CSE251: Electronic Devices and Circuits

Lecture 2

Operational Amplifier:

Introduction, Open Loop Configuration, Closed Loop Introduction

Prepared By:

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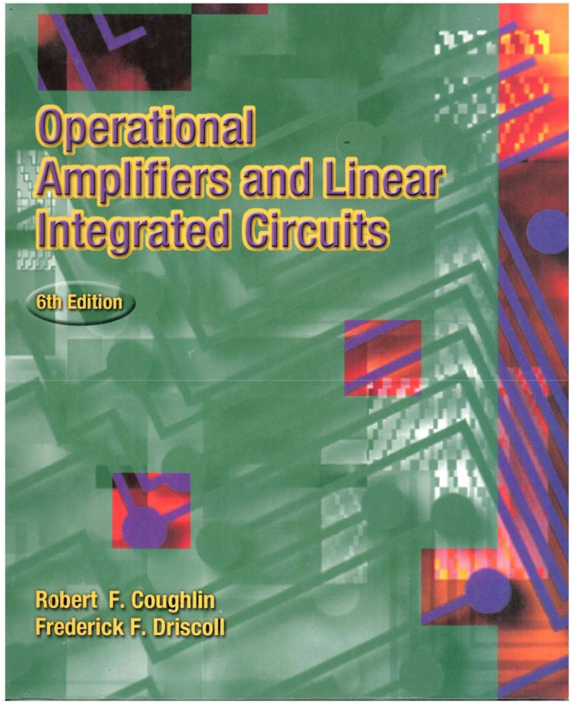
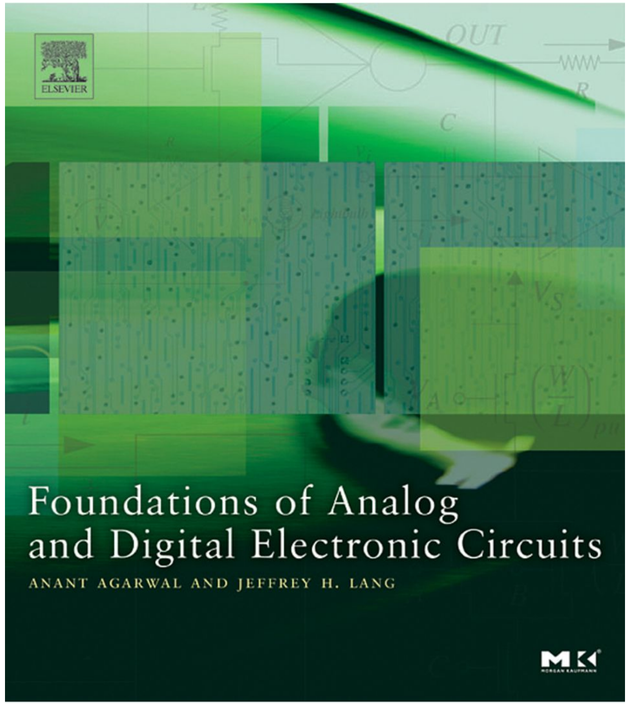
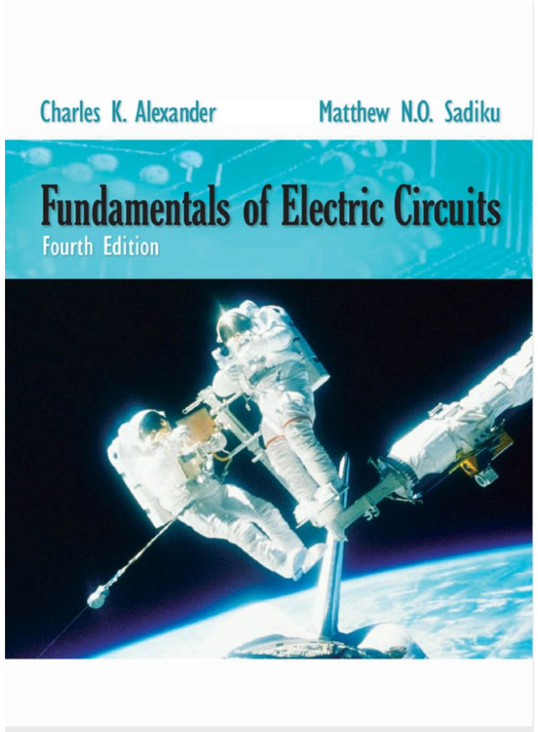
Operational Amplifiers

Textbook







Outline

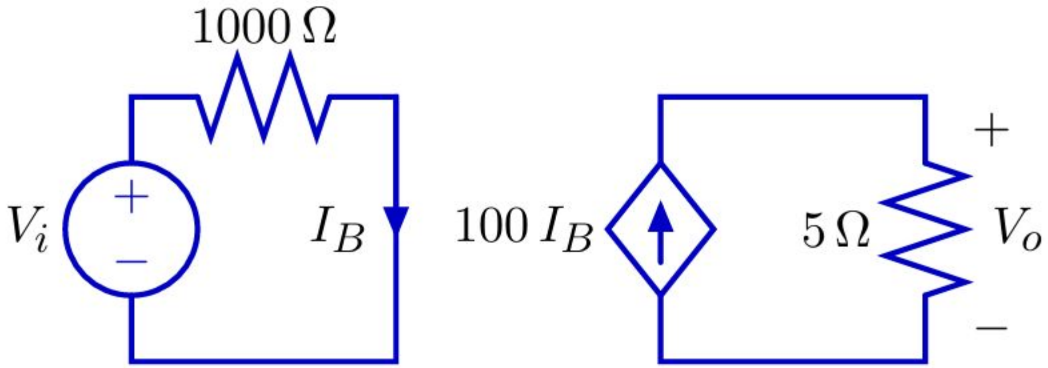
- **Operational Amplifier: Introduction**
  - Dependent Sources
  - Op-Amp: Circuit Symbols and terminal
  - Op-Amp: VTC (Voltage Transfer Characteristics)
    - Linear Amplification
    - (Positive and Negative) Saturation
  - Op-Amp: Examples
  - Op-Amp: Physical Entity

Dependent Sources

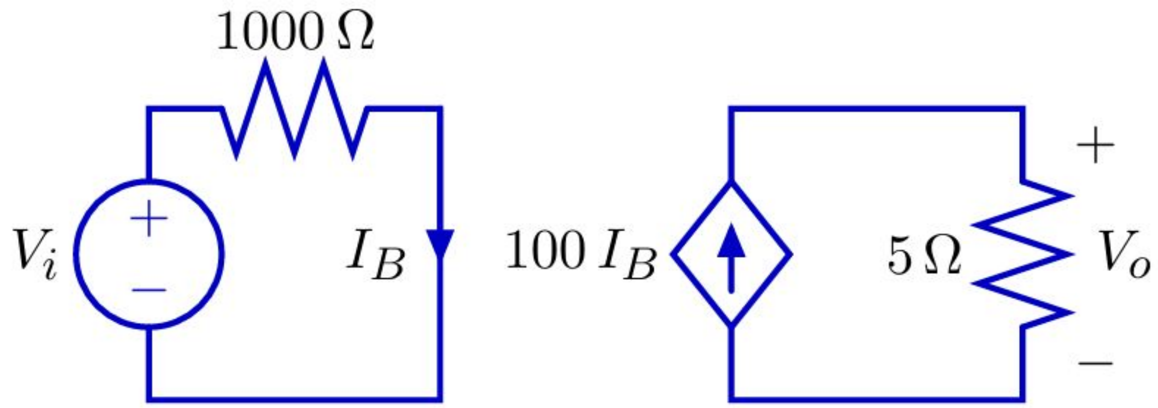
To analyze op-amps, we must understand **dependent source.**

A dependent source generates a voltage or current whose value depends on another voltage or current.

Example: current-controlled current source



Dependent Sources



$$I_B = \frac{V_i}{1000\,\Omega}$$

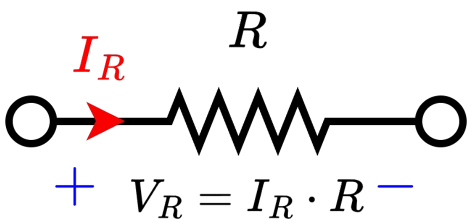
$$V_o = 100\,I_B \times 5\,\Omega$$

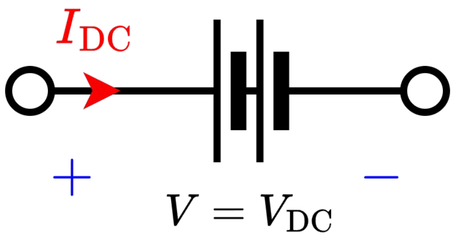
$$= 100\,\frac{V_i}{1000\,\Omega} \times 5\,\Omega = \boxed{\frac{1}{2}V_i}$$

Voltage Gain: $\dfrac{V_o}{V_i} = \dfrac{1}{2}$

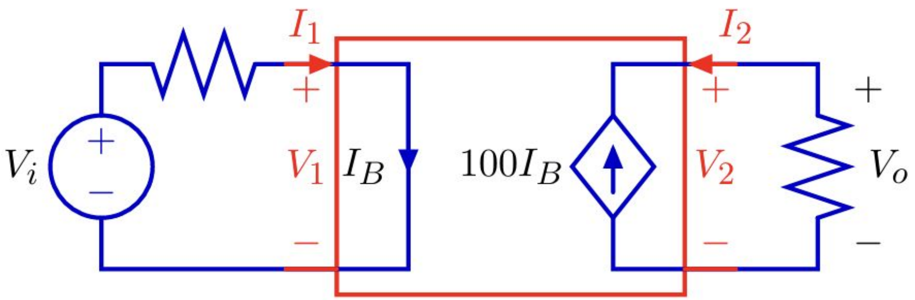
Dependent Sources

Resistors, (Ind.) Voltage sources, (Ind.) Current sources are single "**port**" device. They are characterized by a **single equation**.





Dependent sources are two-ports: characterized by **two** equations.



Here $\boldsymbol{V_1} = 0$ and $\boldsymbol{I_2} = -100\,\boldsymbol{I_1}$.

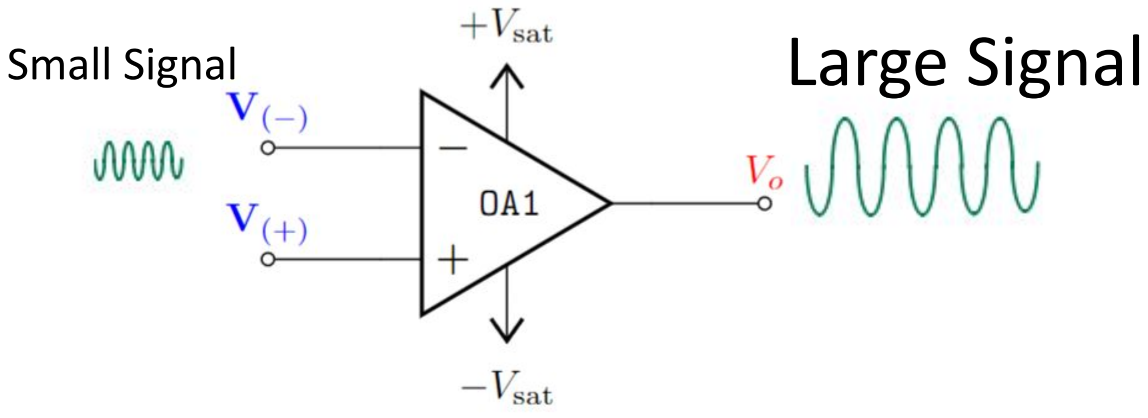
Operational Amplifier: Introduction

- **Operational:**

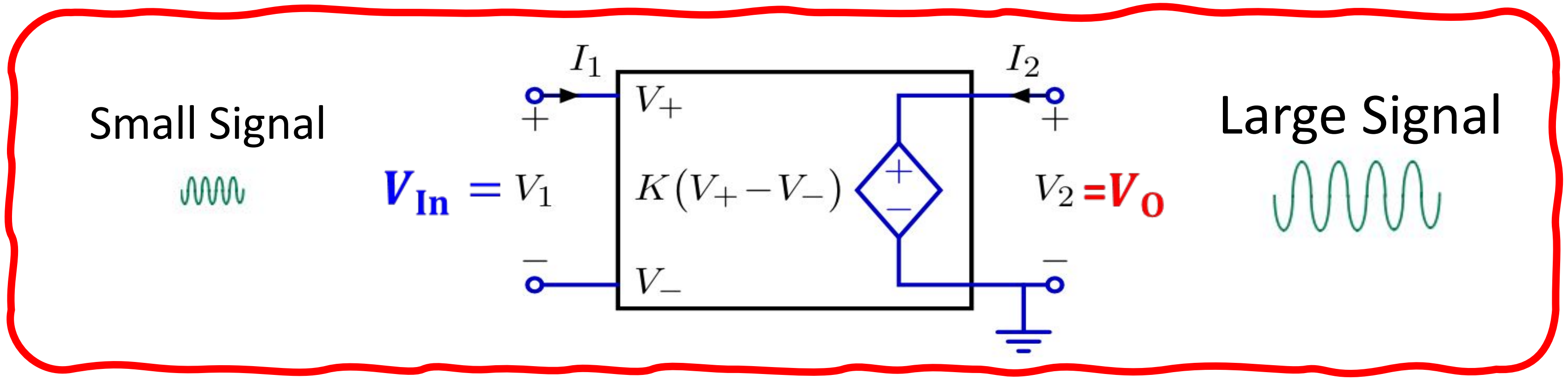
  Mathematical Operations

- **Amplifier:**

  Amplifies input signal/voltage.

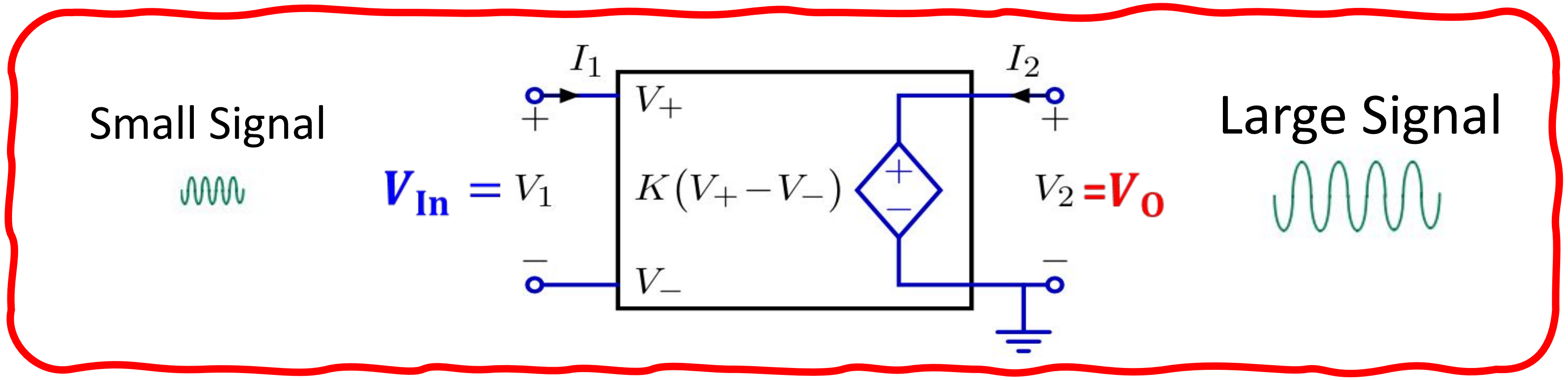


An **op-amp (operational amplifier)** can be modelled by a **voltage- controlled voltage source.**



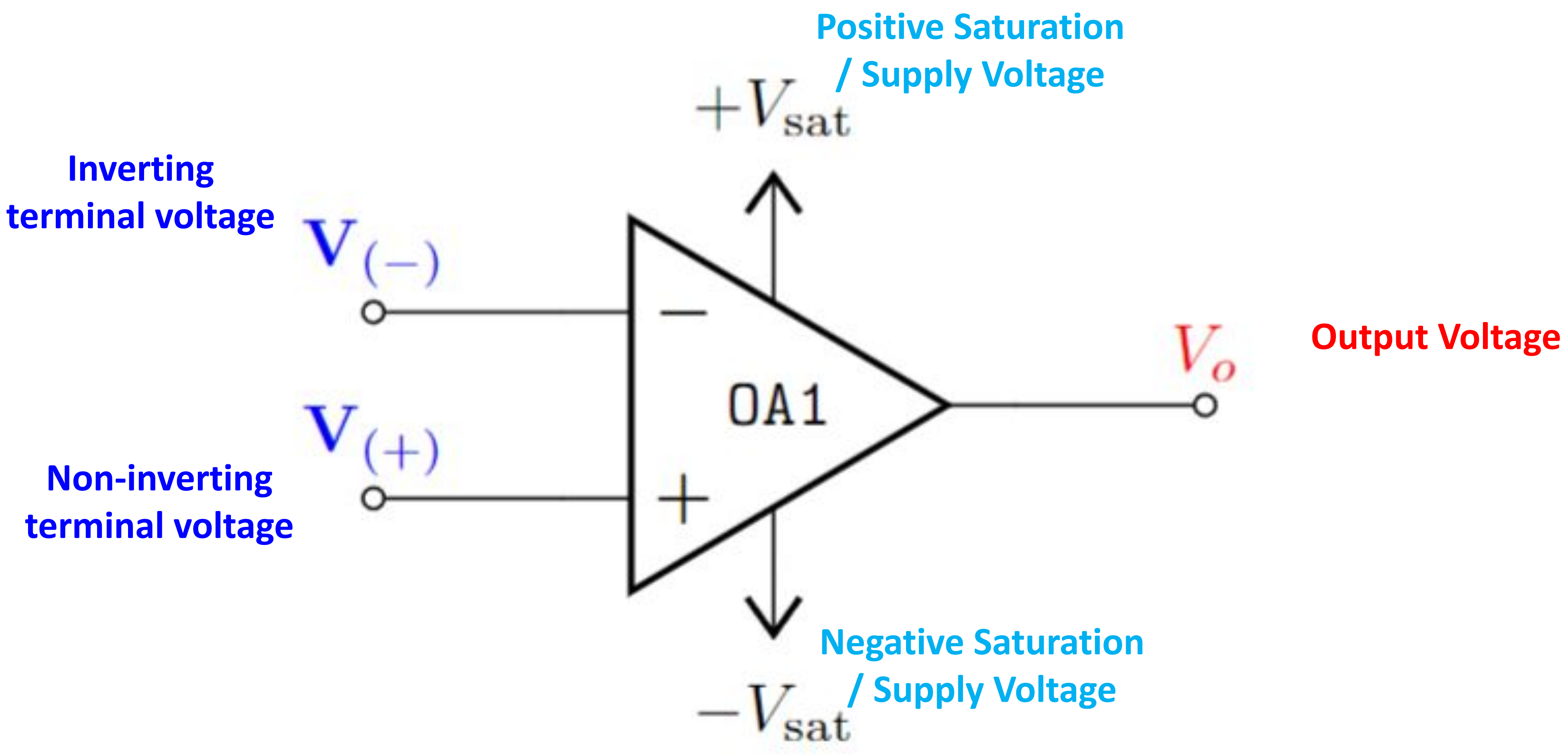
Operational Amplifier: Introduction

An **op-amp (operational amplifier)** can be represented by a **voltage- controlled voltage source.**

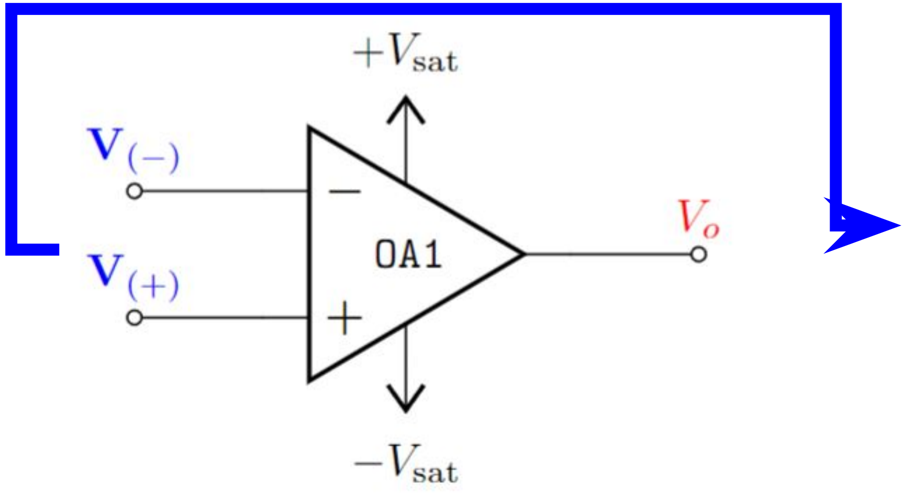


$I_1 = 0$ and $V_O = KV_{In}$ where K is large (typically $K > 10^5$).

Op-Amp: Circuit Symbols and terminal



Op-Amp: Circuit Symbols and terminal

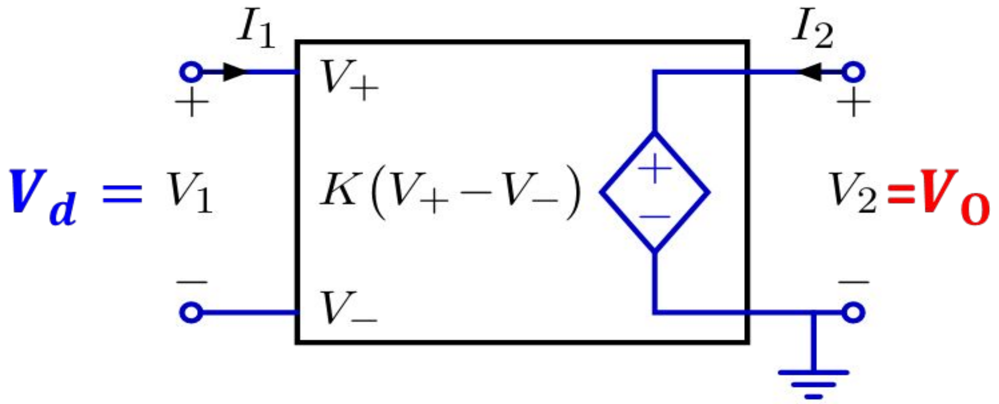


$$\boldsymbol{V_d = V_{(+)} - V_{(-)}}$$

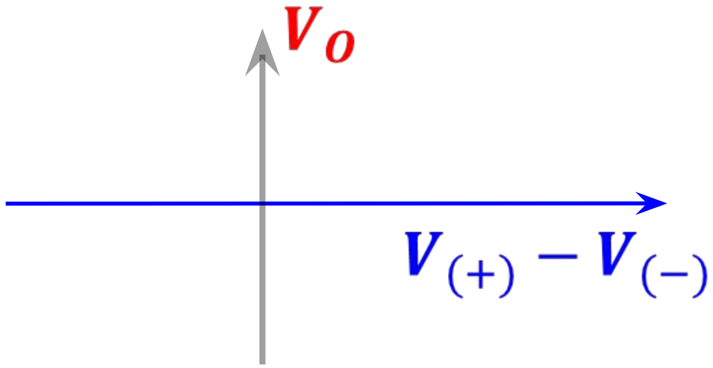
Difference Amplifier –

Amplifies the voltage difference between two terminals.

Differential input voltage



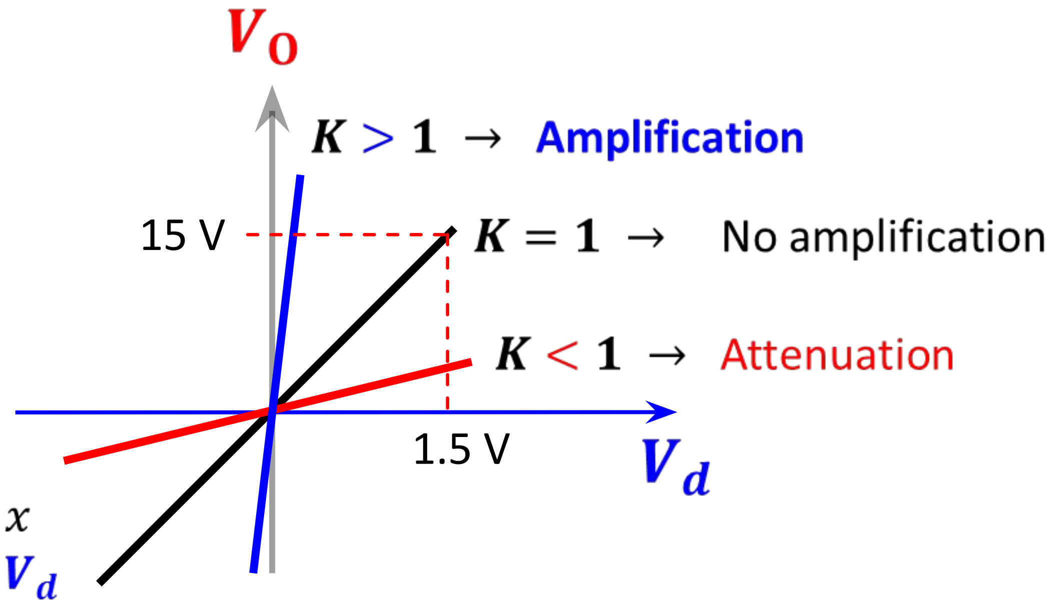
Voltage Transfer Characteristics (VTC)



Op-Amp: VTC – Linear Amplification

Voltage Transfer Characteristics (VTC)

- Shows how the output voltage varies with the input voltage $V_O(V_d)$
- y −axis → V_O
- x −axis → V_d
- Slope: $K = \frac{\Delta V_O}{\Delta V_d} = \frac{V_O}{V_d}$



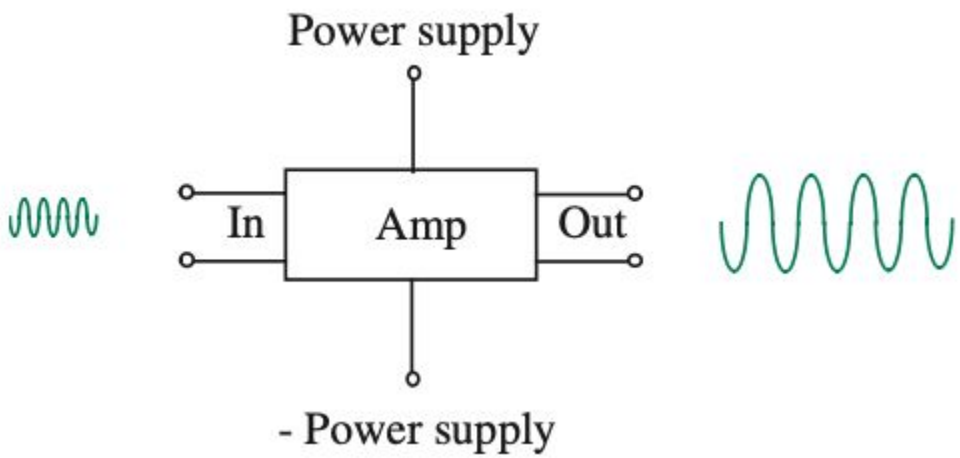
If the line passes through origin:

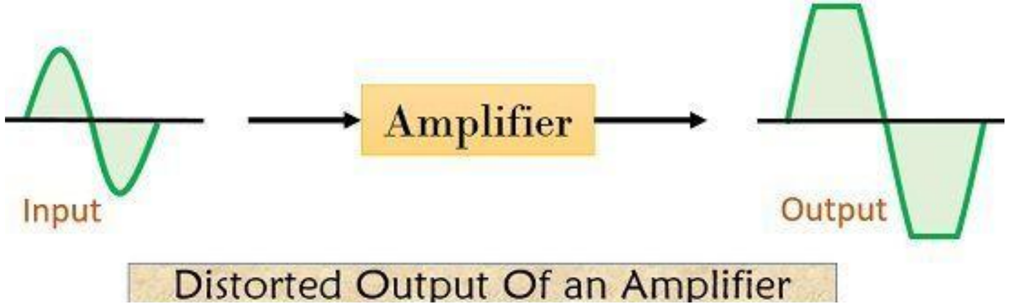
$$y = K \cdot x$$
$$V_O = K \cdot V_d$$

LINEAR AMPLIFICATION

Op-Amp: VTC – Linear Amplification

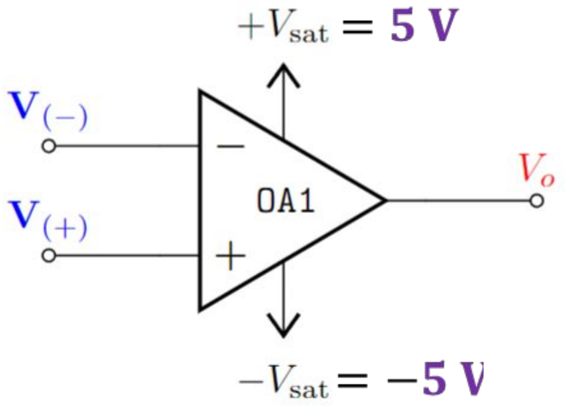
- **Linear Amplification** only takes place within a **valid input range.**
- Otherwise output will be distorted - - Saturation





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

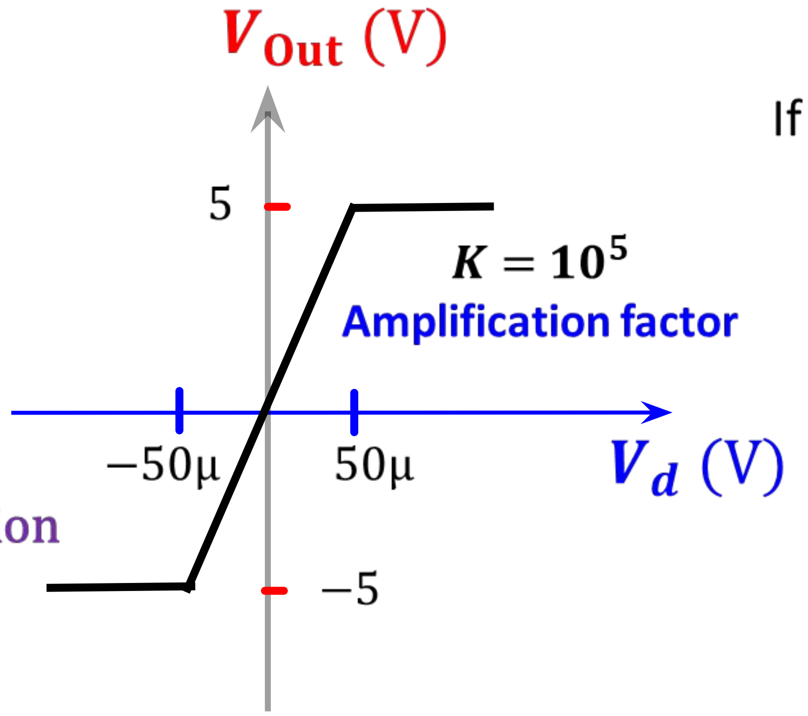
Op-Amp: VTC - Saturation



Non-Linear characteristics

$V_O = K \cdot V_{In}$: When $-5\ \mathrm{V} < V_O < 5\ \mathrm{V}$

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



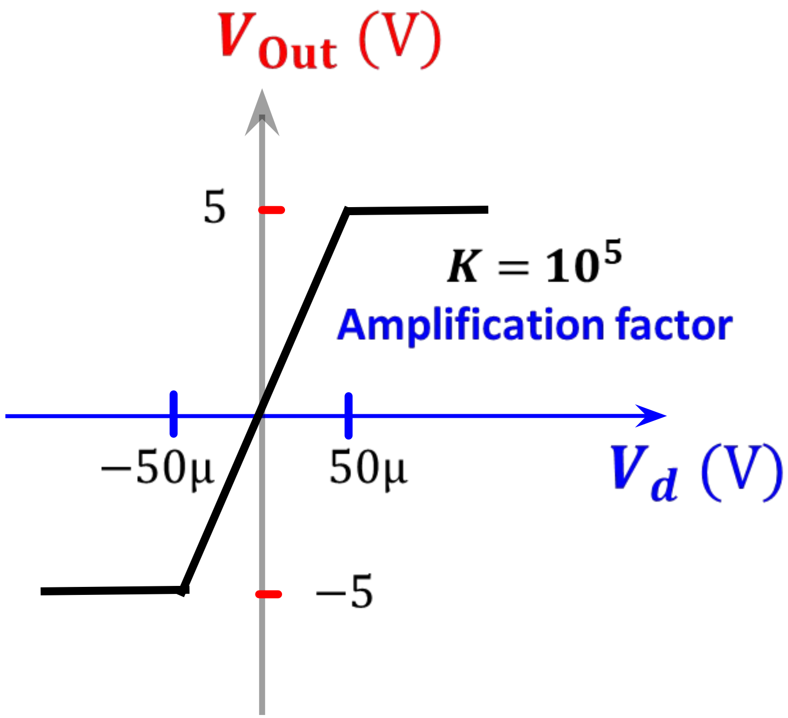
If $V_d > 50\mu$: Positive Saturation

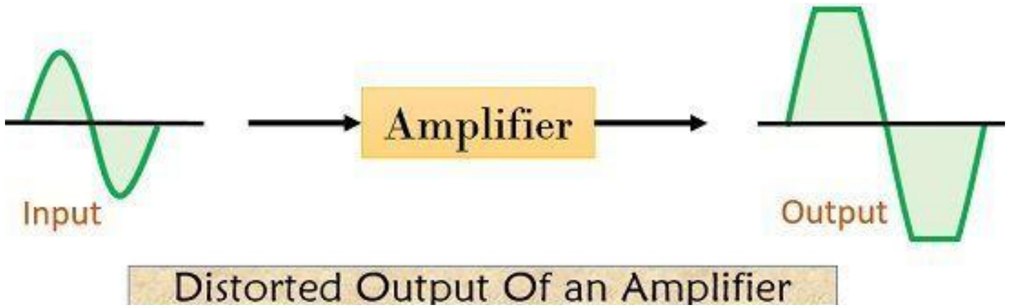
$\Rightarrow V_O = 5$

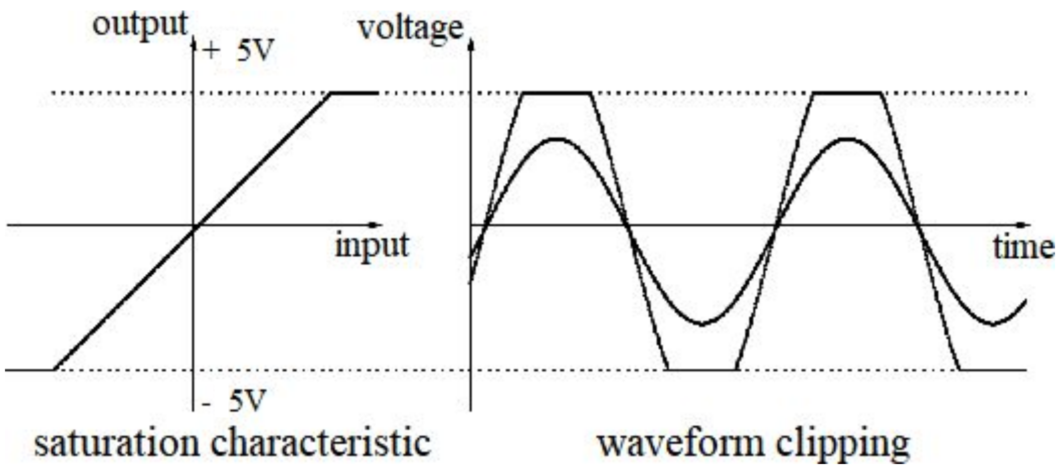
If $V_d < -50\mu$: Negative Saturation

$\Rightarrow V_O = -5$

Op-Amp: VTC - Saturation







Op-Amp: VTC - Summary

Voltage Transfer Characteristics (VTC)

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

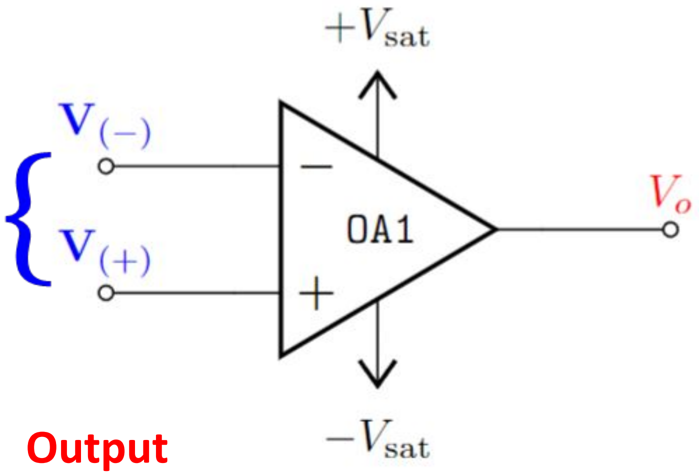
$-V_{sat} < V_o = AV_d < +V_{sat}$

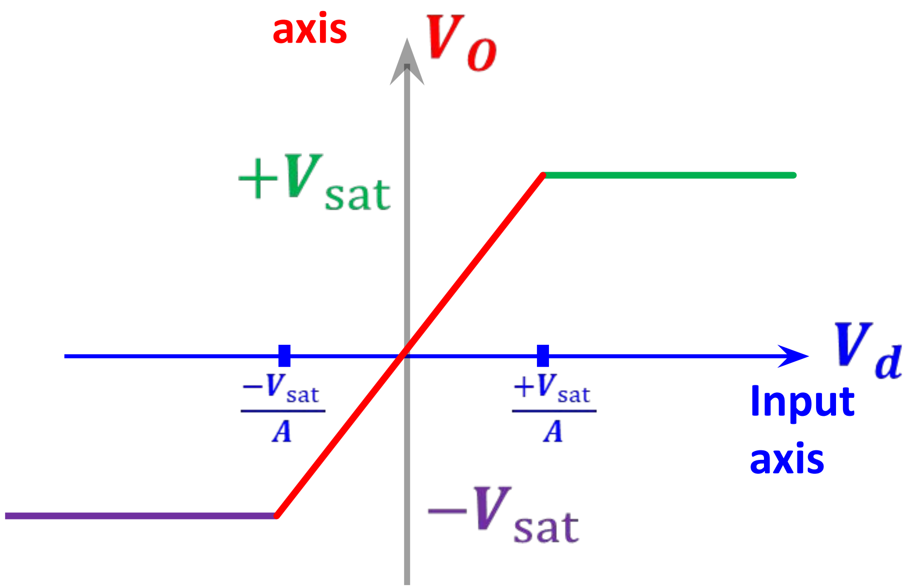
Negative saturation:

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

$\Rightarrow V_o = -V_{sat}$

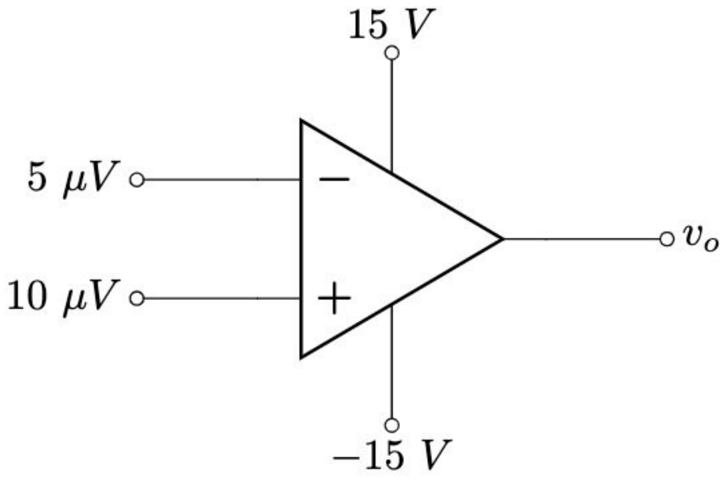
$V_d = V_{(+)} - V_{(-)}$



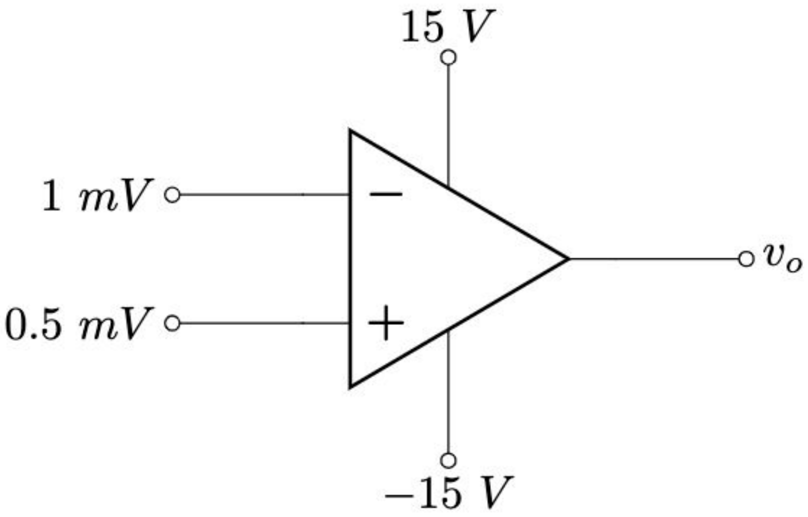


Op-Amp: Examples

Find v_0



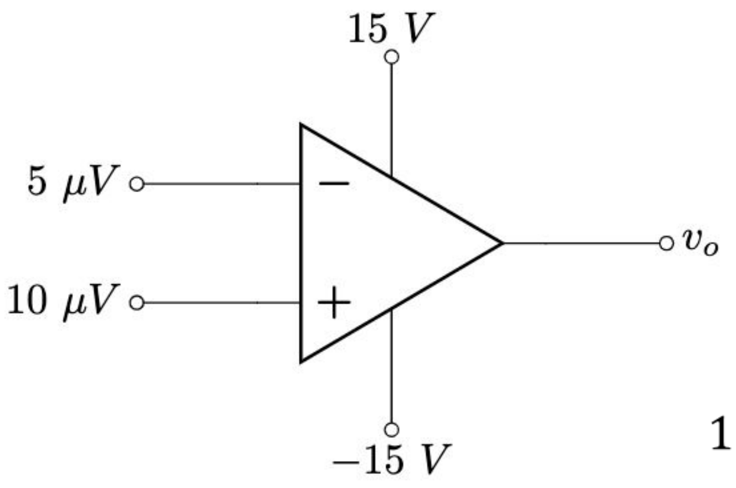
$A = 2 \times 10^5$



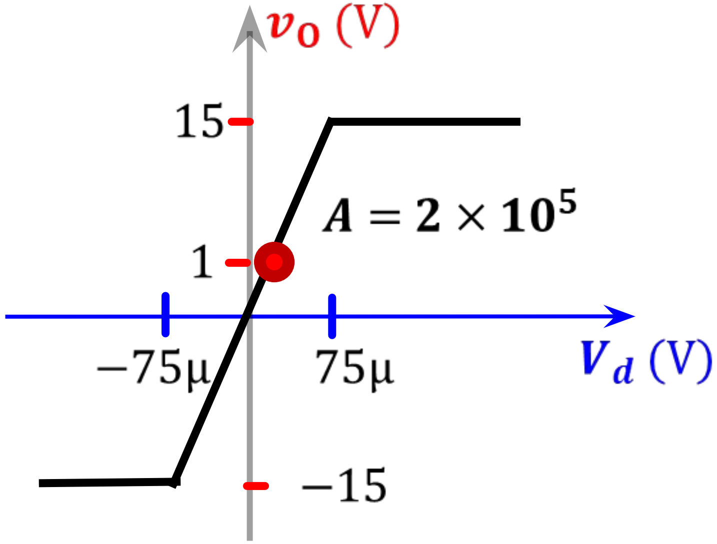
$A = 2 \times 10^5$

Example 1

- Find v_o



$A = 2 \times 10^5$



Solution:

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

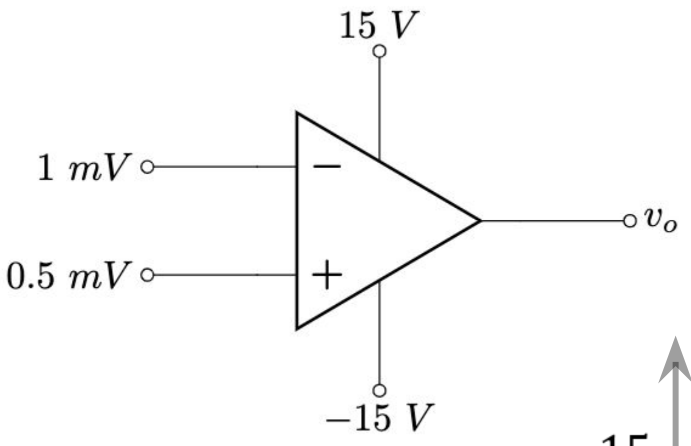
$$AV_d = (2 \times 10^5) \times (5 \times 10^{-6})\ \text{V} = 1\ \text{V}$$

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

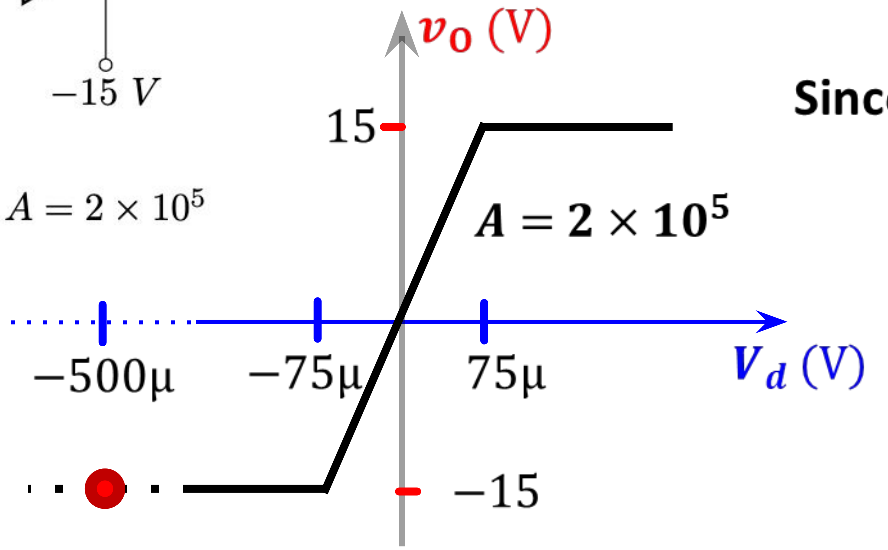
$$V_O = AV_d = 1\ \text{V}$$

Example 2

- Find v_o



$A = 2 \times 10^5$



Solution:

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

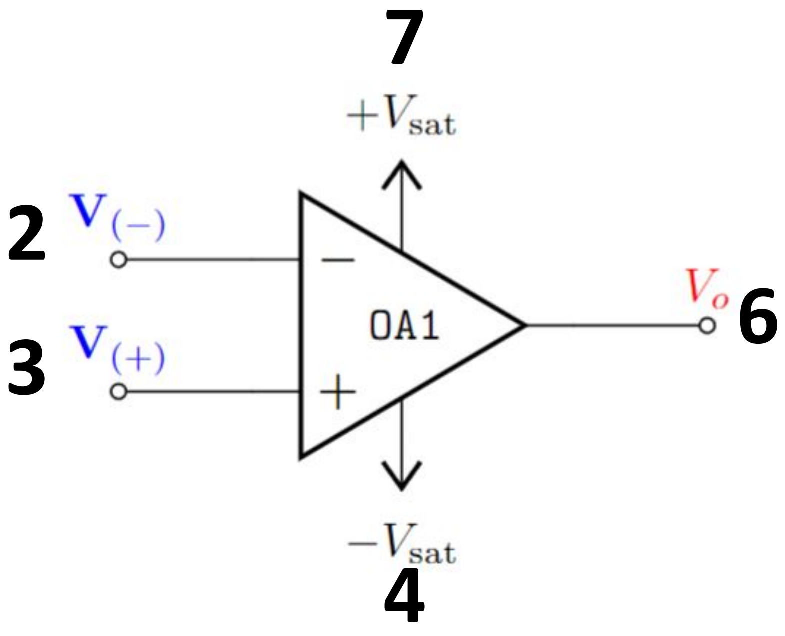
$$AV_d = \left(2 \times 10^5\right) \times \left(-0.5 \times 10^{-3}\right)\ \text{V} = -100\ \text{V}$$

Since $AV_d < -15\ \text{V}$ **(Negative saturation)**

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

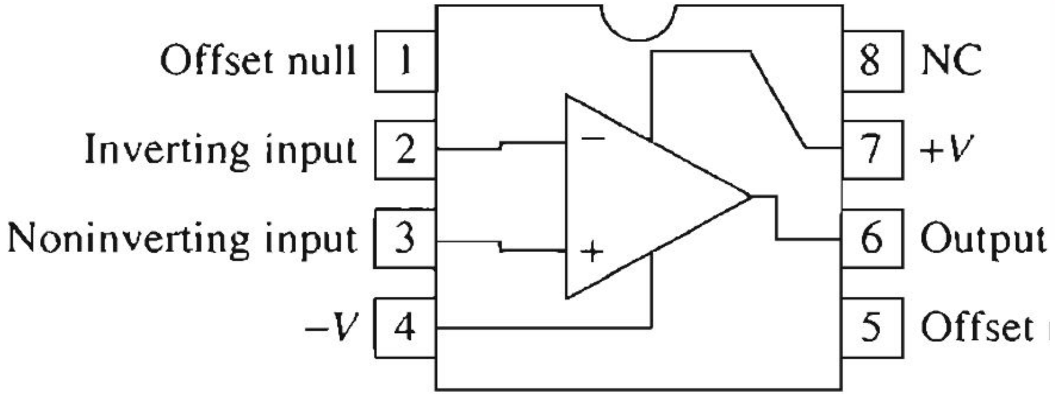
Op-Amp: Physical Entity

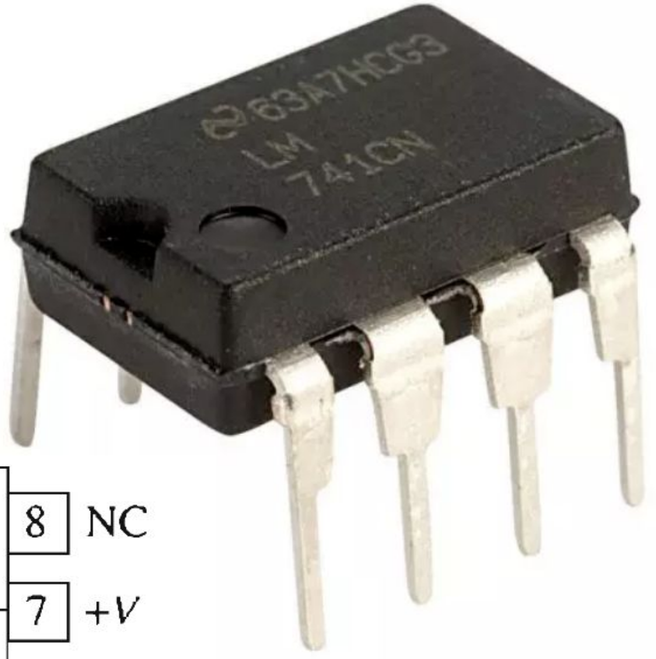
Difference Amplifier – Amplifies the voltage difference between two terminals.



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

NC – No Connection





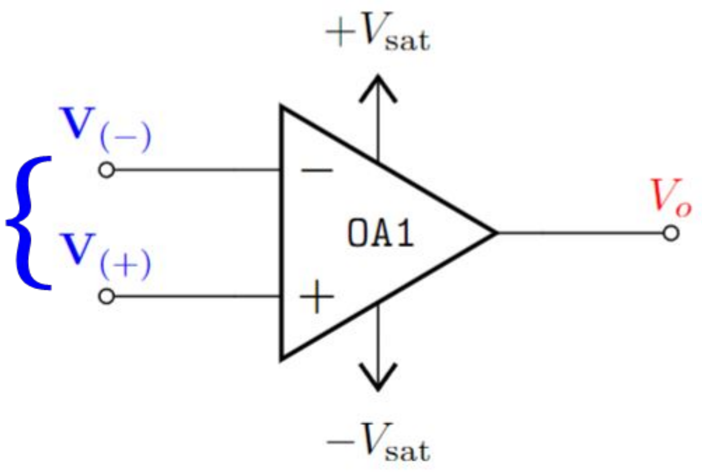
μA-741C

Manufacturer **ID**

Part Identification Number (PIN)

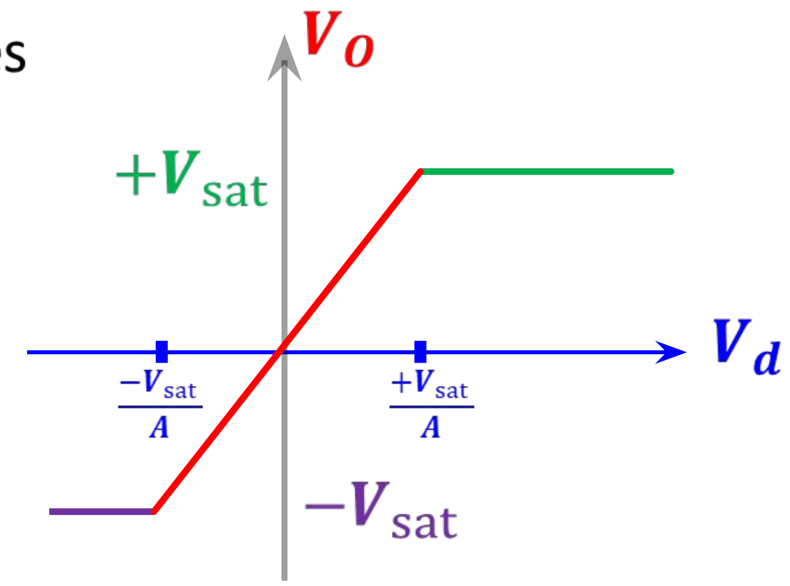
C: Commercial ($0^\circ - 70^\circ$C)
I: Industrial ($-25^\circ - 85^\circ$C)
M: Military ($-55^\circ - 125^\circ$C)

Op-Amp: Summary



Op-Amp **Amplifies** the difference between the voltages at it's two input terminals - $\boldsymbol{V_d}$

However, the **Amplification** is limited within voltage levels defined by the positive and negative saturation voltages $[-V_{sat}, +V_{sat}]$.



The "ideal" op-amp behaves like a **voltage dependent voltage source** within the linear region.

Thank you!

Part 1 ends here

Outline

- **Op-Amp: Open Loop Configuration**
  - Op-Amp: Circuit Modelling
  - Example Problem – Op-amp model

  - Op-amp configuration – open and closed loop
  - Open Loop op-amp: Voltage Transfer Characteristics
  - Open Loop op-amp: Comparators

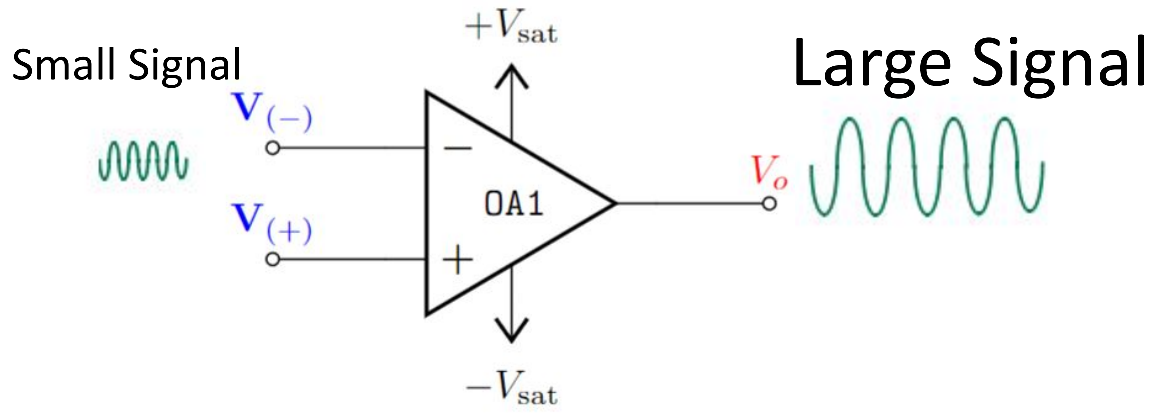
Op-Amp (Recap)

- **Operational:**

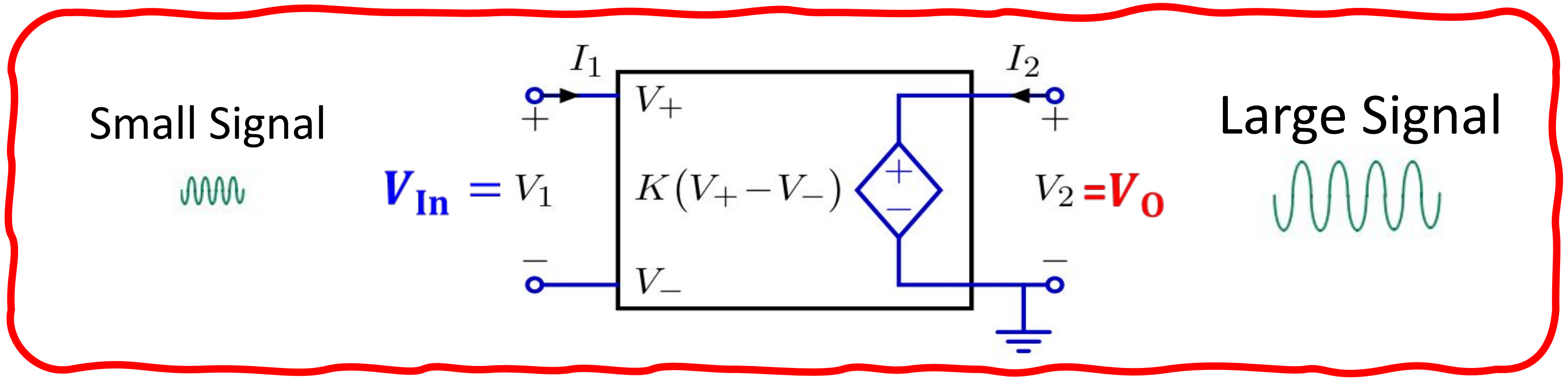
  Mathematical Operations

- **Amplifier:**

  Amplifies input signal/voltage.



An **op-amp (operational amplifier)** can be represented by a **voltage- controlled voltage source.**



Op-Amp: VTC (Recap)

Voltage Transfer Characteristics (VTC)

Positive saturation:

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

$\Rightarrow V_o = +V_{sat}$

Linear Region

$V_o = KV_d$: When V_d is very small

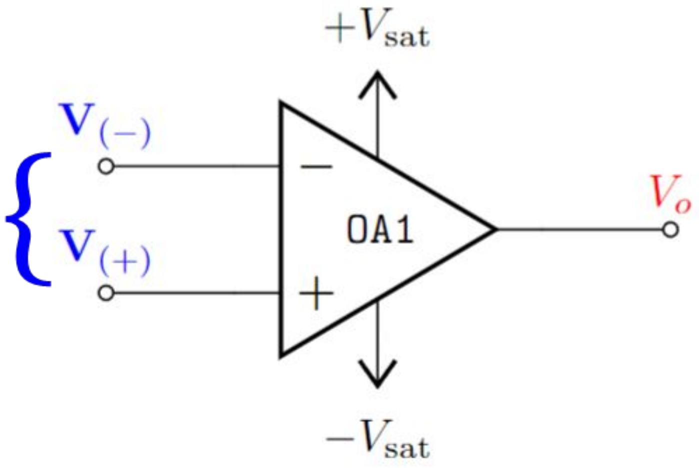
$-V_{sat} < V_o = KV_d < +V_{sat}$

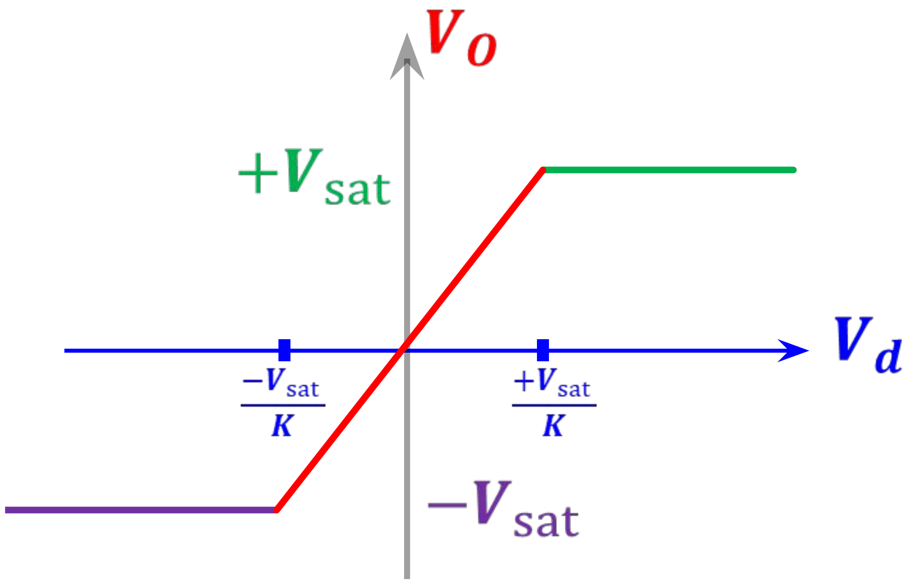
Negative saturation:

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

$\Rightarrow V_o = -V_{sat}$

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



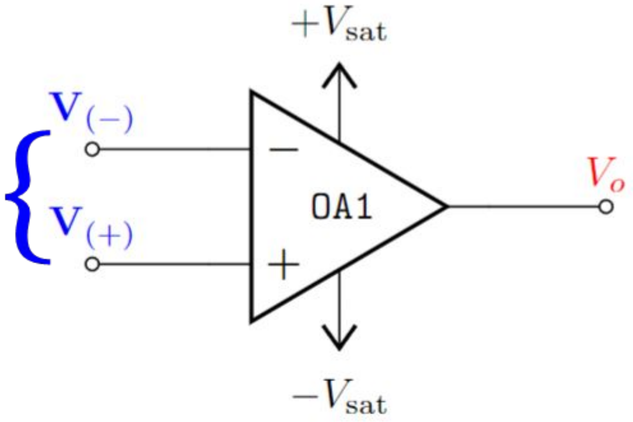


Op-Amp: Circuit Modelling

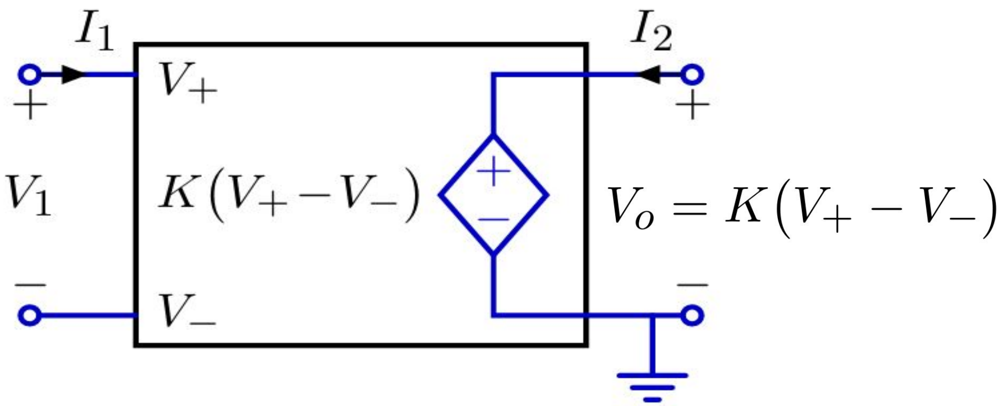
Voltage controlled voltage Source

“Ideal” op-amp approximation

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



$$\boldsymbol{V_d} = V_1$$



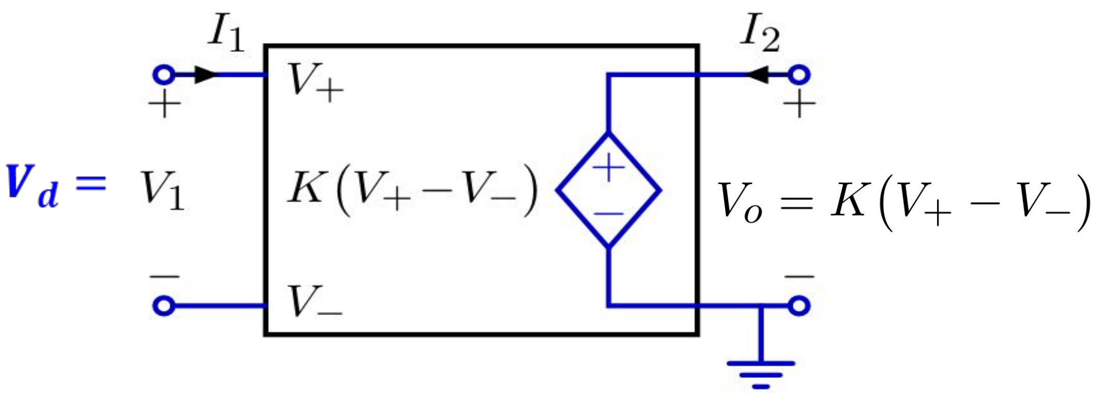
$$\boldsymbol{V_{(+)} \approx V_{(-)}}$$

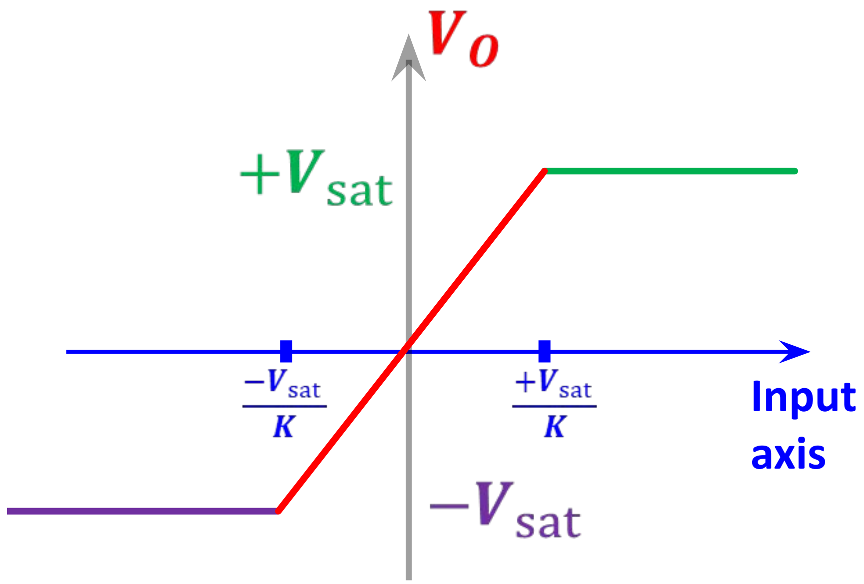
$$\boldsymbol{I_1 \approx 0}$$

Op-amp: Circuit Model and VTC

- **Voltage (Differential/OL) Gain:** A/A_{OL} or K Slope of **VTC**
- Positive Saturation Voltage: $+V/V_{CC}/V_{sat}$
- Negative Saturation Voltage: $-V/V_{EE}/-V_{sat}$

Parameter	Typical Range	Ideally





Op-amp: Circuit Model and VTC

Voltage Transfer Characteristics (VTC)

Positive saturation: $V_d > 0$

$\Rightarrow V_O = +V_{sat}$

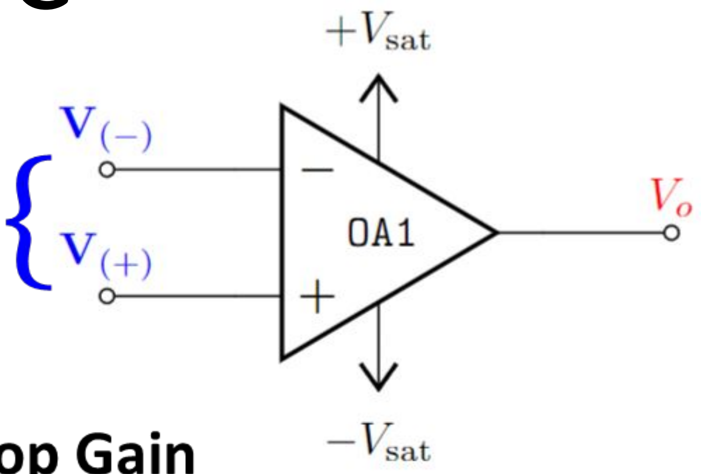
~~Linear Region~~

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

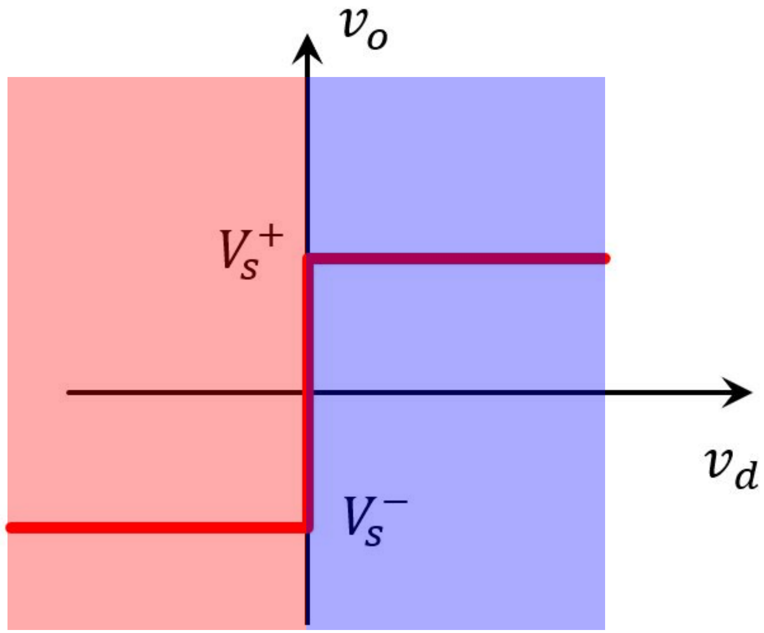
Negative saturation: $V_d < 0$

$\Rightarrow V_O = -V_{sat}$

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



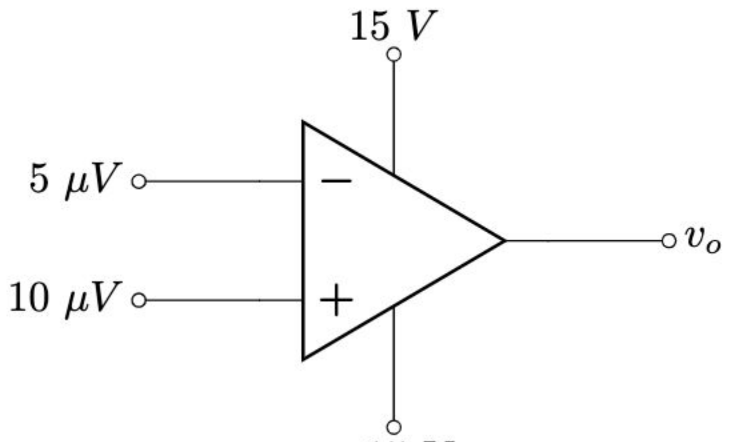
$A \to \infty$ **: Open Loop Gain**



Types of Op-Amp configuration

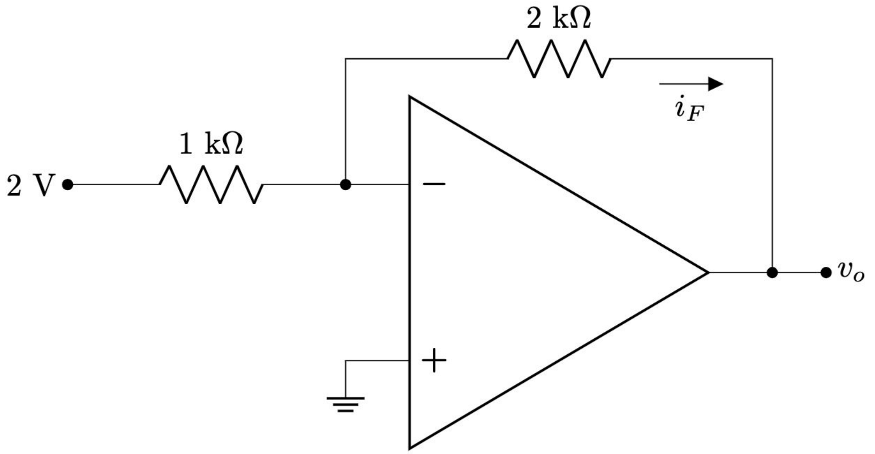
1. Open loop configuration:

   No physical connection between input and output



2. Closed loop configuration:

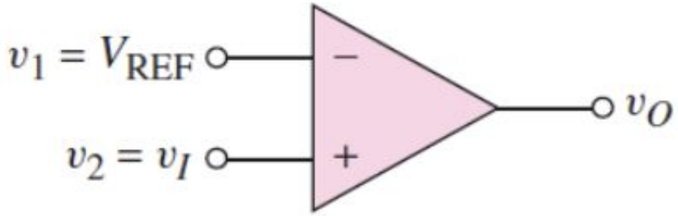
   Feedback from output terminal

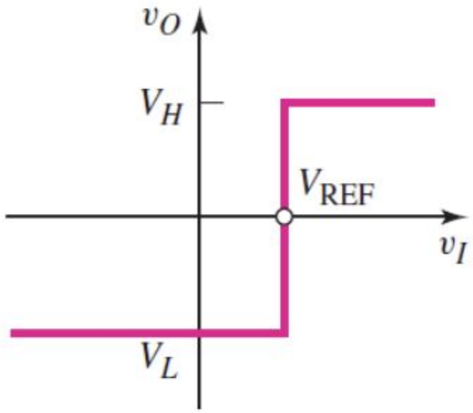


Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

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





NON-INVERTING COMPARATOR

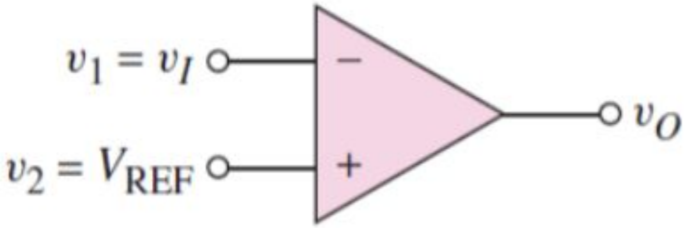
$$\boldsymbol{V_d = v_I - V_{\text{REF}} > 0 \quad \Rightarrow \quad v_O = V_H}$$

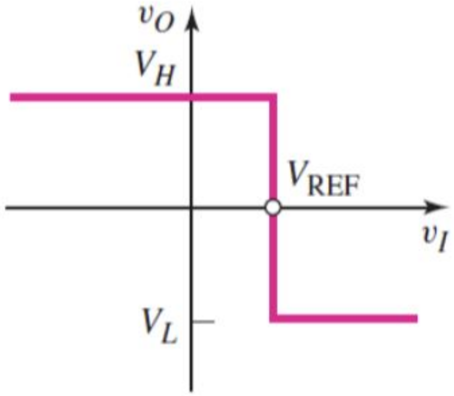
$$\boldsymbol{v_I > V_{\text{REF}} \quad \Rightarrow \quad v_O = V_H}$$

Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

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





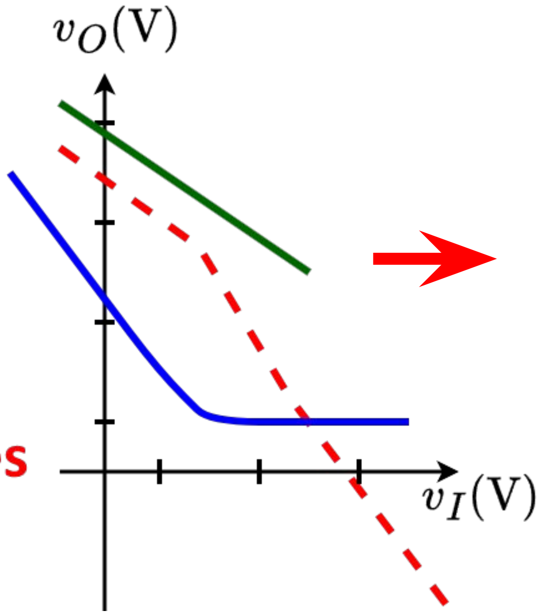
INVERTING COMPARATOR

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

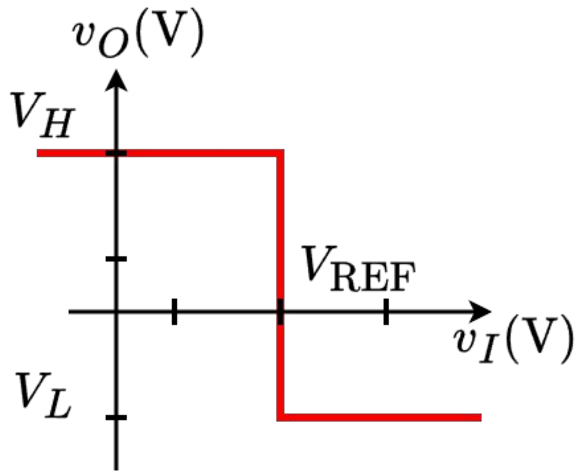
$$v_I < V_{\mathrm{REF}} \quad \Rightarrow \quad v_O = V_H$$

Open Loop Configuration: Comparator

$v_O \rightarrow$ **Decreases**

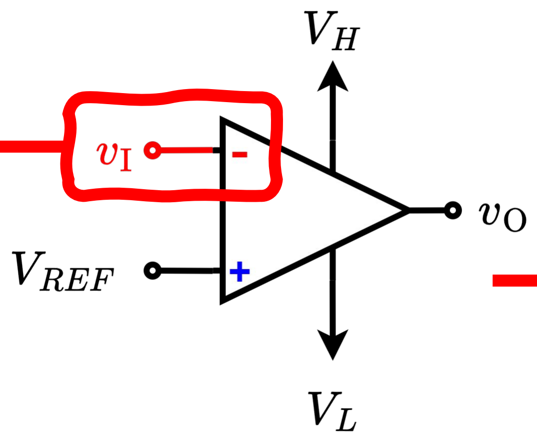


INVERSE RELATIONSHIP!



Downward step (Staircase)

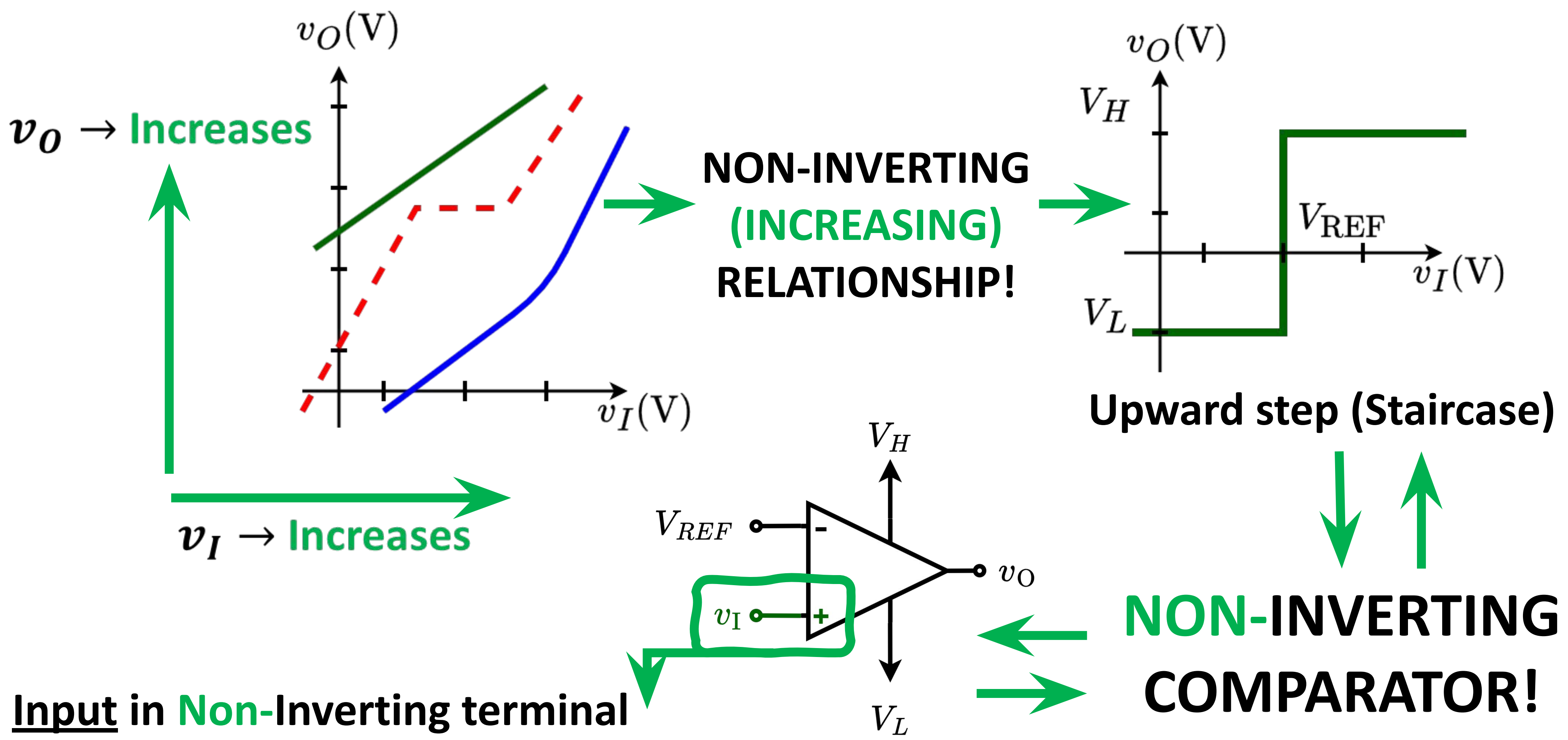
$v_I \rightarrow$ **Increases**



<u>Input</u> in Inverting terminal

INVERTING COMPARATOR VTC!

Open Loop Configuration: Comparator

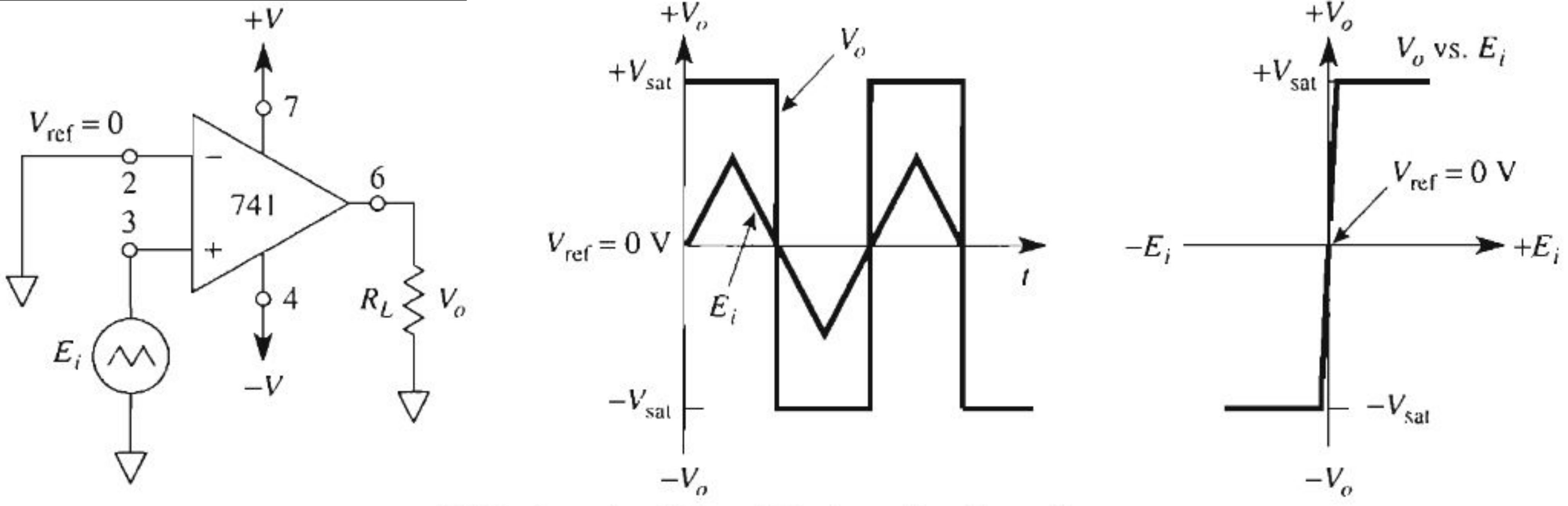


Open Loop Configuration: Comparator

Zero Crossing Detector

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

<u>Non-inverting configuration</u>

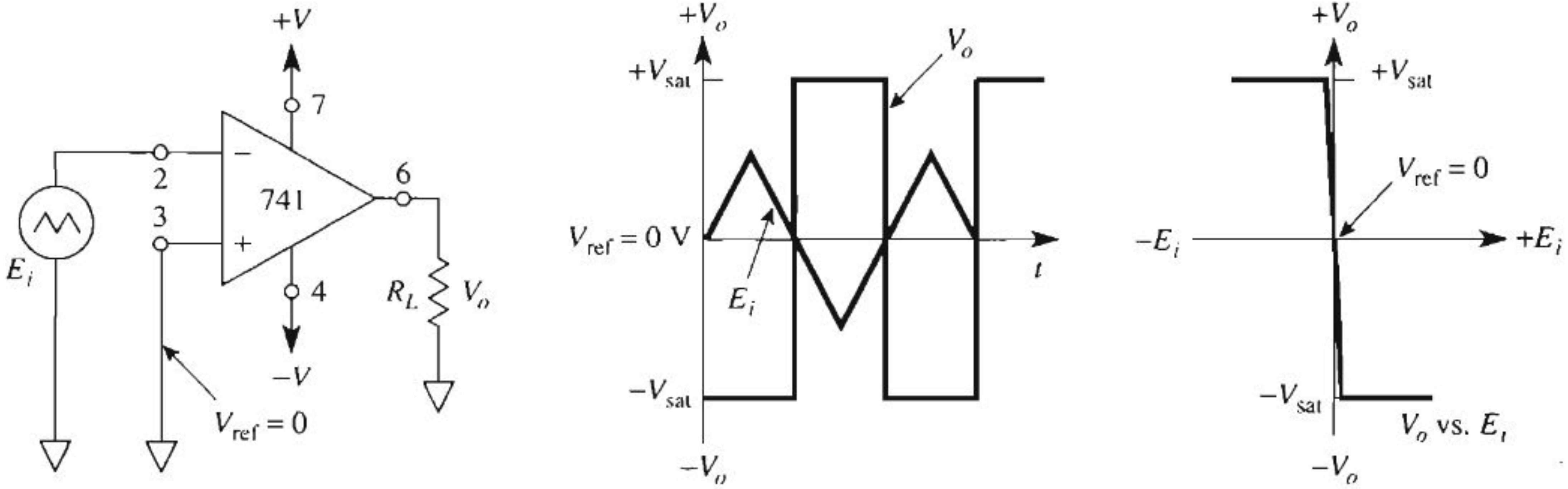


(a) Noninverting: When E_i is above V_{ref}, $V_o = +V_{sat}$.

Open Loop Configuration: Comparator

Zero Crossing Detector

Inverting configuration



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

Summary

Level Crossing Detector / Comparator

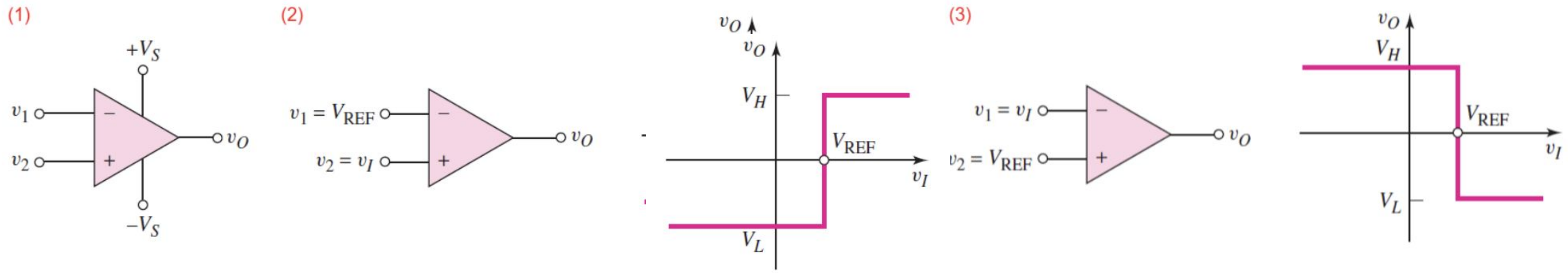


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

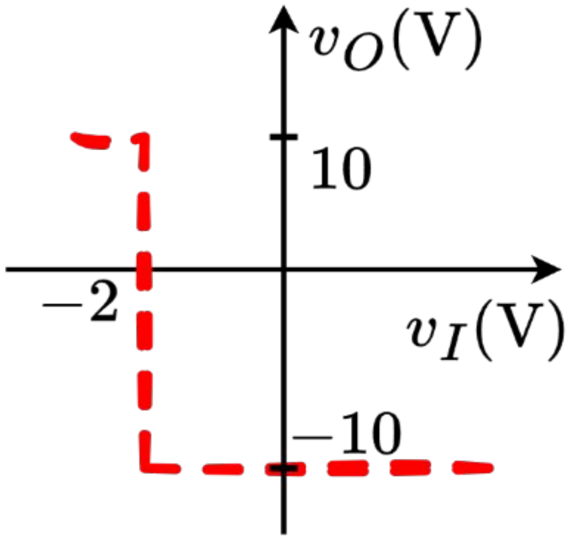
Part 2 ends here

Outline

- **Op-Amp: Comparator**
  - Open Loop Configuration: Example 1
  - Open Loop Configuration: Example 2
  - Open Loop Configuration: Example 3

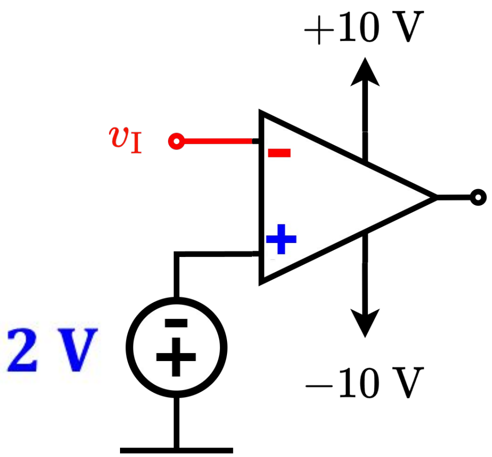
Open Loop Configuration: Example 1

- Design a circuit using **op-amp** that has the voltage transfer characteristics as shown in the figure below. $v_O(V)$ is the **output voltage** and $v_I(V)$ is the **input voltage**.



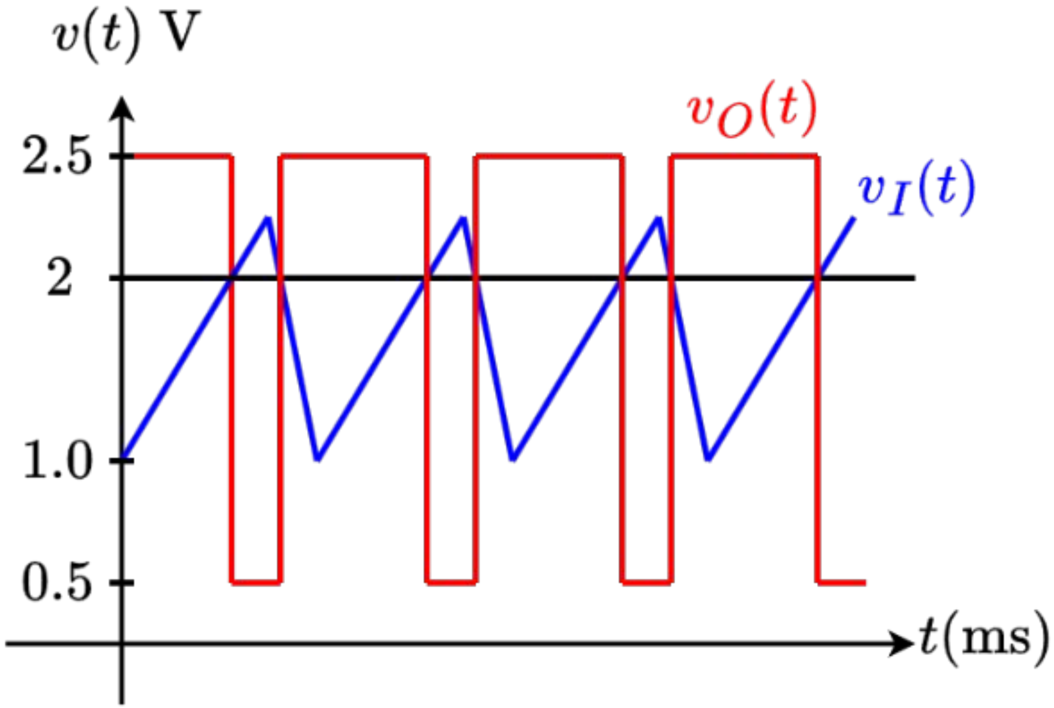
Solution:

Inverting comparator



Open Loop Configuration: Example 2

- Draw the voltage transfer characteristic (VTC) curve (v_O vs v_I) from the adjacent waveform graph. Also draw the **Op-Amp Circuit** that would give rise to such a VTC.

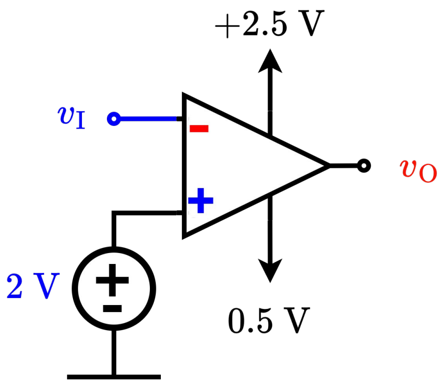


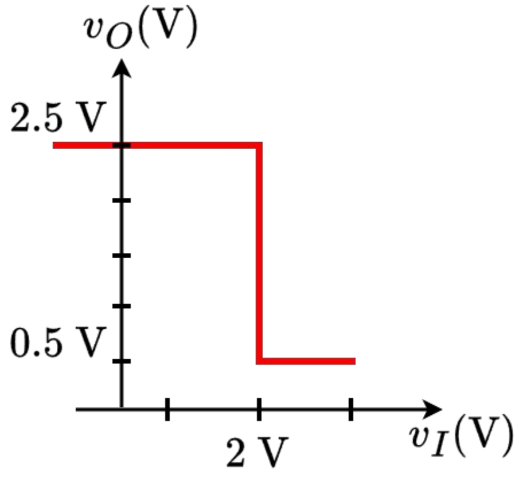
Solution:

v_I **smaller** than 2 V $\Rightarrow v_O = 2.5$ V → **Positive Saturation**

v_I **larger** than 2 V $\Rightarrow v_O = -2.5$ V → **Negative Saturation**

INVERTING CONFIGURATION

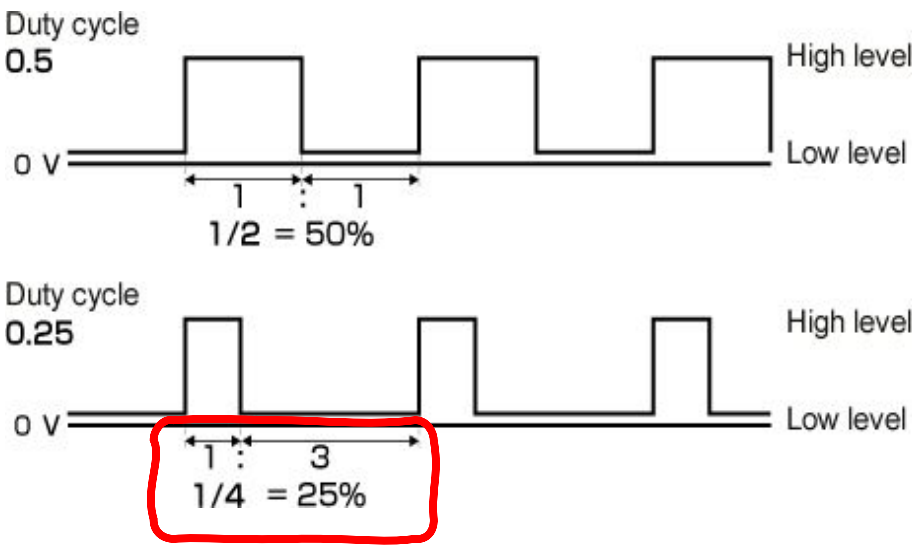


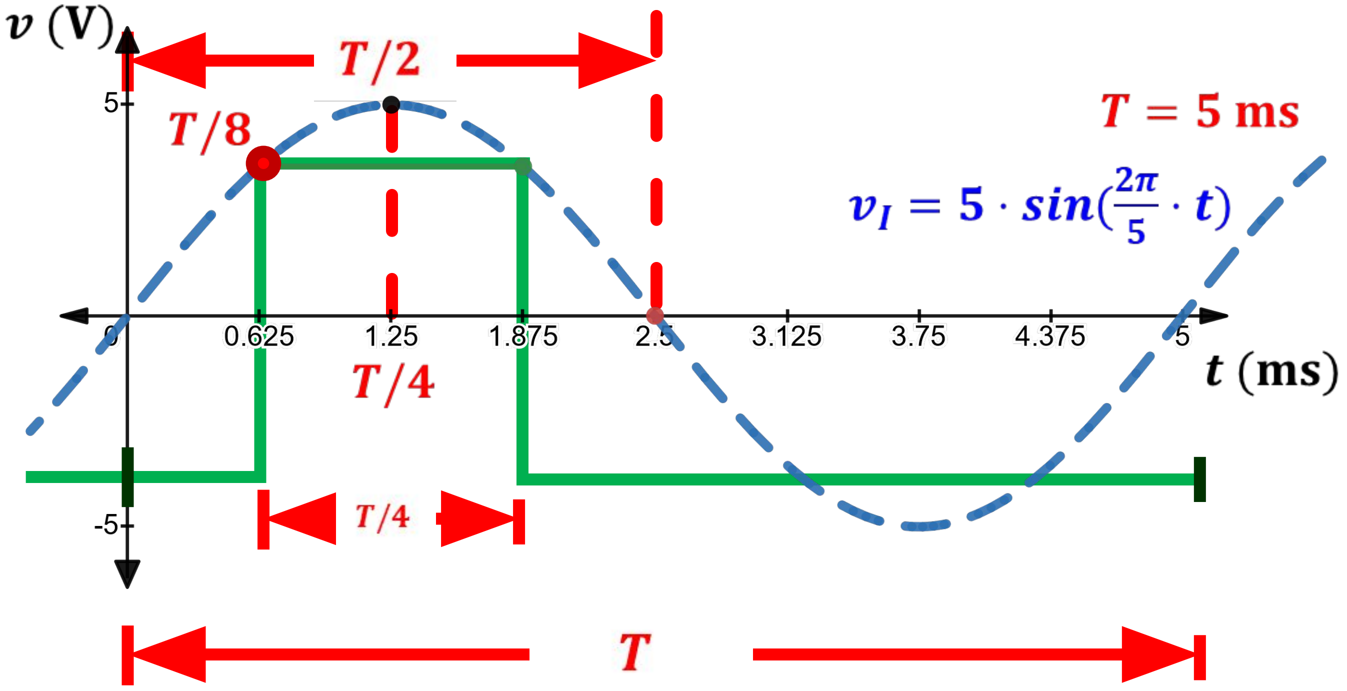


Open Loop Configuration: Example 3

Design an op-amp circuit to transform the sinusoidal voltage, $v_I = 5 \cdot sin(\frac{2\pi}{5} \cdot t)$ (t is in units of ms, and time-period T is 5 ms), to: A square wave with a duty cycle of **25%**.

Solution:





Open Loop Configuration: Example 3

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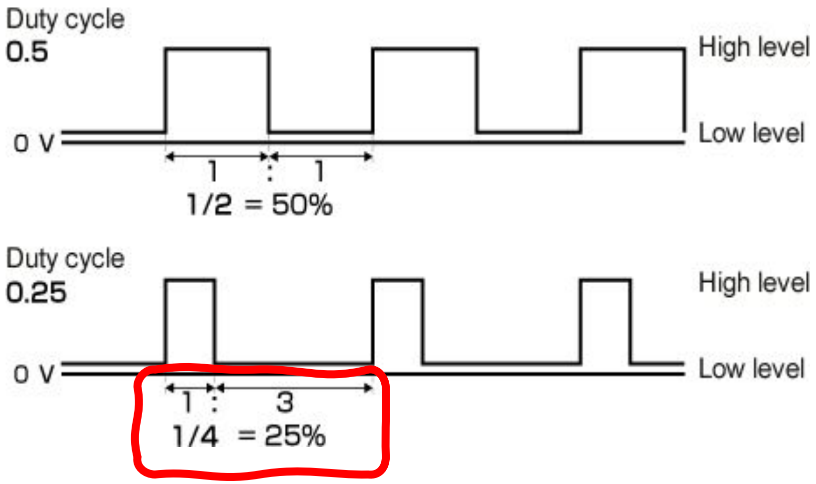
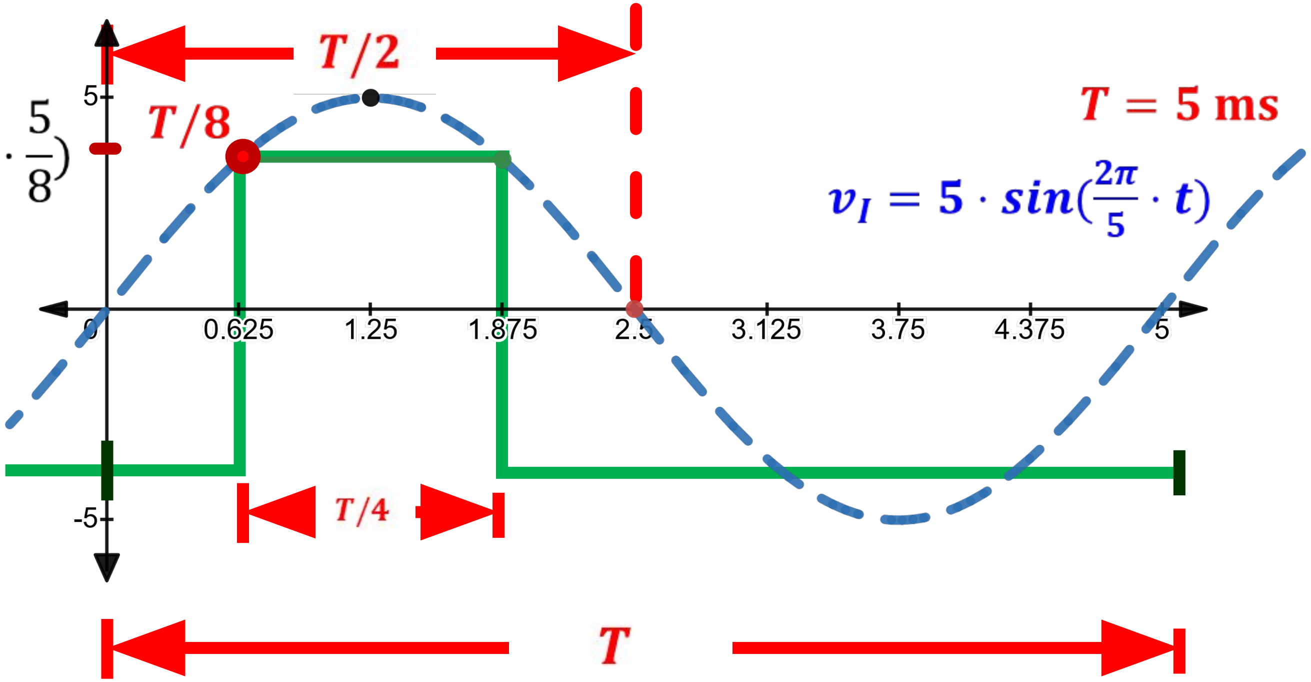
Solution:

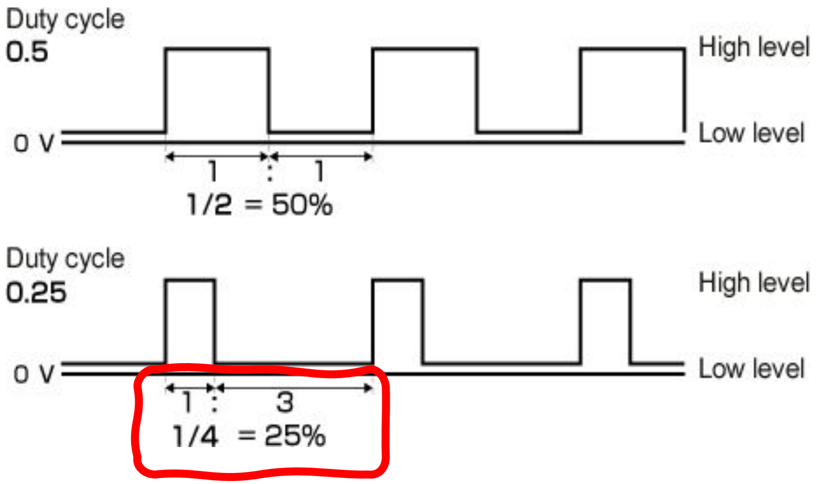
$$V_{REF} = 5\sin(\frac{2\pi}{5} \cdot \frac{5}{8})$$





Open Loop Configuration: Example 3

Design an op-amp circuit to transform the sinusoidal voltage, $v_I = 5 \cdot sin(\frac{2\pi}{5} \cdot t)$ (t is in units of ms, and time-period T is $5\ ms$), to: A square wave with a duty cycle of **25%**.



Solution:

$$V_{REF} = 5\sin(\frac{2\pi}{5} \cdot \frac{5}{8})$$

$$V_{REF} = 5 \cdot \frac{1}{\sqrt{2}}\ \mathbf{V}$$

$$\boldsymbol{V_{REF} = 3.535\ \mathrm{V}}$$

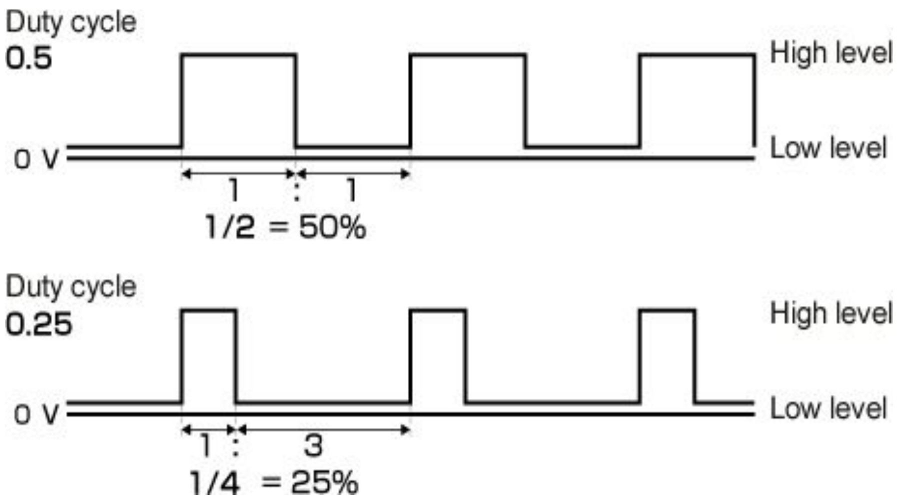
$v_I \geq$ $\boxed{3.535\ \mathrm{V} : v_o}$ $\rightarrow$ **Positive Saturation**

$v_I \leq$ $\boxed{3.535\ \mathrm{V} : v_o}$ $\rightarrow$ **Negative Saturation**

NON-INVERTING CONFIGURATION

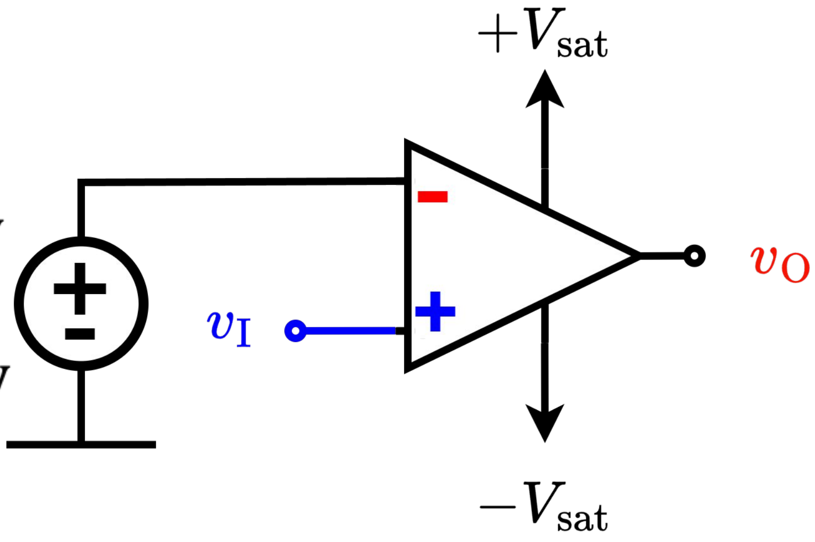
Open Loop Configuration: Example 3

Design an op-amp circuit to transform the sinusoidal voltage, $\boldsymbol{v_I = 5 \cdot sin(\frac{2\pi}{5} \cdot t)}$ ($\boldsymbol{t}$ is in units of ms, and time-period T is $\mathbf{5}\ \boldsymbol{ms}$), to: A square wave with a duty cycle of **25%**.



$$V_{REF} = 5 \cdot \frac{1}{\sqrt{2}}\ \mathbf{V}$$

$$\boldsymbol{V_{REF} = 3.535\ V}$$



Part 3 ends here

Outline

- Comparator Application - Smoke Detectors
- Smoke Detector – Operation
- Comparator Application – Automatic AC
- General Principle - Comparator

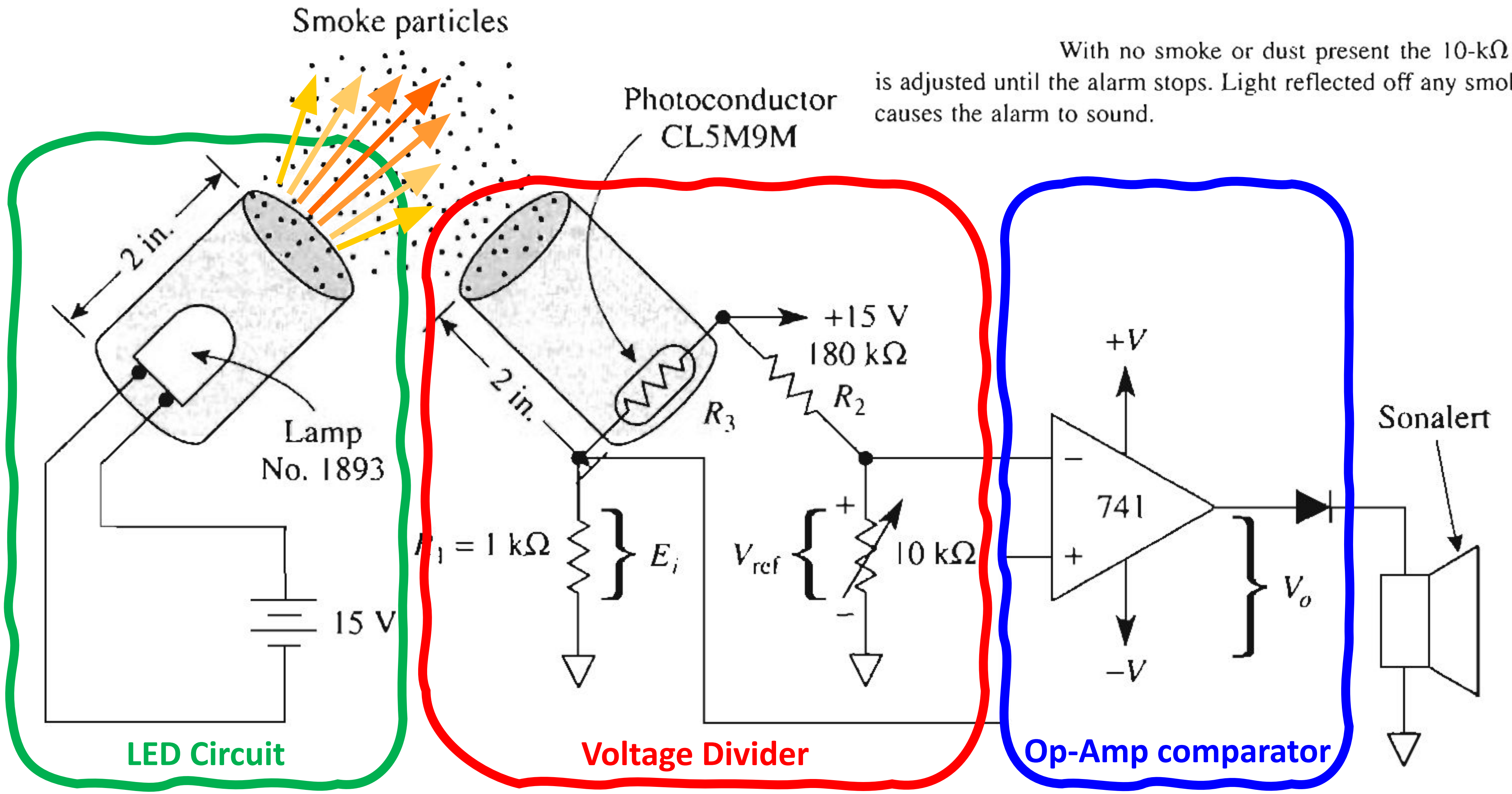
Comparator Application - Smoke Detectors

•

Since the **alarm** is an <u>electrically driven device</u>, we need some method to convert smoke levels to proportionate voltage.

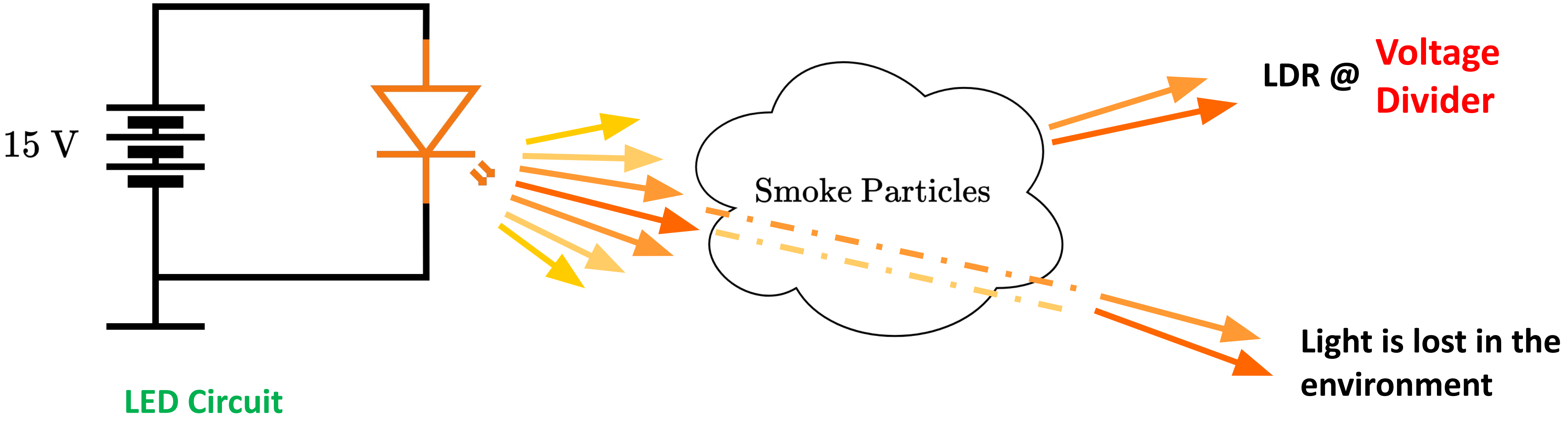
Comparator Application - Smoke Detectors

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.

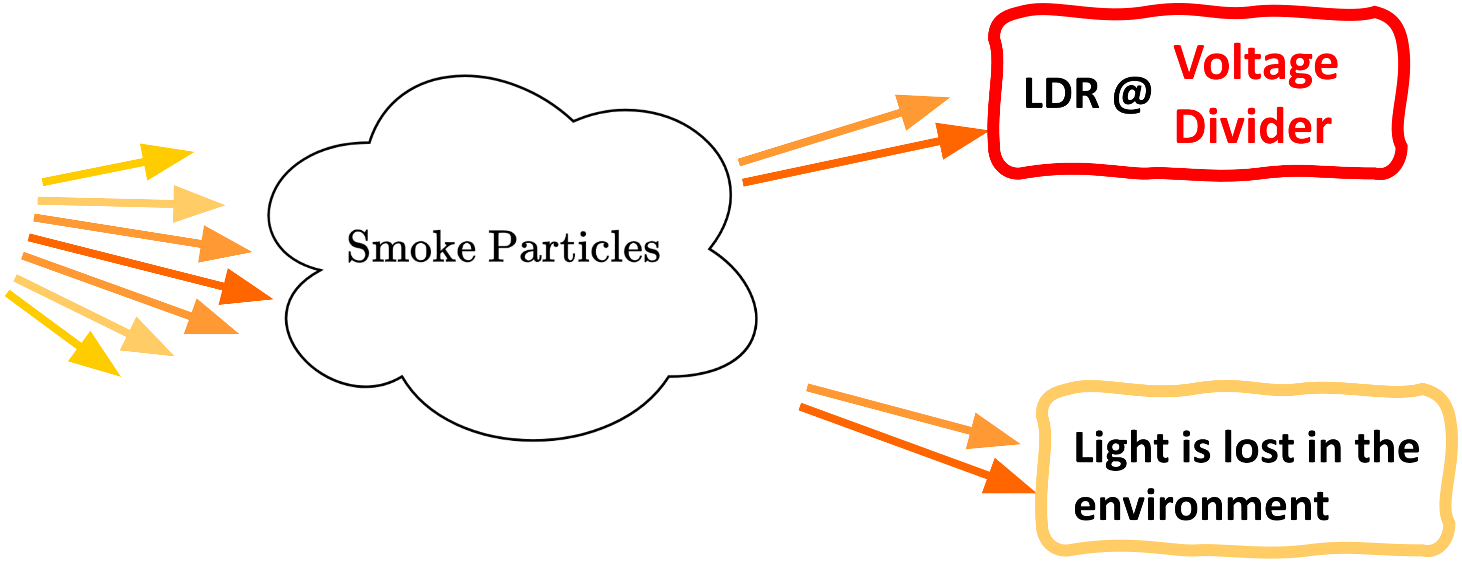


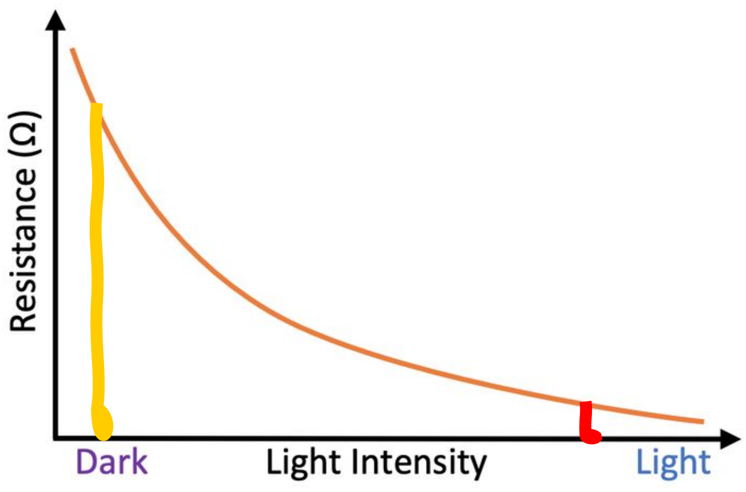
Smoke Detector - Operation

Light from the LED is reflected off the smoke particles on to the photoconductor –
Light Dependent Resistor (LDR).

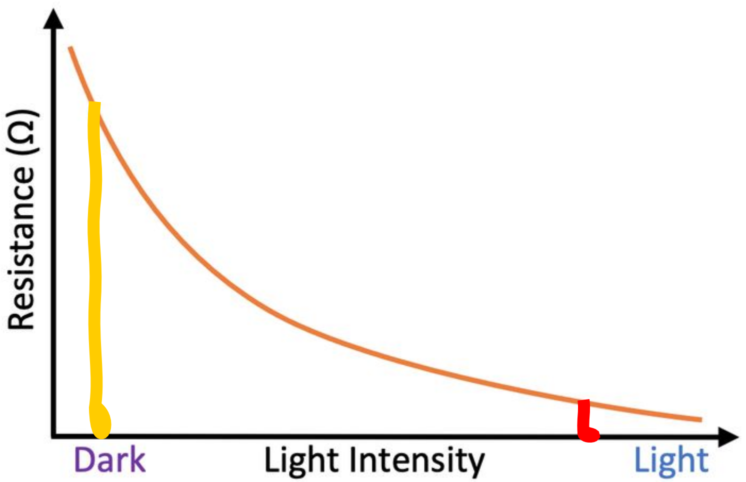


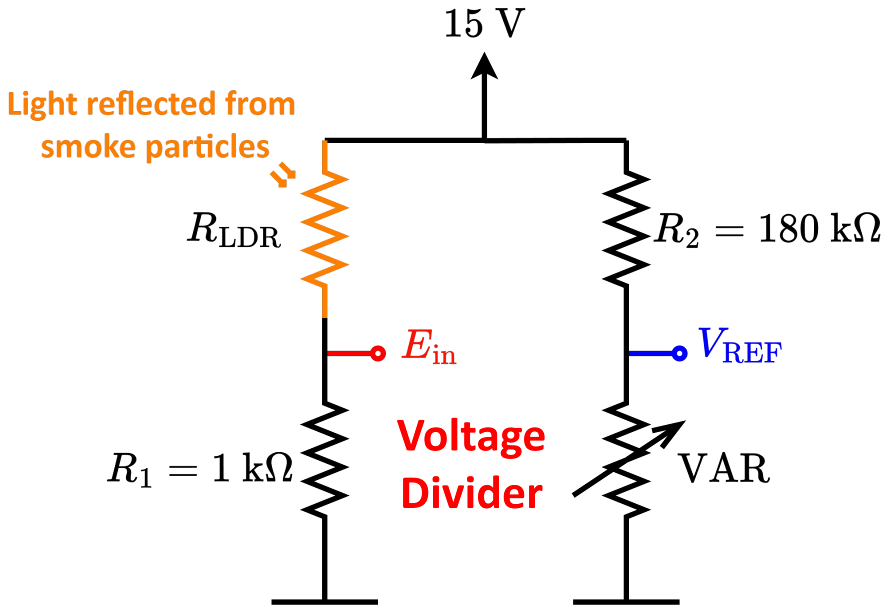
Smoke Detector - Operation



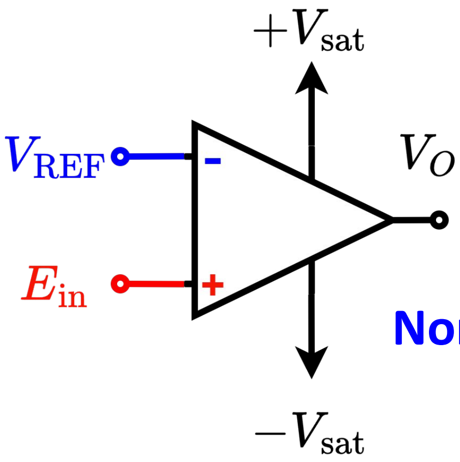


Smoke Detector - Operation





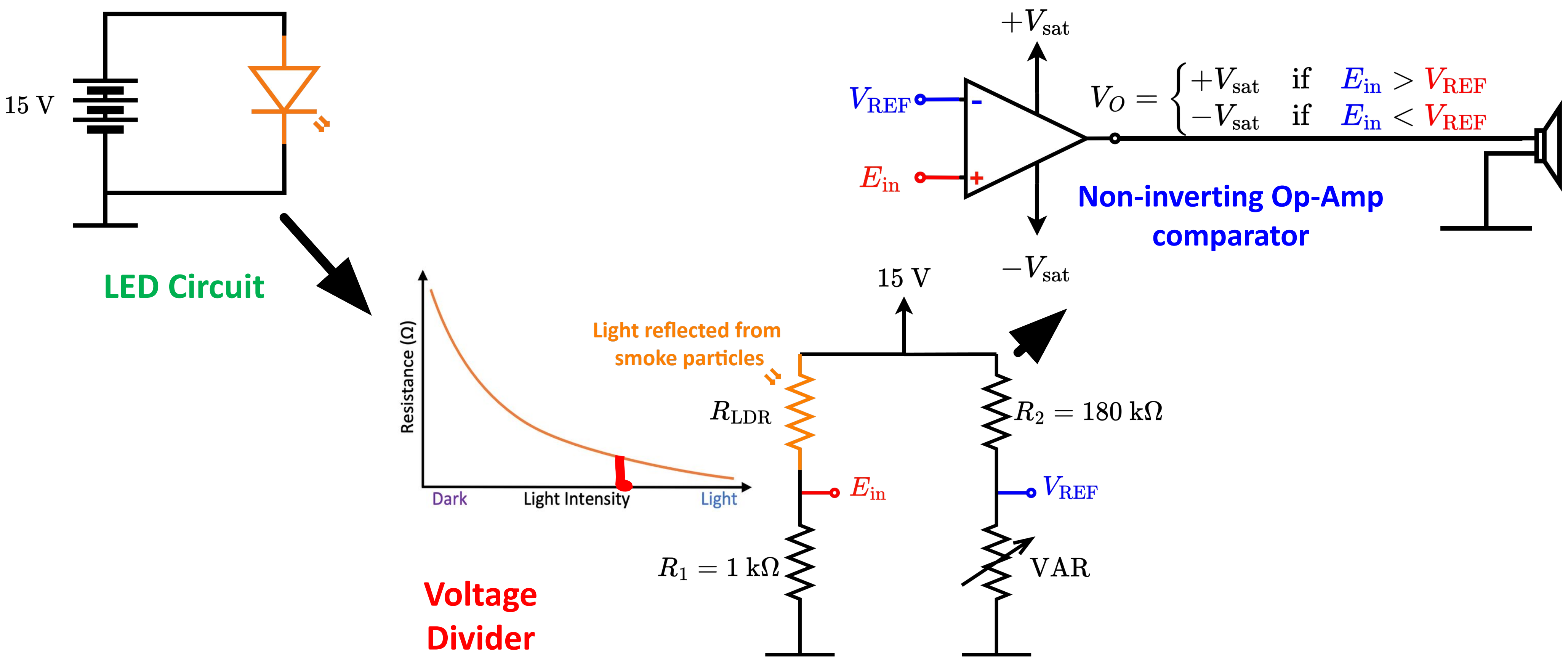
Smoke Detector - Operation



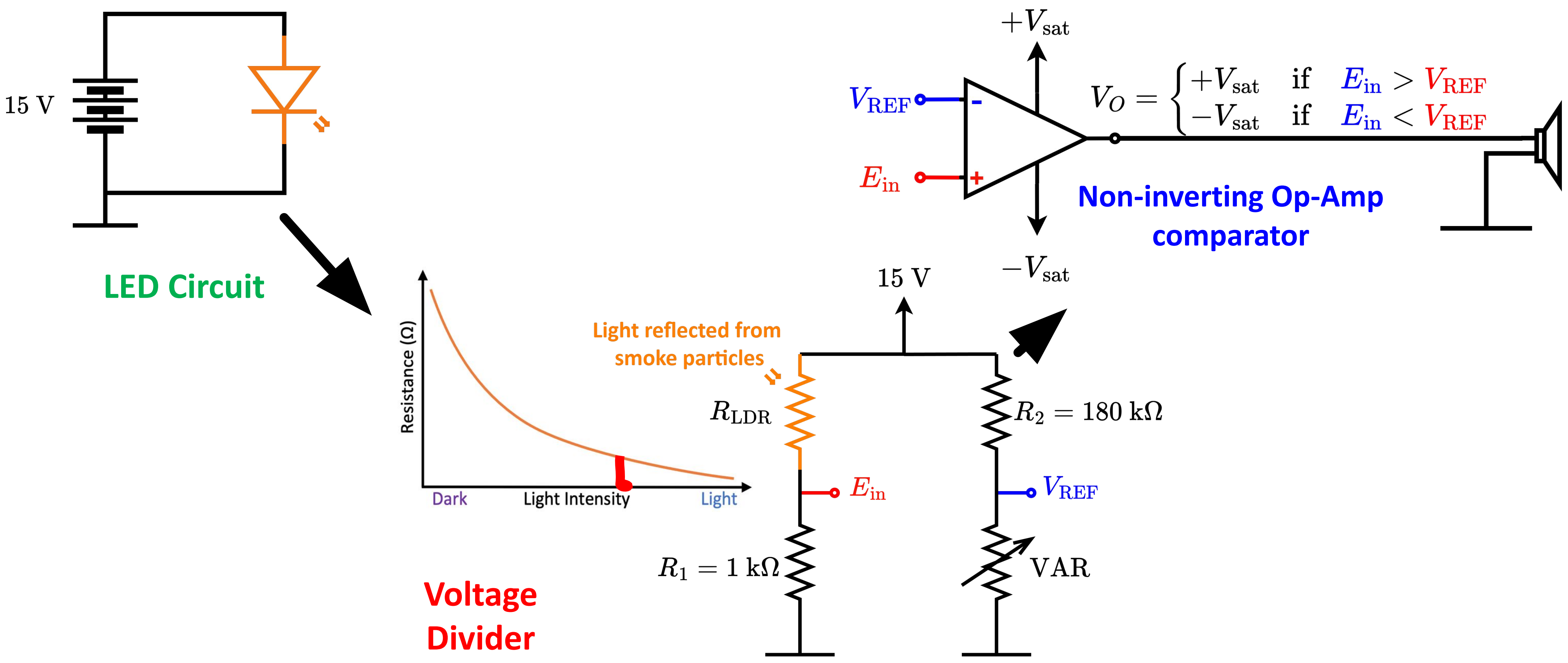
$$V_O = \begin{cases} +V_{\text{sat}} & \text{if} \quad E_{\text{in}} > V_{\text{REF}} \\ -V_{\text{sat}} & \text{if} \quad E_{\text{in}} < V_{\text{REF}} \end{cases}$$

Non-inverting Op-Amp comparator

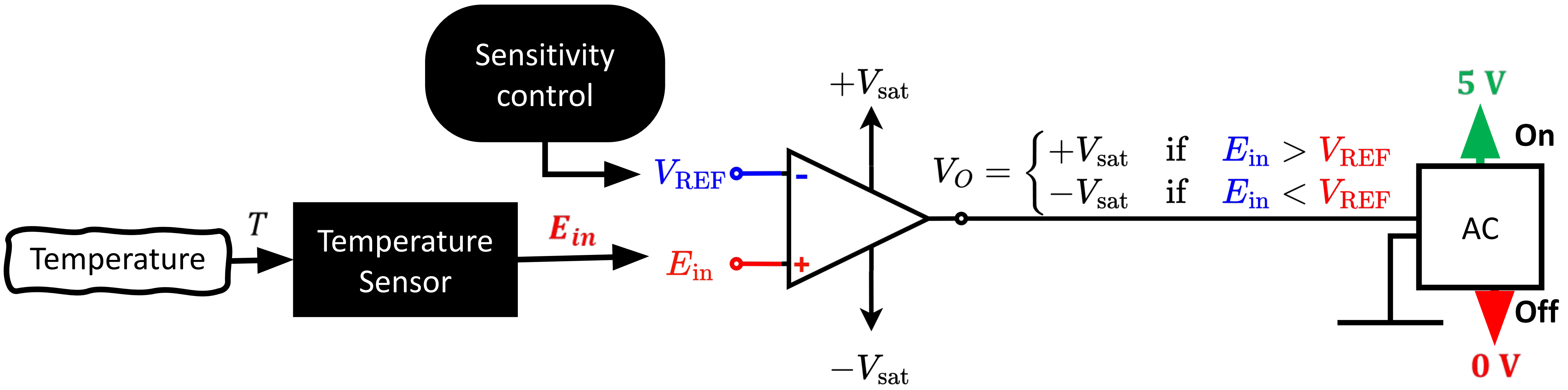
Smoke Detector - Operation



Smoke Detector - Operation



Comparator Application – Automatic AC



- Comparators can be used to switch on an **AC** based on a **Temperature**.

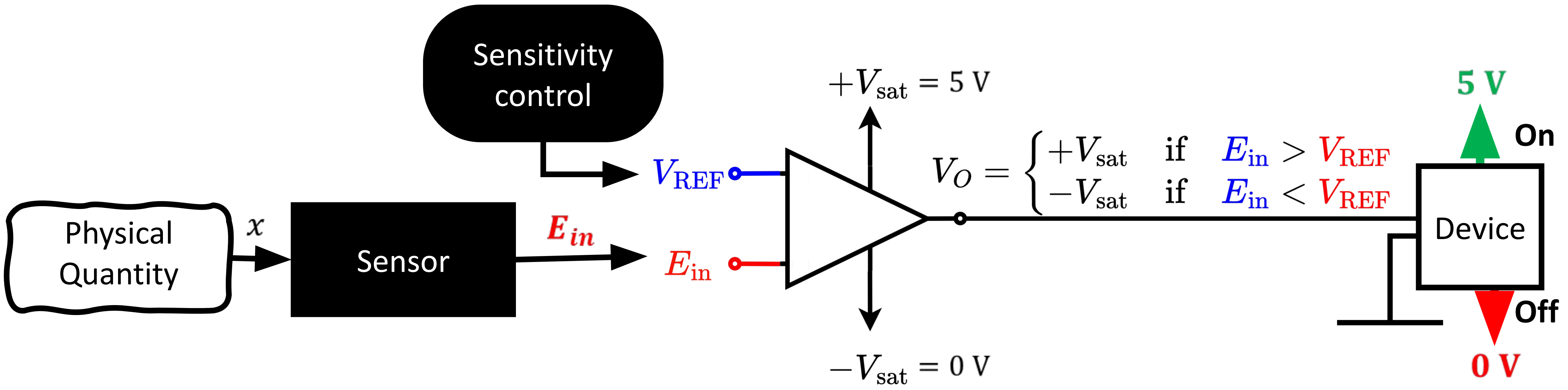
  Temp. ↑ **AC** - ON

  Temp. ↓ **AC** – OFF

  Temp ↑ ∝ $\boxed{E_{in} \uparrow \rightarrow \textbf{AC} \text{ - ON}}$ → **NON-INVERTING RELATIONSHIP: NON INVERTING COMPARATOR**

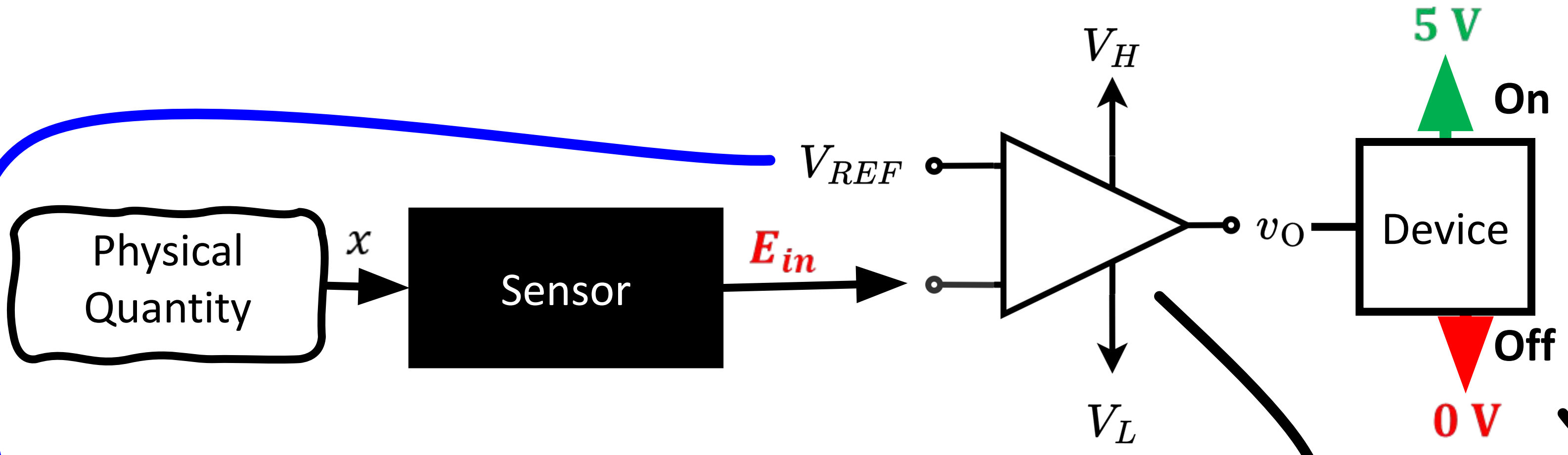
- The sensitivity of **switching on the** **AC** is determined by V_{REF}

Comparator Application – Summary



- Comparators can be used to switch on **any device** based on a **Physical Quantity**.
  - Phys. Qnty. ↑ **DEVICE** – ON / OFF
  - Phys. Qnty. ↓ **DEVICE** – OFF / ON
  - Phys. Qnty. → E_{in} ↓↑ → **DEVICE** – ON/OFF → **This Relationship: Determines the type of Comparator**
- The sensitivity of **switching on the AC** is determined by V_{REF}

Solving Comparator Problems



1. Determine type of comparator from the $E_{in} \rightarrow v_O$ relationship.
2. Determine V_{REF} from the switching condition from the provided information
3. Determine the saturation voltages V_H/V_L from the output device

Part 4 ends here

Outline

- **Operational Amplifier: Non-ideal Circuit Modelling**

  - Ideal VS Non-Ideal Model

  - Op-Amp: Circuit Symbols and terminal

  - Op-Amp: VTC (Voltage Transfer Characteristics)

    Linear Amplification

    (Positive and Negative) Saturation

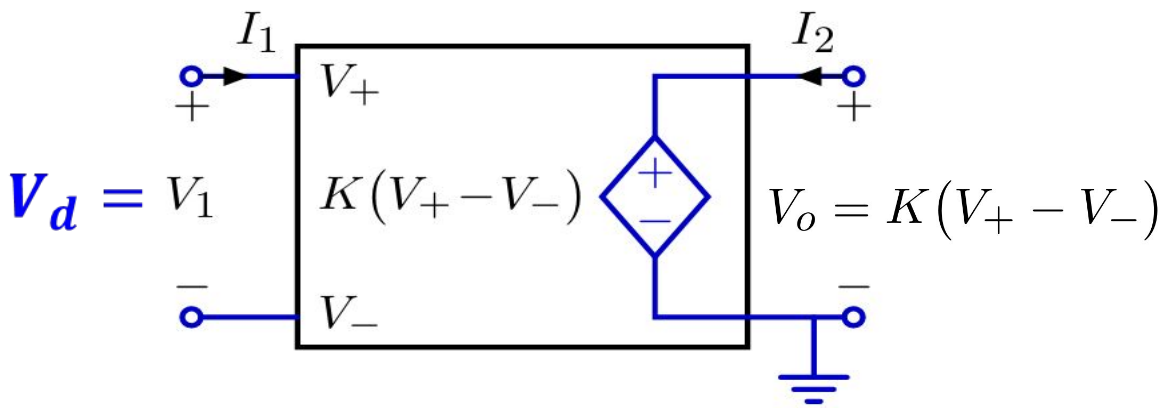
  - Op-Amp: Examples

  - Op-Amp: Physical Entity

Op-Amp: Circuit Modelling

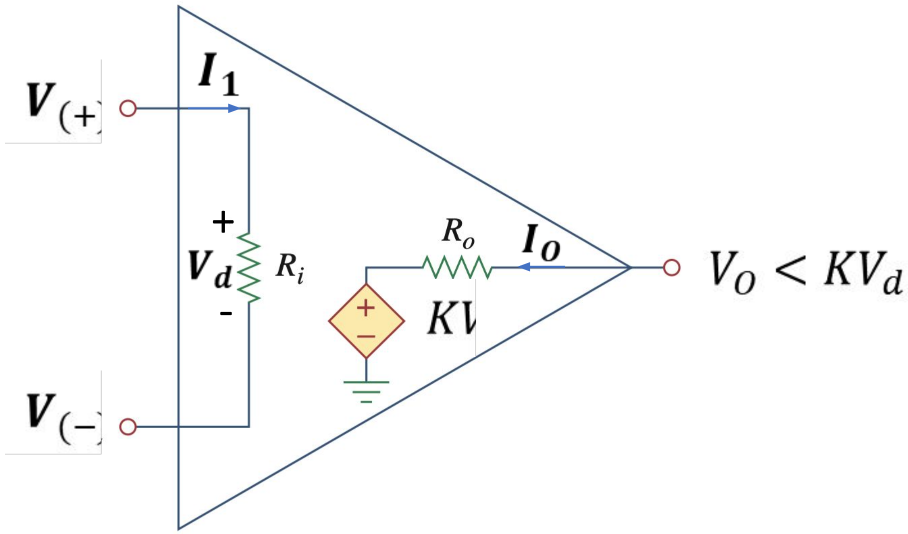
Voltage controlled voltage Source

"Ideal" op-amp approximation



$$V_{(+)} \approx V_{(-)}$$
$$I_1 \approx 0$$

"Non-Ideal" op-amp approximation

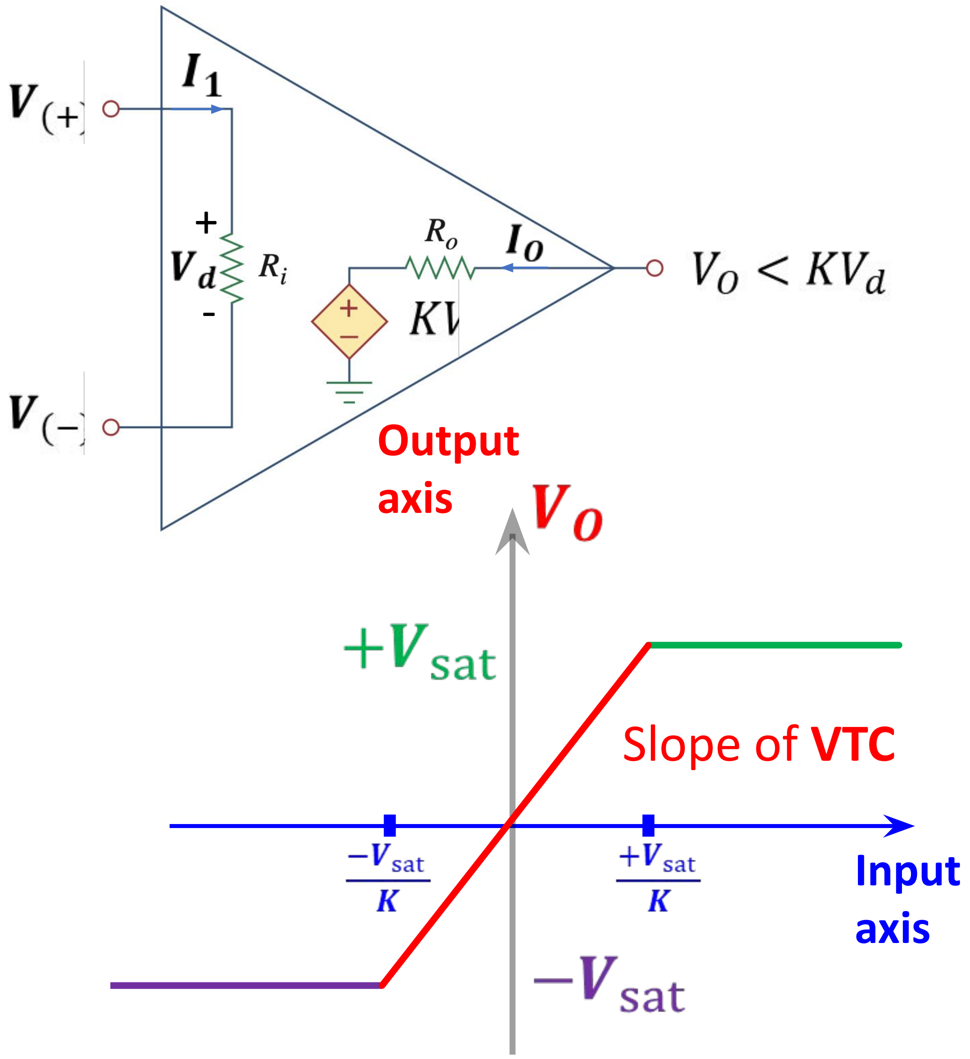


$$V_d = V_{(+)} - V_{(-)} \neq 0$$
$$I_1 > 0$$

Op-amp Model parameters

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

Parameter	**Typical Range**	**Ideally**

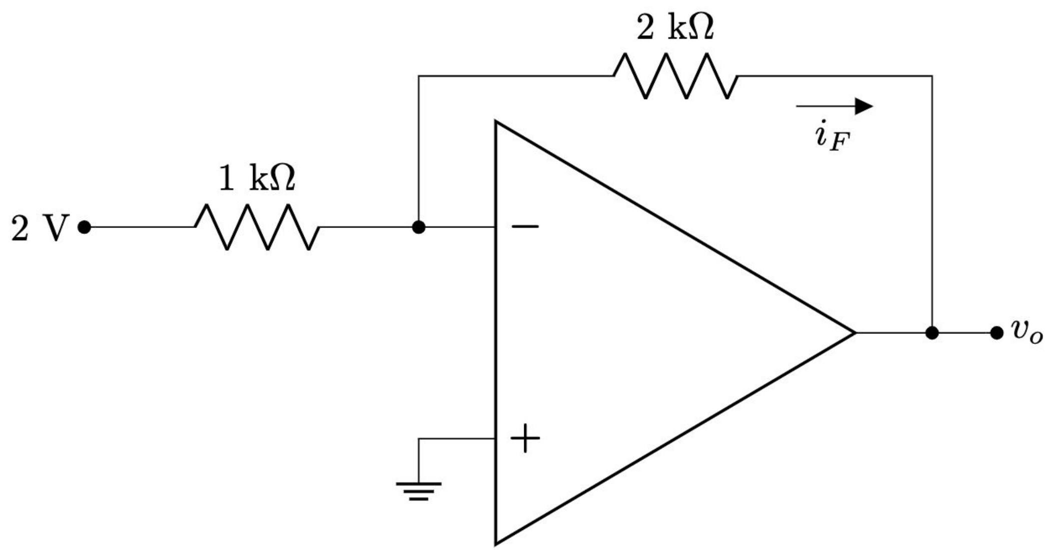


Practice Problem – op-amp

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

Here,

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



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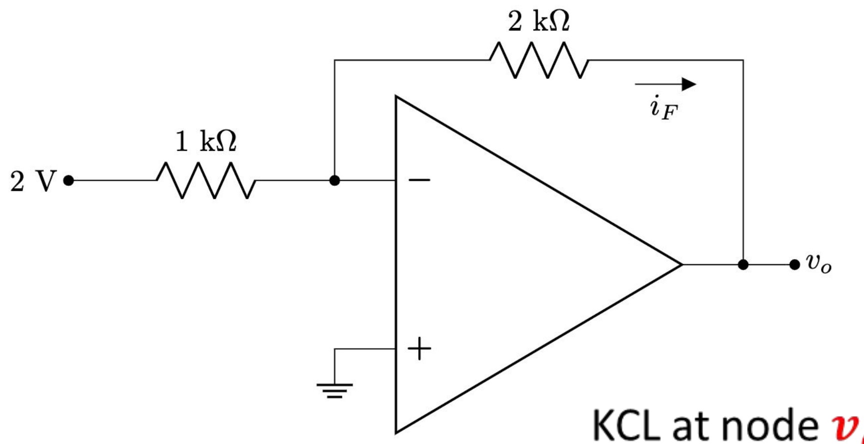


KCL at node $\boldsymbol{v_i}$

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

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

KCL at node $\boldsymbol{v_o}$

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

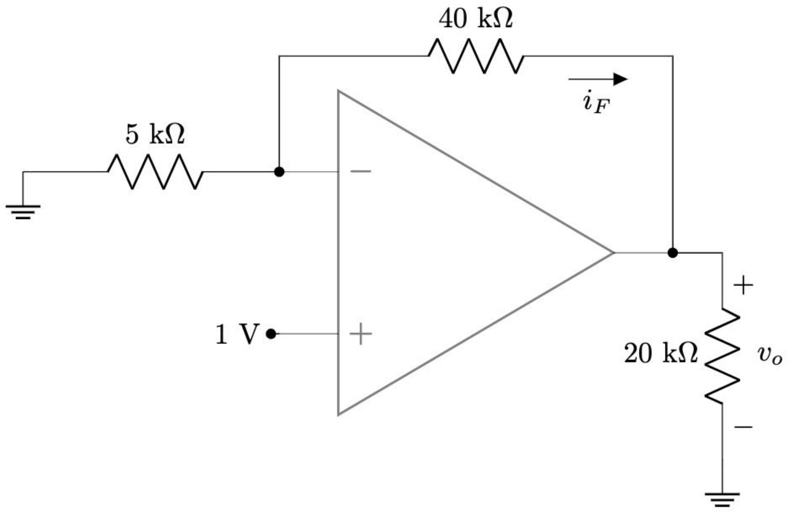
$$(2 \times 10^6 + 0.5)v_i - 10.5v_o = 0$$

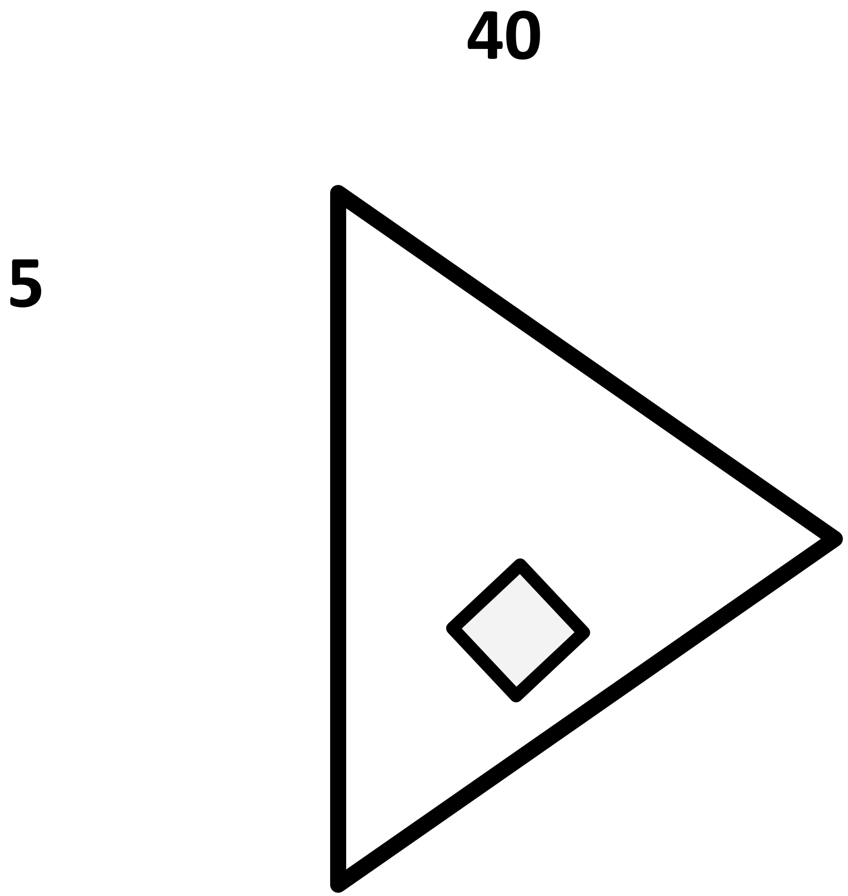
$$\boxed{\begin{gathered}\boldsymbol{v_i = -21\ \mu V} \\ \boldsymbol{v_o = -3.999\ V} \\ \boldsymbol{i_F = 2\ mA}\end{gathered}}$$

Some circuits with OP-AMP

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

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

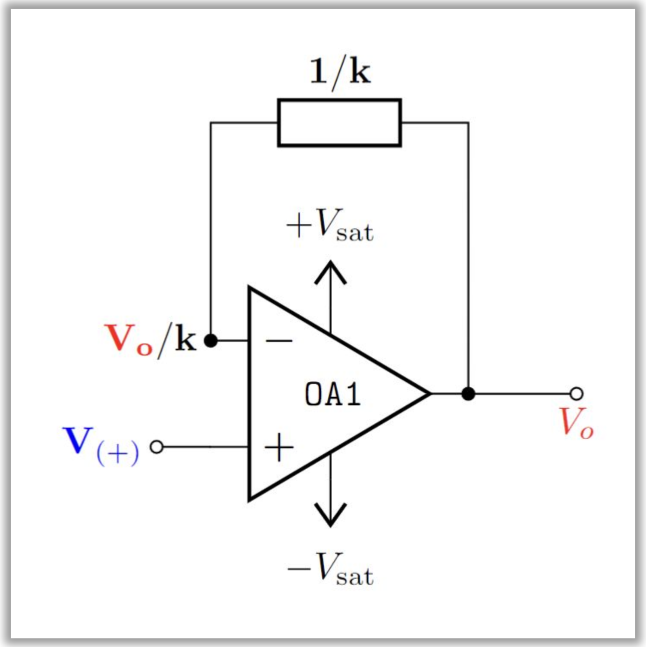




Part 5 ends here

Closed Loop Configuration

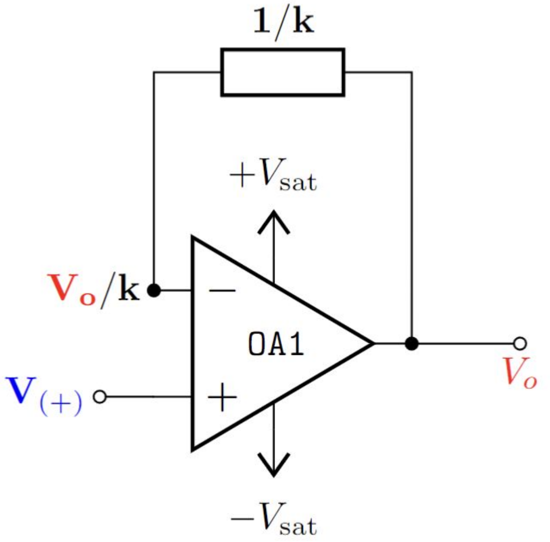
Feedback



Outline

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

Feedback in Op-Amp circuit



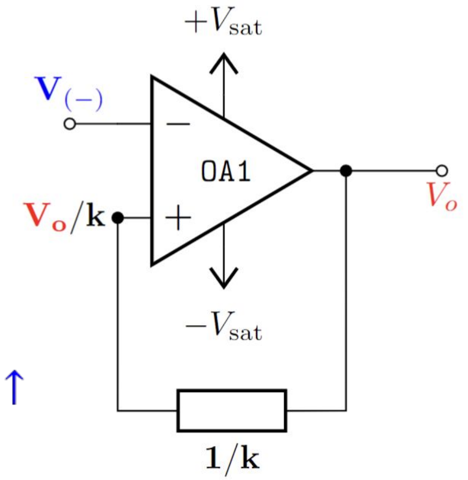
Two types of feedback

1. Negative Feedback:

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

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

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



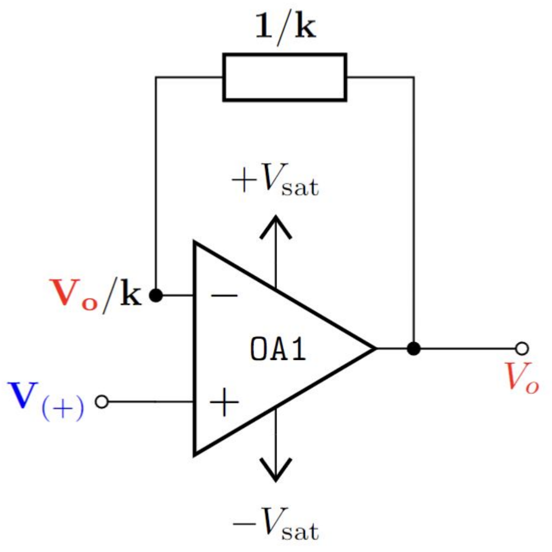
2. Positive Feedback:

   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



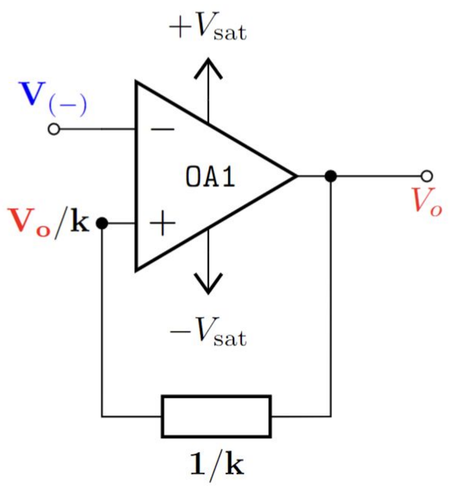
Two types of feedback

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 in Op-Amp circuit

Negative Feedback:

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

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

Here, $V_{(-)} = \frac{V_O}{\mathbf{k}}$

We know, $V_o = AV_d$

$V_o = A(V_{(+)} - V_{(-)})$

$= A\left(V_{(+)} - \frac{V_O}{\mathbf{k}}\right)$

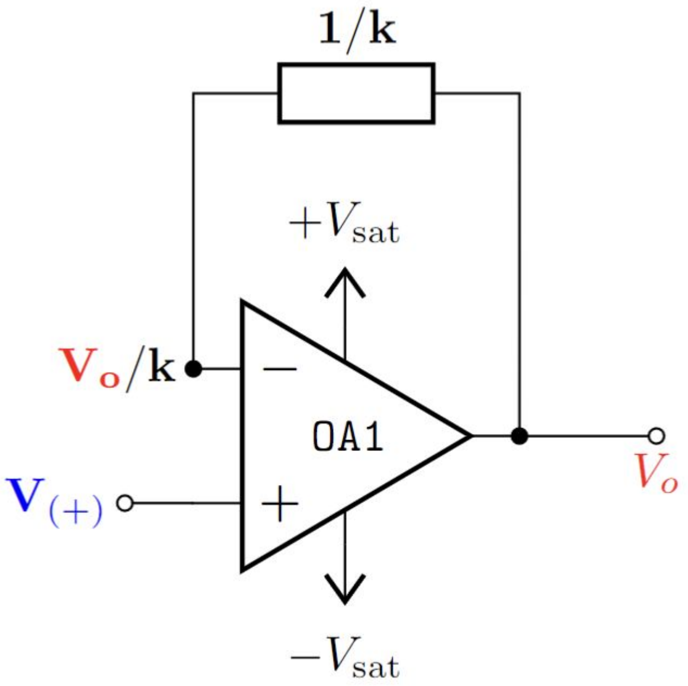
$= AV_{(+)} - \frac{A}{k}V_O$

$\Rightarrow V_o(1 + \frac{A}{k}) = AV_{(+)}$

$$\frac{V_O}{V_{(+)}} = \frac{A}{1 + \frac{A}{k}} = \frac{1}{\frac{1}{A} + \frac{1}{k}}$$

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

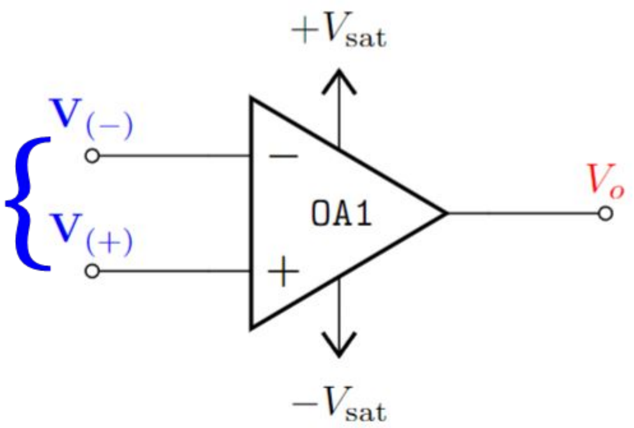
$\therefore \frac{V_O}{V_{(+)}} = k$ **This is the new amplification factor / Gain**



Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration

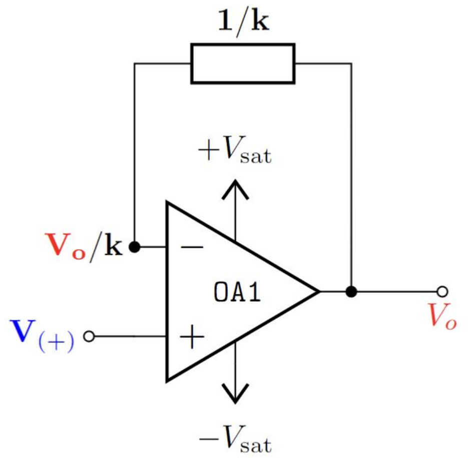
$$V_d = V_{(+)} - V_{(-)}$$



Input Voltage: V_d
Output Voltage: V_O

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

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



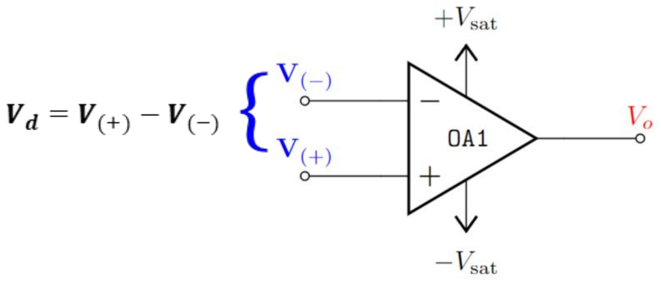
Input Voltage: $V_{(+)}$
Output Voltage: V_O

$\therefore$ Voltage Gain: $\dfrac{V_O}{V_{(+)}} = k$

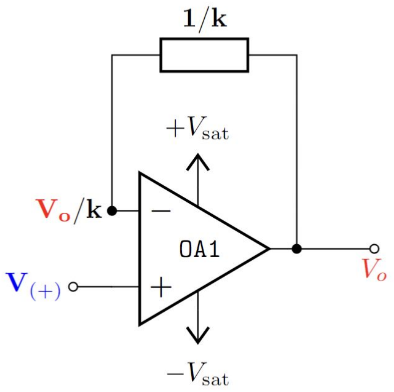
OL Gain	CL Gain

Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration



Closed Loop (CL) Configuration



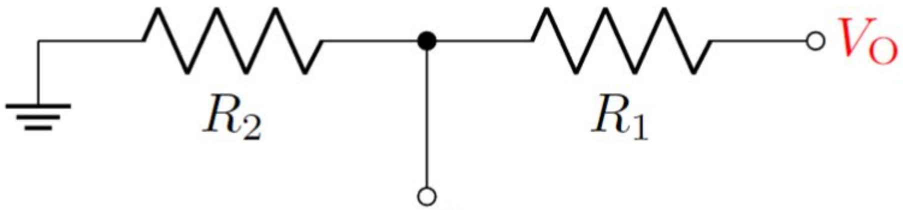
OL Gain	CL Gain
Can’t be controlled	Can be controlled by the feedback element
*Used as “**Comparator**”*	*Used as “**Linear Amplifier**”*

Negative Feedback in Op-Amp circuit

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

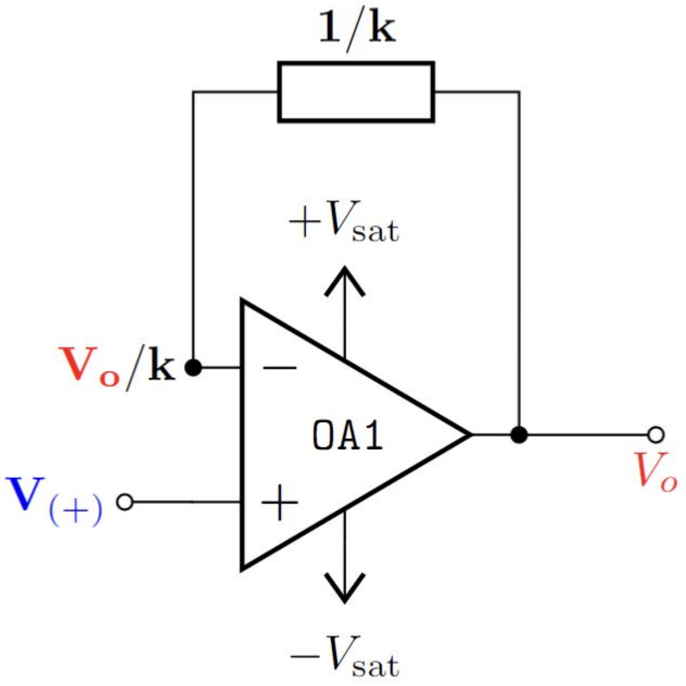
$$V_{(-)} = \frac{1}{k} \cdot V_O$$

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



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

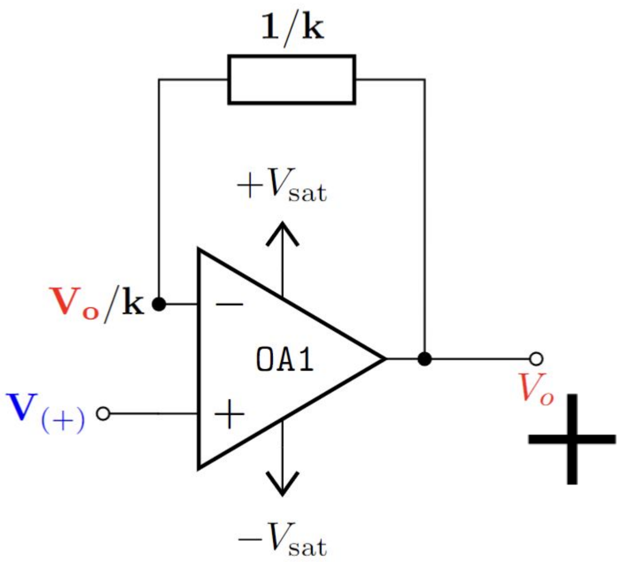
$$\boxed{\frac{1}{k} = \frac{R_2}{R_1 + R_2}}$$



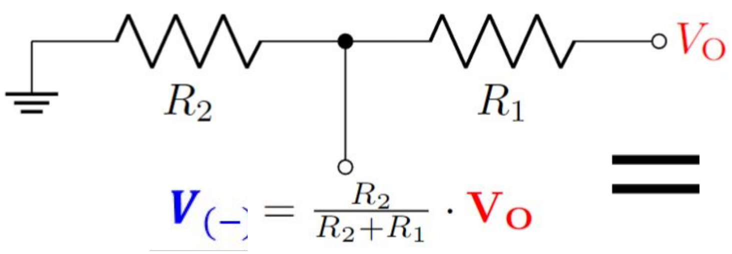
A voltage divider can act as a **multiplier/factor** in the feedback branch

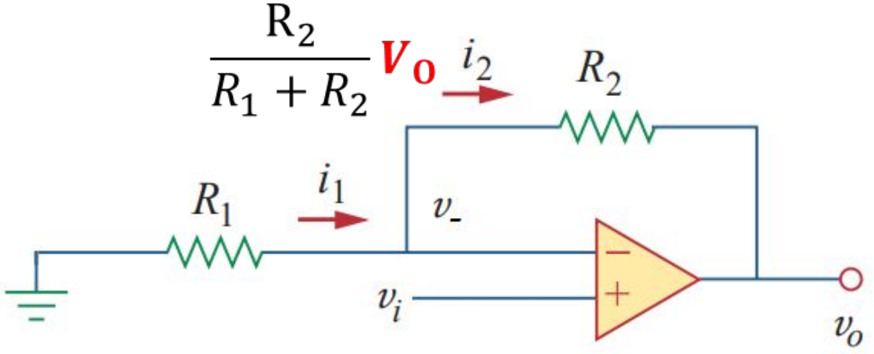
Negative Feedback in Op-Amp circuit

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



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

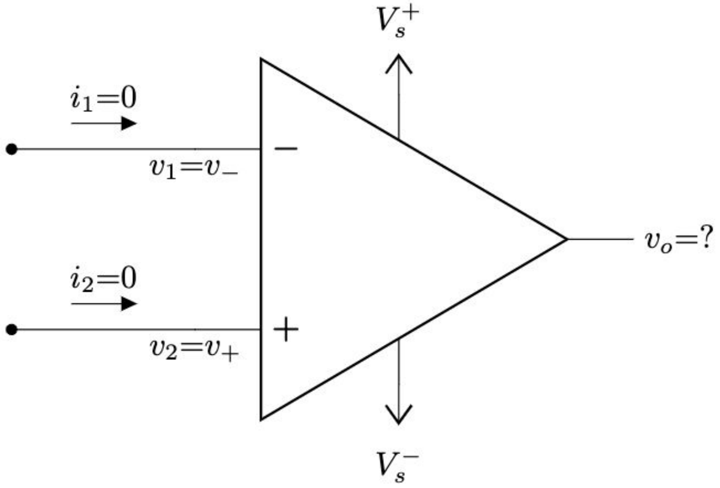




If $\boldsymbol{k}$ = 10 (meaning we feed back one tenth of the output to negative input), we will get $\boldsymbol{v_o}$=10*$\boldsymbol{v_i}$. that is 10-fold gain.

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**