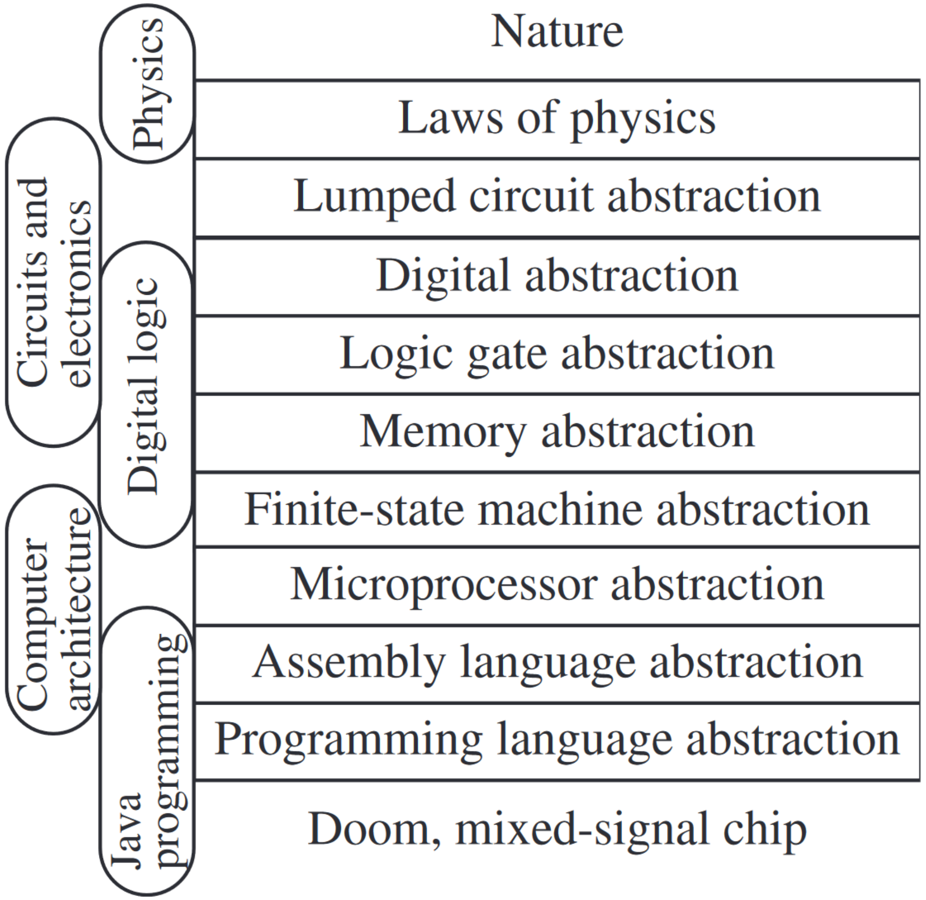
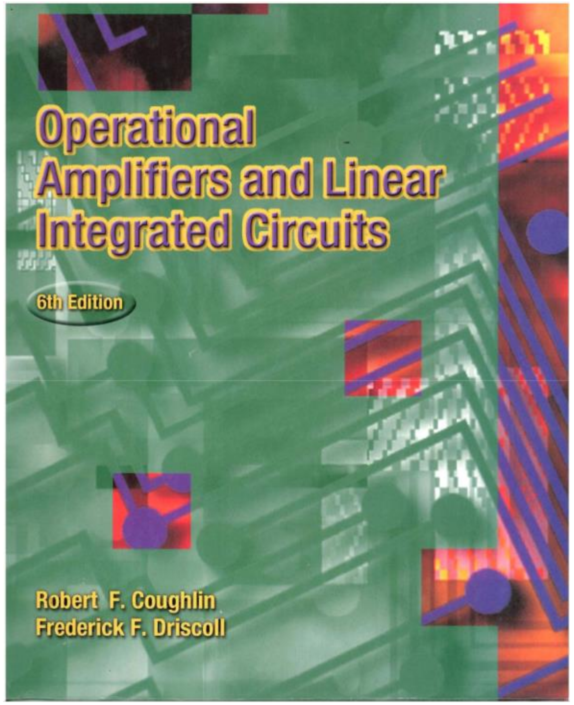
The Circuit Abstraction

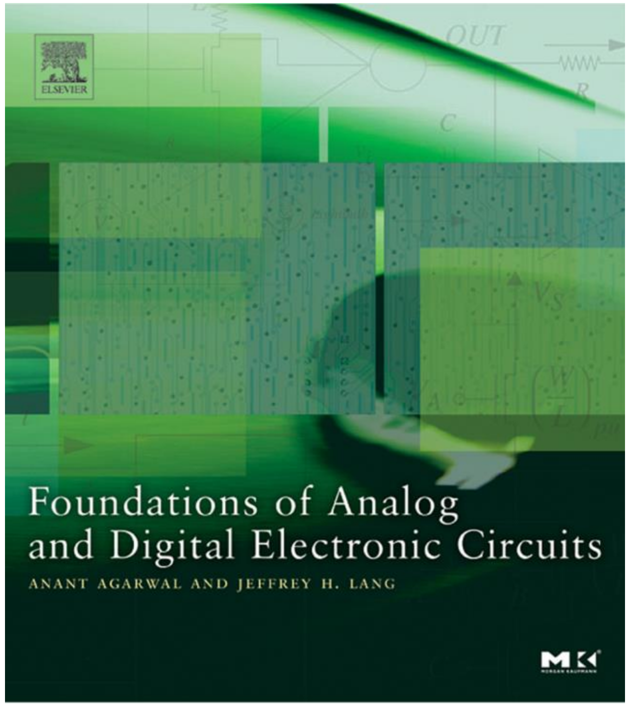


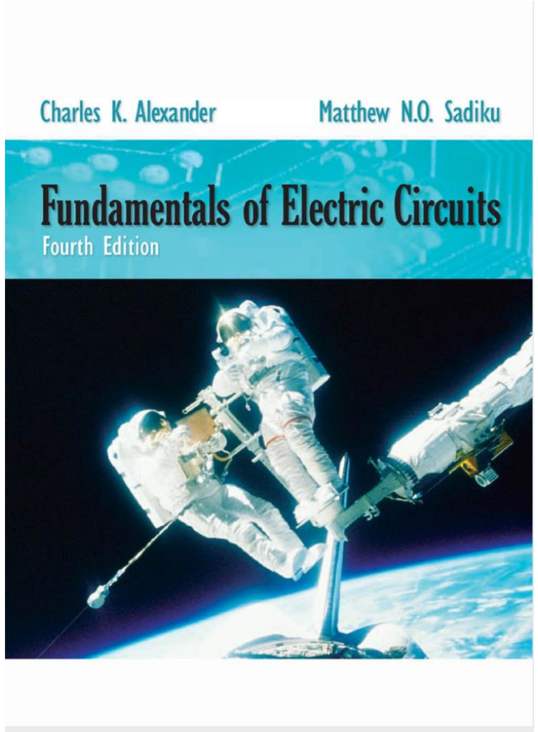
Sequence of courses and the abstraction layers

Operational Amplifiers

Textbook







Operational Amplifier

- **Operational:**

  Mathematical Operations

- **Amplifier:**

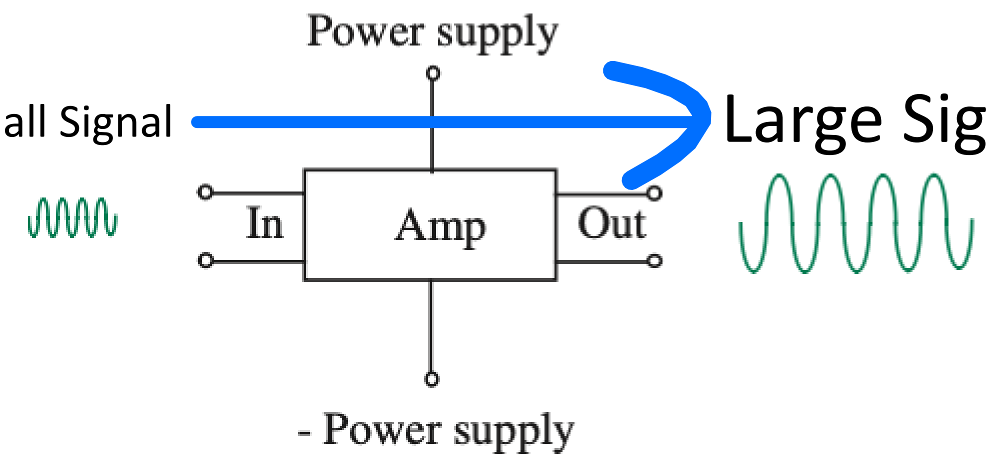
  Amplifies input signal/voltage.

Voltage Transfer Characteristics (VTC)

Shows how the output voltage varies with the input voltage $V_{\mathrm{Out}}(V_{\mathrm{In}})$

Small Signal

Large Signal

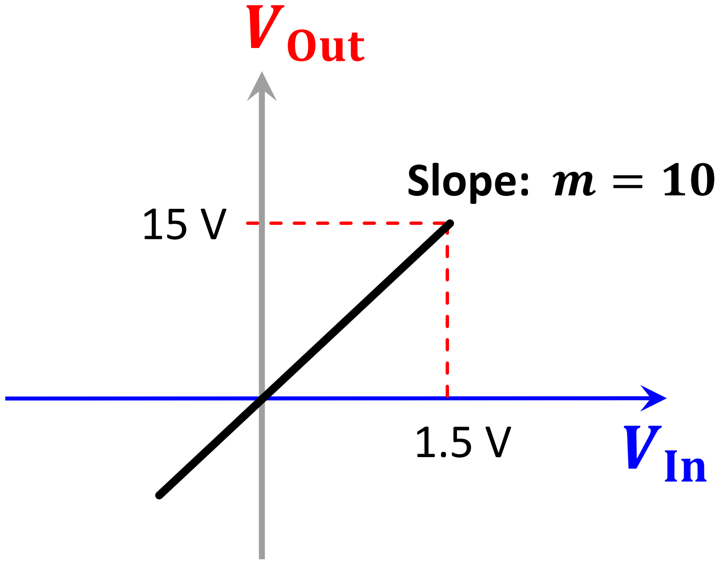


Operational Amplifier: Amplification

Voltage Transfer Characteristics (VTC)

Shows how the output voltage varies with the input voltage $V_{\mathrm{Out}}(V_{\mathrm{In}})$

$V_{\mathrm{In}}(\mathrm{V})$	$V_{\mathrm{Out}}(\mathrm{V})$
0.5	5
1.0	10
1.5	15
2.5	25
3.5	35



Amplification: VTC

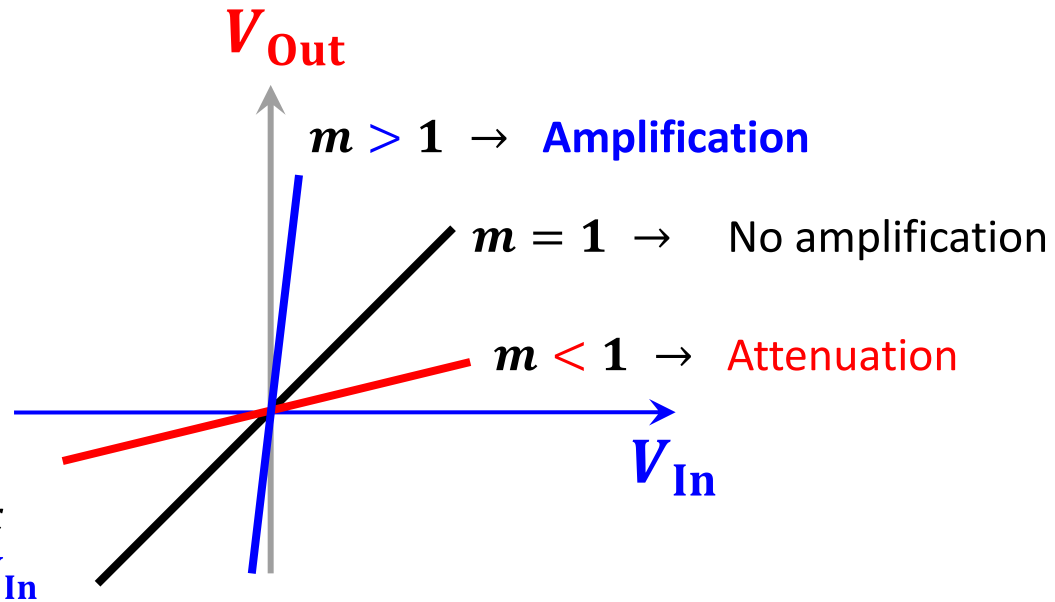
Voltage Transfer Characteristics (VTC)

- Shows how the output voltage varies with the input voltage $V_{\mathrm{Out}}(V_{\mathrm{In}})$
- y –axis → $\boldsymbol{V_{\mathrm{Out}}}$
- x –axis → $\boldsymbol{V_{\mathrm{In}}}$

- Slope: $\boldsymbol{m} = \dfrac{\Delta \boldsymbol{V_{\mathrm{Out}}}}{\Delta \boldsymbol{V_{\mathrm{In}}}} = \dfrac{\boldsymbol{V_{\mathrm{Out}}}}{\boldsymbol{V_{\mathrm{In}}}}$

Since the line passes through origin: $y = \boldsymbol{m} \cdot x$

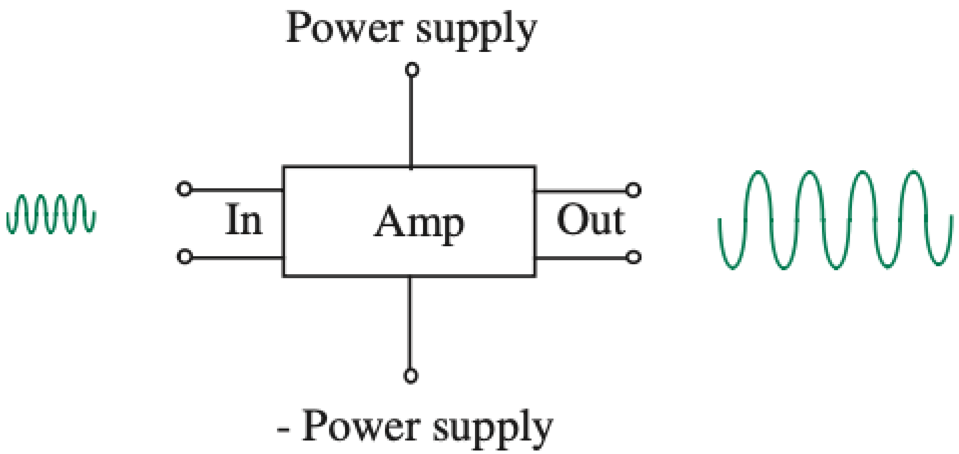
$$\boldsymbol{V_{\mathrm{Out}}} = \boldsymbol{m} \cdot \boldsymbol{V_{\mathrm{In}}}$$

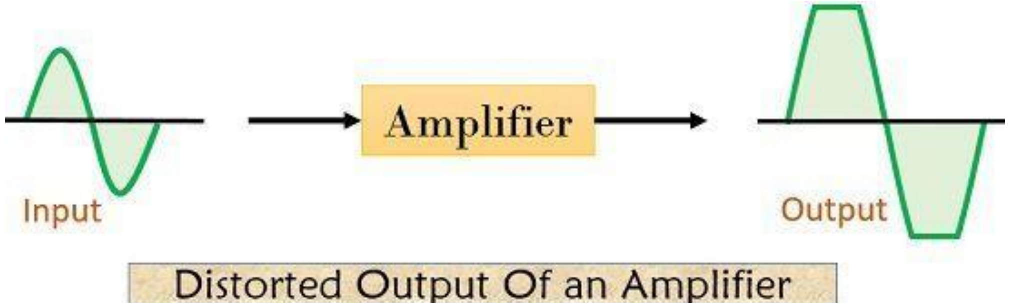


LINEAR RELATION (AMPLIFICATION)

Amplification: VTC

- **Linear Amplification** only takes place within a **valid input range.**
- Otherwise output will be distorted - - Saturation





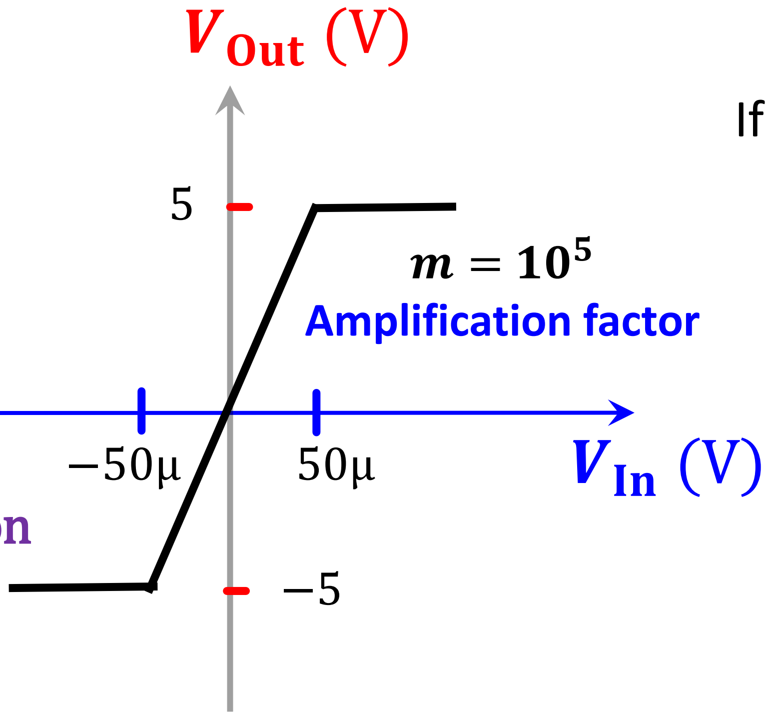
The limiting factor of **linear amplification** is determined by the **power supply** to the amplifier

Amplification: VTC - Saturation

$V_{\text{Out}} = m \cdot V_{\text{In}}$: When $-50\mu < V_{\text{In}} < 50\mu$

$m \rightarrow 10^5$: Gain / Amplification

Non-Linear characteristics



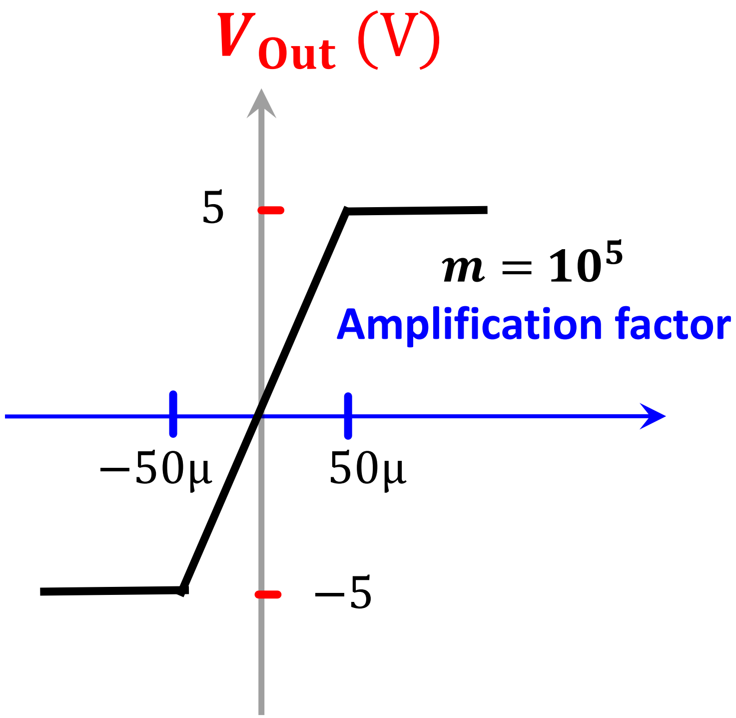
If $V_{\text{In}} > 50\mu$: Positive Saturation

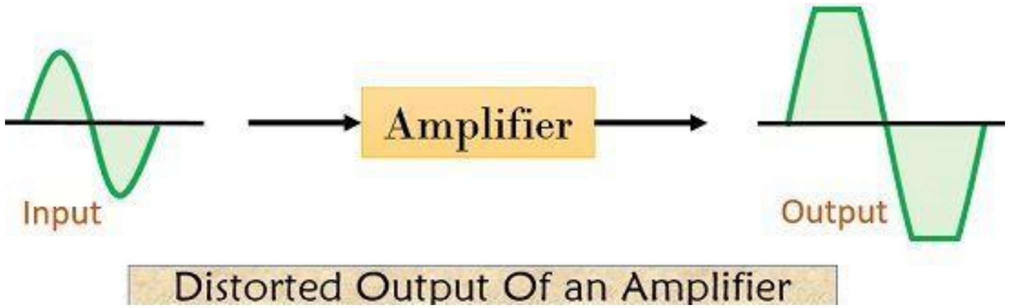
$\Rightarrow V_O = 5$

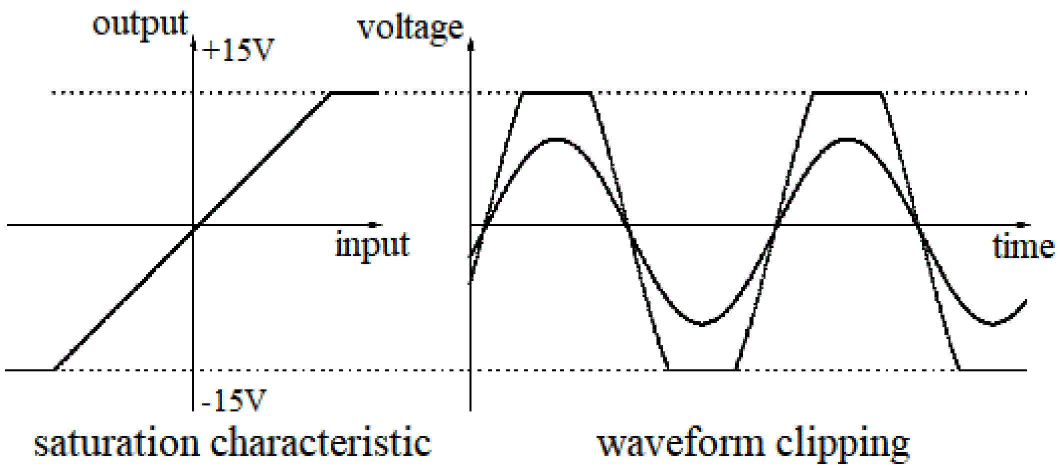
If $V_{\text{In}} < -50\mu$: Negative Saturation

$\Rightarrow V_O = -5$

Amplification: VTC

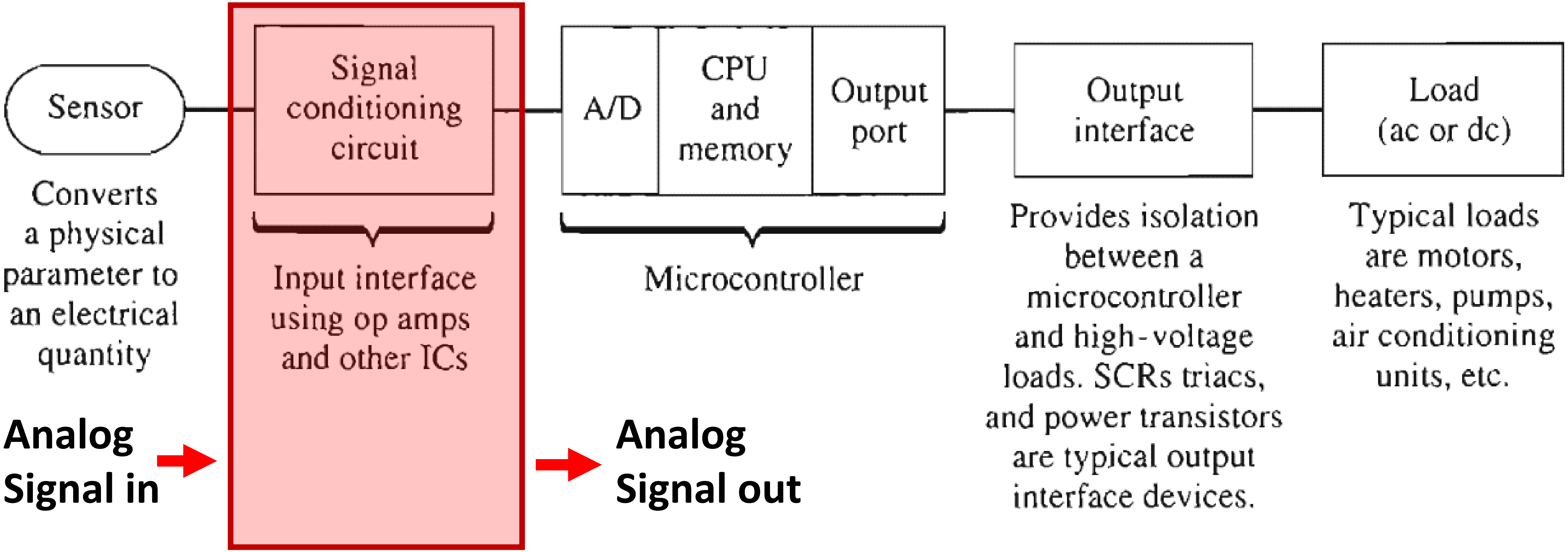






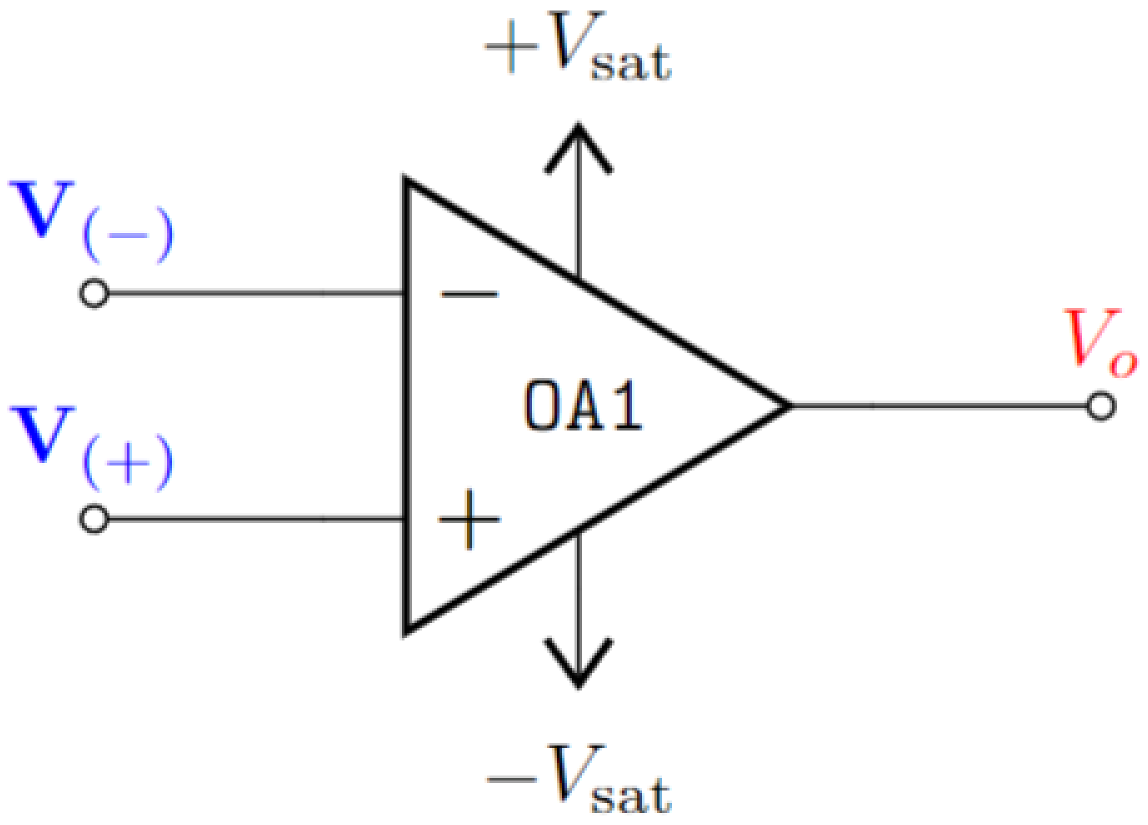
Operational Amplifier

Analog Electronics: Deals with **analog (continuous)** signals.



- The word operational in operational-amplifier originally stood for mathematical operations

Circuit Symbols and terminal

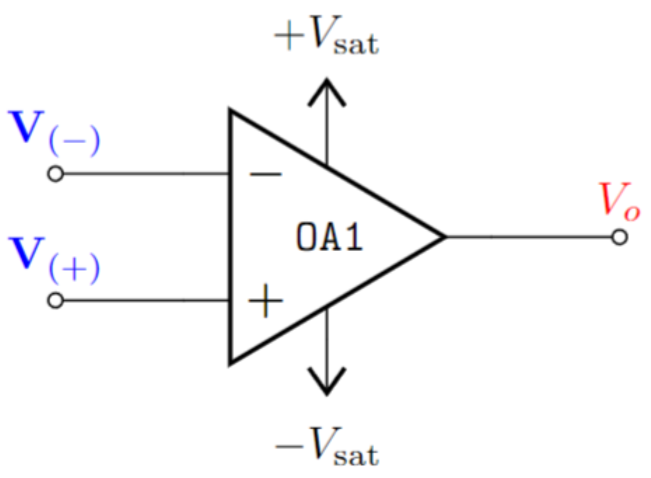


Circuit Symbols and Terminals

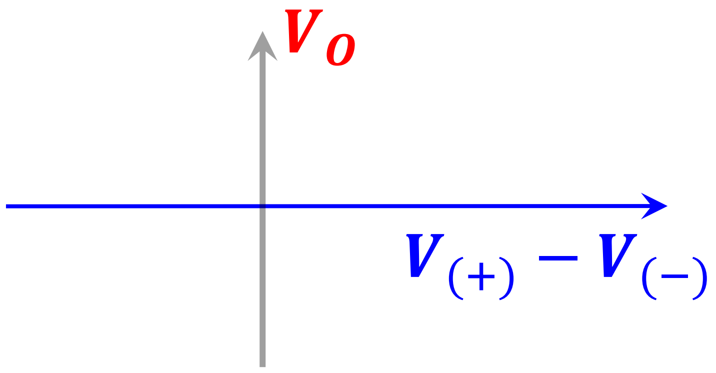
Difference Amplifier – Amplifies the voltage difference between two terminals.

$V_{(+)}$	Non-inverting terminal voltage
$V_{(-)}$	Inverting terminal voltage
V_d	Differential input voltage
$+V_{\text{sat}}$	Positive Saturation Voltage
$-V_{\text{sat}}$	Negative Saturation Voltage
V_O	Output Voltage

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

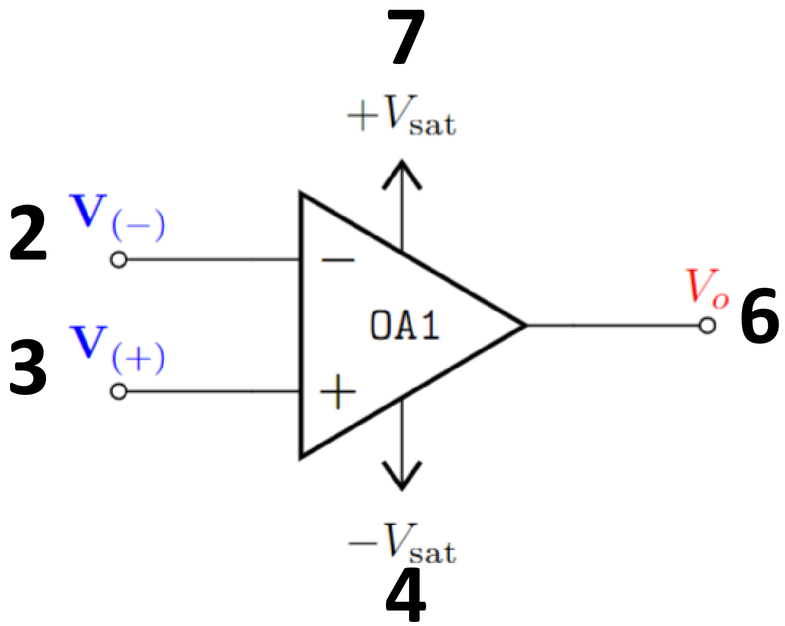


Voltage Transfer Characteristics (VTC)

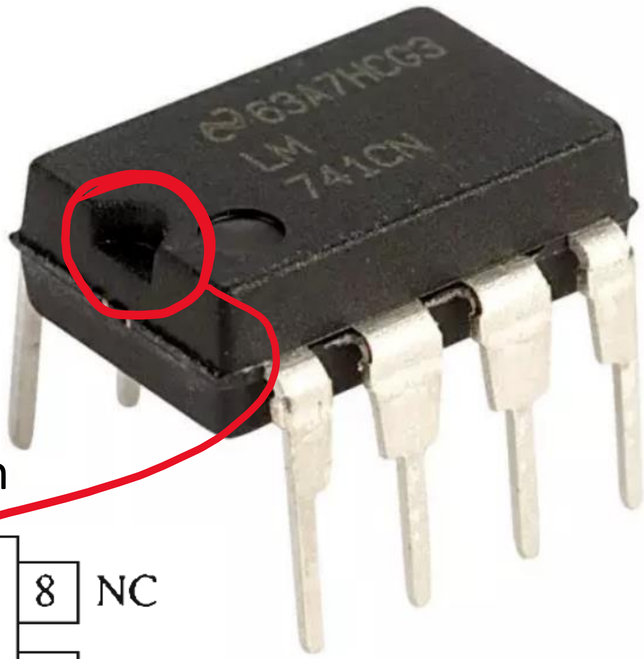


Circuit Symbols and Terminals

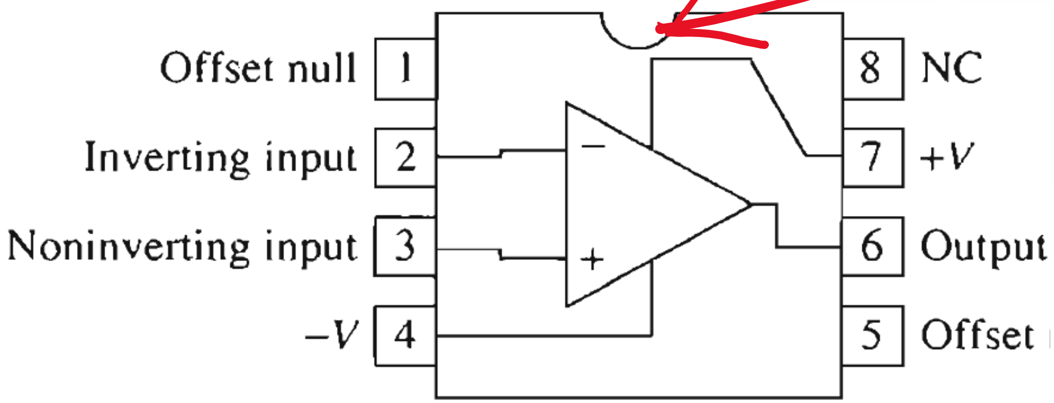
Difference Amplifier – Amplifies the voltage difference between two terminals.



Circuit symbol for the general-purpose op amp. Pin numbering is that for an **8-pin mini-DIP package**



NC – No Connection

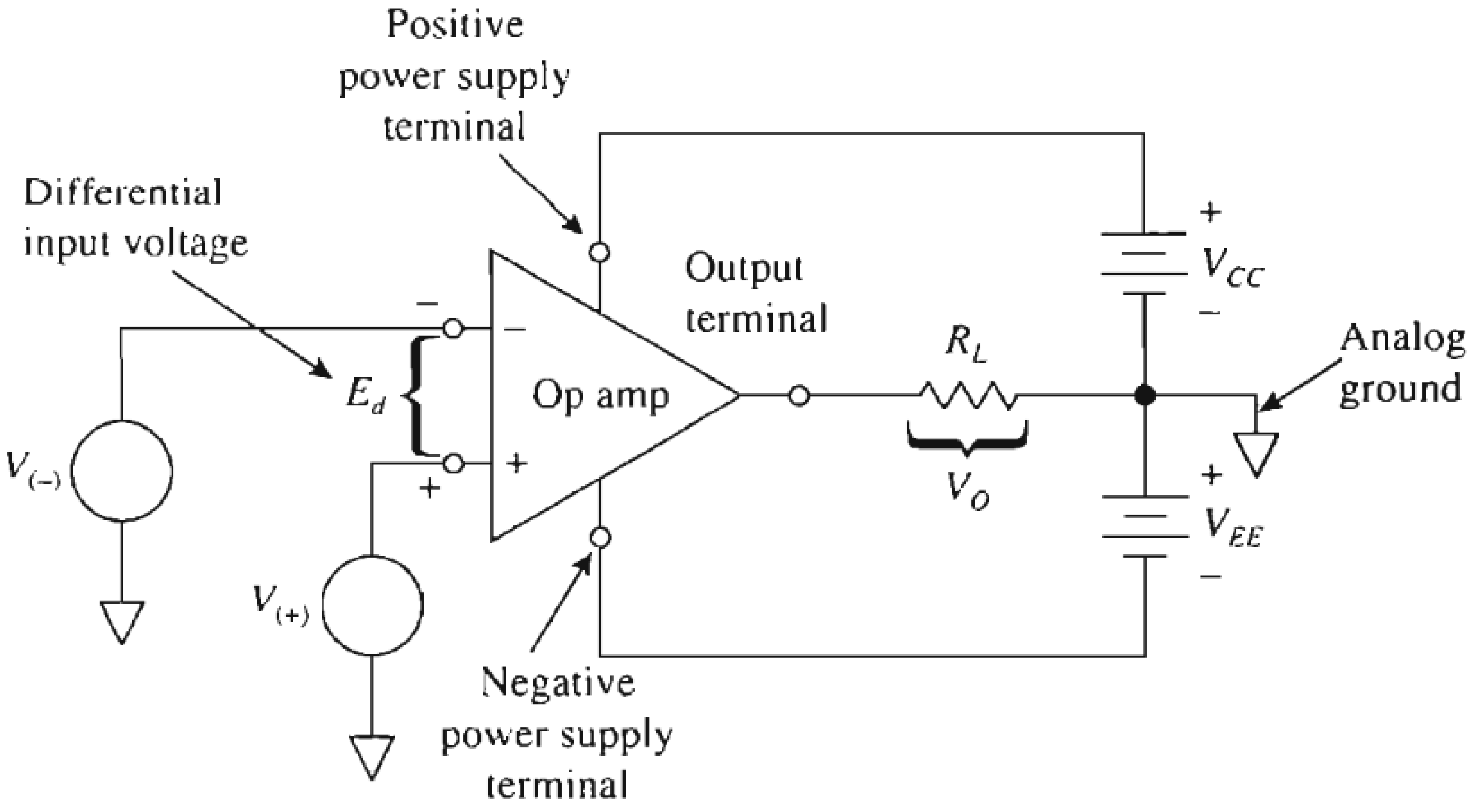


UA-741C → **C**: Commercial ($0° - 70°C$)
I: Industrial ($-25° - 85°C$)
M: Military ($-55° - 125°C$)

Manufacturer **ID**

Part Identification Number (PIN)

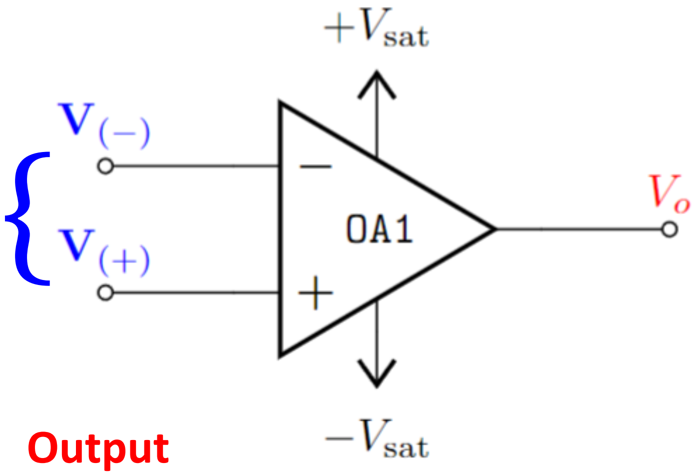
Circuit Symbols and Terminals



Op-Amp VTC: Modes of operation

Voltage Transfer Characteristics (VTC)

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



Positive saturation:

If $V_d > \frac{+V_{sat}}{A}$: Positive

$\Rightarrow V_O = +V_{sat}$

Linear Region

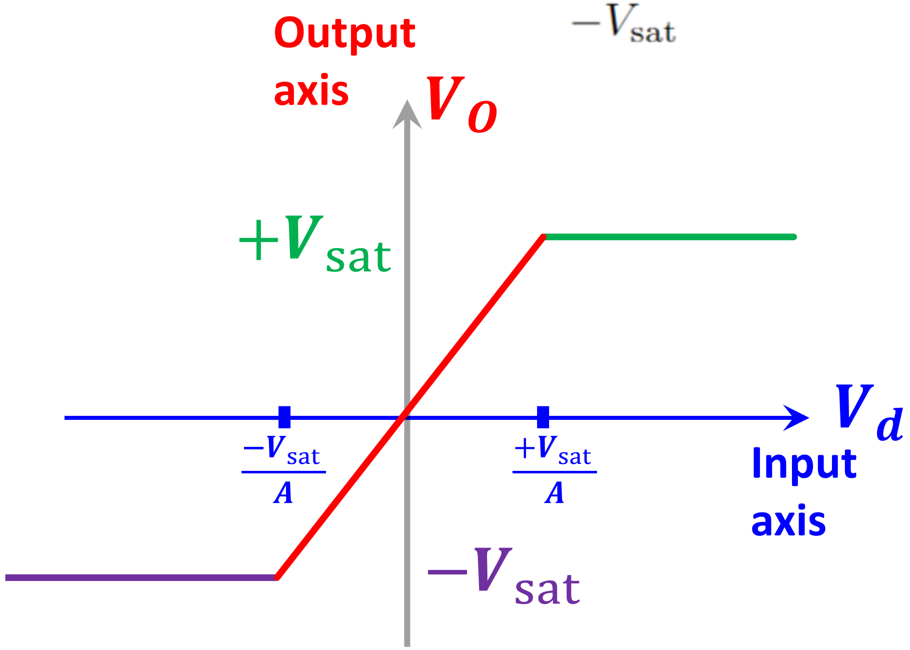
$V_O = AV_d$: When V_d is very small

$-V_{sat} < V_o = AV_d < +V_{sat}$

Negative saturation:

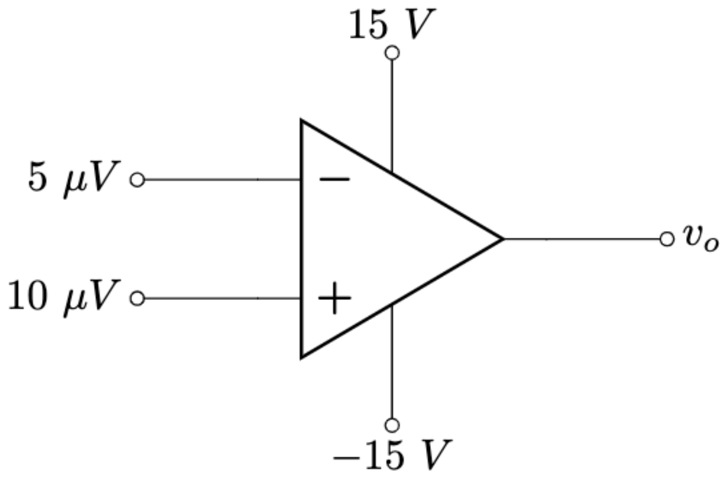
If $V_d < \frac{-V_{sat}}{A}$: Negative

$\Rightarrow V_O = -V_{sat}$

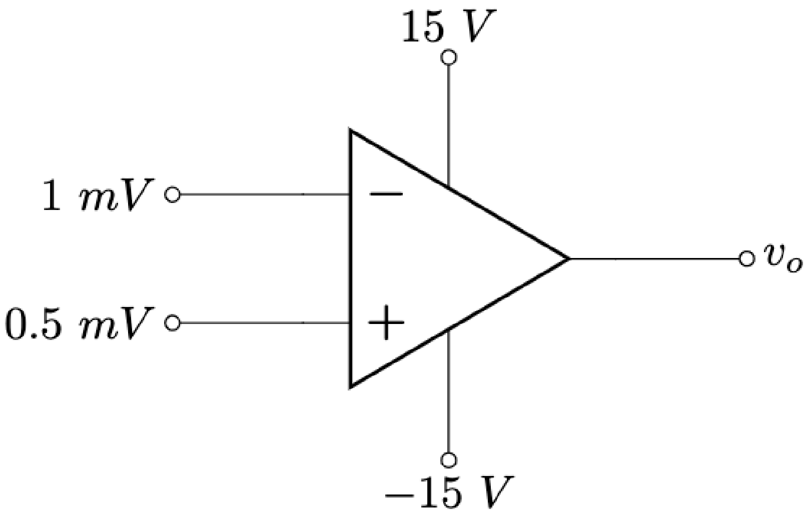


Some op-amp circuits

Find v_0



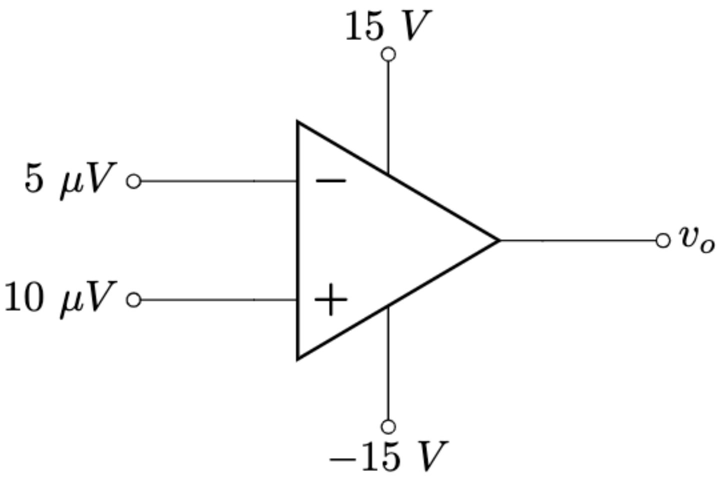
$A = 2 \times 10^5$



$A = 2 \times 10^5$

Example 1

- Find v_o



$A = 2 \times 10^5$

Solution:

$$V_d = V_{(+)} - V_{(-)} = (10 - 5)\ \mu\text{V} = 5\ \mu\text{V}$$

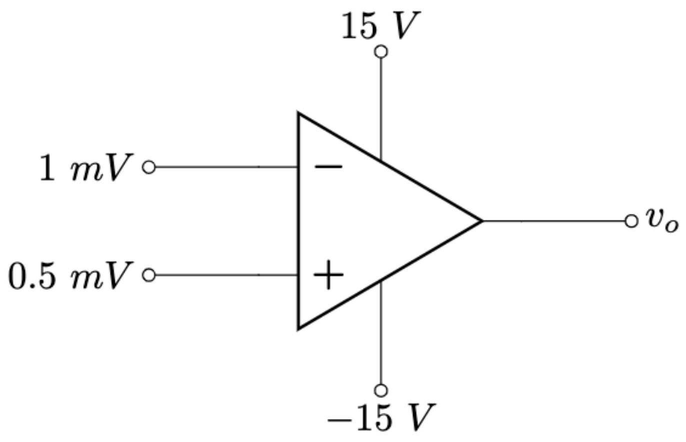
$$AV_d = (2 \times 10^5) \times (5 \times 10^{-6})\ \text{V} = 1\ \text{V}$$

Since $-15\ \text{V} < AV_d < +15\ V$

$$V_o = AV_d = 1\ \text{V}$$

Example 2

- Find v_o



$A = 2 \times 10^5$

Solution:

$$V_d = V_{(+)} - V_{(-)} = (0.5 - 1)\ \text{mV} = -0.5\ \text{mV}$$

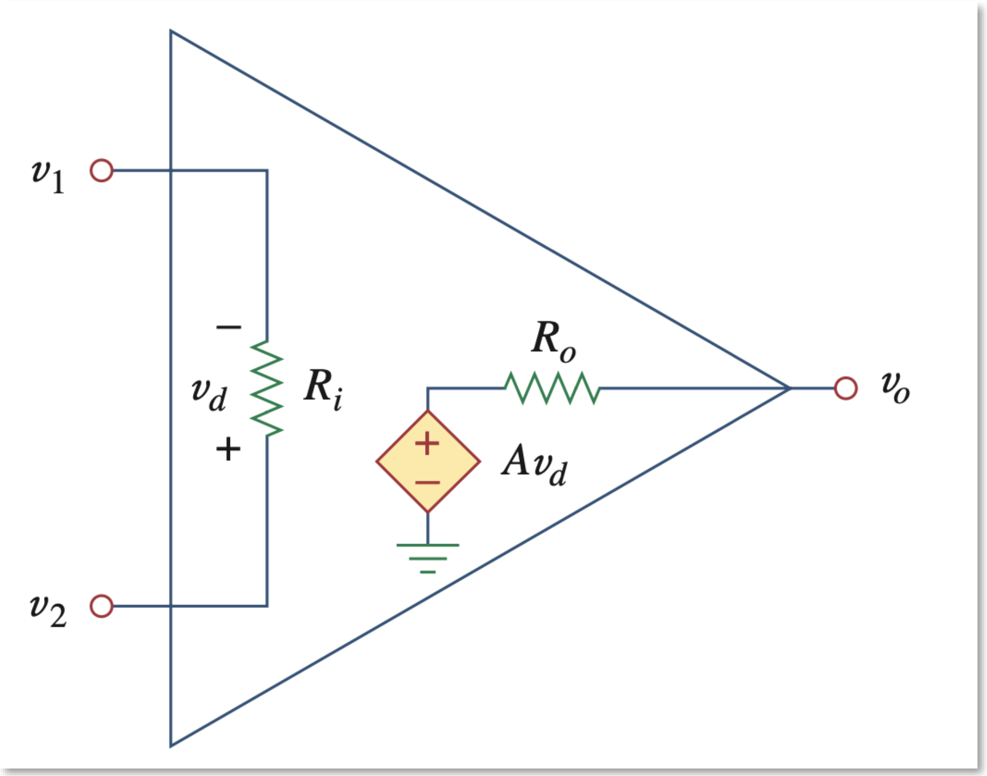
$$AV_d = (2 \times 10^5) \times (-0.5 \times 10^{-3})\ \text{V} = -100\ \text{V}$$

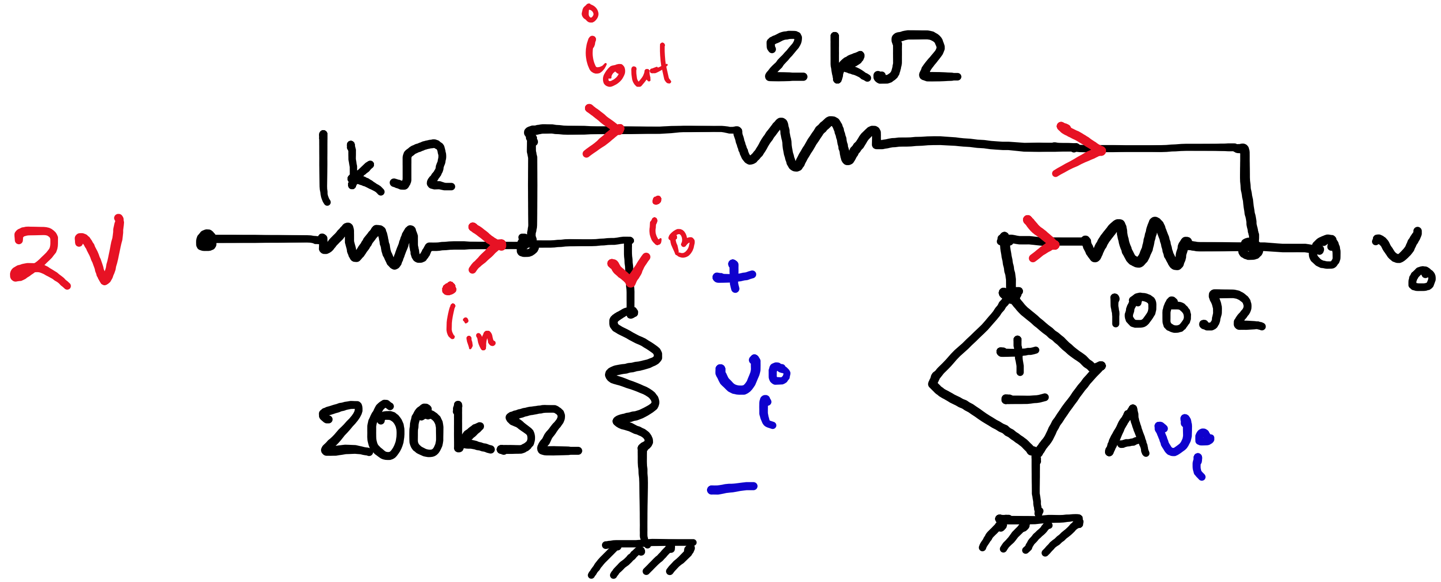
Since $-15\ \text{V} > AV_d$

$$V_O = AV_d = -15\ \text{V}$$

Op-Amp Internal configuration

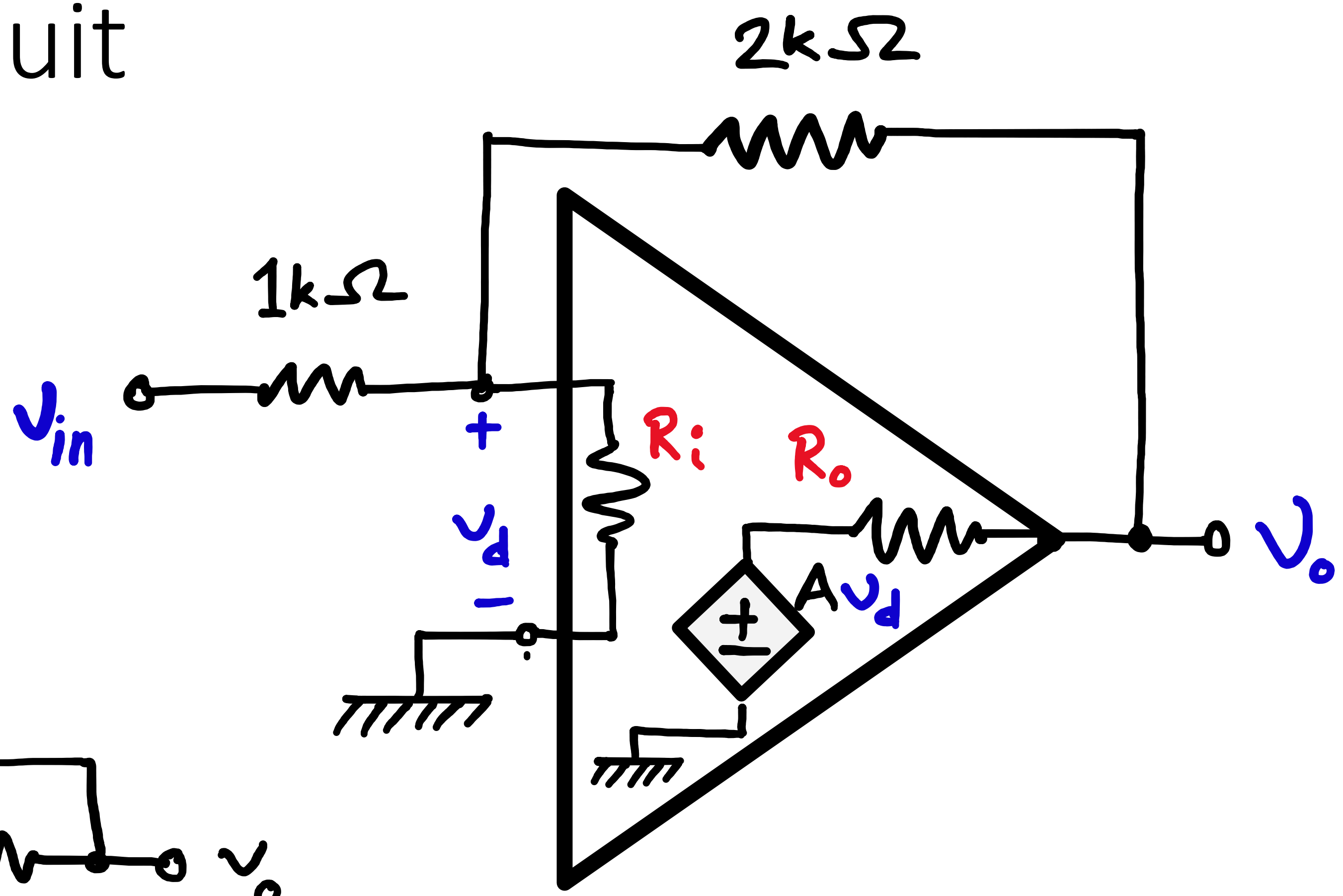
Voltage controlled voltage Source

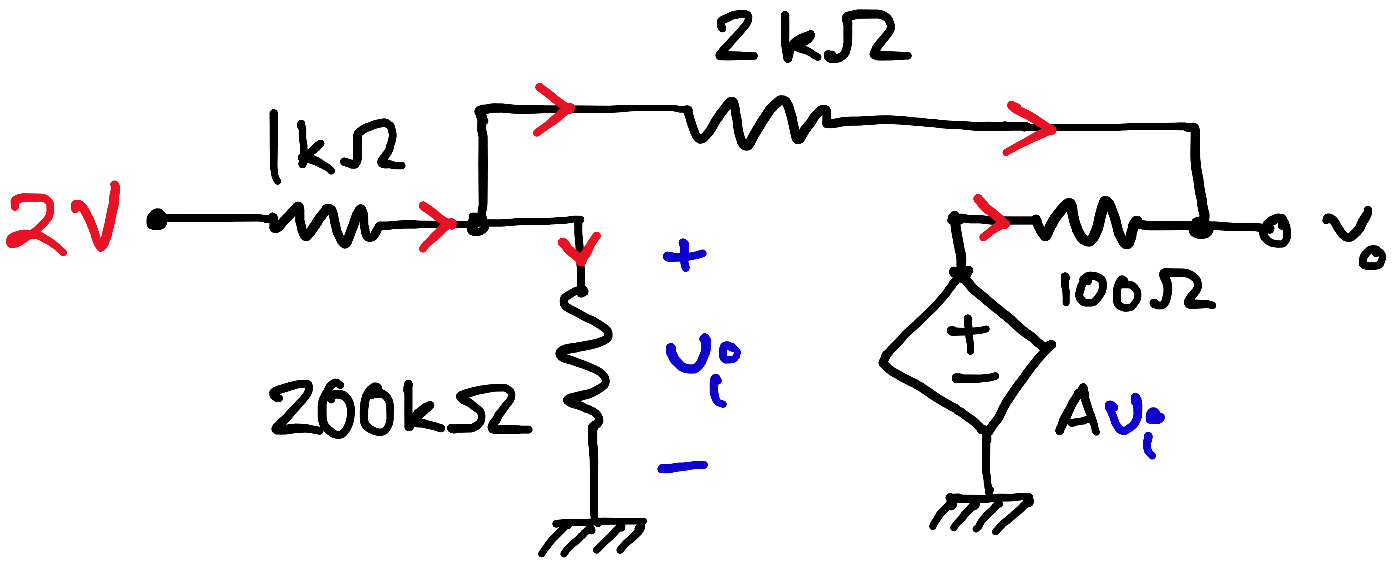




$$A = 2 \times 10^5$$

Op-Amp Internal Circuit

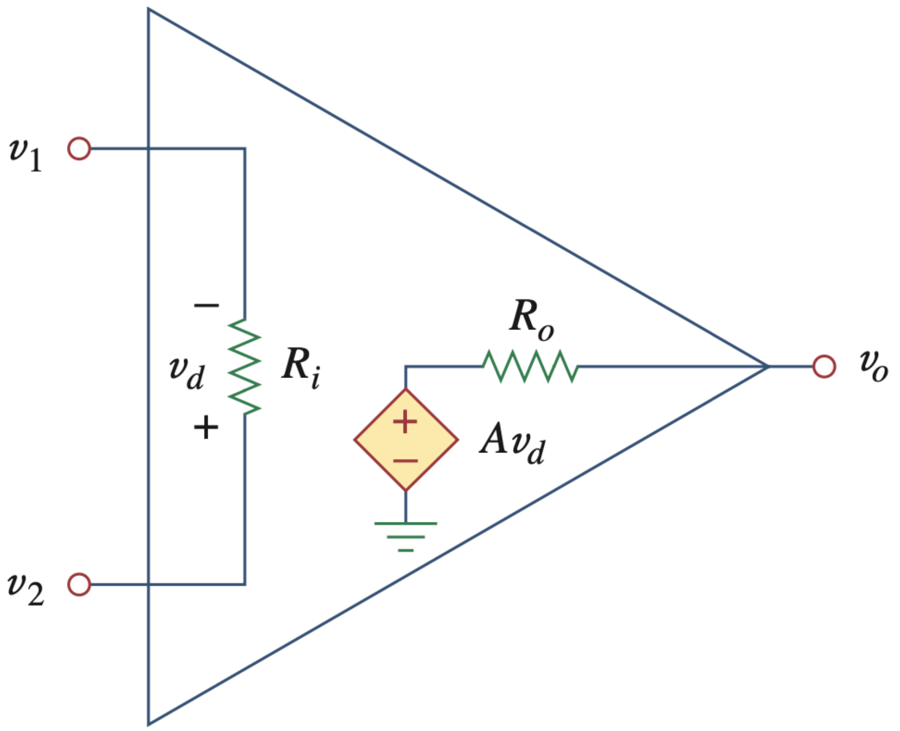




Important parameters of an Op-amp

- **Input resistance:** R_i
- **Output resistance:** R_O
- **Voltage (Differential/OL) Gain:** A/A_{OL} Slope of **VTC**
- **Positive Saturation Voltage:** $+V/V_{CC}/V_{sat}$
- **Negative Saturation Voltage:** $-V/V_{EE}/-V_{sat}$

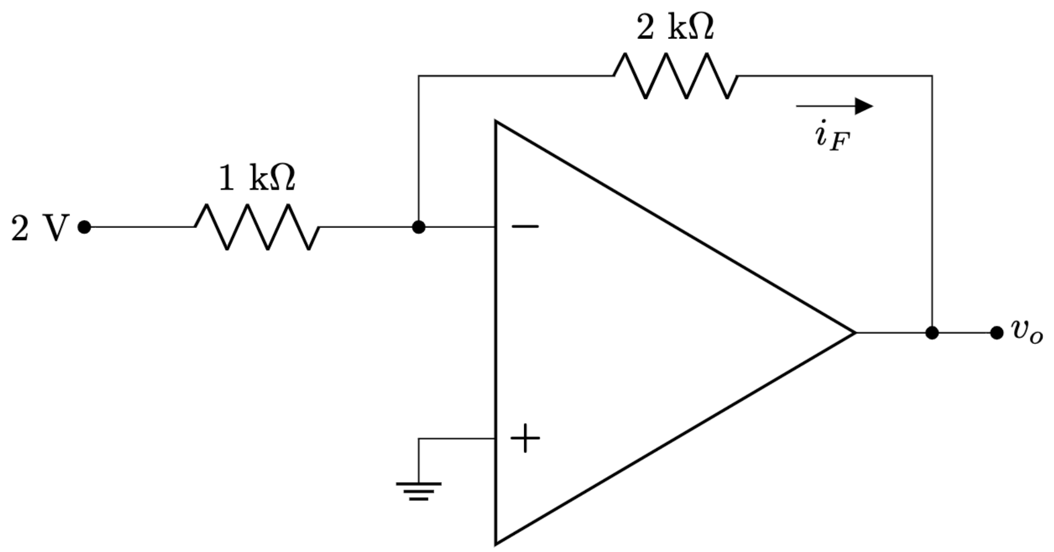
Parameter	Typical Range	Ideally
A	$10^4 - 10^8$	∞
R_i	$100\ k\Omega - 10^{10}\ k\Omega$	∞
R_o	$0.01\ k\Omega - 0.1\ k\Omega$	0

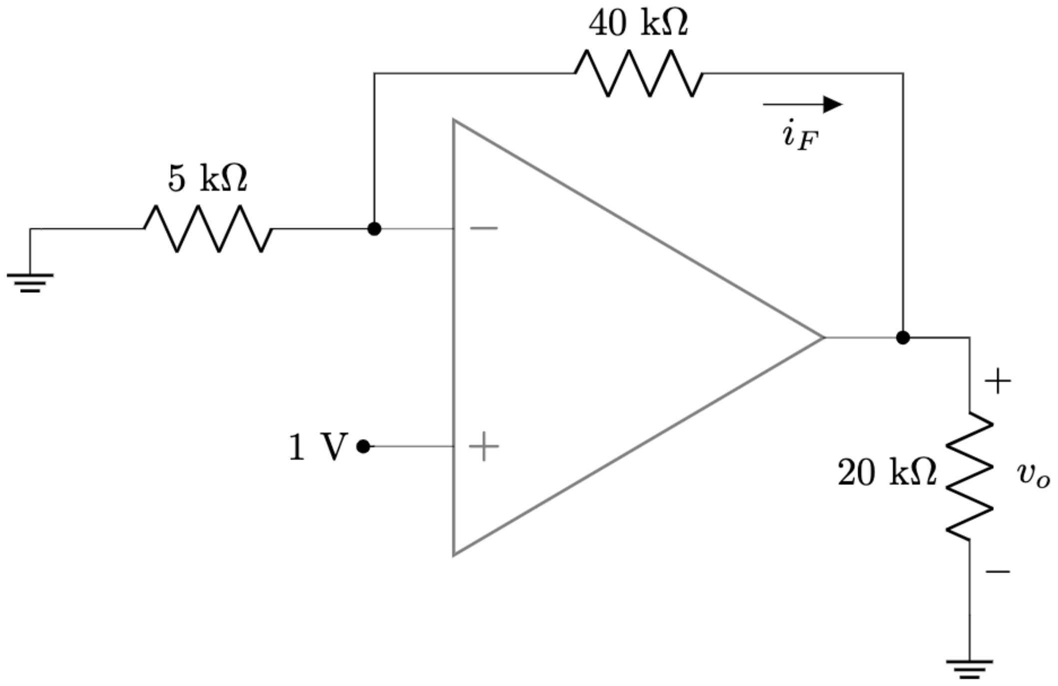


Some more circuits with OP AMP

Find $\boldsymbol{i_F}$ and $\boldsymbol{v_o}$.
Here,

$$\boldsymbol{R_i} = 200\ k\Omega$$
$$\boldsymbol{R_o} = 0.1\ k\Omega$$
$$\boldsymbol{A} = 2 \times 10^5$$

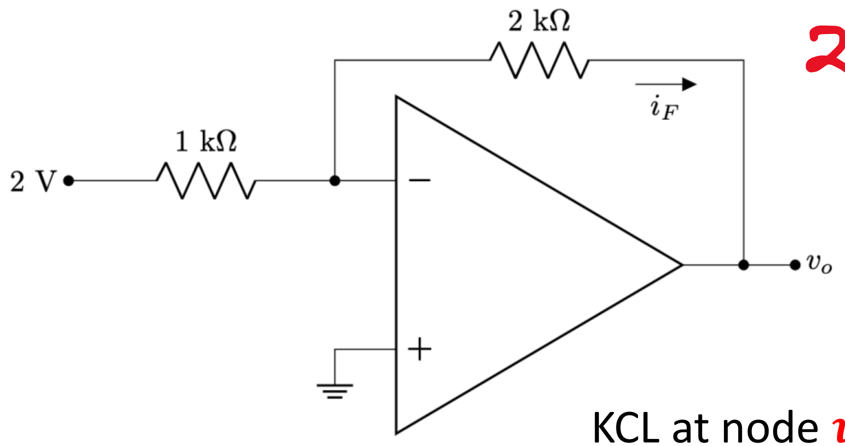


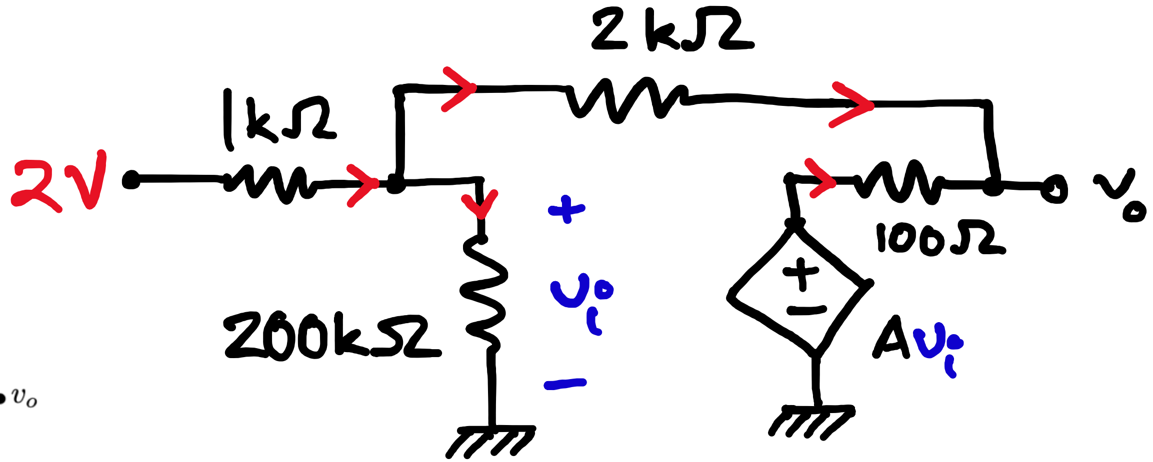


Example – Inverting Amplifier

Find $\boldsymbol{i_F}$ and $\boldsymbol{v_o}$.
Here,

$\boldsymbol{R_i} = 200\ k\Omega$
$\boldsymbol{R_o} = 0.1\ k\Omega$
$\boldsymbol{A} = 2 \times 10^5$





KCL at node $\boldsymbol{v_i}$

$$\frac{2 - v_i}{1} = \frac{v_i - v_o}{2} + \frac{v_i}{200}$$

$$\frac{301}{200} v_i - \frac{1}{2} v_o = 2$$

KCL at node $\boldsymbol{v_o}$

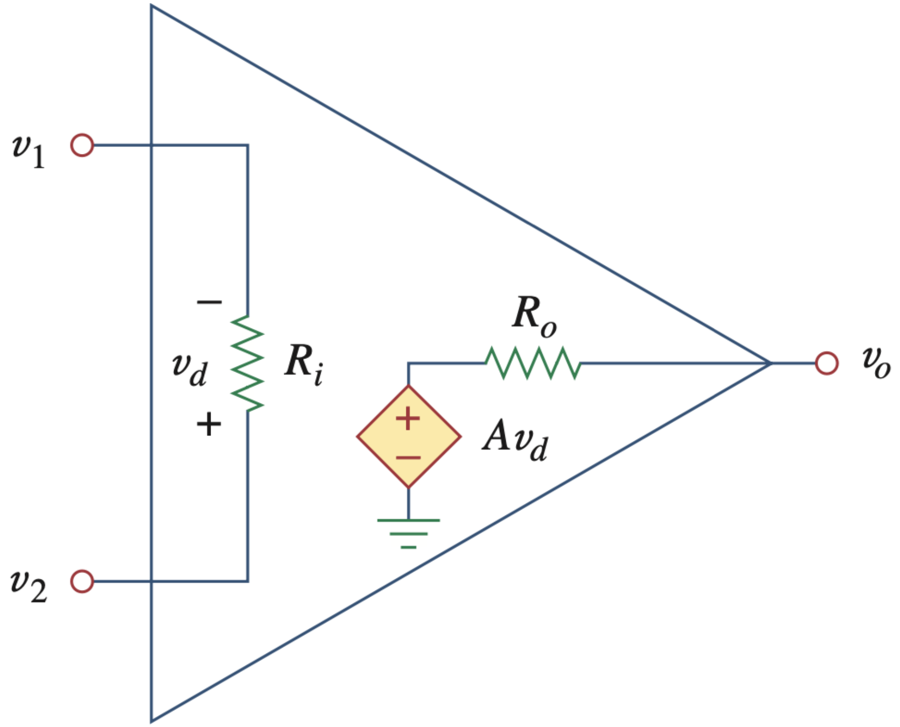
$$\frac{v_i - v_o}{2} + \frac{Av_i - v_o}{0.1} = 0$$

$$(2 \times 10^6 + 0.5)v_i - 10.5v_o = 0$$

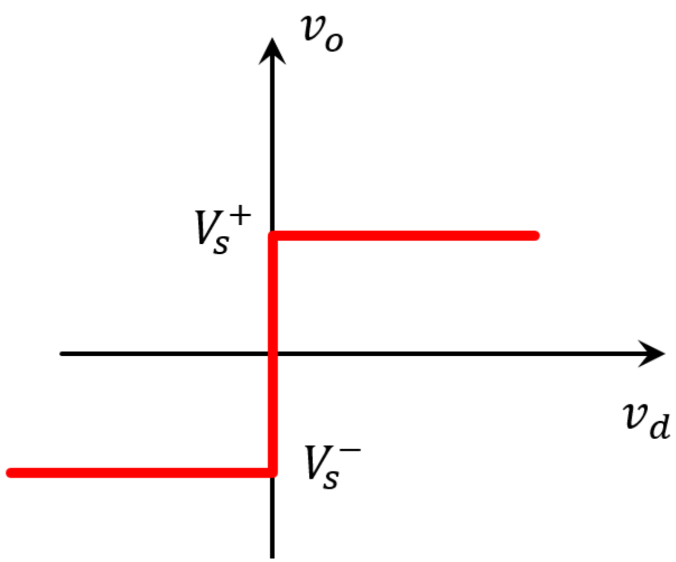
$$\boxed{\begin{array}{c} \boldsymbol{v_i = -21\ \mu V} \\ \boldsymbol{v_o = -3.999\ V} \\ \boldsymbol{i_F = 2\ mA} \end{array}}$$

Characteristics of an Ideal Op-amp

Parameter	Typical Range	Ideally
A	$10^4 - 10^8$	∞
R_i	$100\ k\Omega - 10^{10}\ k\Omega$	∞
R_o	$0.01\ k\Omega - 0.1\ k\Omega$	0

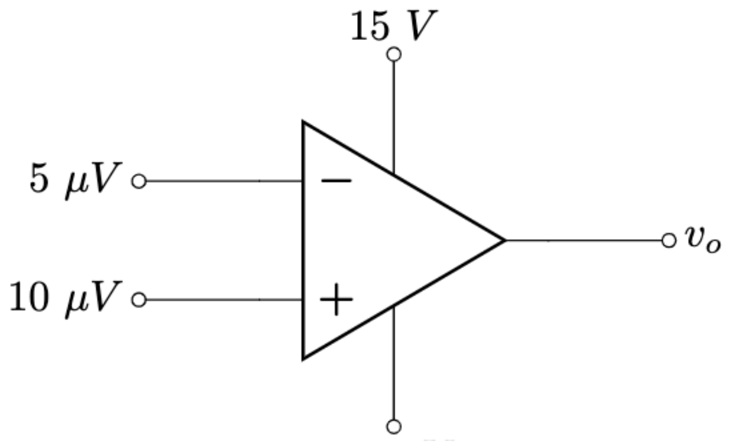


VTC

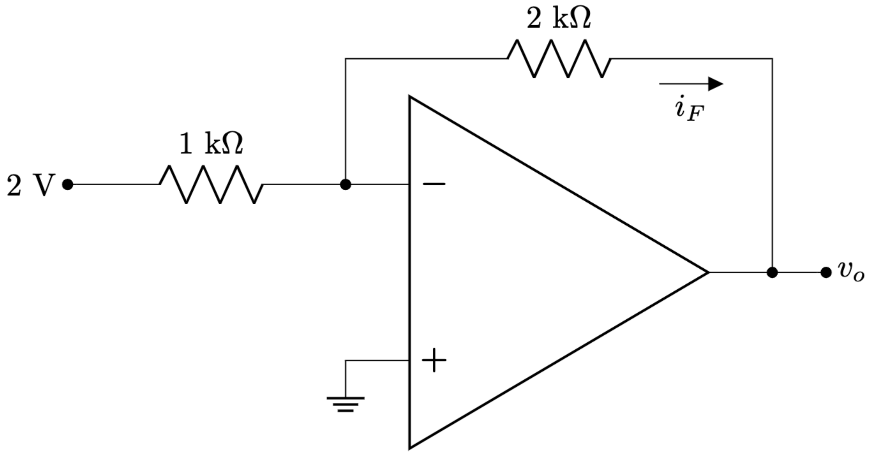


Types of Op-Amp configuration

1. Open loop configuration:
   No physical connection between input and output



2. Closed loop configuration:
   Feedback from output terminal



Open Loop Configuration → Ideal Op Amp

Voltage Transfer Characteristics (VTC)

Positive saturation:

$$\Rightarrow V_O = +V_{sat}$$

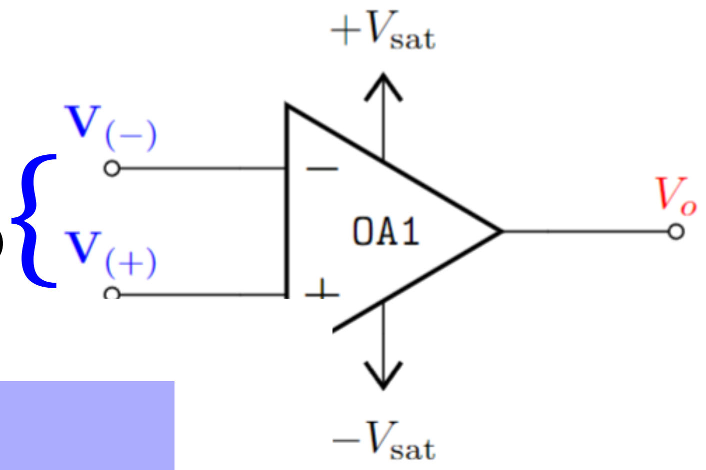
~~**Linear Region**~~

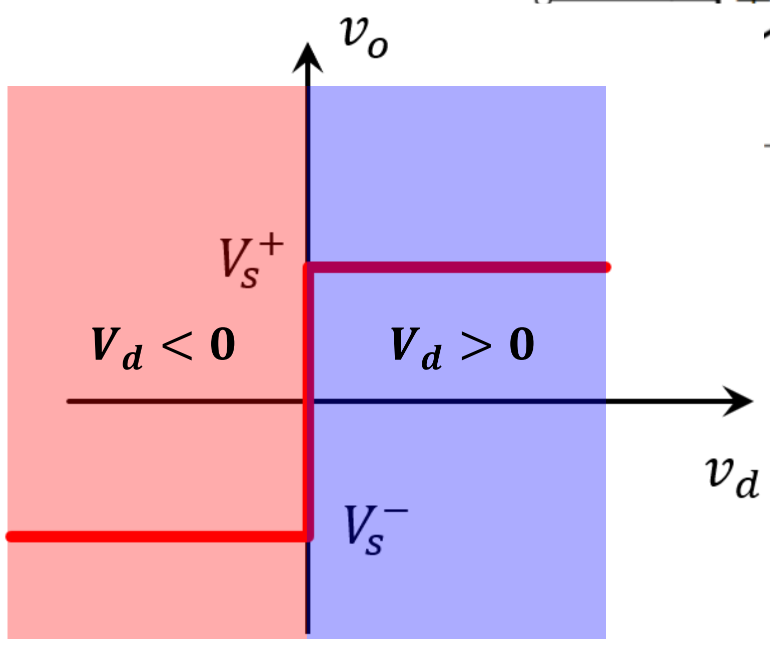
$$\cancel{-V_{sat} < V_O = AV_d < +V_{sat}}$$

Negative saturation:

$$\Rightarrow V_O = -V_{sat}$$

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



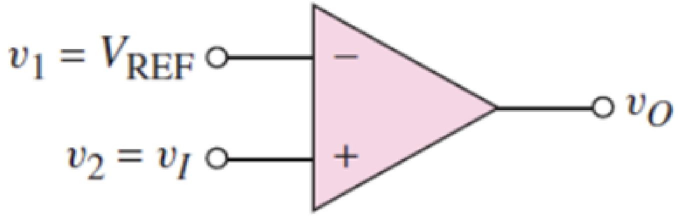


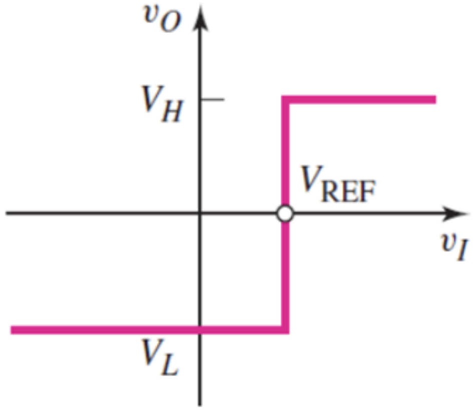
$A \to \infty$ **: Open Loop Gain**

Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

$$V_d = v_I - V_{\text{REF}}$$





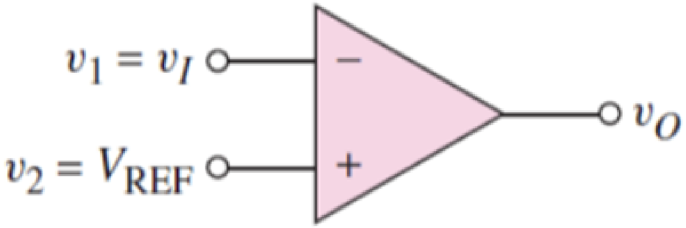
$$V_d = v_I - V_{\text{REF}} > 0 \quad \Rightarrow \quad v_O = V_H$$

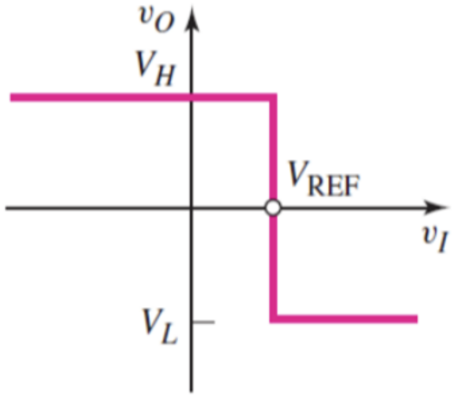
$$v_I > V_{\text{REF}} \quad \Rightarrow \quad v_O = V_H$$

Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

$$V_d = V_{\mathrm{REF}} - v_I \quad \Big\{$$





$$V_d = V_{\mathrm{REF}} - v_I > 0 \quad \Rightarrow \quad v_O = V_H$$

$$v_I < V_{\mathrm{REF}} \quad \Rightarrow \quad v_O = V_H$$

Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

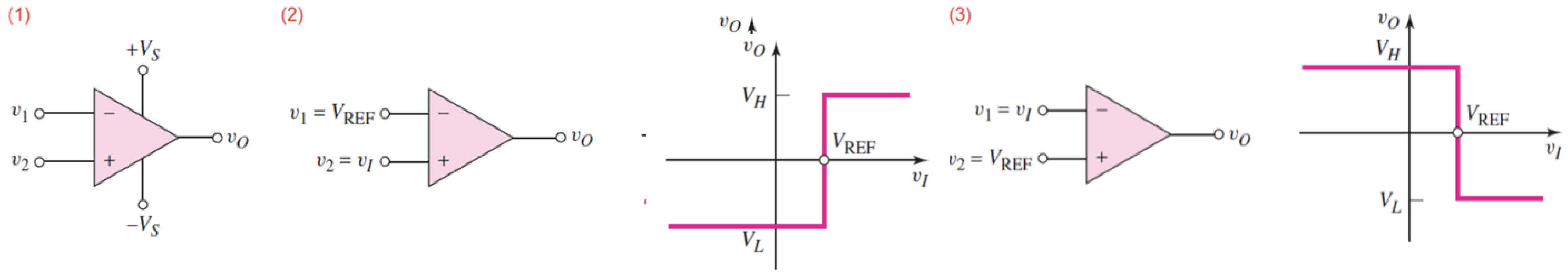


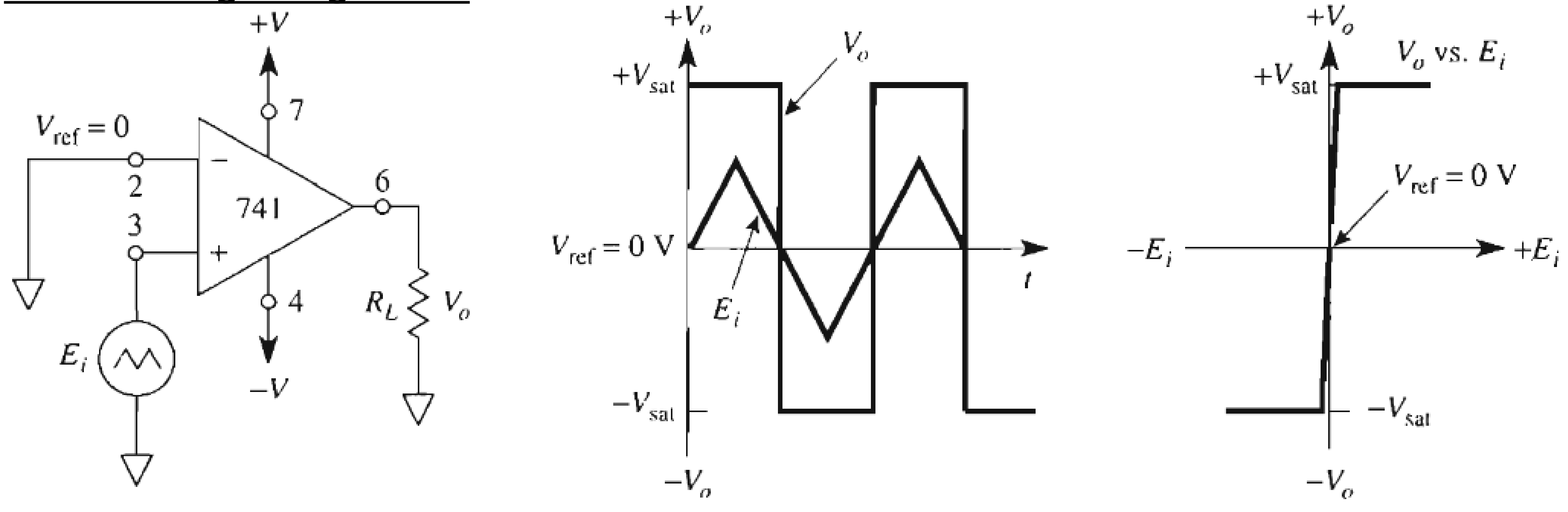
Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

Open Loop Configuration: Comparator

Zero Crossing Detector

Compare values with a reference and pin value to $+\boldsymbol{V_{sat}}$ if voltage is above or to below that.

Non-inverting configuration

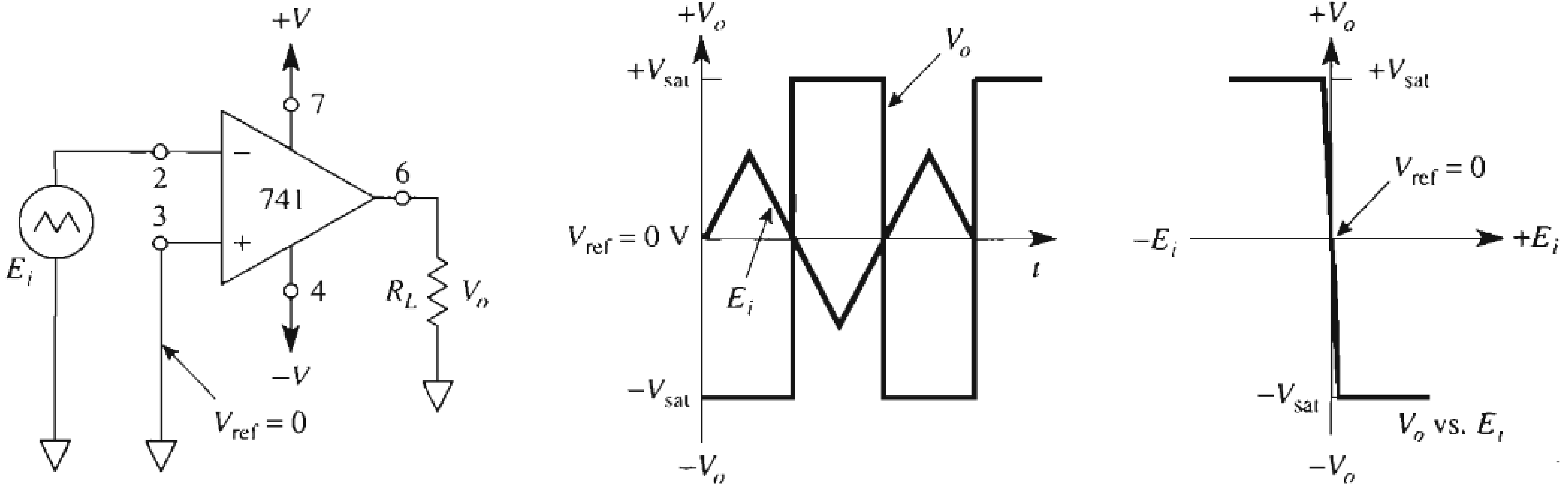


(a) Noninverting: When E_i is above V_{ref}, $V_o = +V_{sat}$.

Open Loop Configuration: Comparator

Zero Crossing Detector

Inverting configuration



(b) Inverting: When E_i is above V_{ref}, $V_o = -V_{sat}$.

Comparator Application - Smoke Detectors

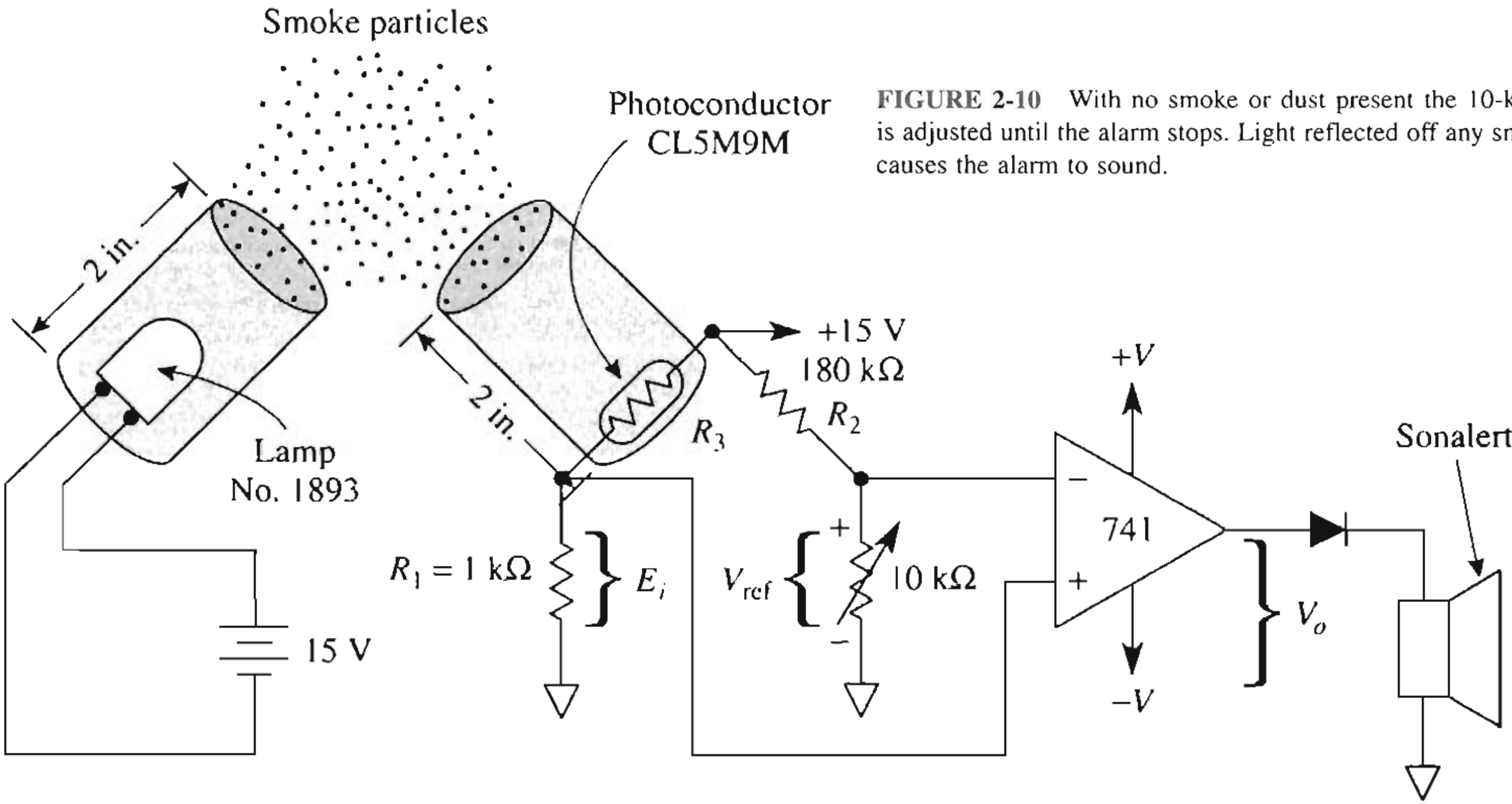
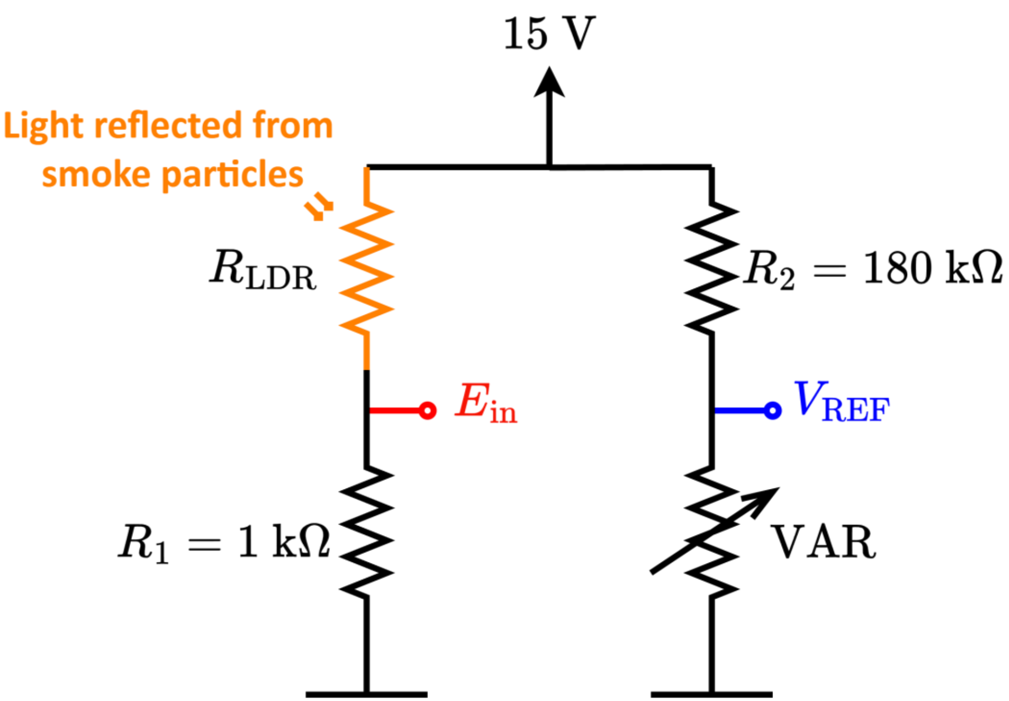


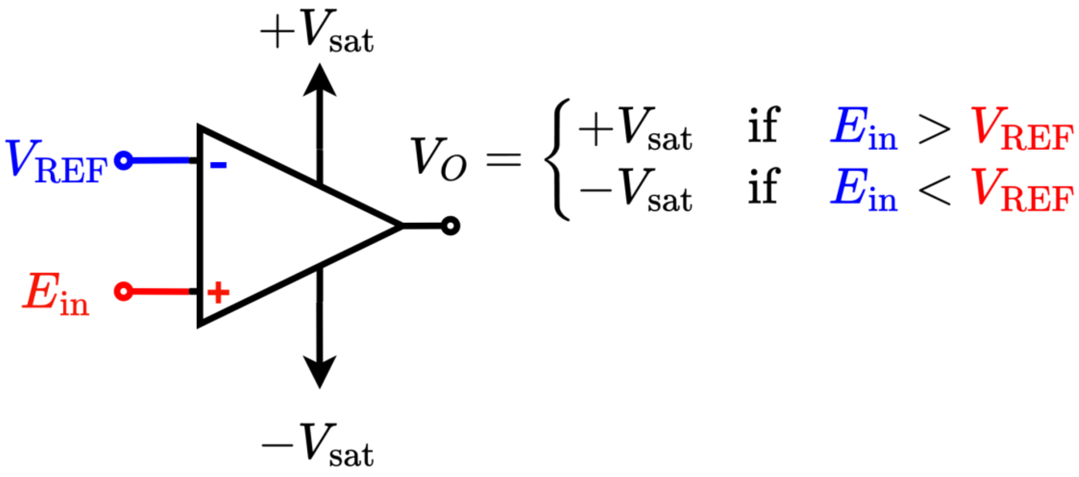
FIGURE 2-10 With no smoke or dust present the 10-kΩ sensitivity control is adjusted until the alarm stops. Light reflected off any smoke or dust particles causes the alarm to sound.

Comparator Application Smoke Detectors

Input Voltage $\boldsymbol{E_{\text{in}}}$ from the light reflected off the smoke



Reference voltage $\boldsymbol{V_{\text{REF}}}$ adjusted via the variable resistor (VAR)



Comparator Application - Smoke Detectors

Light from lamp is reflected from dust particles (if any) to the photoconductor.

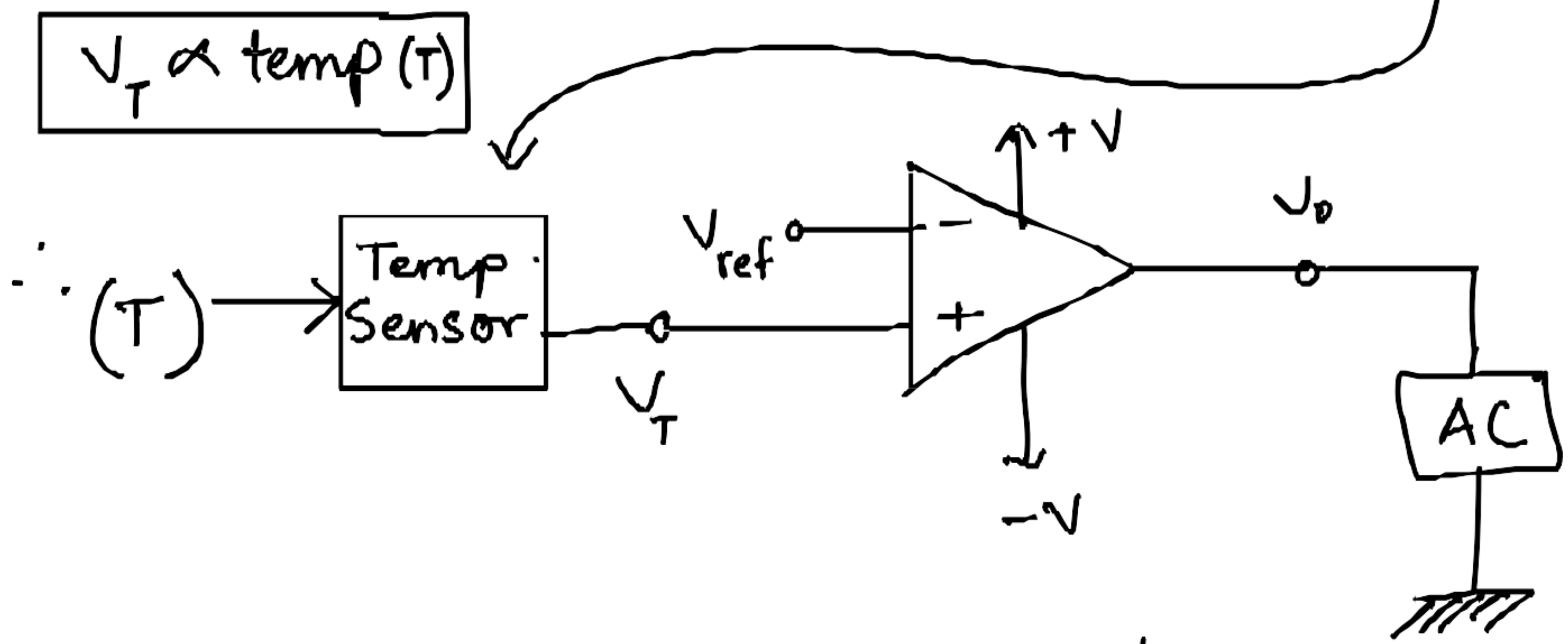
Photoconductor: Low Resistance (R_3) if light incidents.
PC High Resistance (R_3) if no light incidents.

$\therefore$ Smoke $\rightarrow$ light on PC $\rightarrow$ low R_3 $\rightarrow$ high E_i $\rightarrow$ $\boxed{V_o = +V}$ $\rightarrow$ Alarm

No Smoke $\rightarrow$ no light on PC $\rightarrow$ high R_3 $\rightarrow$ low E_i $\rightarrow$ $\boxed{V_o = -V}$ $\rightarrow$ No Alarm

Comparator Application – Automatic AC

Reference temperature $\longrightarrow$ Reference Voltage (V_{ref})

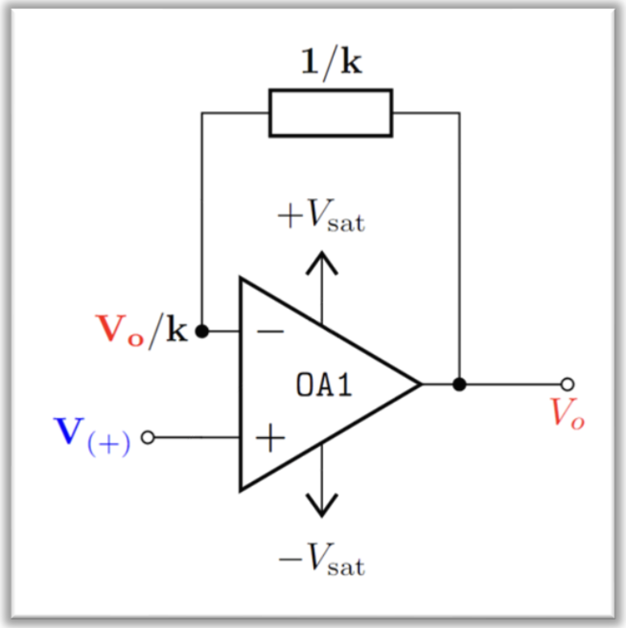


AC turns on when voltage $V_o = +V$.

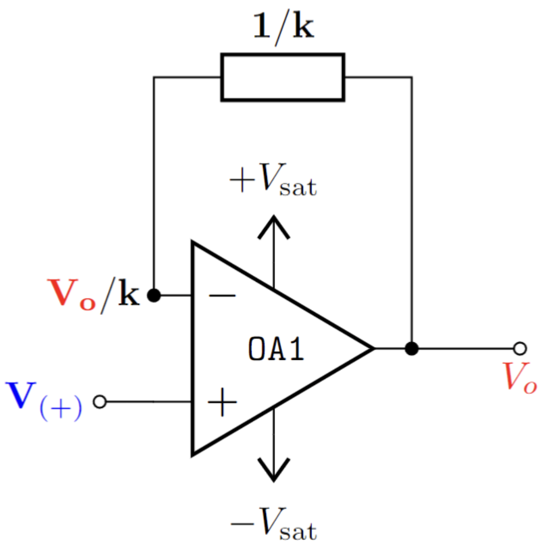
" is off " " $V_o = -V$ (low voltage can be 0 too)

Closed Loop Configuration

Feedback



Feedback in Op-Amp circuit



Two types of feedback

1. Negative Feedback:

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

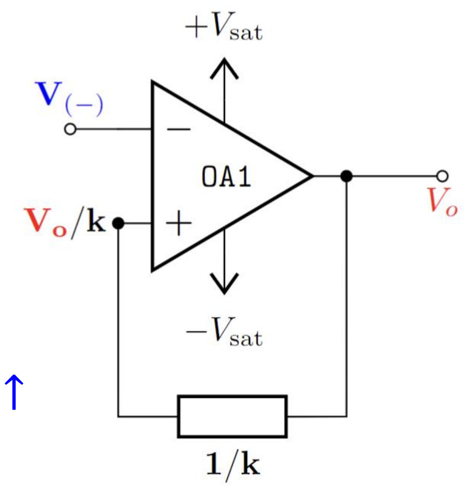
   The output voltage is connected to the **inverting** terminal

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

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

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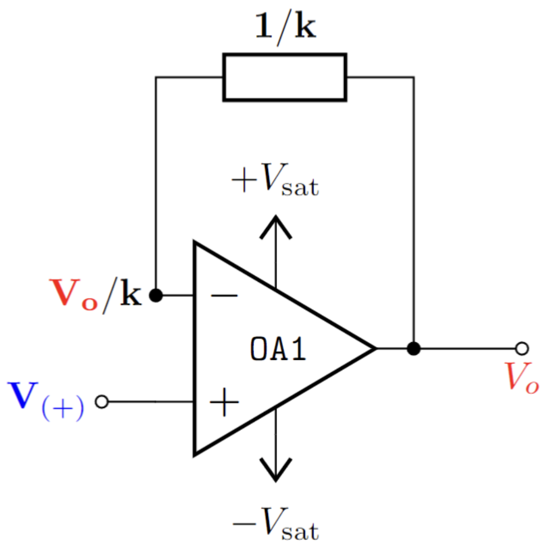

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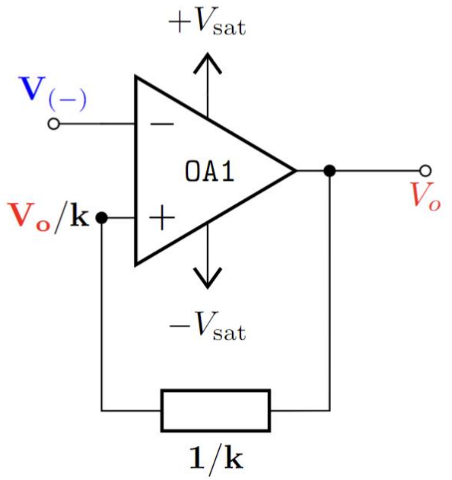


Feedback in Op-Amp circuit

Negative Feedback:

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

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

Here, $\boldsymbol{V}_{(-)} = \frac{\boldsymbol{V_o}}{\mathbf{k}}$

We know, $\boldsymbol{V_o} = A\boldsymbol{V_d}$

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

$$= A\left(\boldsymbol{V}_{(+)} - \frac{\boldsymbol{V_o}}{\mathbf{k}}\right)$$

$$= A\boldsymbol{V}_{(+)} - \frac{A}{k}V_O$$

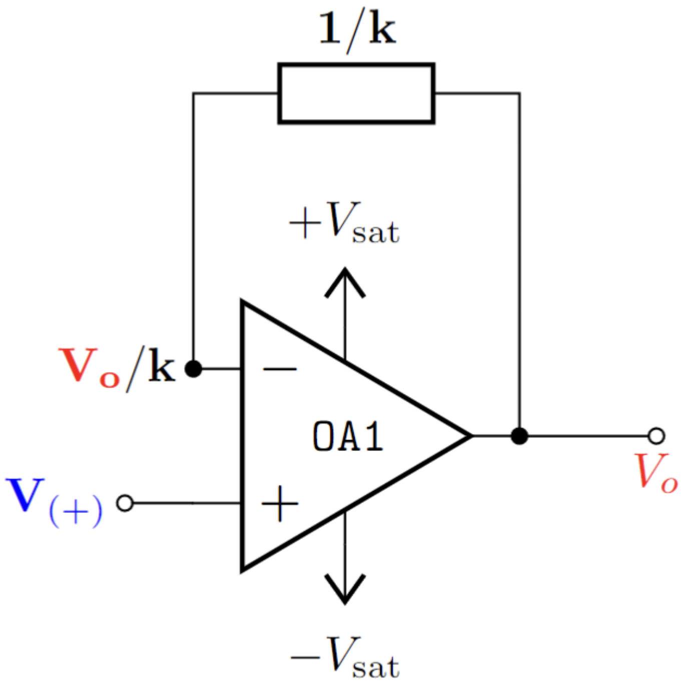
$$\Rightarrow \boldsymbol{V_o}(1 + \tfrac{A}{k}) = A\boldsymbol{V}_{(+)}$$

$$\frac{\boldsymbol{V_o}}{\boldsymbol{V}_{(+)}} = \frac{A}{1 + \frac{A}{k}} = \frac{1}{\frac{1}{A} + \frac{1}{k}}$$

If $A \to \infty$ then $\frac{1}{A} \to 0$.

$$\therefore \frac{\boldsymbol{V_o}}{\boldsymbol{V}_{(+)}} = k$$

This is the new amplification factor / Gain



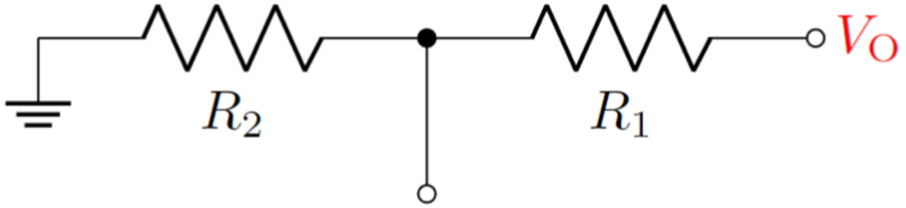
Negative Feedback in Op-Amp circuit

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

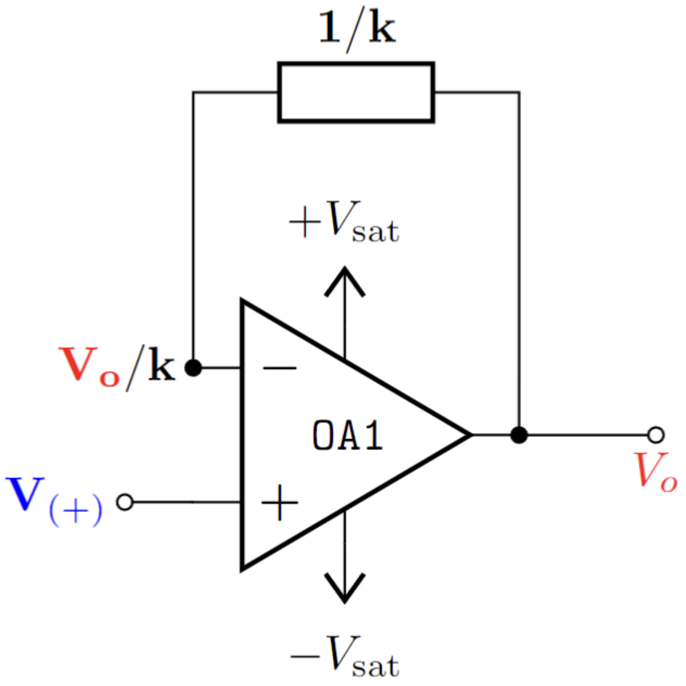
$$V_{(-)} = \frac{1}{k} \cdot V_O$$

This factor of $1/k$ can be achieved with a voltage divider network.

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



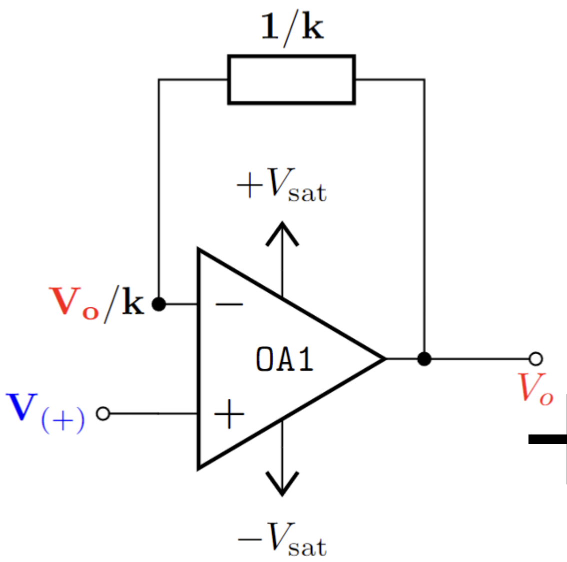
$$V_{(-)} = \frac{R_2}{R_2+R_1} \cdot V_O$$



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

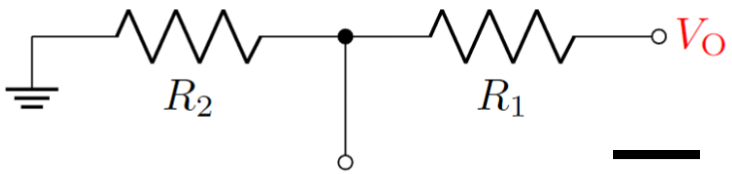
Negative Feedback in Op-Amp circuit

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



+

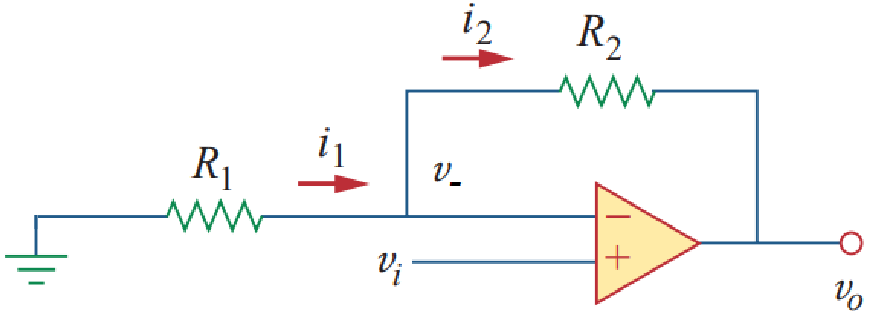
$$\frac{R_2}{R_1 + R_2} = \frac{\mathbf{1}}{\boldsymbol{k}}$$



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

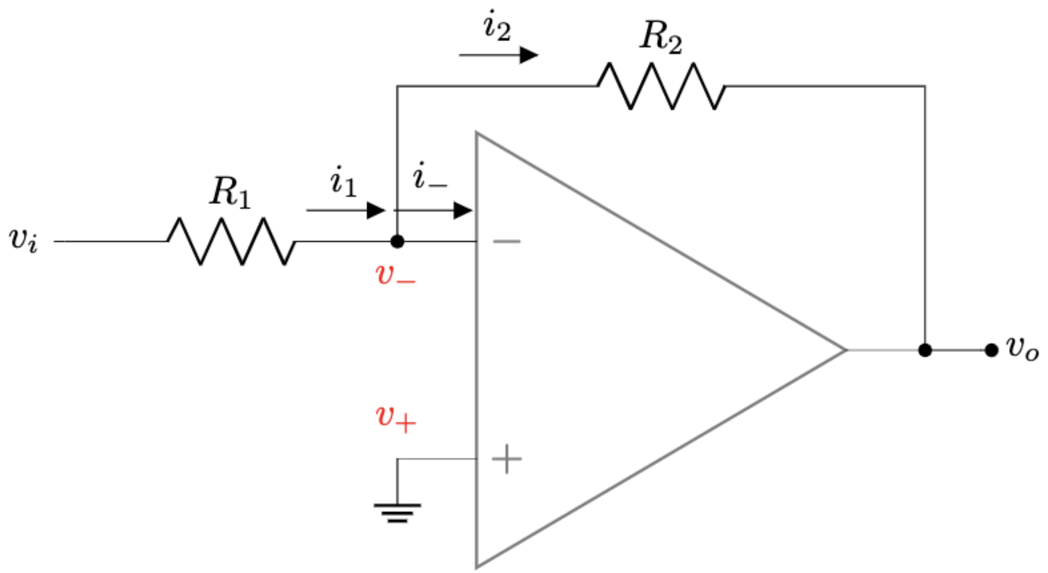
=

$$\frac{R_2}{R_1 + R_2} \boldsymbol{V_O}$$



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



$$\text{Gain} = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Since $\boldsymbol{v_+}$ is connected to ground, $\boldsymbol{v_+ = 0}$ **V**

Since there is negative feedback, from virtual short, $\boldsymbol{v_- = v_+ = 0}$ **V**

From Ohm's law for $\mathrm{R_1} \Rightarrow i_1 = \frac{v_i - 0}{R_1} = \frac{v_i}{R_1}$

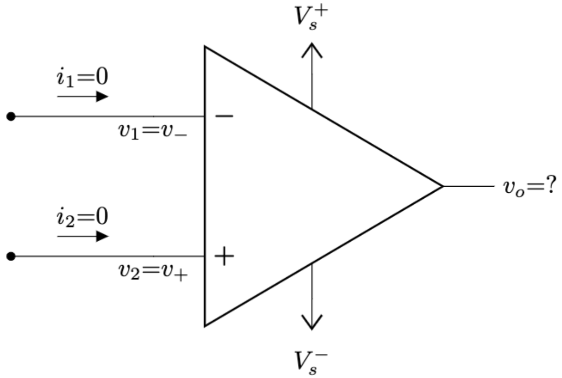
Since ideal op-amp, $i_- = i_+ = 0$

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]

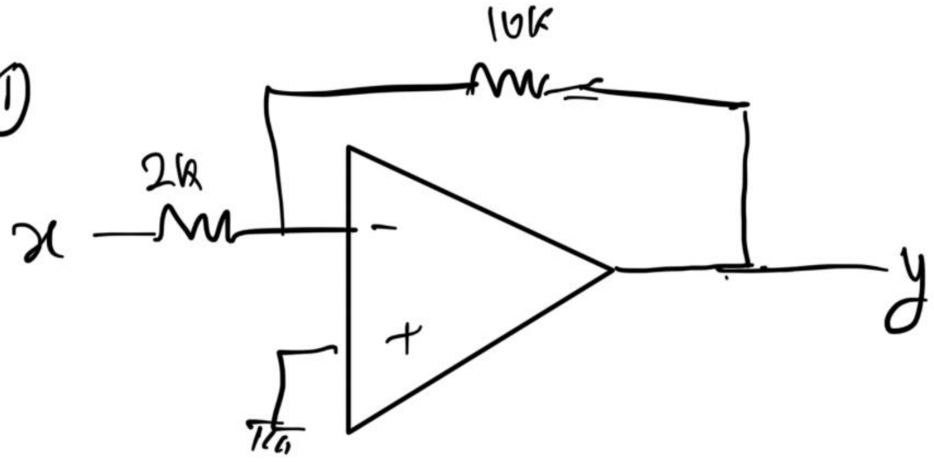
Solving Closed Loop Op-Amp Circuit

- 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 $i_+ = 0$
- ***When there is negative feedback***, 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

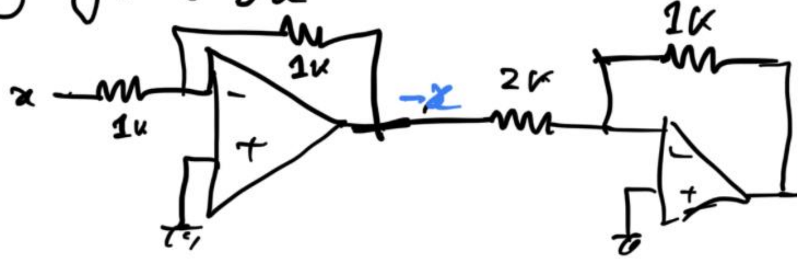


Example

①



② $y = 0.5x$



https://forms.gle/foiEHQvKDAh2KM3i6