CSE 251: Electronic Devices and Circuits

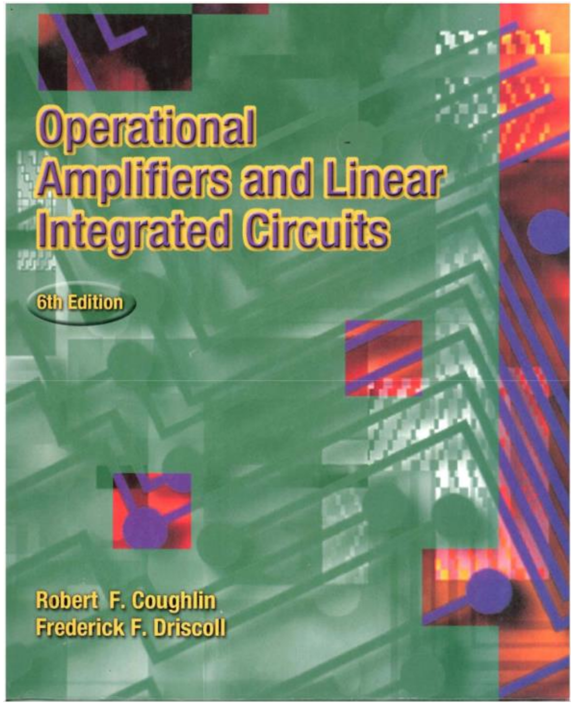
Lecture 2

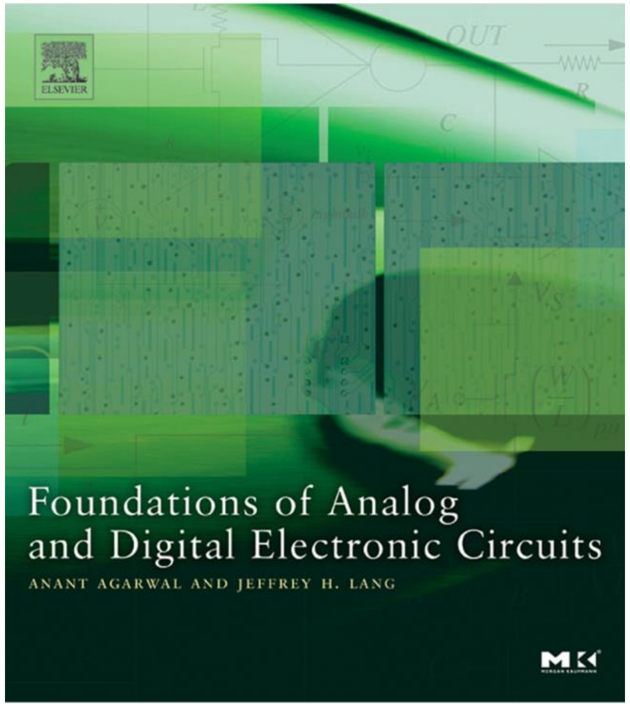
Operational Amplifier:

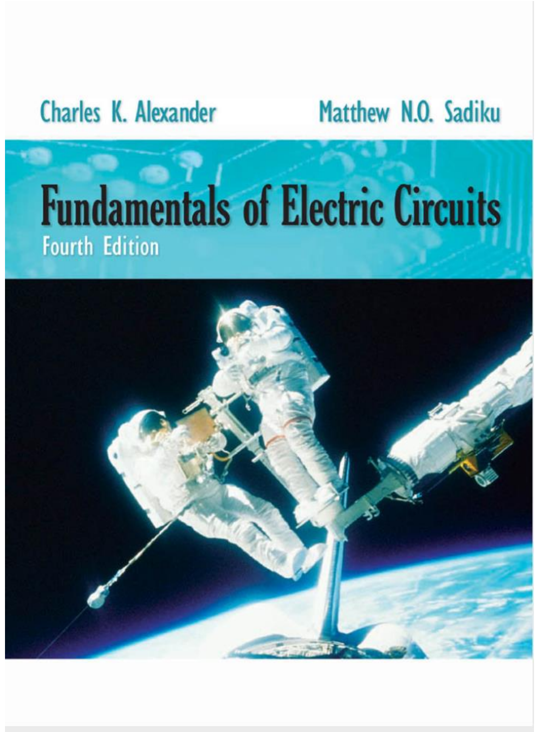
Introduction, Open Loop Configuration, Circuit Modeling

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

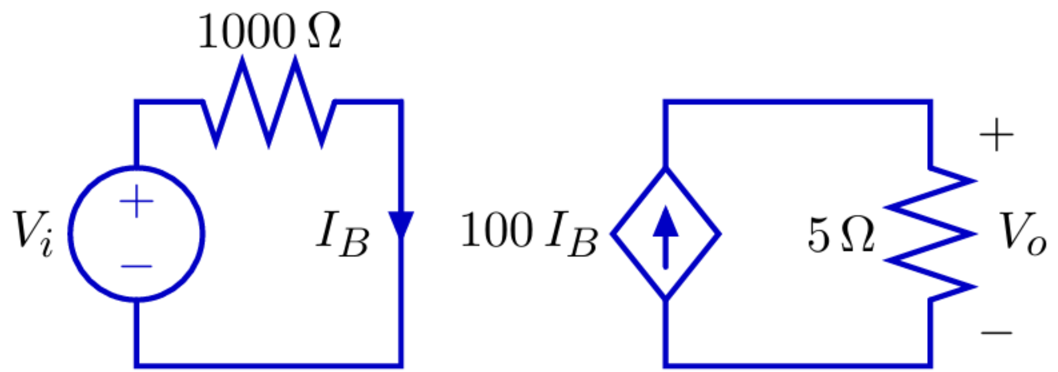
  - Op-Amp: Physical Entity

Dependent Sources

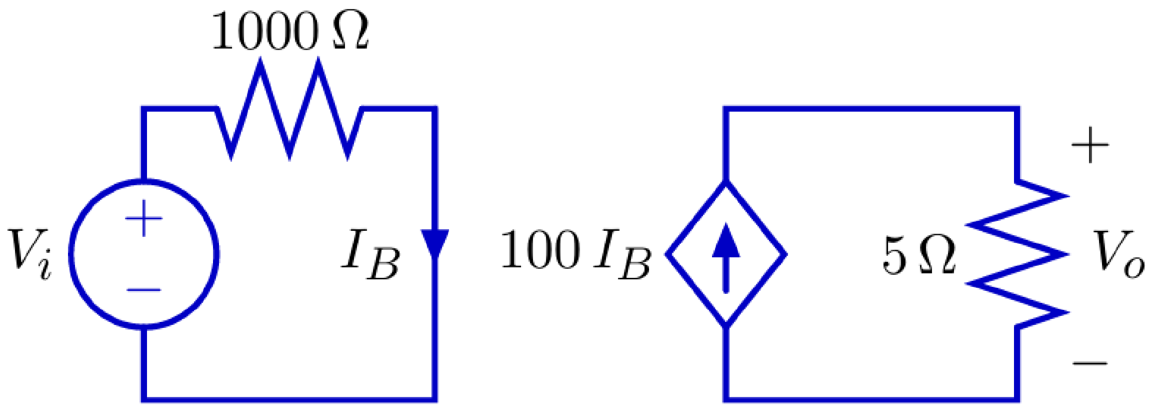
To analyze op-amps, we must understand **dependent source.**

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

Example: current-controlled current source



Dependent Sources



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

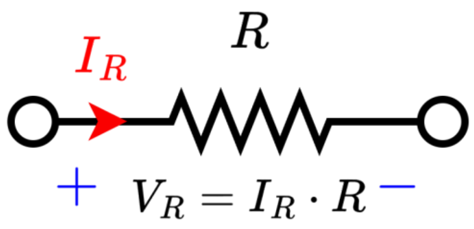
$$V_o = 100\,I_B \times 5\,\Omega$$

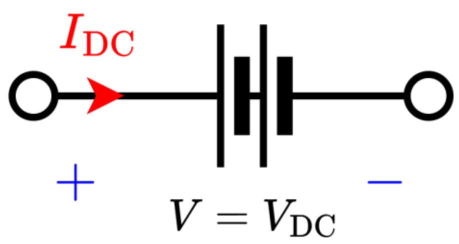
$$= 100\,\frac{V_i}{1000\,\Omega} \times 5\,\Omega = \boxed{\frac{1}{2}V_i}$$

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

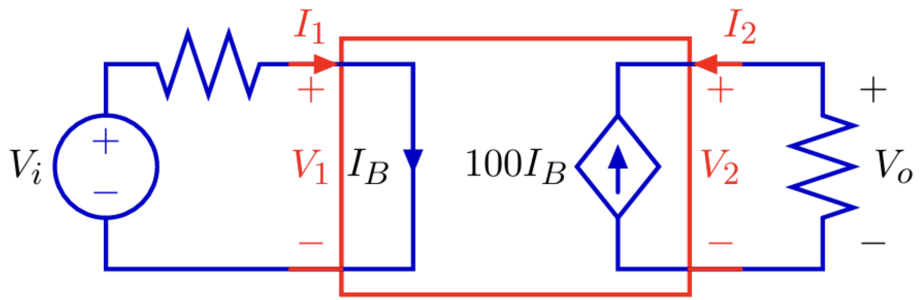
Dependent Sources

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 $\boldsymbol{I_2} = -100\, \boldsymbol{I_1}$.

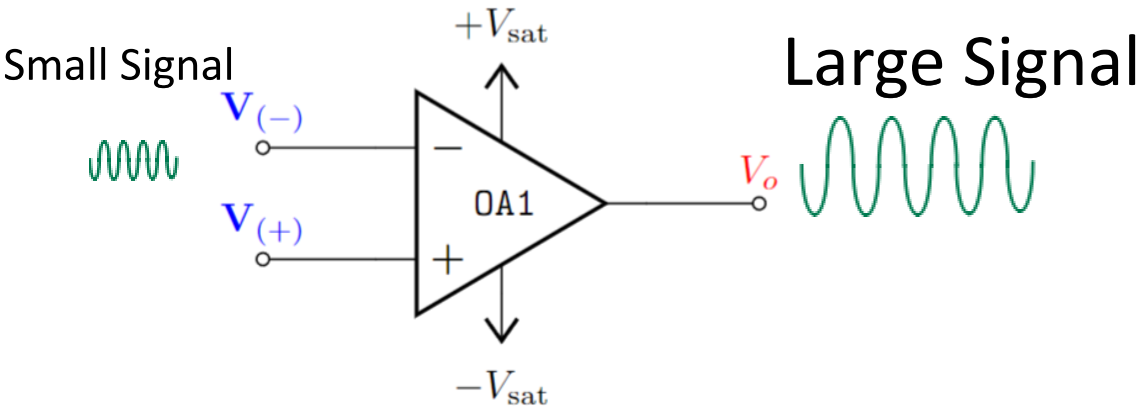
Operational Amplifier: Introduction

- **Operational:**

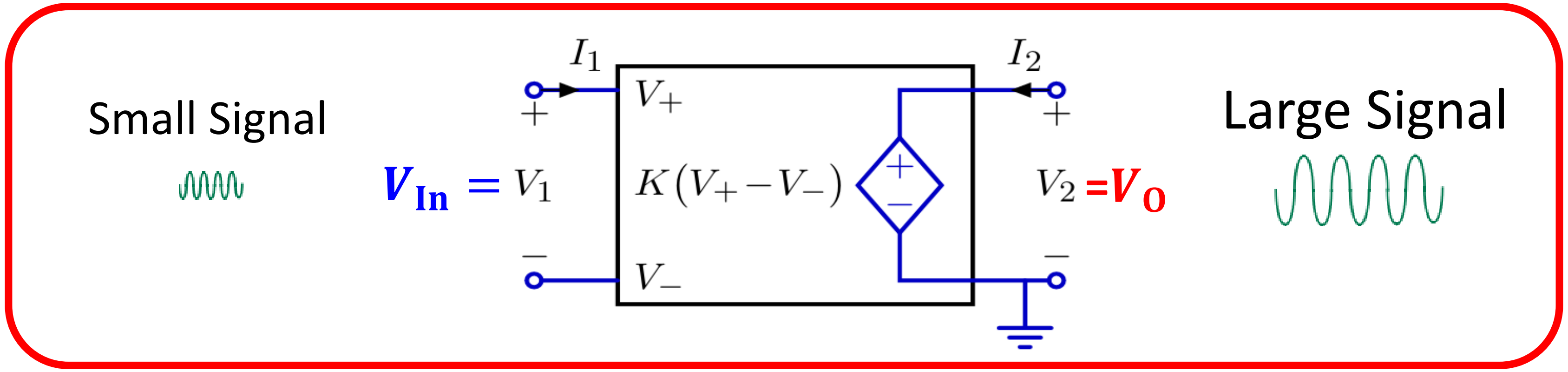
  Mathematical Operations

- **Amplifier:**

  Amplifies input signal/voltage.

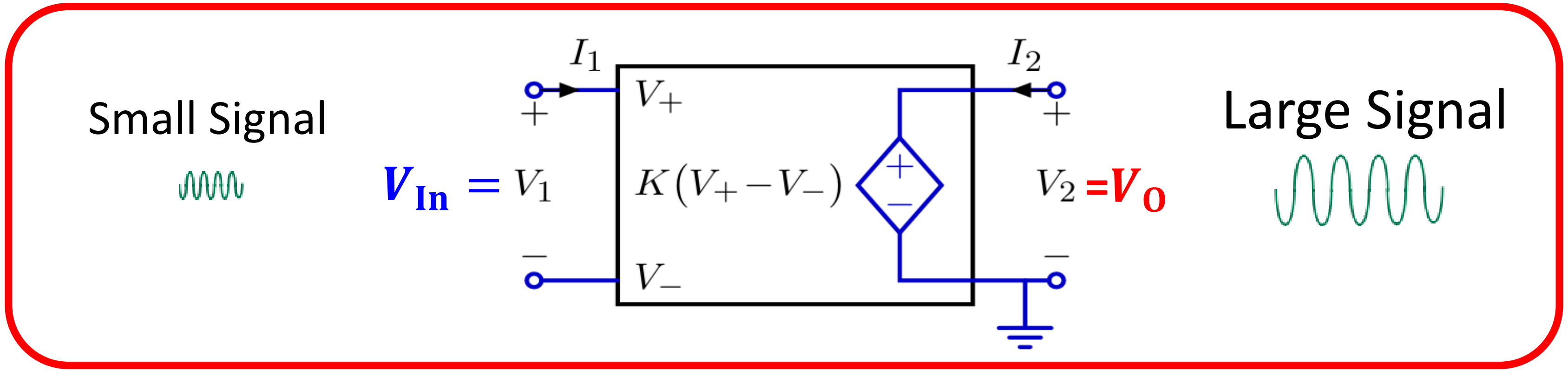


An **op-amp (operational amplifier)** can be modelled by a **voltage- controlled voltage source.**



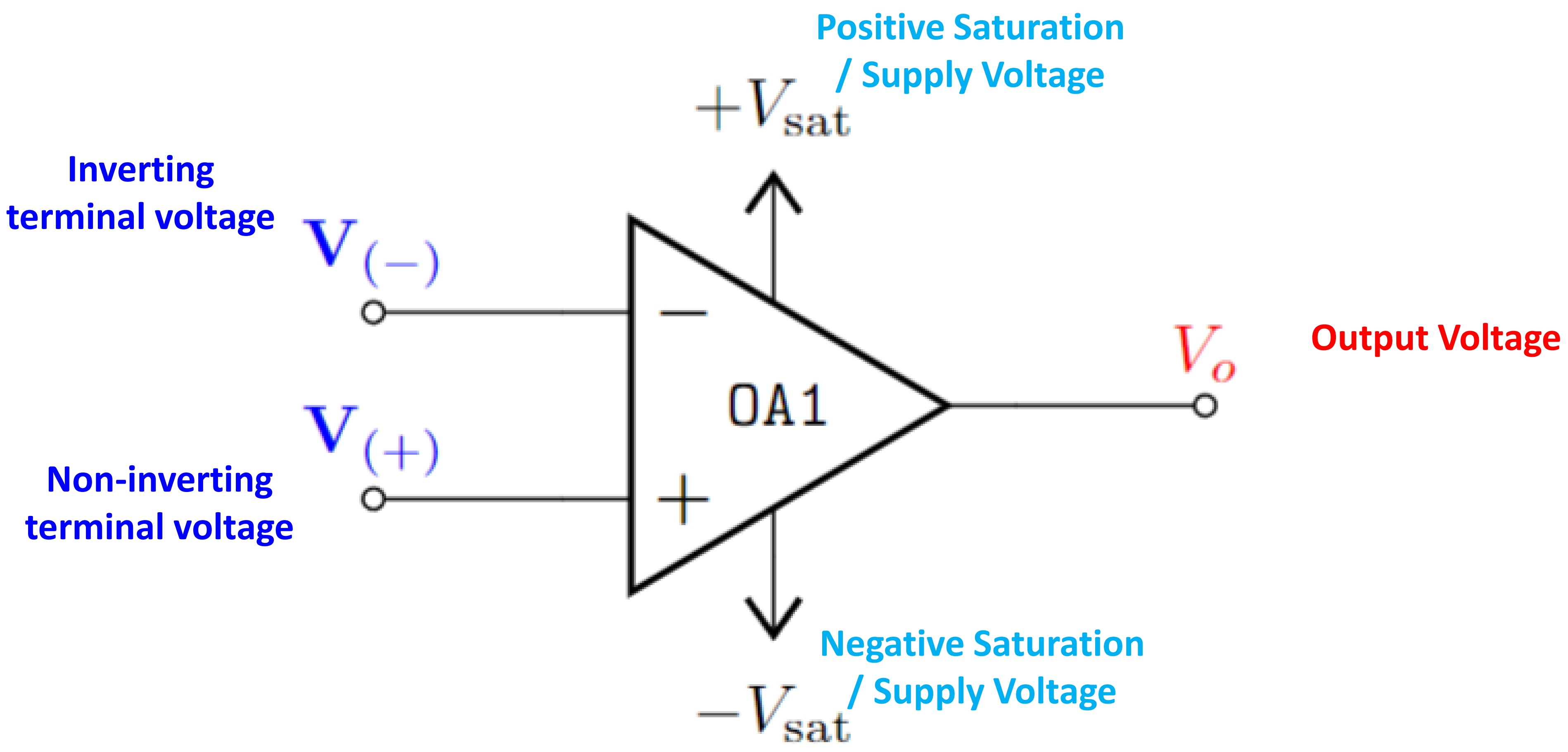
Operational Amplifier: Introduction

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

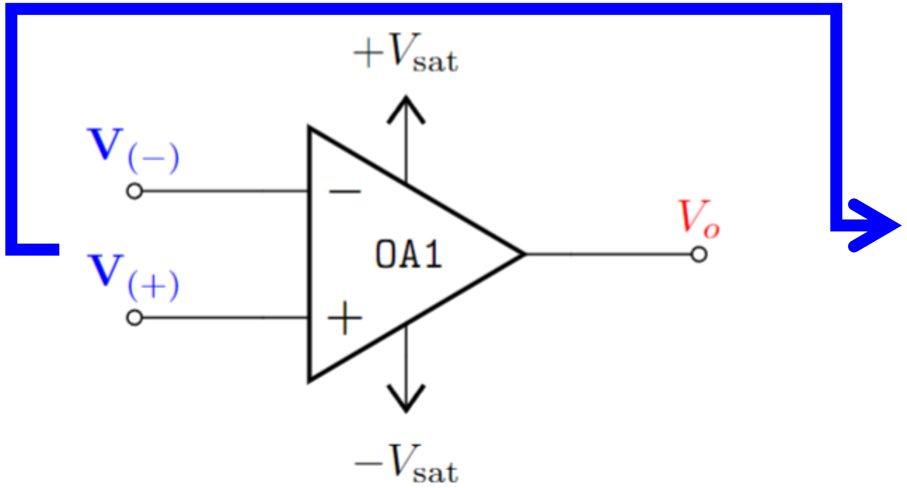


$I_1 = 0$ and $V_O = KV_{In}$ where K is large (typically $K > 10^5$).

Op-Amp: Circuit Symbols and terminal



Op-Amp: Circuit Symbols and terminal

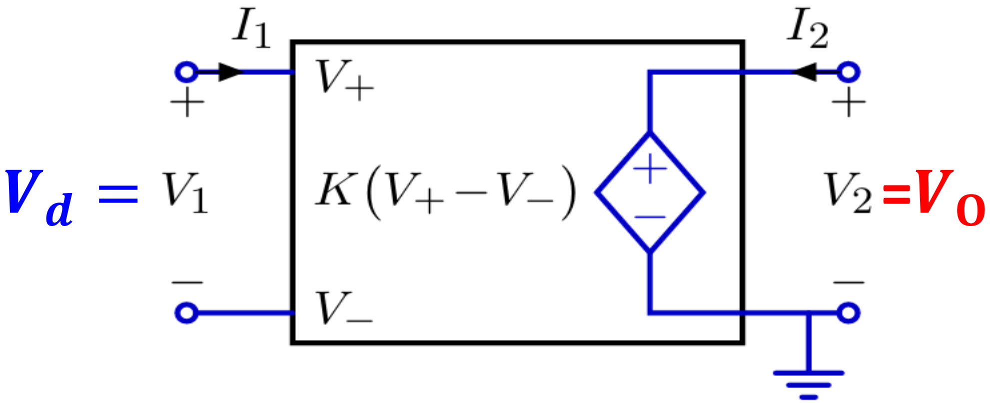


$$V_d = V_{(+)} - V_{(-)}$$

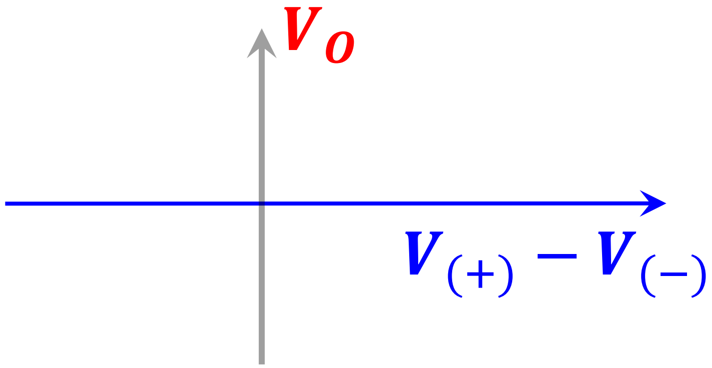
Difference Amplifier –

Amplifies the voltage difference between two terminals.

V_d **Differential input voltage**



Voltage Transfer Characteristics (VTC)



Op-Amp: VTC – Linear Amplification

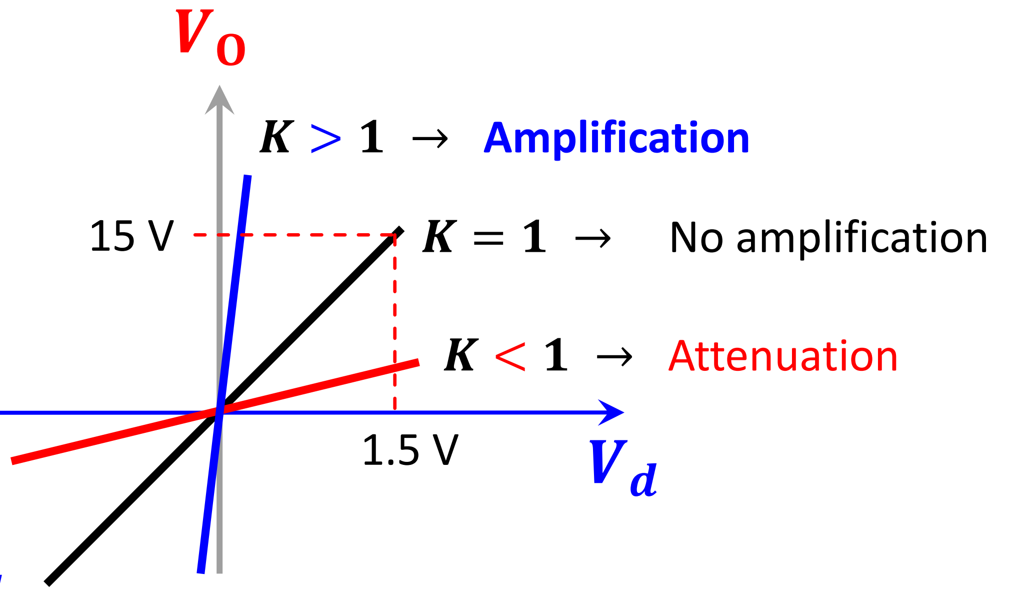
Voltage Transfer Characteristics (VTC)

- Shows how the output voltage varies with the input voltage $V_O(V_d)$
- y –axis → $\boldsymbol{V_O}$
- x –axis → $\boldsymbol{V_d}$

- Slope: $\boldsymbol{K} = \frac{\Delta \boldsymbol{V_O}}{\Delta \boldsymbol{V_d}} = \frac{\boldsymbol{V_O}}{\boldsymbol{V_d}}$

If the line passes through origin:

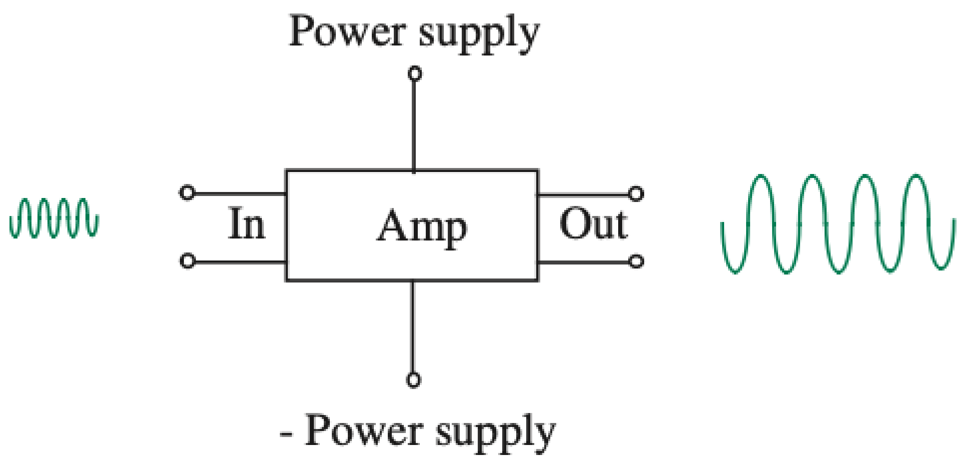
$$y = \boldsymbol{K} \cdot x$$
$$\boldsymbol{V_O} = \boldsymbol{K} \cdot \boldsymbol{V_d}$$

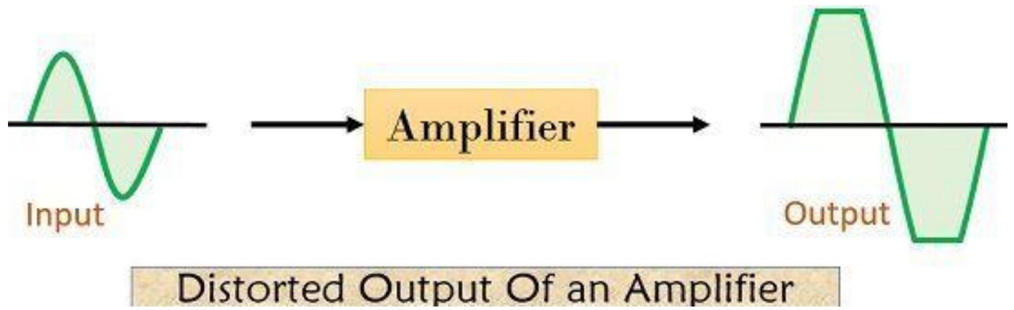


LINEAR AMPLIFICATION

Op-Amp: VTC – Linear Amplification

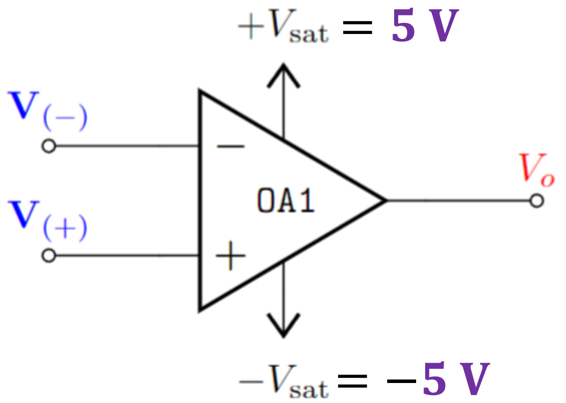
- **Linear Amplification** only takes place within a **valid input range.**
- Otherwise output will be distorted - - Saturation





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

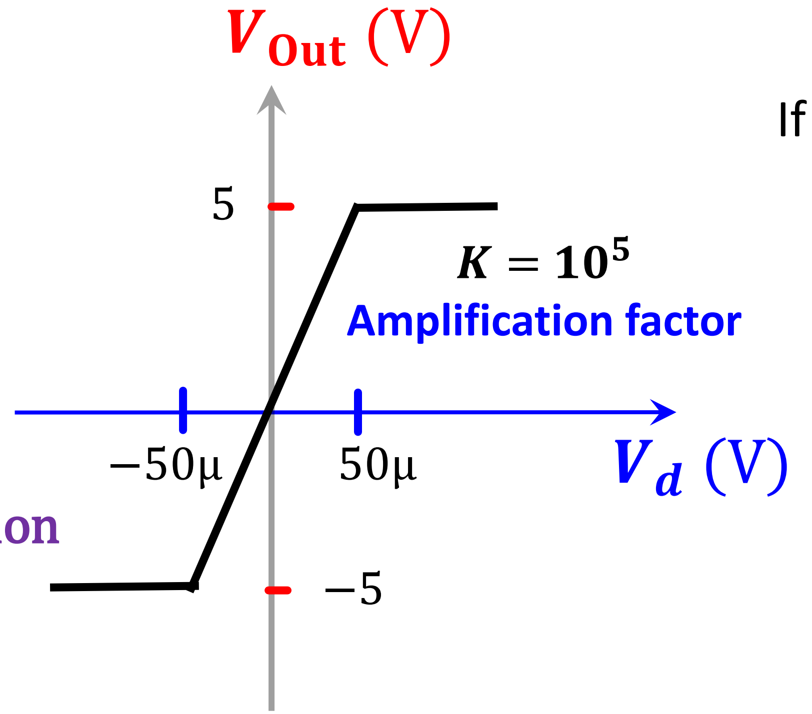
Op-Amp: VTC - Saturation



Non-Linear characteristics

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

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



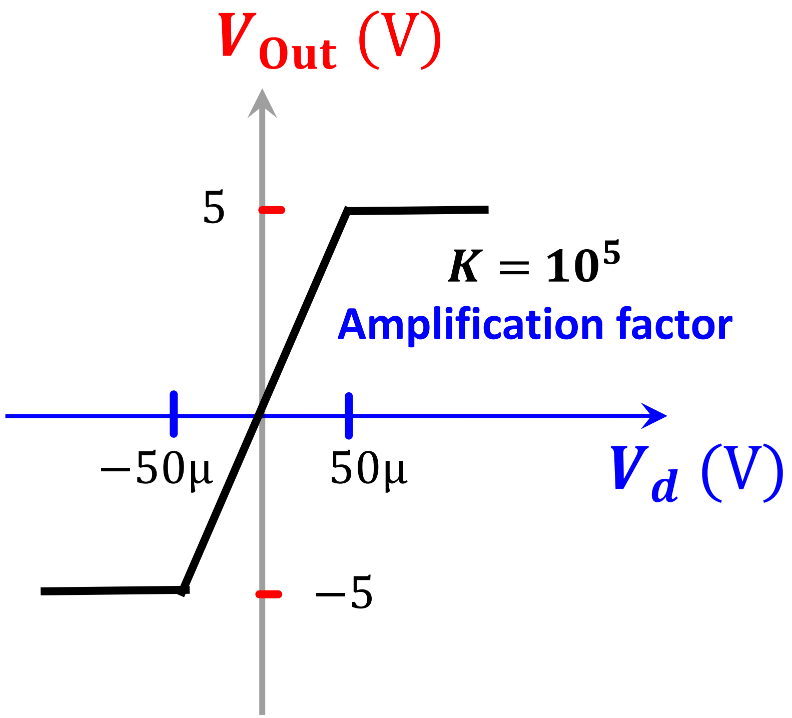
If $V_d > 50\mu$: Positive Saturation

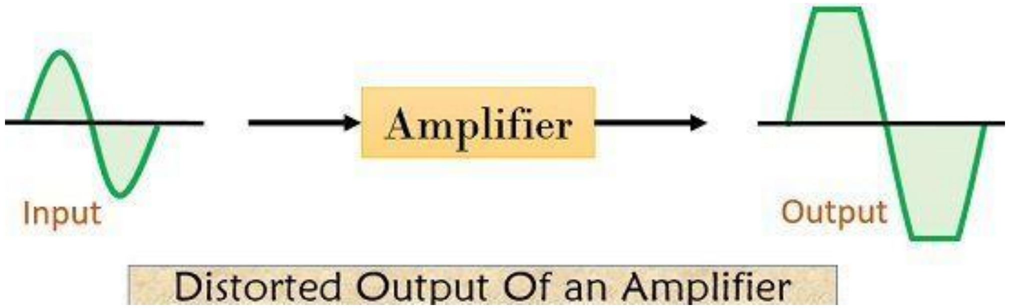
$\Rightarrow V_O = 5$

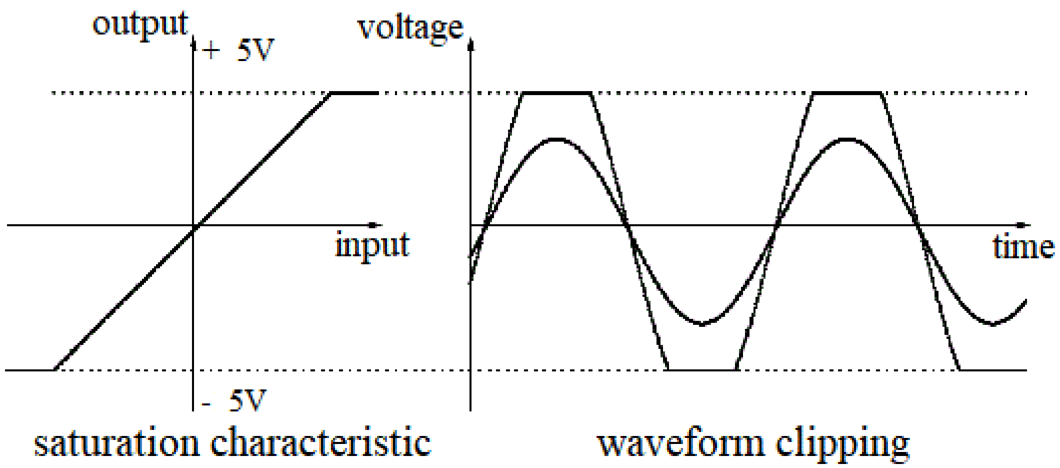
If $V_d < -50\mu$: Negative Saturation

$\Rightarrow V_O = -5$

Op-Amp: VTC - Saturation







Op-Amp: VTC - Summary

Voltage Transfer Characteristics (VTC)

Positive saturation:

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

$\Rightarrow V_o = +V_{\text{sat}}$

Linear Region

$V_o = AV_d$: When V_d is very small

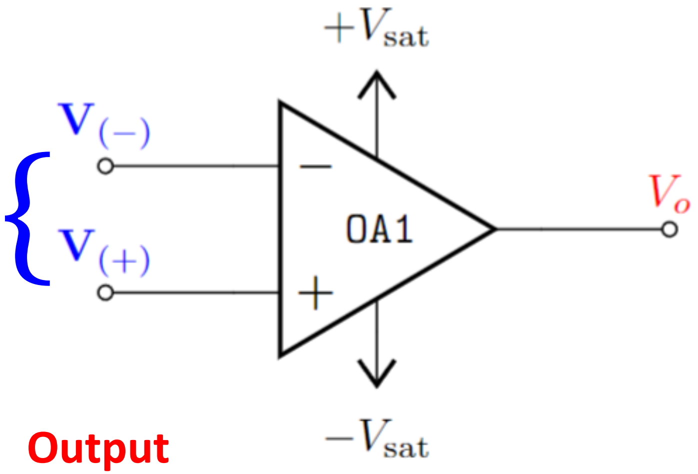
$-V_{\text{sat}} < V_o = AV_d < +V_{\text{sat}}$

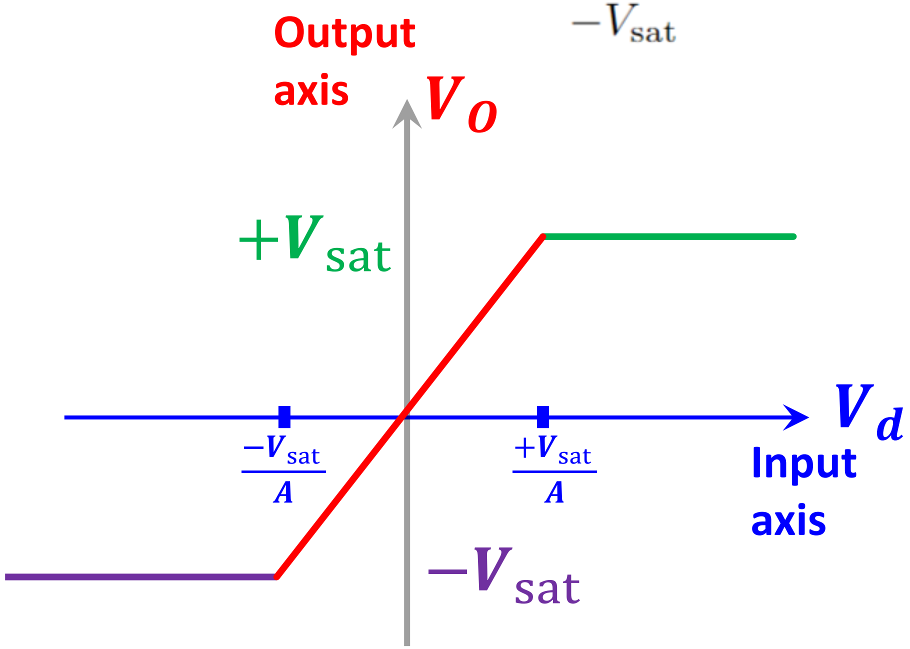
Negative saturation:

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

$\Rightarrow V_o = -V_{\text{sat}}$

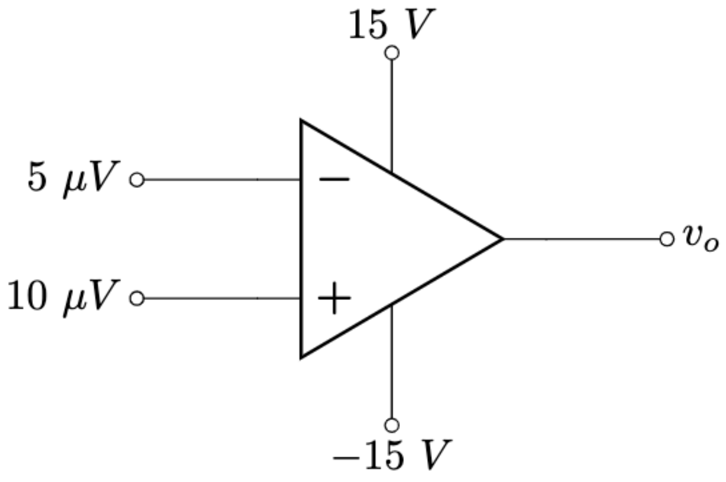
$V_d = V_{(+)} - V_{(-)}$



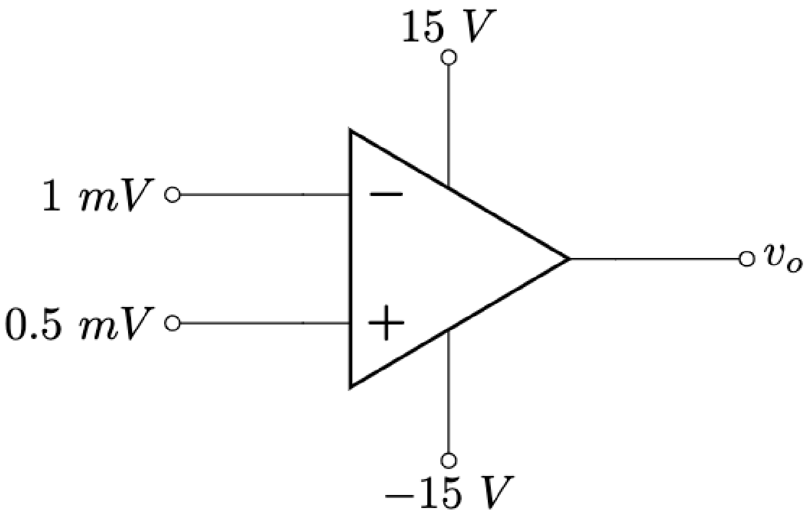


Op-Amp: Examples

Find v_0



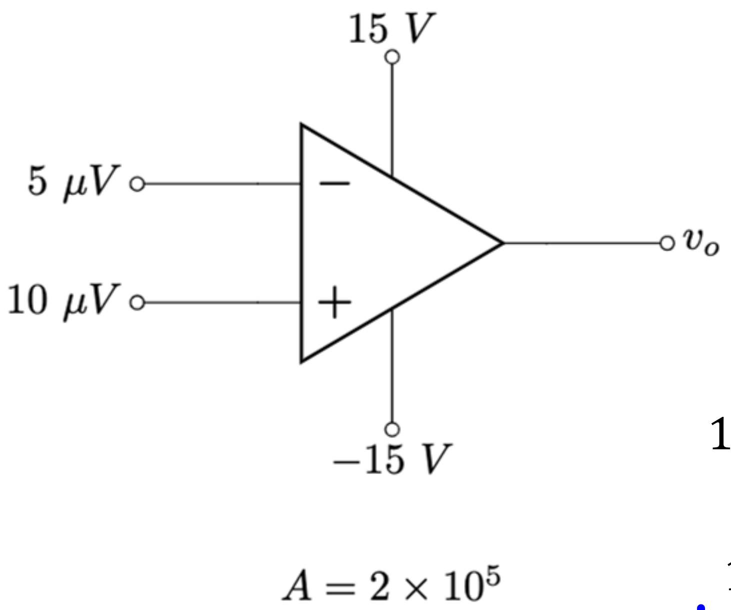
$A = 2 \times 10^5$

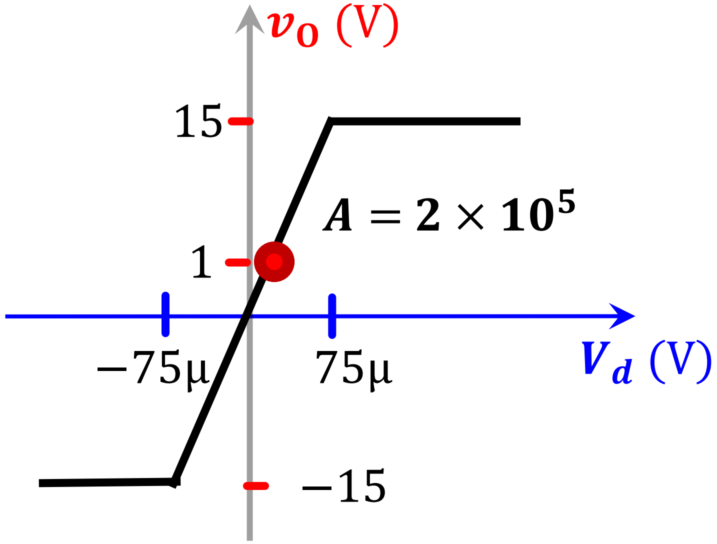


$A = 2 \times 10^5$

Example 1

- Find v_o





Solution:

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

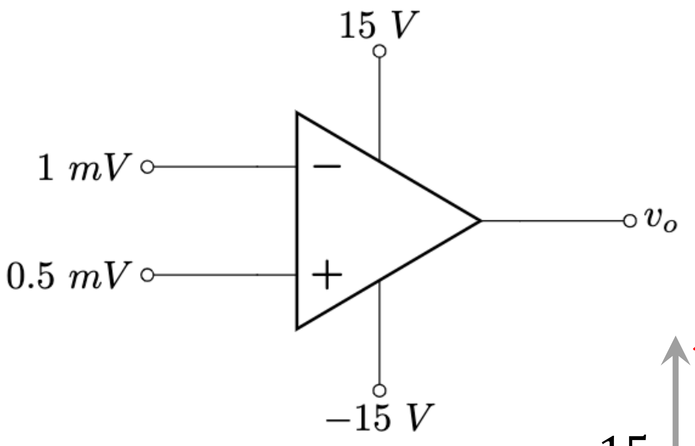
$$AV_d = (2 \times 10^5) \times (5 \times 10^{-6})\ \text{V} = 1\ \text{V}$$

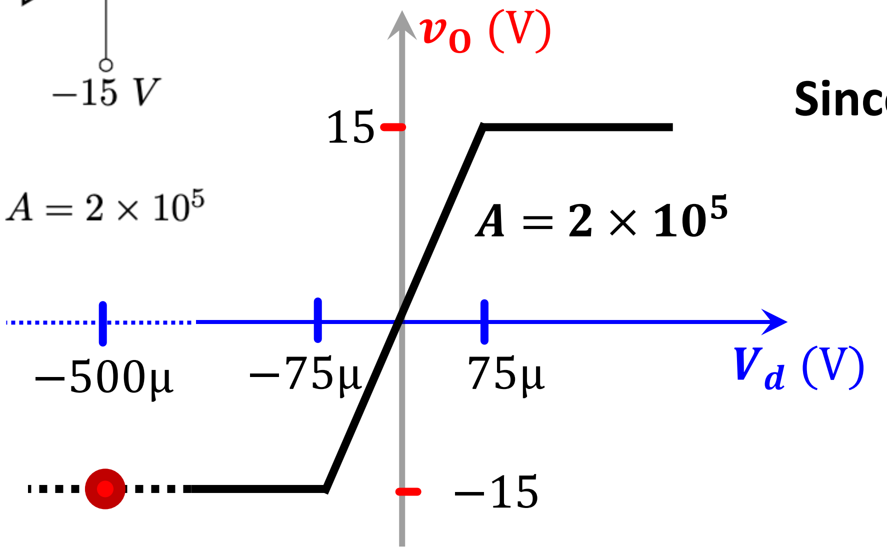
Since $-15\ \text{V} < AV_d < +15\ V$

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

Example 2

- Find v_o





Solution:

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

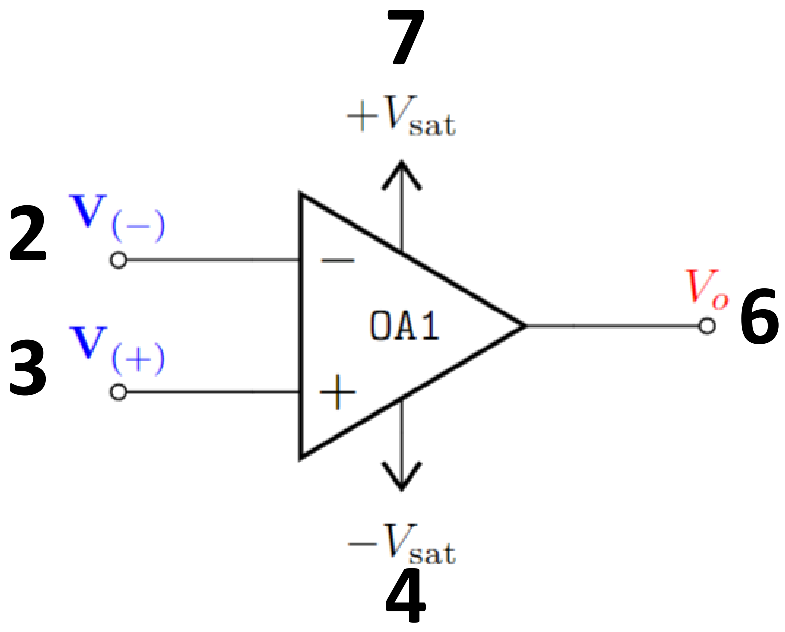
$$AV_d = \left(2 \times 10^5\right) \times \left(-0.5 \times 10^{-3}\right)\ \text{V} = -100\ \text{V}$$

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

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

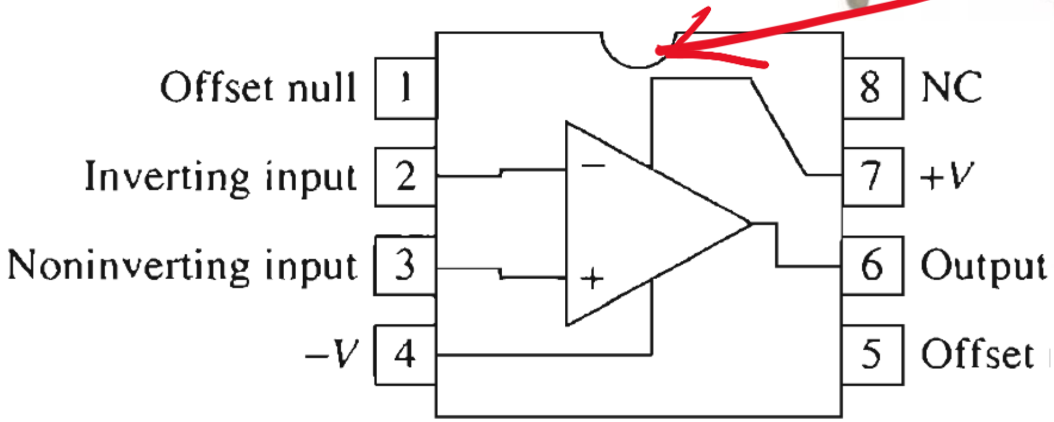
Op-Amp: Physical Entity

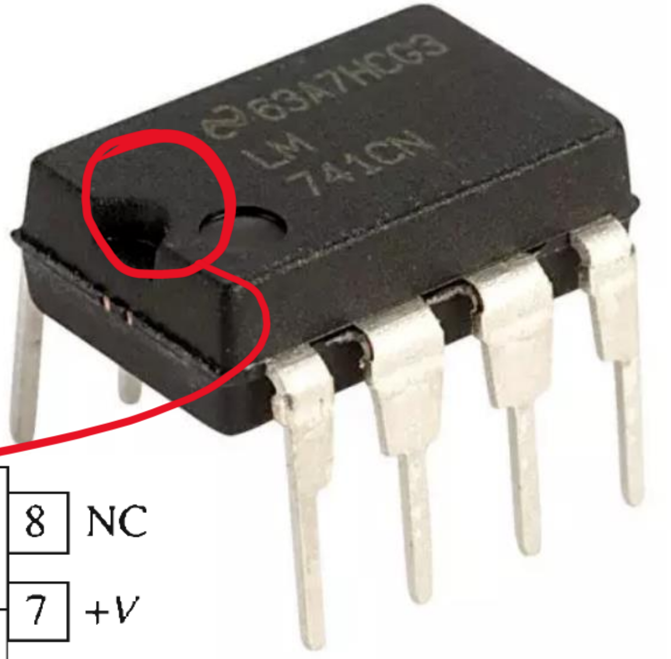
Difference Amplifier – Amplifies the voltage difference between two terminals.



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

NC – No Connection





μ**A-741C**

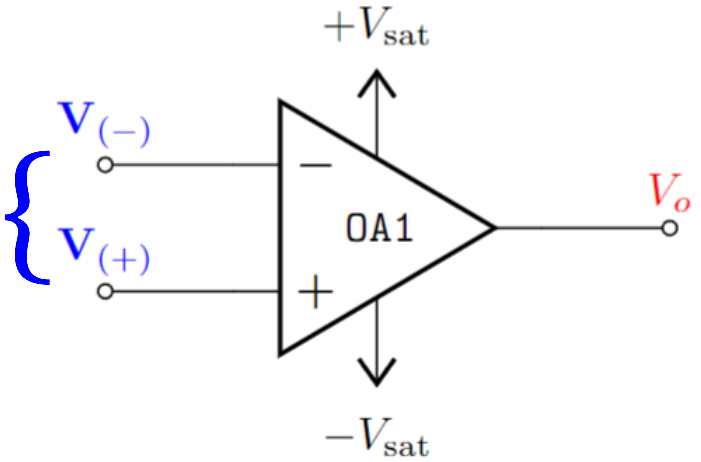
C: Commercial (0° – 70°C)
I: Industrial (−25° – 85°C)
M: Military (−55° – 125°C)

Manufacturer **ID**

Part Identification Number (PIN)

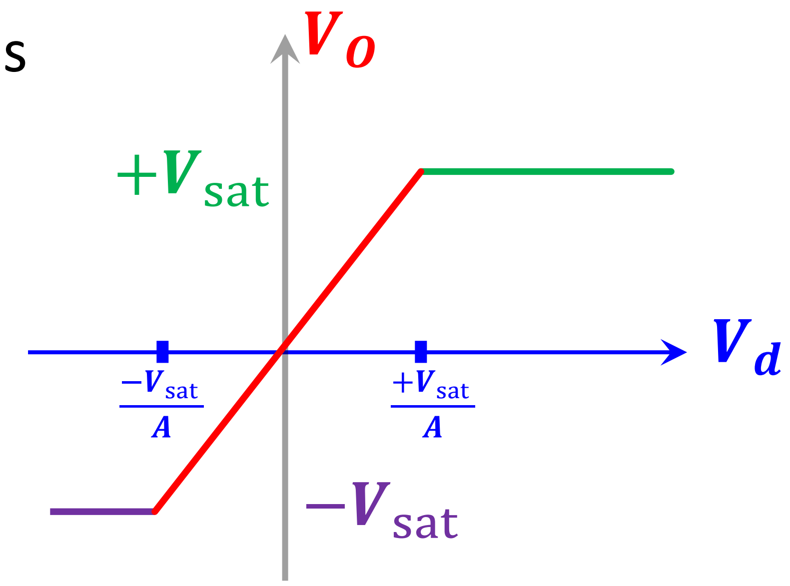
Op-Amp: Summary

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

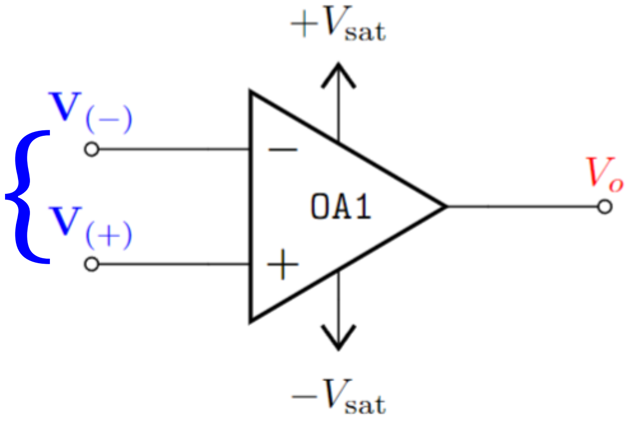
  - Op-amp configuration – open and closed loop
  - Open Loop op-amp: Voltage Transfer Characteristics
  - Open Loop op-amp: Comparators

Op-Amp: Circuit Modelling

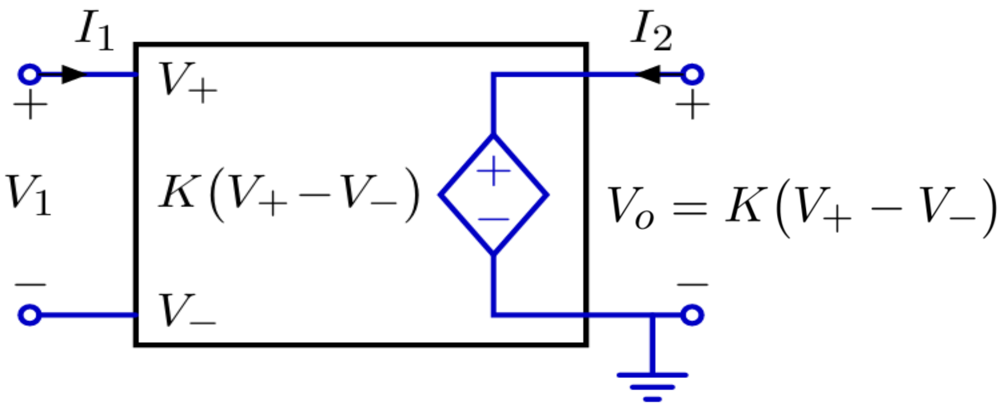
Voltage controlled voltage Source

"Ideal" op-amp approximation

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



$$\boldsymbol{V_d} = V_1$$



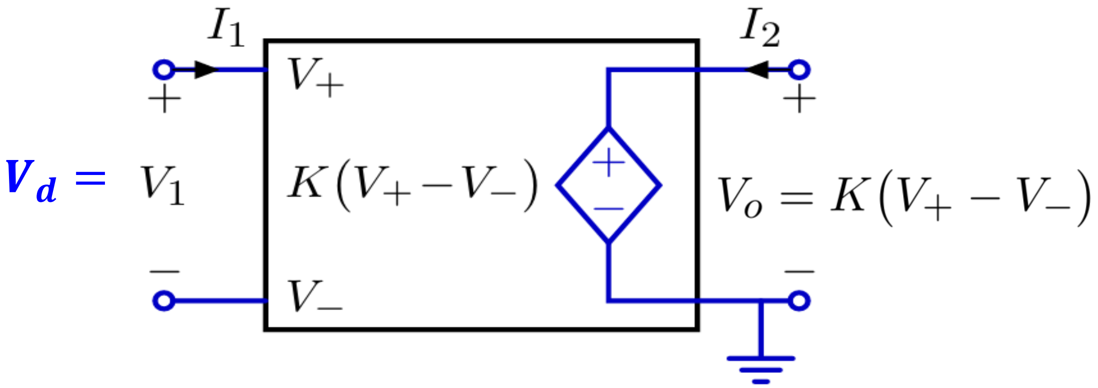
$$\boldsymbol{V_{(+)} \approx V_{(-)}}$$

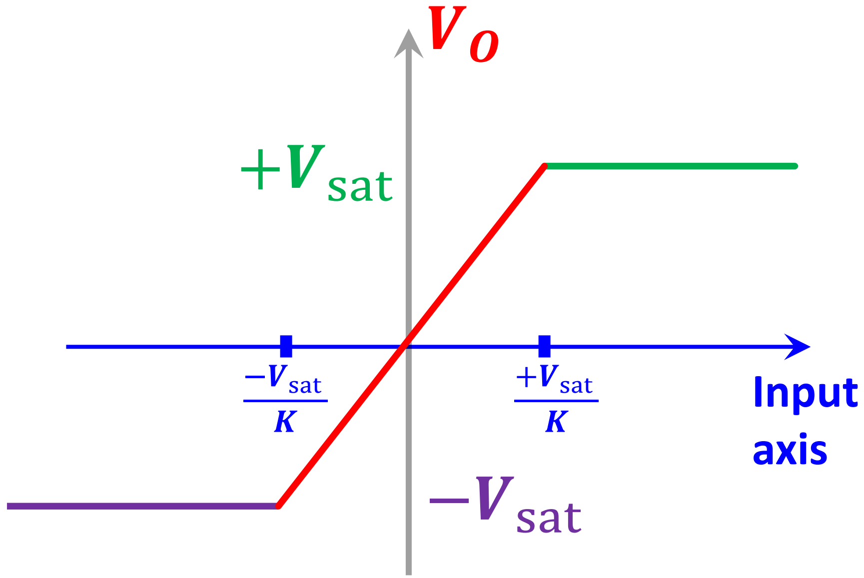
$$\boldsymbol{I_1 \approx 0}$$

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
A or K	$10^4 - 10^8$	∞





Op-amp: Circuit Model and VTC

Voltage Transfer Characteristics (VTC)

Positive saturation: $V_d > 0$

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

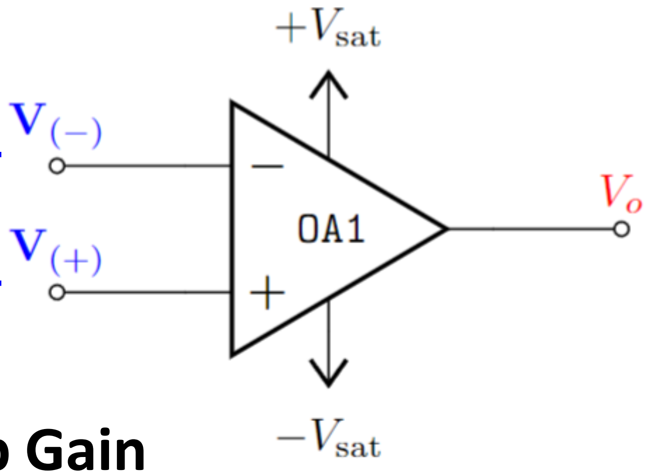
~~**Linear Region**~~

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

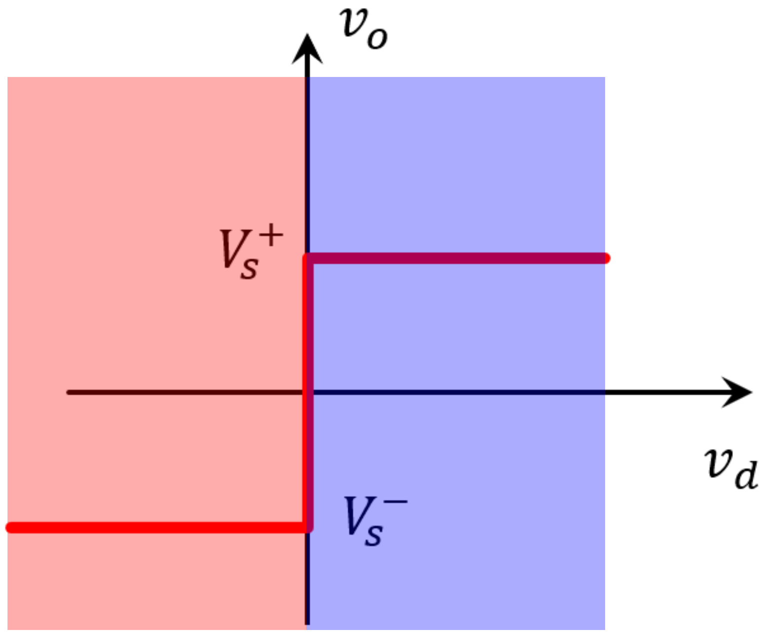
Negative saturation: $V_d < 0$

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

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



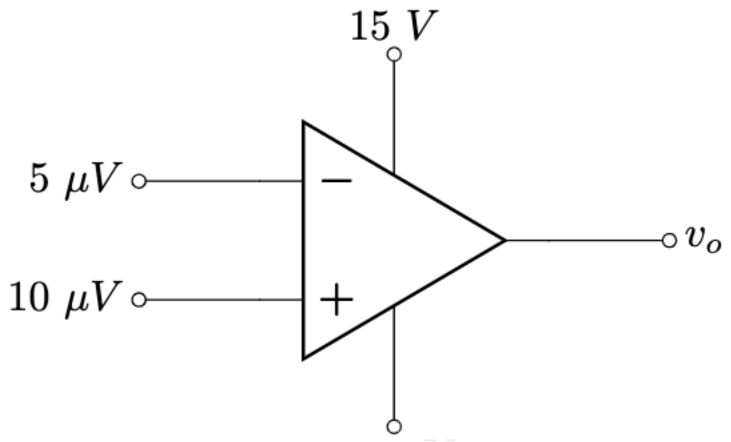
$A \to \infty$ **: Open Loop Gain**



Types of Op-Amp configuration

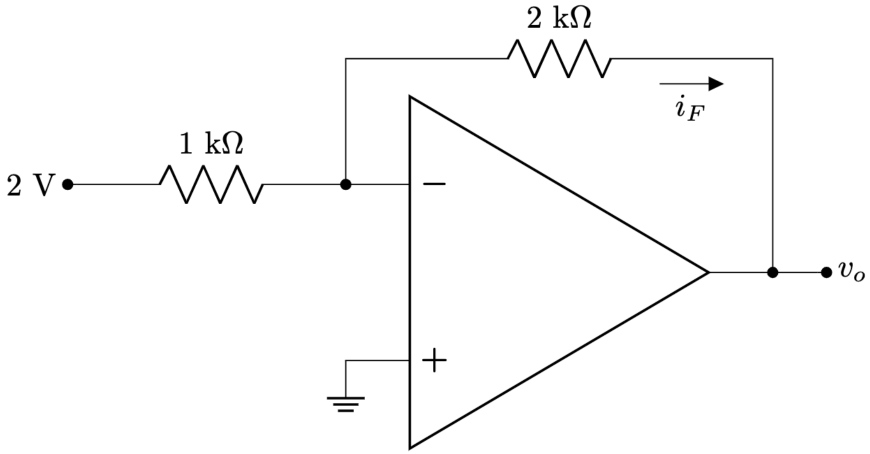
1. Open loop configuration:

   No physical connection between input and output



2. Closed loop configuration:

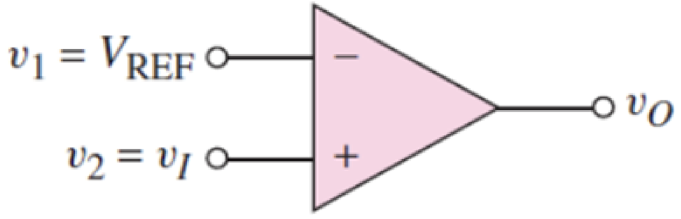
   Feedback from output terminal

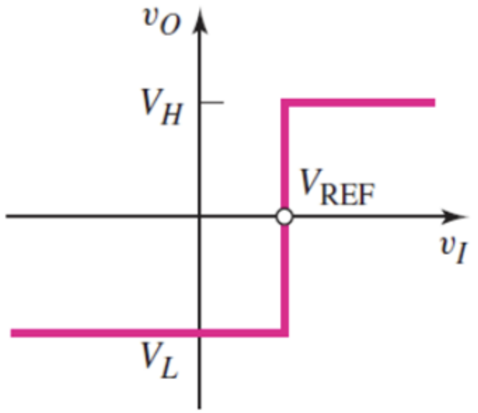


Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

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





NON-INVERTING COMPARATOR

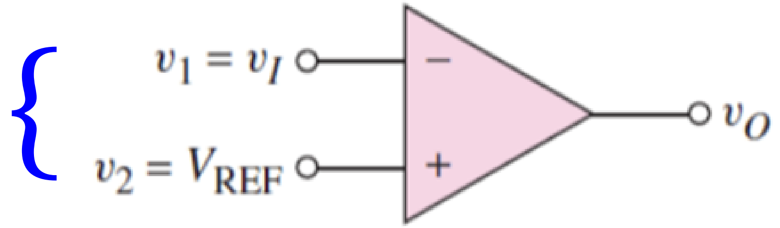
$$V_d = v_I - V_{\text{REF}} > 0 \quad \Rightarrow \quad v_O = V_H$$

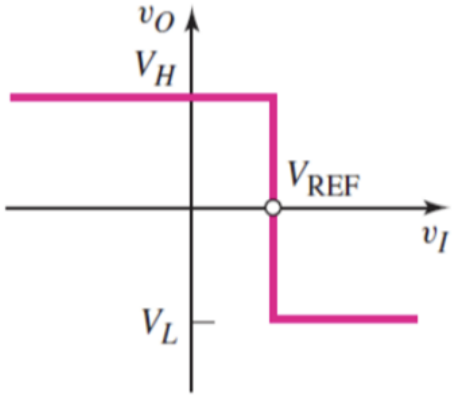
$$v_I > V_{\text{REF}} \quad \Rightarrow \quad v_O = V_H$$

Open Loop Configuration: Comparator

Level Crossing Detector / Comparator

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





INVERTING COMPARATOR

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

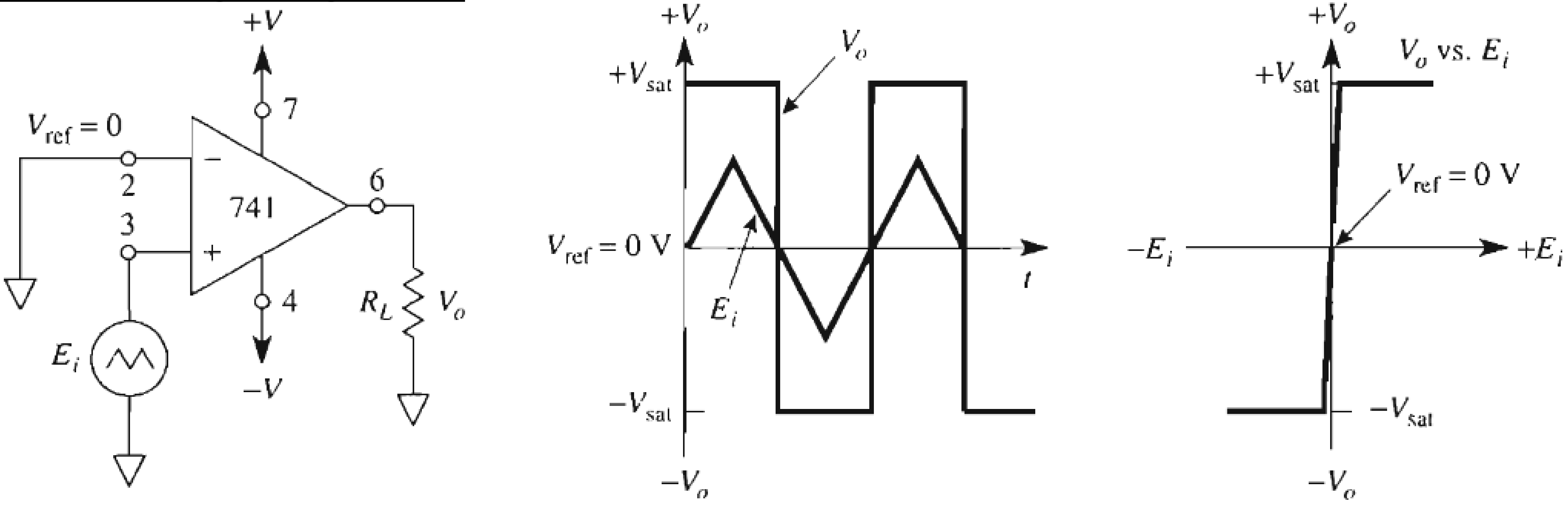
$$v_I < V_{\text{REF}} \quad \Rightarrow \quad v_O = V_H$$

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>

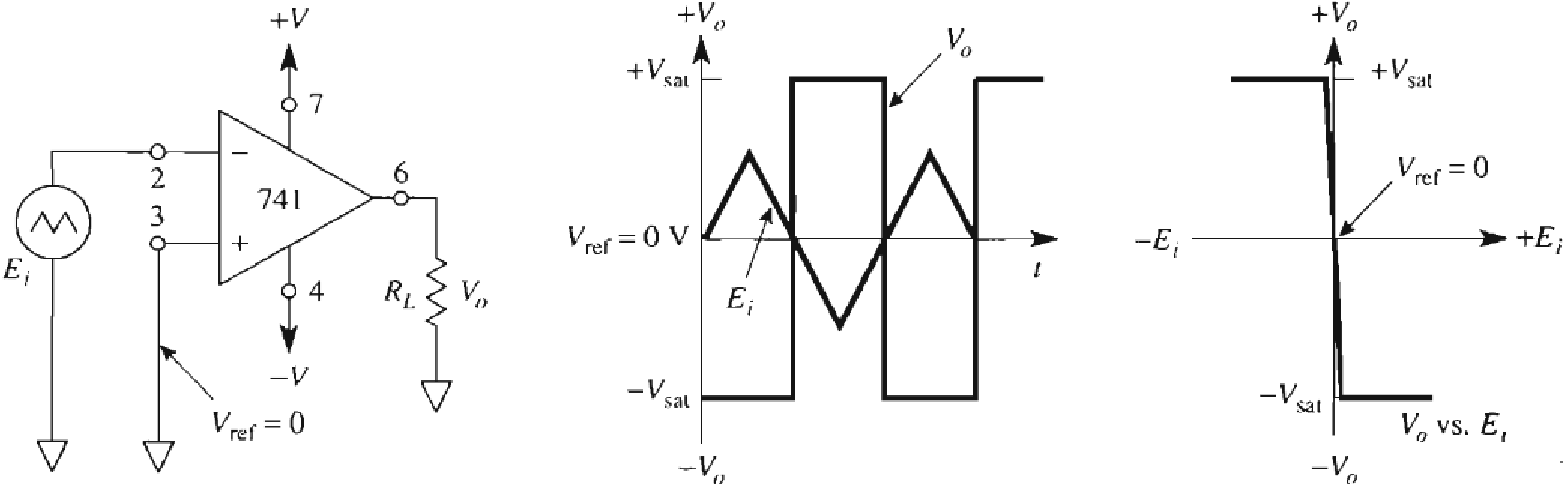


(a) Noninverting: When E_i is above V_{ref}, $V_o = +V_{sat}$.

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

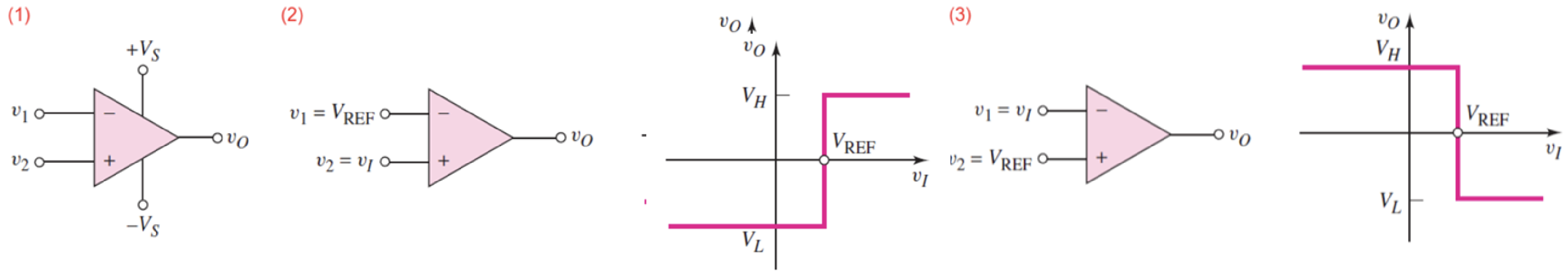


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

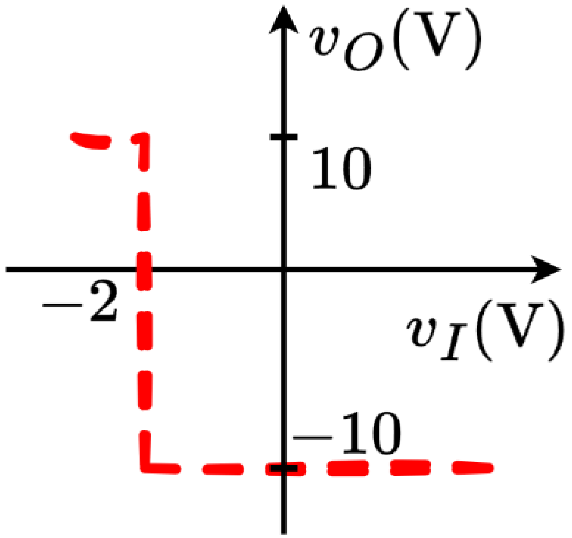
Part 2 ends here

Outline

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

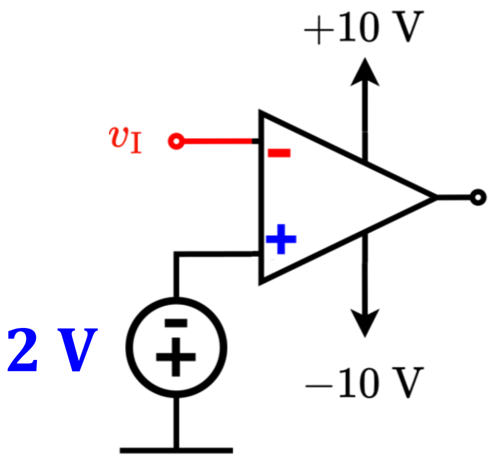
Open Loop Configuration: Example 1

- 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**.



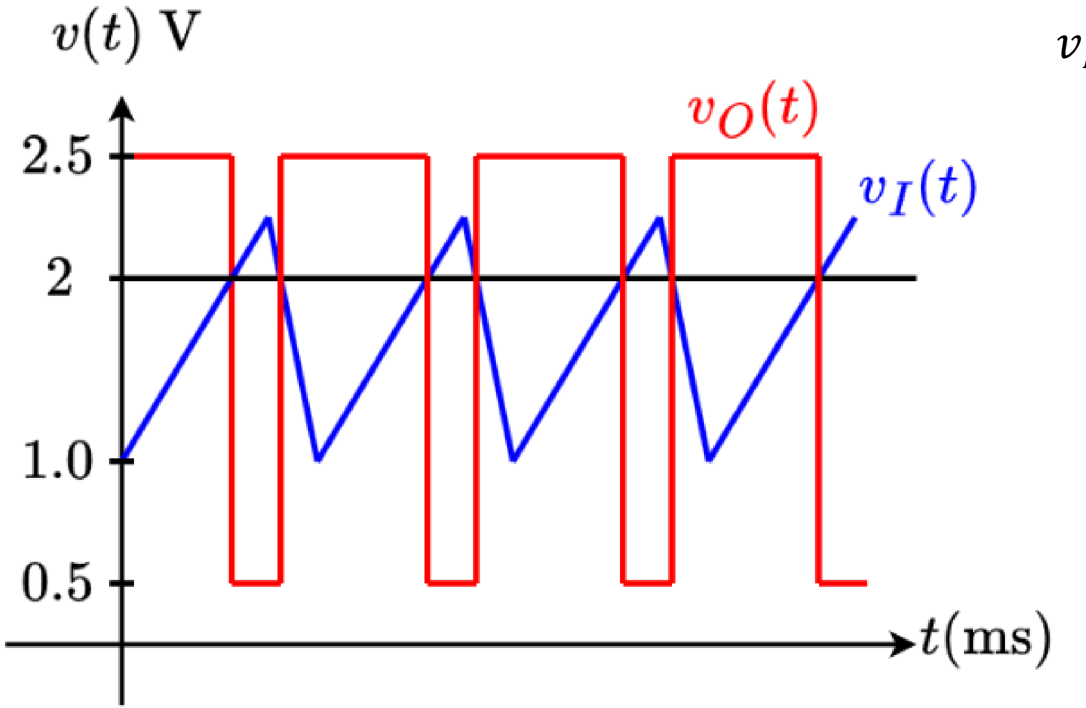
Solution:

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.

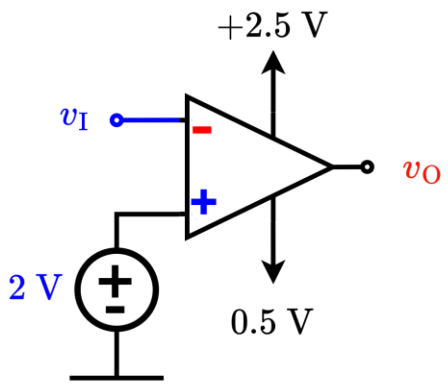


Solution:

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

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

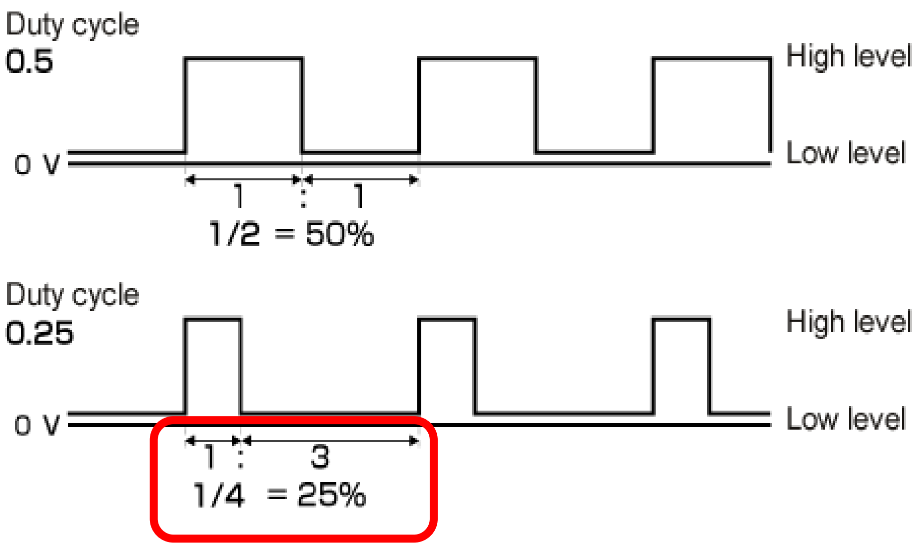
INVERTING CONFIGURATION

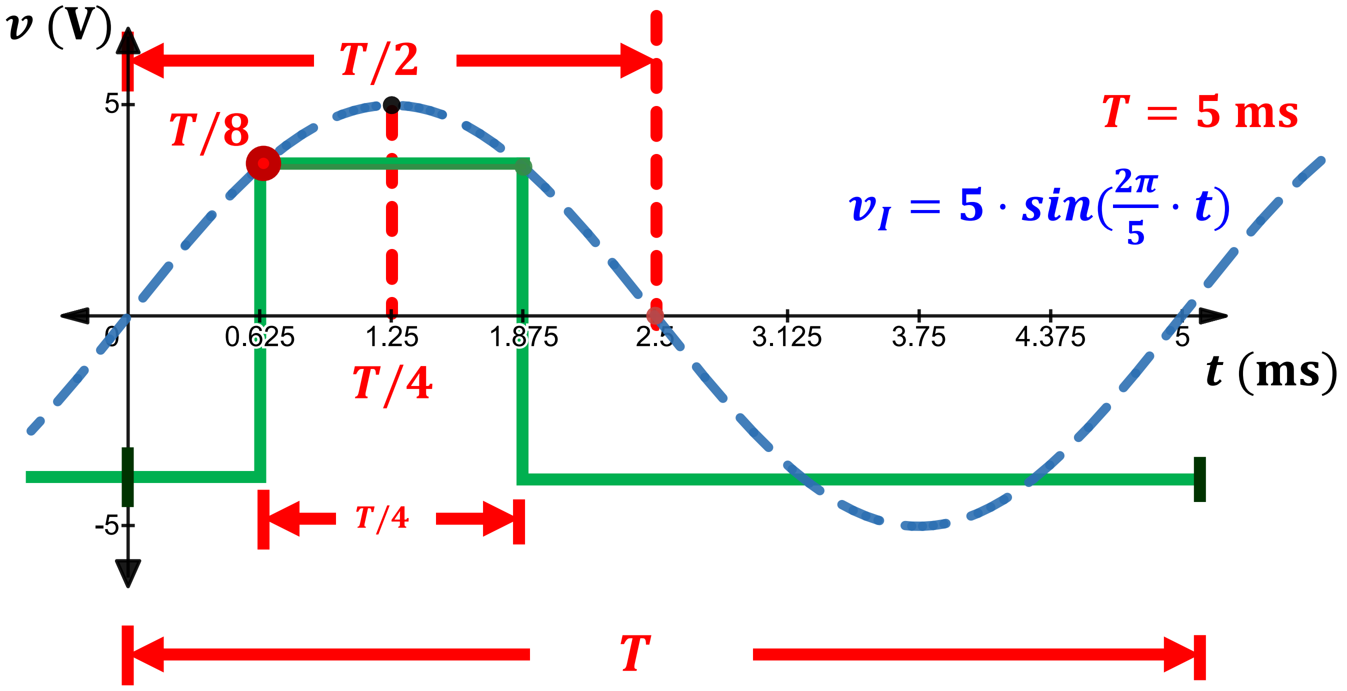


Open Loop Configuration: Example 3

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:



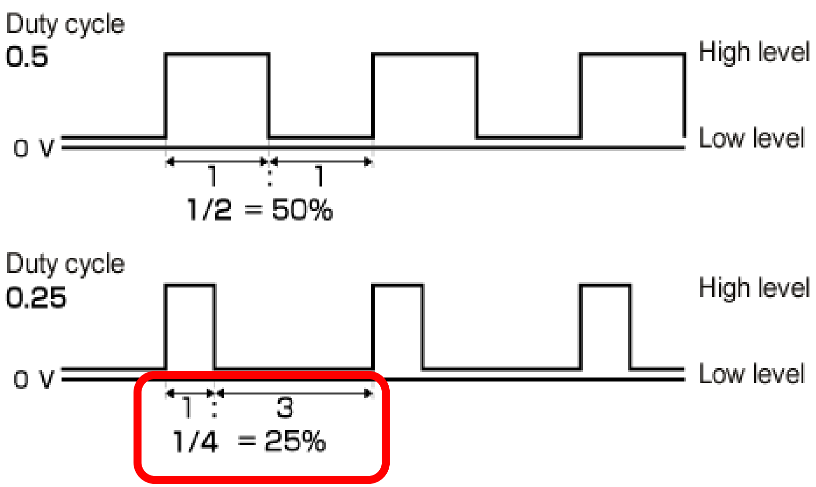


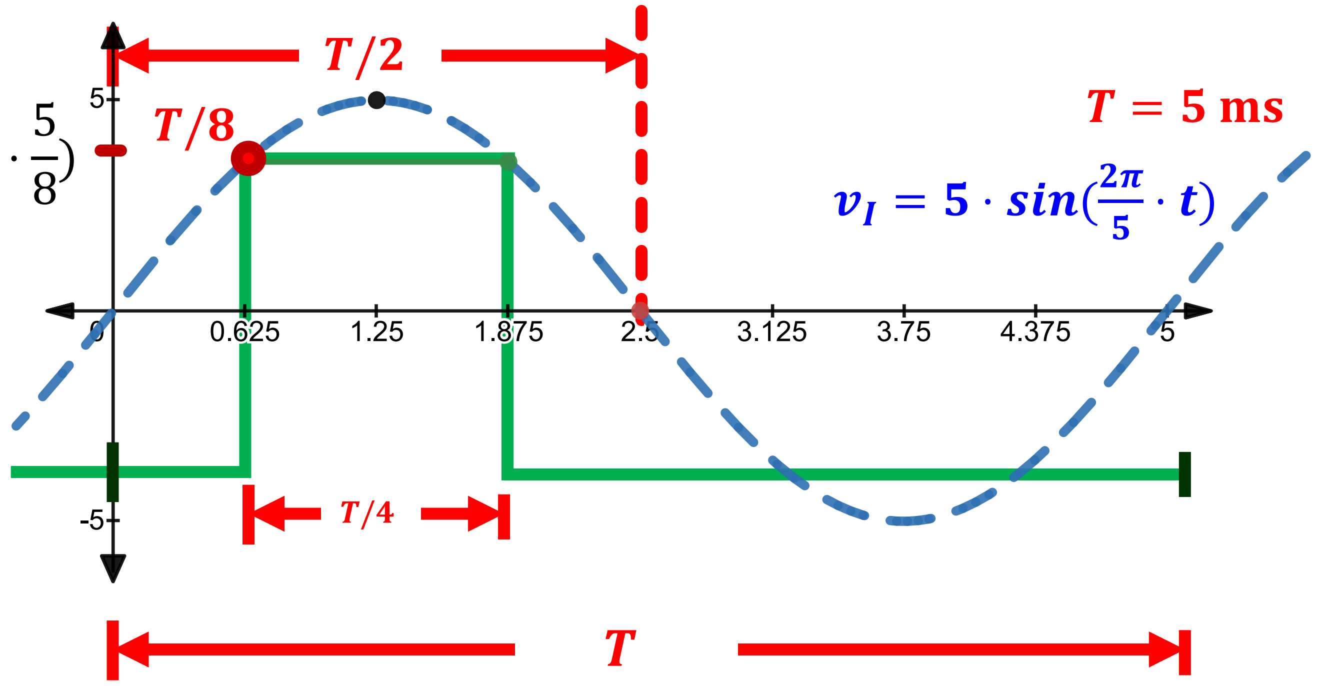
Open Loop Configuration: Example 3

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 **5** $\boldsymbol{ms}$), to: A square wave with a duty cycle of **25%**.

Solution:

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





Open Loop Configuration: Example 3

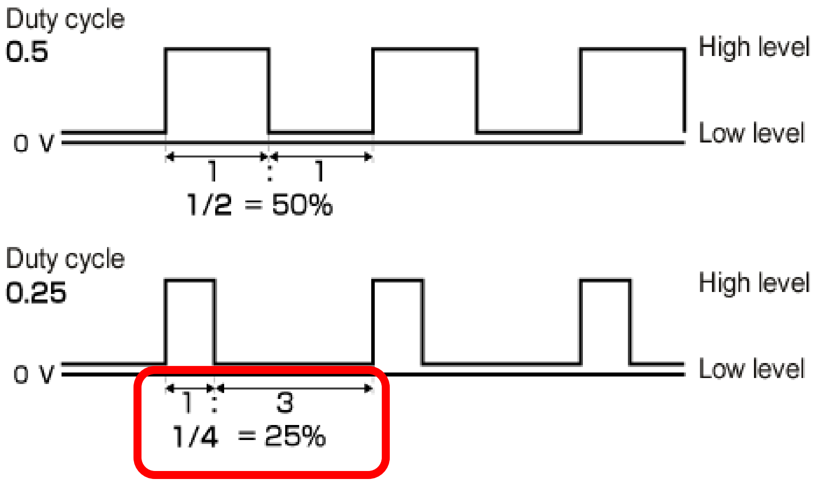
Design an op-amp circuit to transform the sinusoidal voltage, $\boldsymbol{v_I = 5 \cdot sin(\frac{2\pi}{5} \cdot t)}$ ($\boldsymbol{t}$ is in units of ms, and time-period T is $\mathbf{5}\ \boldsymbol{ms}$), to: A square wave with a duty cycle of **25%**.

Solution:

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

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

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



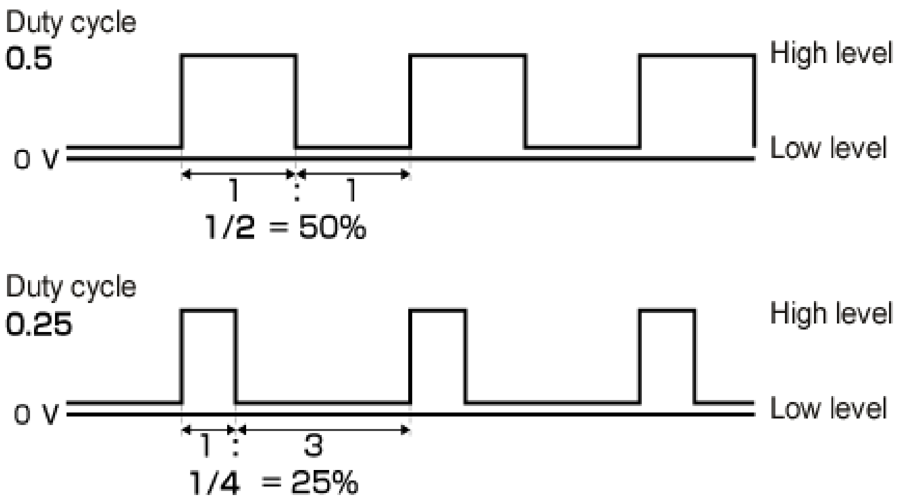
$\boldsymbol{v_I \geq 3.535\ \mathrm{V} : v_o} \rightarrow$ **Positive Saturation**

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

NON-INVERTING CONFIGURATION

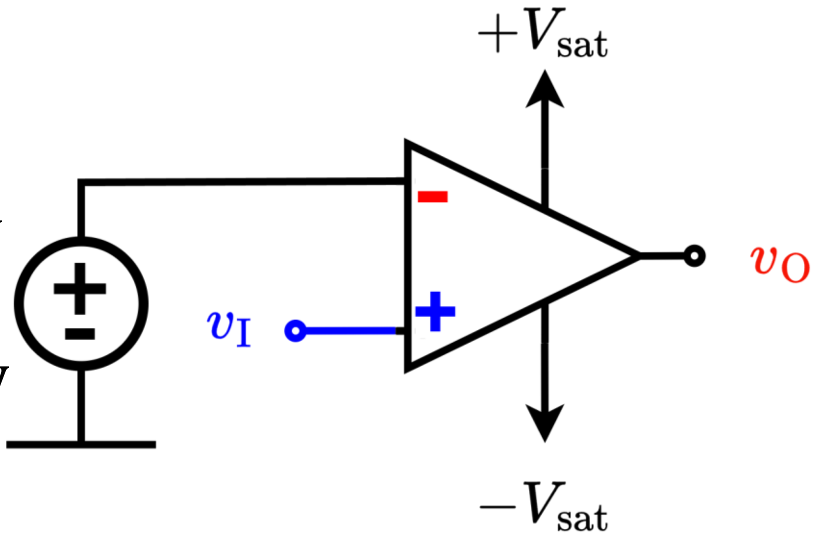
Open Loop Configuration: Example 3

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%**.



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

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



Part 3 ends here

Outline

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

Comparator Application - Smoke Detectors

Working Principle:

Smoke present → Alarm rings

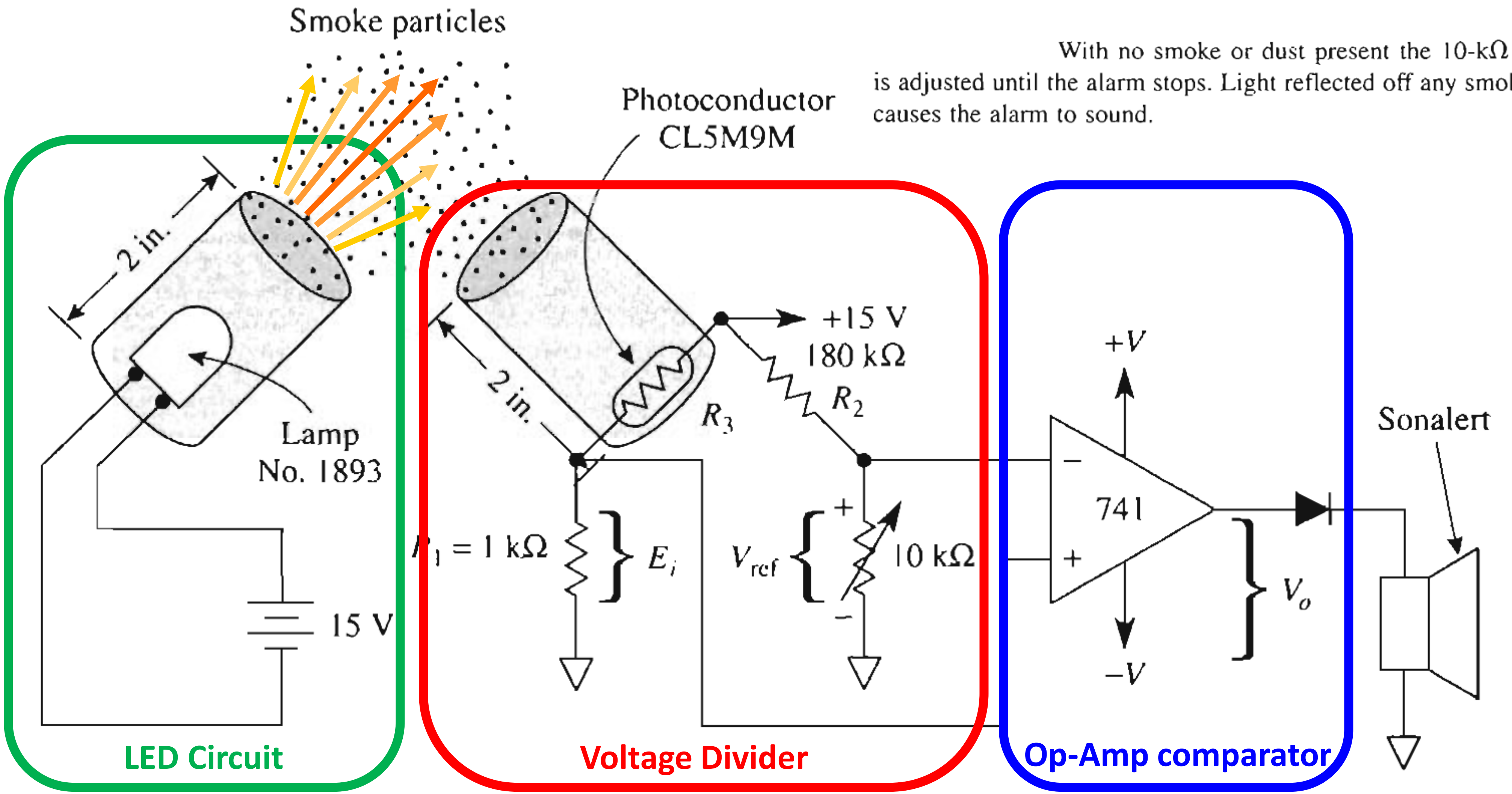
No smoke present → No Alarm rings.

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

Smoke levels → 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

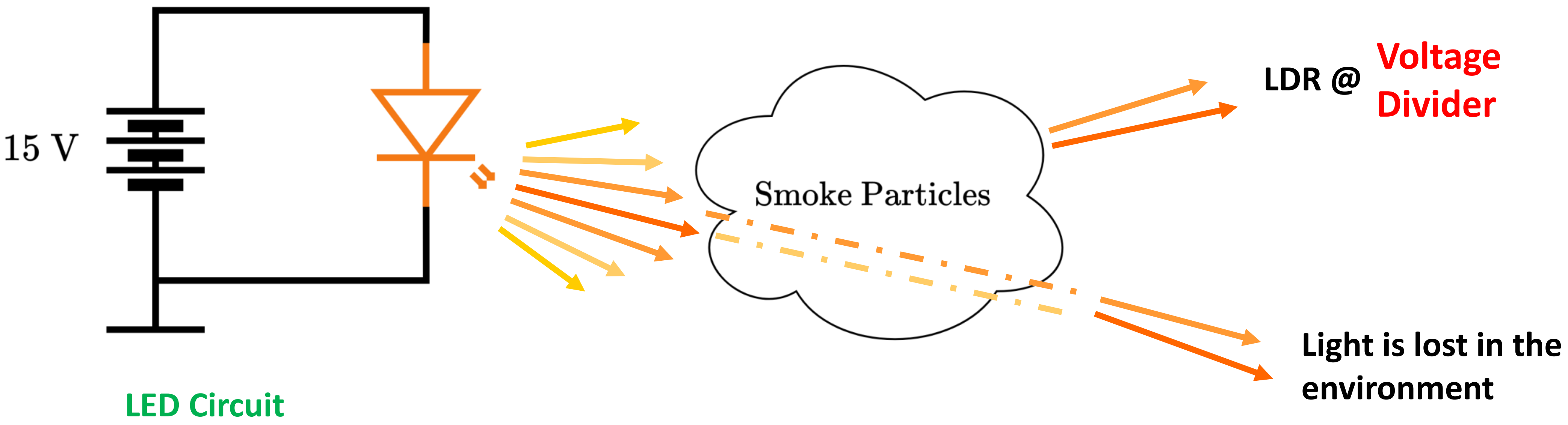
Light from the LED is reflected off the smoke particles on to the photoconductor – **Light Dependent Resistor (LDR)**.

No Smoke

- No scattering
- Low intensity at LDR (Dark - $I \downarrow$)

Smoke Present

- High scattering from smoke particles
- High intensity at LDR (Light - $I \uparrow$)



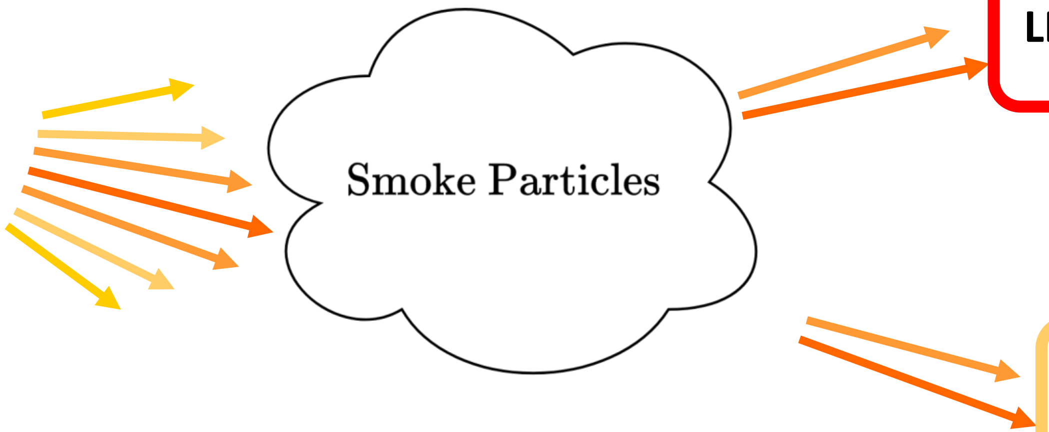
Smoke Detector - Operation

No Smoke

- No scattering
- Low intensity at LDR (Dark - $\boldsymbol{I} \downarrow$)
- High resistance across LDR ($\boldsymbol{R}_{\mathbf{LDR}} \uparrow$)

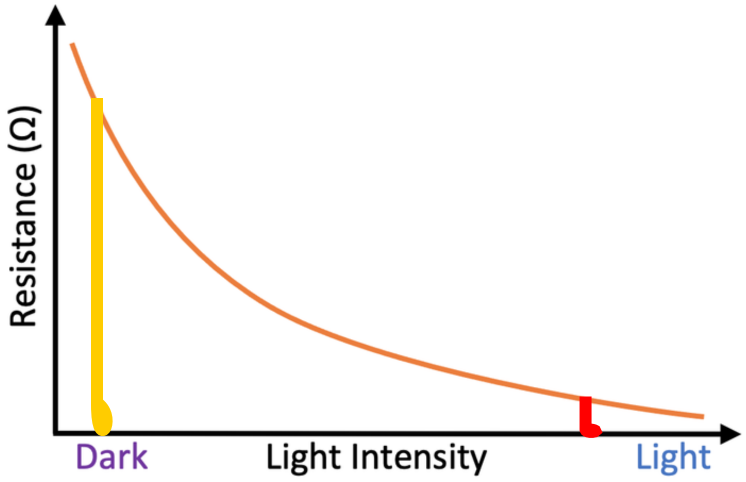
Smoke Present

- High scattering from smoke particles
- High intensity at LDR (Light - $\boldsymbol{I} \uparrow$)
- Low resistance across LDR ($\boldsymbol{R}_{\mathbf{LDR}} \downarrow$)



LDR @ Voltage Divider

Light is lost in the environment



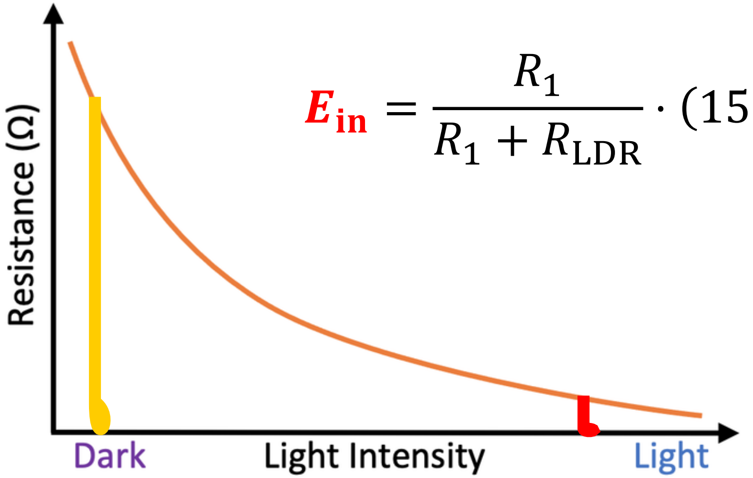
Smoke Detector - Operation

No Smoke

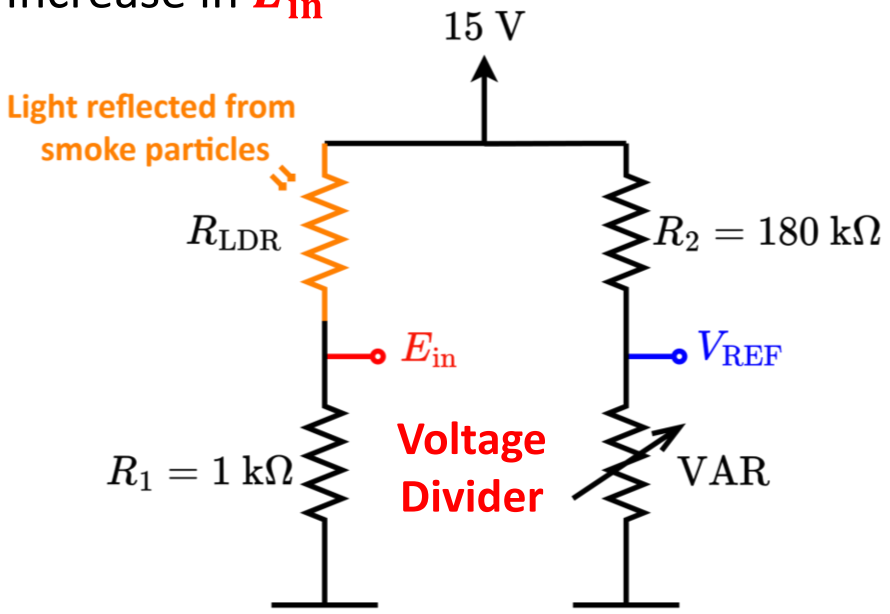
- No scattering
- Low intensity at LDR (Dark - $\boldsymbol{I}$ ↓)
- High resistance across LDR ($\boldsymbol{R}_{\mathbf{LDR}}$ ↑)
- Decrease in $\boldsymbol{E}_{\mathbf{in}}$

Smoke Present

- High scattering from smoke particles
- High intensity at LDR (Light - $\boldsymbol{I}$ ↑)
- Low resistance across LDR ($\boldsymbol{R}_{\mathbf{LDR}}$ ↓)
- Increase in $\boldsymbol{E}_{\mathbf{in}}$



$$\boldsymbol{E}_{\mathbf{in}} = \frac{R_1}{R_1 + R_{\mathrm{LDR}}} \cdot (15\ \mathrm{V}) \propto \frac{\mathbf{15}}{\boldsymbol{R_{LDR}}}\ \mathbf{V}$$



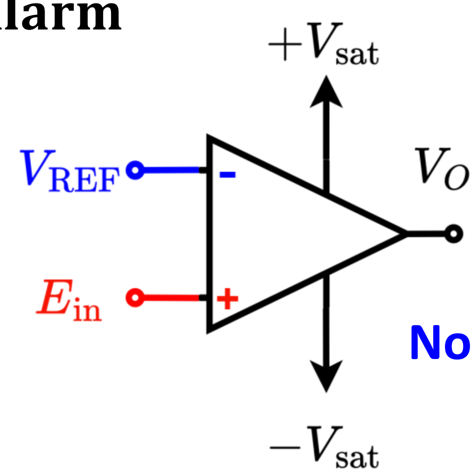
Smoke Detector - Operation

No Smoke

- No scattering
- Low intensity at LDR (Dark - $\boldsymbol{I} \downarrow$)
- High resistance across LDR ($\boldsymbol{R_{\mathrm{LDR}}} \uparrow$)
- Decrease in $\boldsymbol{E_{\mathrm{in}}}$
- **Possibility of** $(\boldsymbol{E_{\mathrm{in}}} < \boldsymbol{V_{\mathrm{REF}}})$
- $\boldsymbol{V_O = -V_{\mathrm{sat}} \rightarrow}$ **No Alarm**

Smoke Present

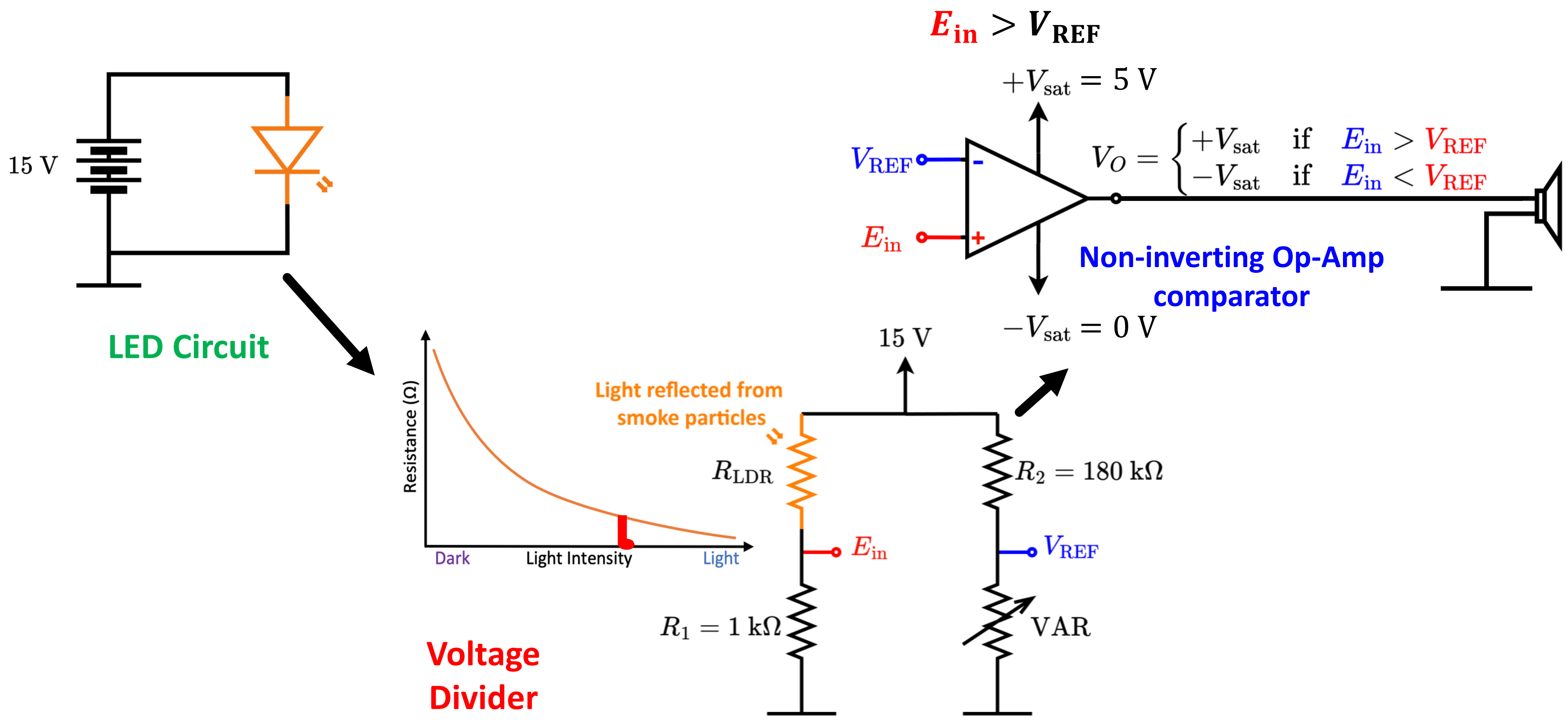
- High scattering from smoke particles
- High intensity at LDR (Light - $\boldsymbol{I} \uparrow$)
- Low resistance across LDR ($\boldsymbol{R_{\mathrm{LDR}}} \downarrow$)
- Increase in $\boldsymbol{E_{\mathrm{in}}}$
- **Possibility of** $(\boldsymbol{E_{\mathrm{in}}} > \boldsymbol{V_{\mathrm{REF}}})$
- $\boldsymbol{V_O = +V_{\mathrm{sat}} \rightarrow}$ **Alarm Rings!**



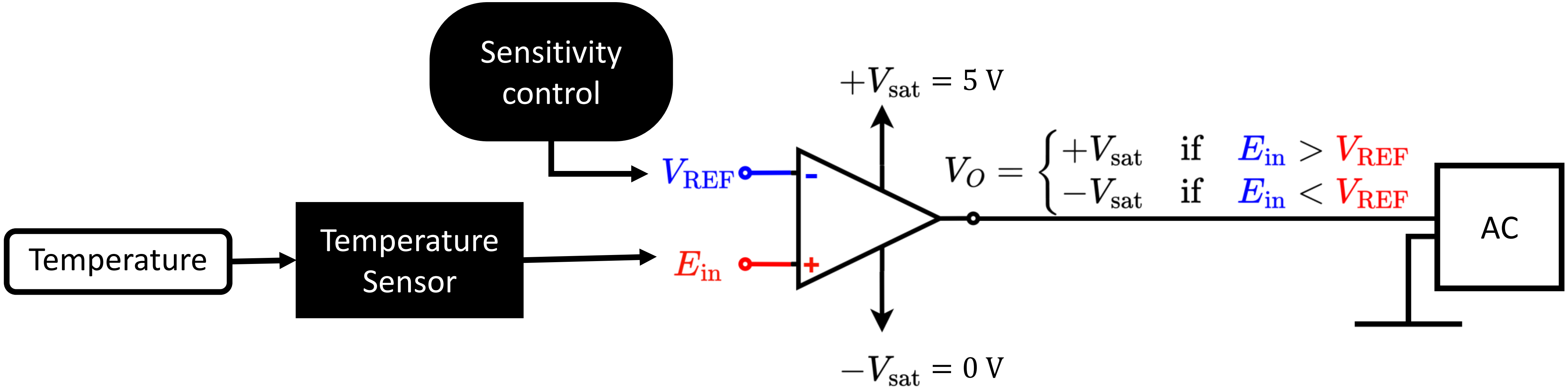
$$V_O = \begin{cases} +V_{\mathrm{sat}} & \text{if} \quad E_{\mathrm{in}} > V_{\mathrm{REF}} \\ -V_{\mathrm{sat}} & \text{if} \quad E_{\mathrm{in}} < V_{\mathrm{REF}} \end{cases}$$

Non-inverting Op-Amp comparator

Smoke Detector - Operation



Comparator Application – Automatic AC

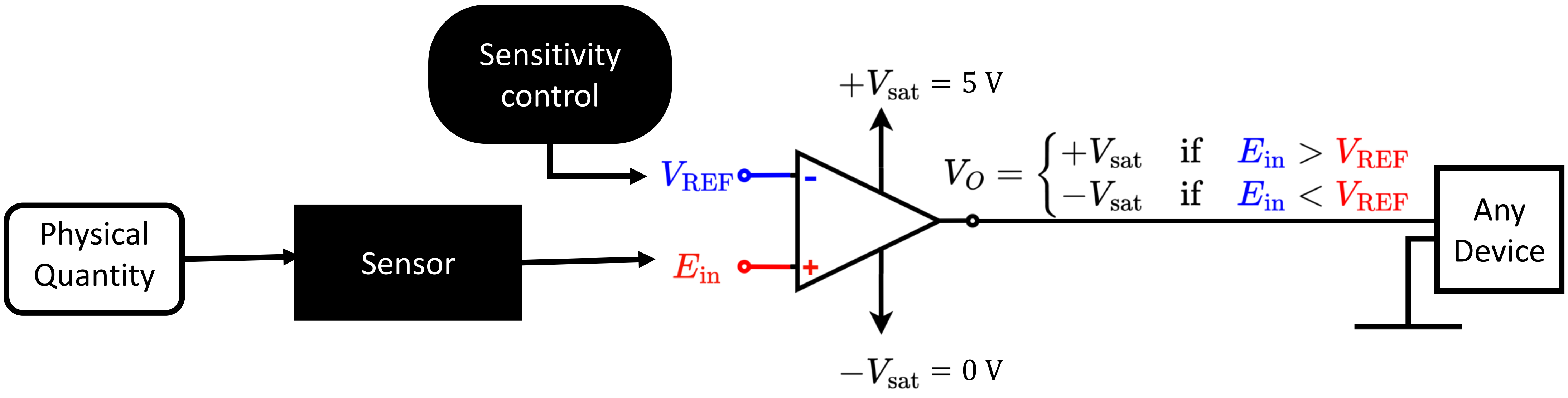


- Comparators can be used to switch on an **AC** based on a **Temperature**.

  Temp. ↑ **AC** - ON

  Temp. ↓ **AC** – OFF – Non-inverting relationship
- The sensitivity of **switching on the AC** is determined by $\boldsymbol{V_{REF}}$

Summary



- Comparators can be used to switch on **any device** based on a **physical quantity**.
- The sensitivity of **switching** is determined by $\boldsymbol{V_{REF}}$

Question: 01

An automatic AC switching system using an Op-Amp comparator that will turn on automatically whenever the temperature is higher than 20° Celsius. The output waveform of an Op-Amp comparator should be between the voltage range **of [-4V 5V].** The temperature sensor used with the circuit produces a voltage signal of 1.5V for a temperature value of 20° Celsius.

a) Design and draw the comparator circuit with the required inputs. [3]

b) Draw the VTC curve for your designed comparator. [2]

Question: 02

Design an **automatic room heater** switching system using an Op-Amp comparator that will turn on automatically whenever the temperature is lower than **20° Celsius**. The output waveform of the comparator should be between the voltage range of **[-4V 5V].** The temperature sensor produces a voltage signal of **2.5V** for a temperature value of **20° Celsius**.

a) Design and draw the comparator circuit with the required inputs. [3]

b) Draw the VTC curve for your designed comparator. [2]

Question: 03

An automated **smoke detector** system using an Op-Amp comparator that will turn on automatically whenever the particle density in the air is higher than **2.5×10^{26}** m^{-3}. The output waveform of an Op-Amp comparator should be between the voltage range of **[-6V 6V].** The smoke particle sensor used with the circuit produces a voltage signal of **2.0V** for a particle density of **2.5×10^{26}** m^{-3}.

a) **Design** and **draw** the comparator circuit with the required inputs. [3]

b) **Draw** the VTC curve for your designed comparator. [2]

Question: 04

Farhan, CEO of Rajshahi WASA, is building a water level indicator for an overhead tank. For this, he placed three sensors at three different levels of the tank. The voltage outputs of the three sensors are denoted as V_1 (lowest level), V_2 (mid-level), and V_3 (highest level). Farhan decided that the indicator for the water level would be,

$$V_{\text{indicator}} = \frac{1}{k}(V_1 + V_2 + V_3)$$

(a) Assuming $k = 1$, **design** the circuit using op amps that will take V_1, V_2, and V_3 as *input* and will produce $V_{\text{indicator}}$ as *output*. [3]

Upon further experimentation, Farhan realized that the maximum values of V_1, V_2, and V_3 are 5 V. Hence, the maximum value of $V_1 + V_2 + V_3$ can be 15 V. However, Farhan only has access to +5 V and −5 V as power supplies, meaning that the $V_{\text{indicator}}$ cannot be greater than +5 V or less than −5 V.

(b) **Choose** a value of k such that the maximum value of $V_{\text{indicator}}$ is within the given range. [1]

(c) **Design** the circuit in part (a) again using this new value of k. [2]

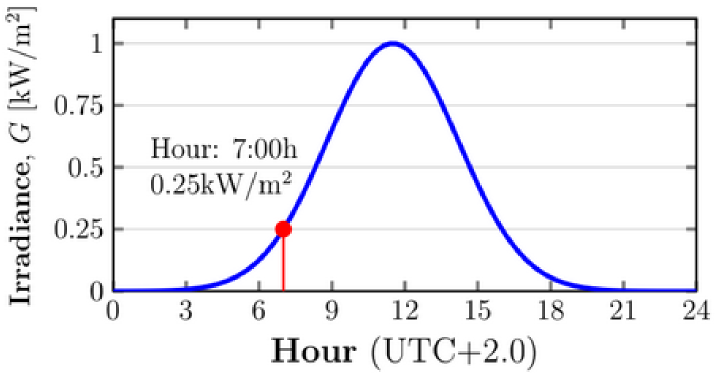
Question: 05

Figure 1 shows the variation of direct solar irradiance, **G** (in units of $\mathbf{kW/m^2}$) throughout the day in Greece. The irradiance is $\mathbf{0.25\ kW/m^2}$ at **7:00 hours**. A photodetector generates a voltage of $\mathbf{V_S}$ by converting solar irradiance **G** (in units of $\mathbf{kW/m^2}$) according to the following equation:

$$V_S(G) = 4G^2 + 9G \qquad (1)$$

You have to design an automatic system with an Op-Amp comparator circuit. This system will take $\mathbf{V_S}$ as an input from a photodetector and control a street fan, ensuring it meets the following **conditions**:

- The fan has to switch **ON** after **7:00 hours**.
- The fan switches **ON** when system output is **5 V**.
- The fan switches **OFF** when system output is **0 V**.



Based on the above scenario, answer the following questions:

a. Calculate the photodetector voltage $\mathbf{V_S}$ **at 7:00 hours**. **Determine** how V_S changes before and after 7:00 hours. (2 marks)

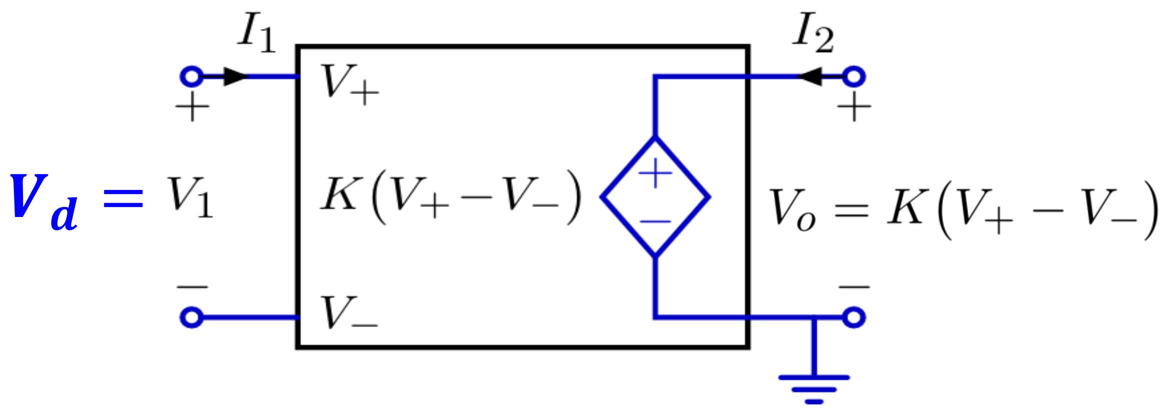
b. Determine whether the Op-Amp comparator circuit of the system should be in an **inverting or non-inverting** configuration. **Justify** your choice by explaining briefly how this configuration meets the conditions mentioned above. (3 marks)

c. Draw the completed Op-Amp comparator circuit marking the input and output terminals and the positive and negative saturation voltages. Also clearly **indicate the reference voltage** against which the input of the comparator is compared. (5 marks)

Op-Amp: Circuit Modelling

Voltage controlled voltage Source

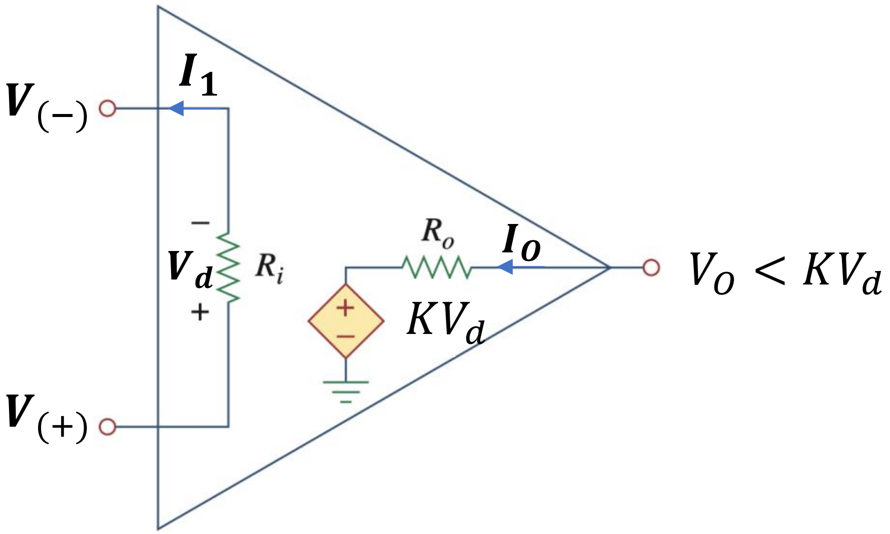
“Ideal” op-amp approximation



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

$$I_1 \approx 0$$

“Non-Ideal” op-amp approximation



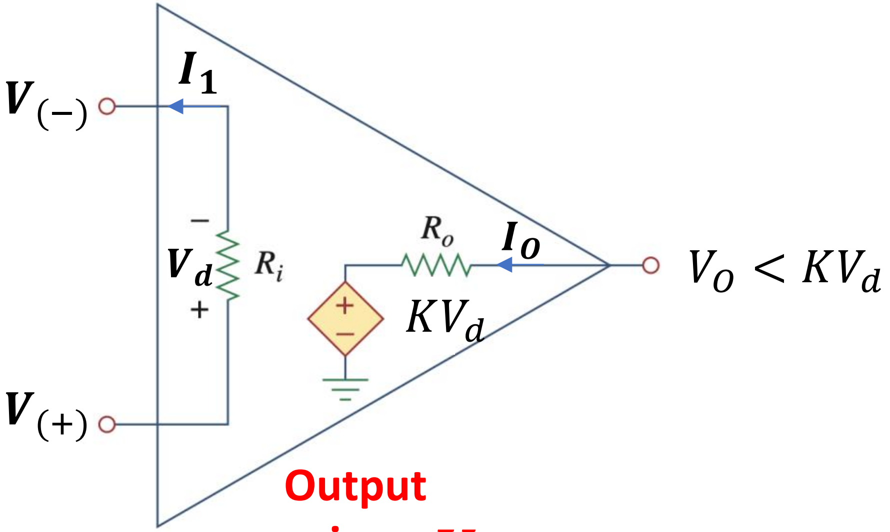
$$V_d = V_{(+)} - V_{(-)} \neq 0$$

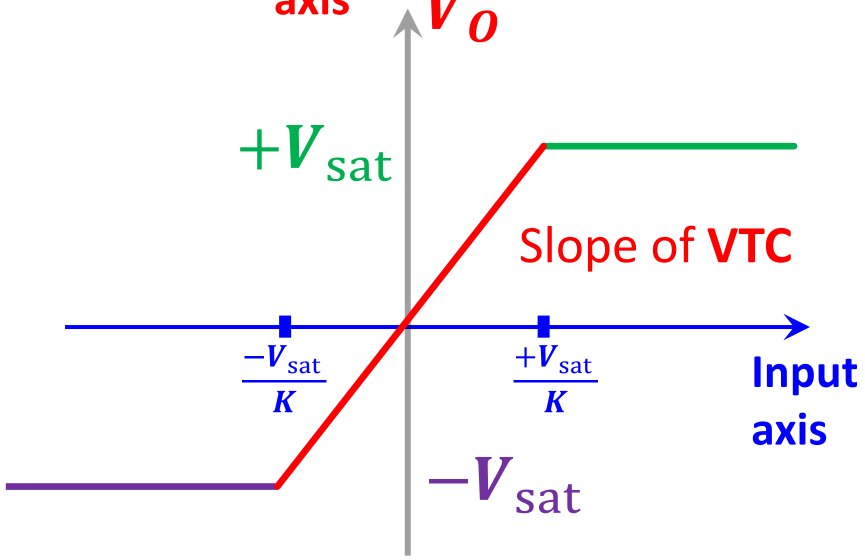
$$I_1 > 0$$

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
A or K	$10^4 - 10^8$	∞
R_i	$100\ k\Omega - 10^{10}\ k\Omega$	∞
R_o	$0.01\ k\Omega - 0.1\ k\Omega$	0

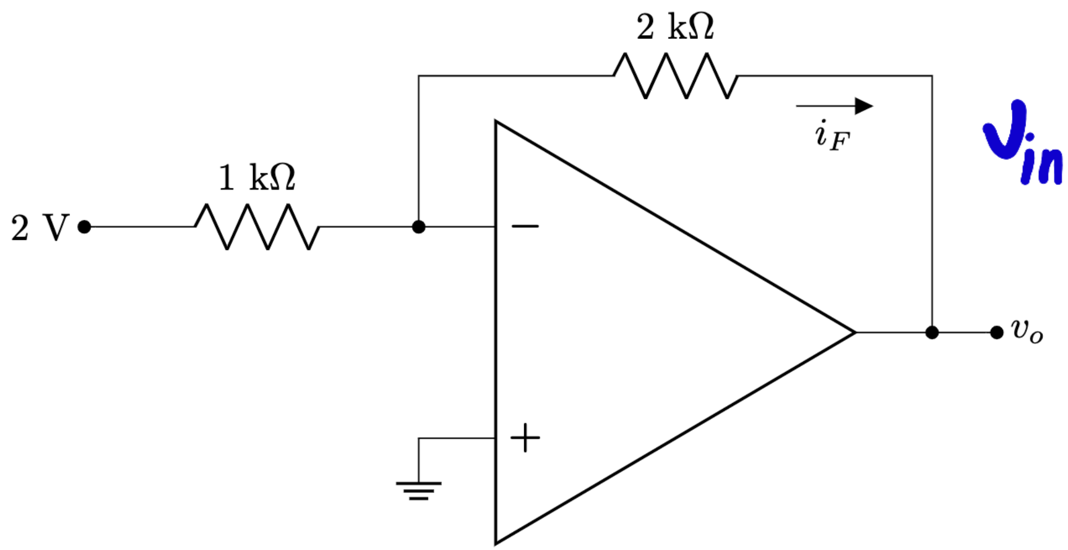


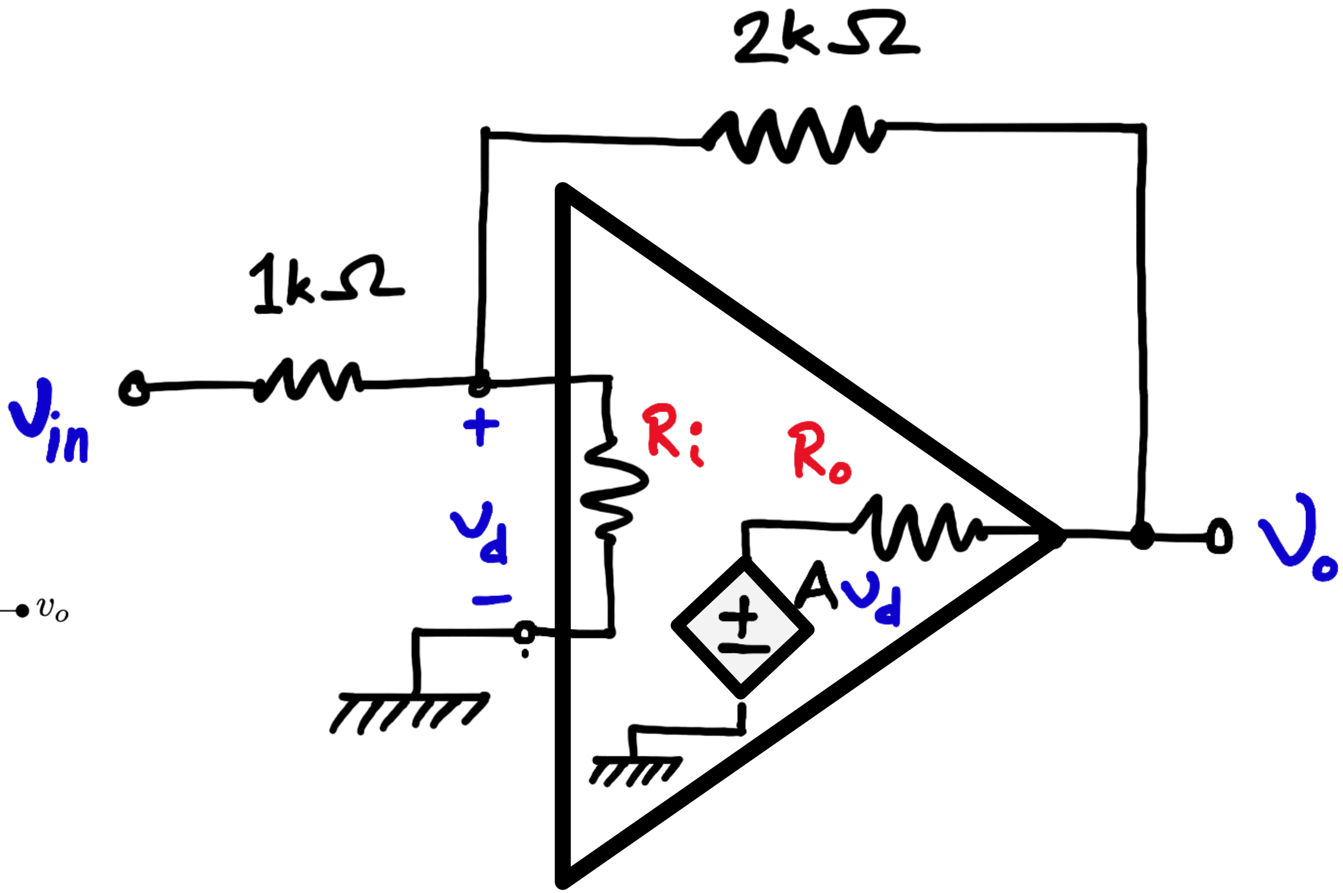


Practice Problem – op-amp

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

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





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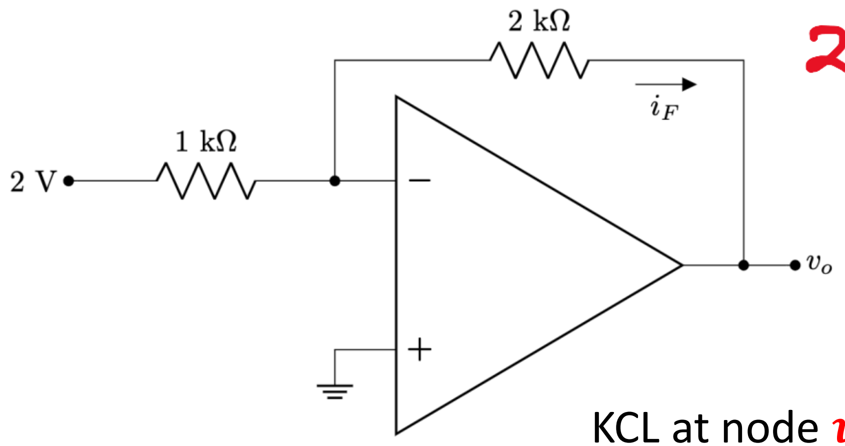
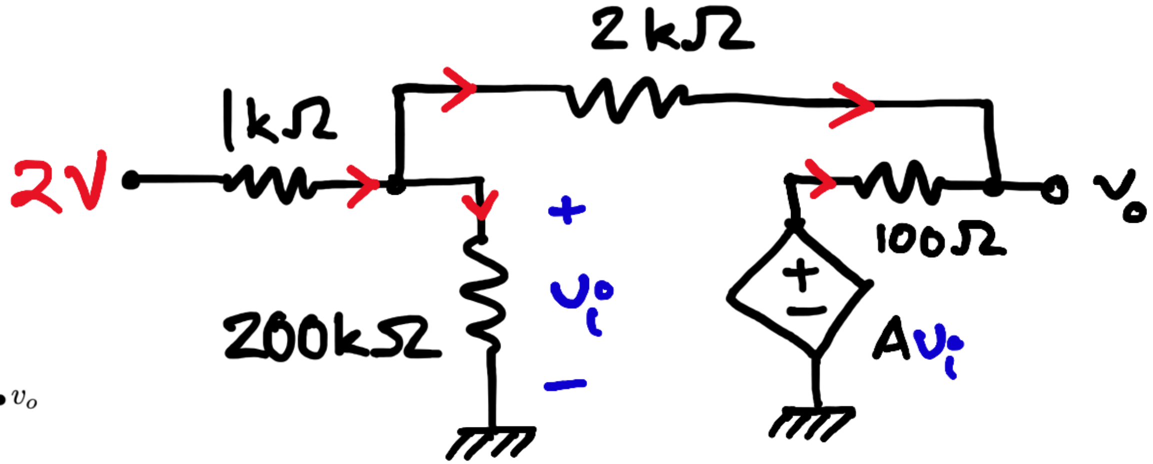




KCL at node $\boldsymbol{v_i}$

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

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

KCL at node $\boldsymbol{v_o}$

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

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

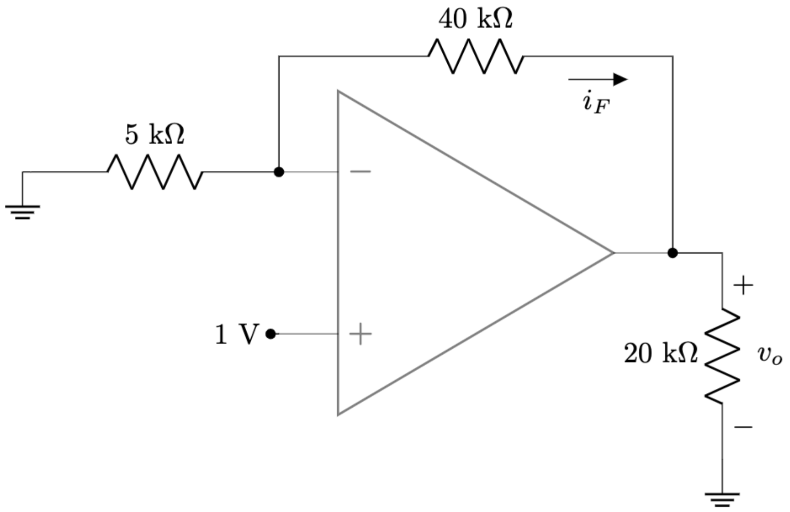
$$\boxed{\begin{array}{c} \boldsymbol{v_i = -21\ \mu V} \\ \boldsymbol{v_o = -3.999\ V} \\ \boldsymbol{i_F = 2\ mA} \end{array}}$$

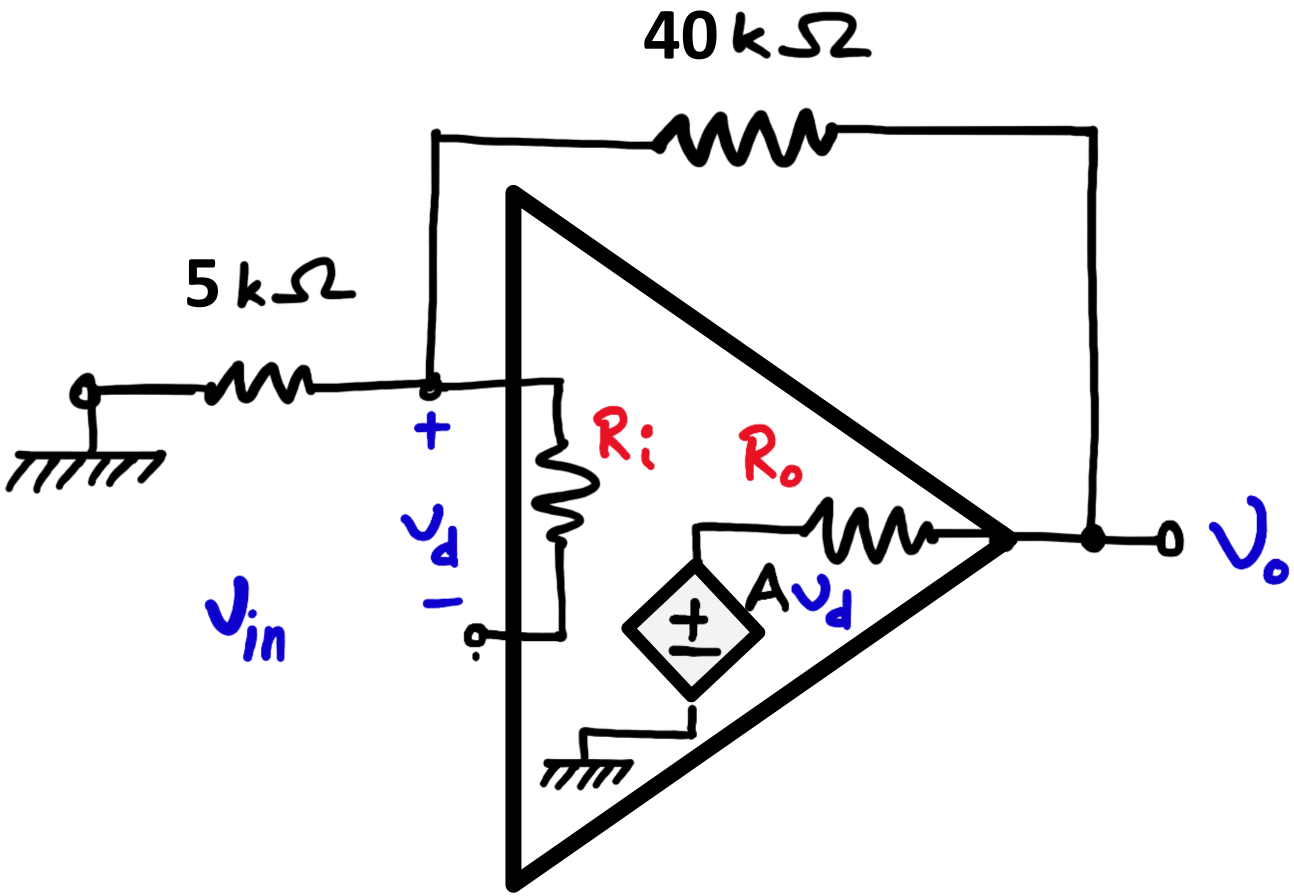
Some circuits with OP-AMP

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

Here,

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

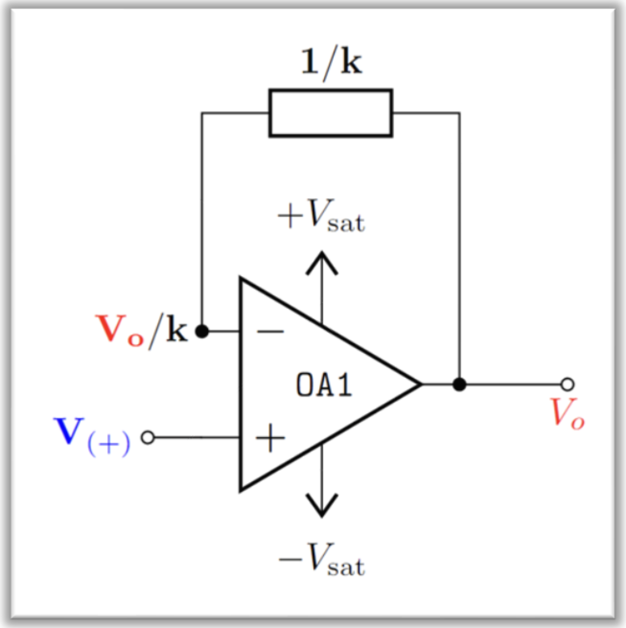




Part 5 ends here

Closed Loop Configuration

Feedback



Outline

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

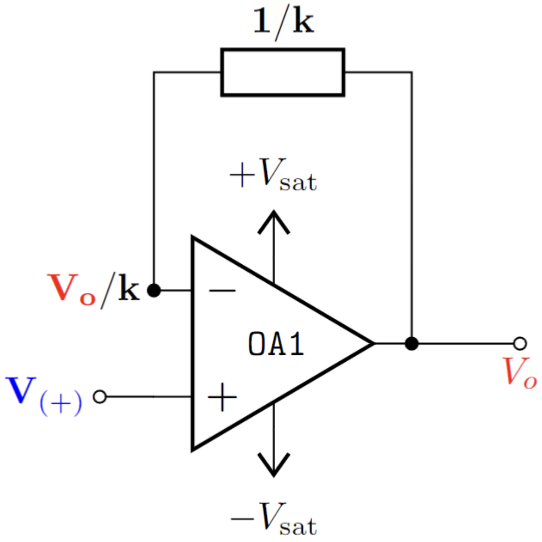
Feedback in Op-Amp circuit

Two types of feedback

1. Negative Feedback:

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

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

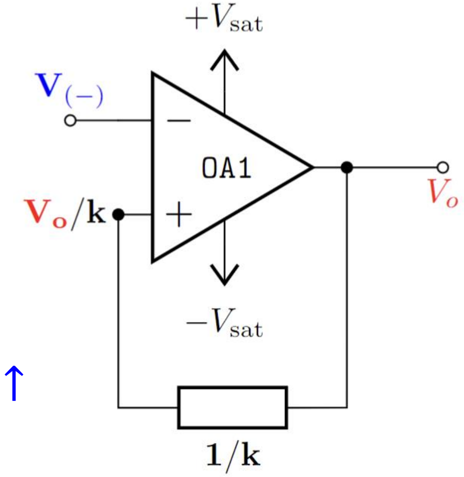


$$V_o \uparrow \quad \Rightarrow \frac{V_o}{k} \uparrow \quad \Rightarrow V_{(-)} \uparrow \quad \boxed{\Rightarrow V_d \downarrow = V_{(+)} - V_{(-)} \uparrow} \quad \Rightarrow V_o \propto V_d \downarrow$$

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

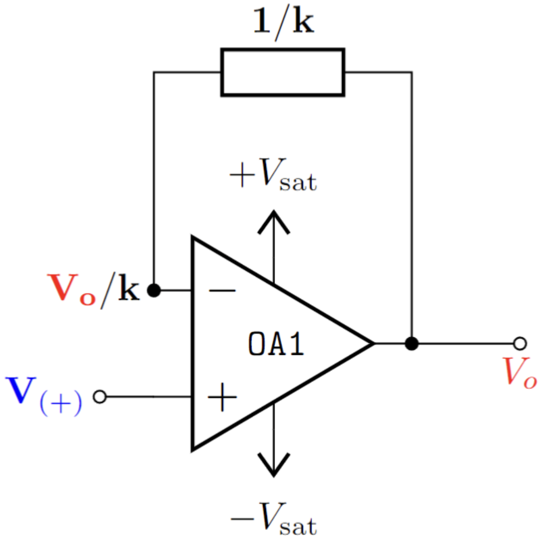
Two types of feedback

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:

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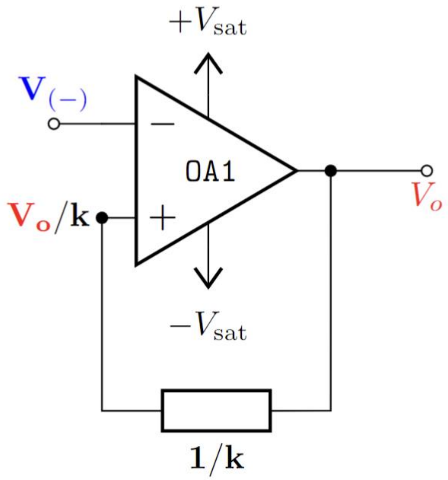
   The output voltage is connected to the **non-inverting** terminal

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



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

We know, $V_o = AV_d$

$$V_o = A\left(V_{(+)} - V_{(-)}\right)$$

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

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

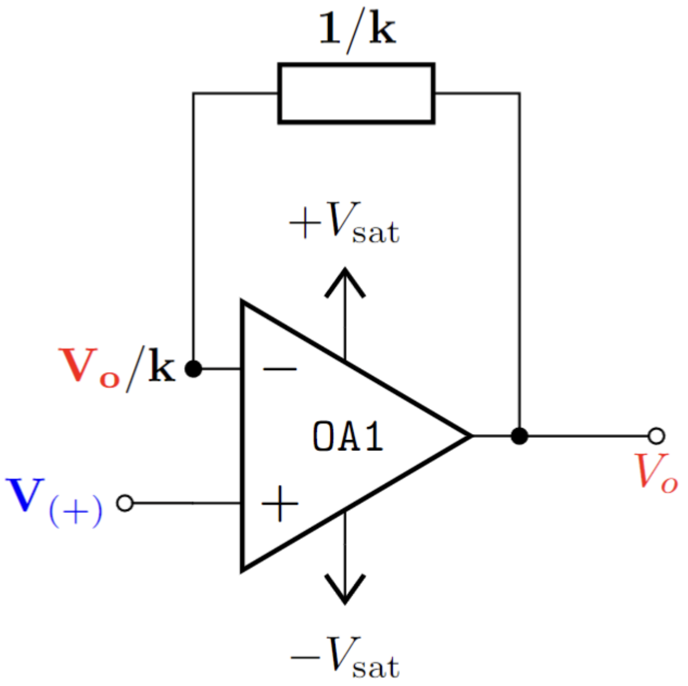
$$\Rightarrow V_o\left(1 + \frac{A}{k}\right) = AV_{(+)}$$

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

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

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

This is the new amplification factor / Gain

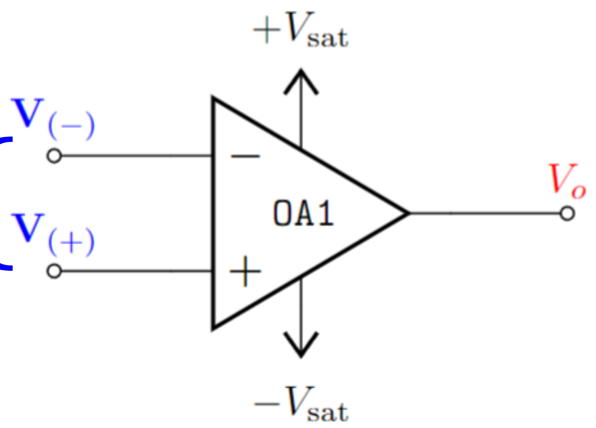


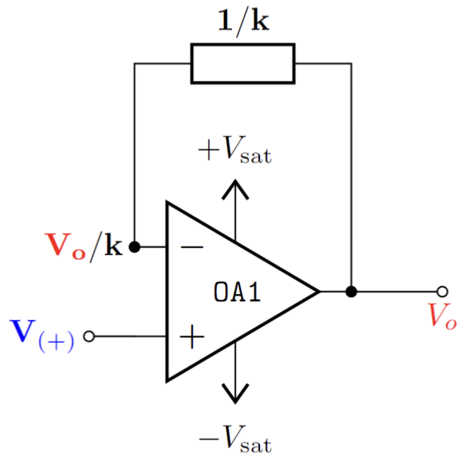
Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration

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

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





Input Voltage: $\boldsymbol{V_d}$
Output Voltage: $\boldsymbol{V_O}$

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

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

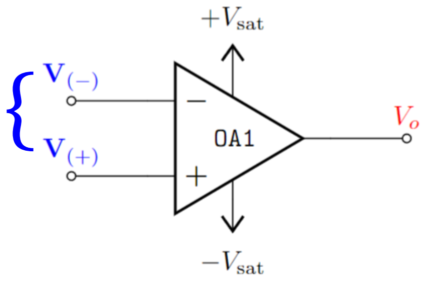
Input Voltage: $\boldsymbol{V_{(+)}}$
Output Voltage: $\boldsymbol{V_O}$

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

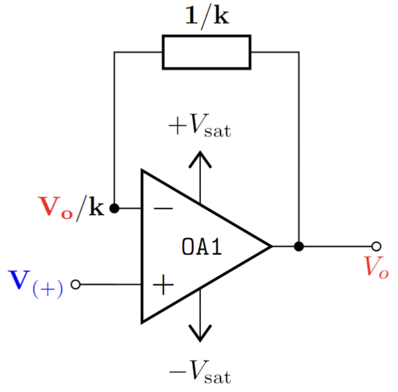
Open Loop Gain VS Closed Loop Gain

Open Loop (OL) Configuration

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



Closed Loop (CL) Configuration



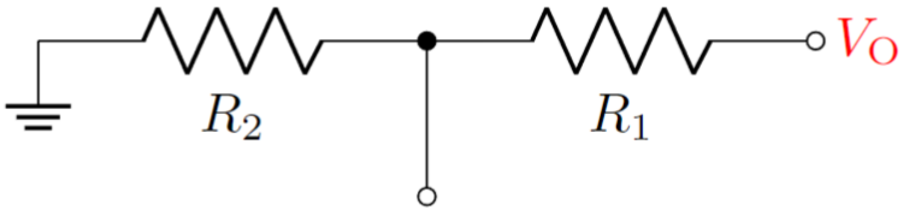
OL Gain	CL Gain
$\frac{V_o}{V_d} = A \text{ or } K \sim 10^5$	$\frac{V_o}{V_{(+)}} = k \ll A$ $k < 100$
Can't be controlled	Can be controlled by the feedback element
*Used as "**Comparator**"*	*Used as "**Linear Amplifier**"*

Negative Feedback in Op-Amp circuit

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

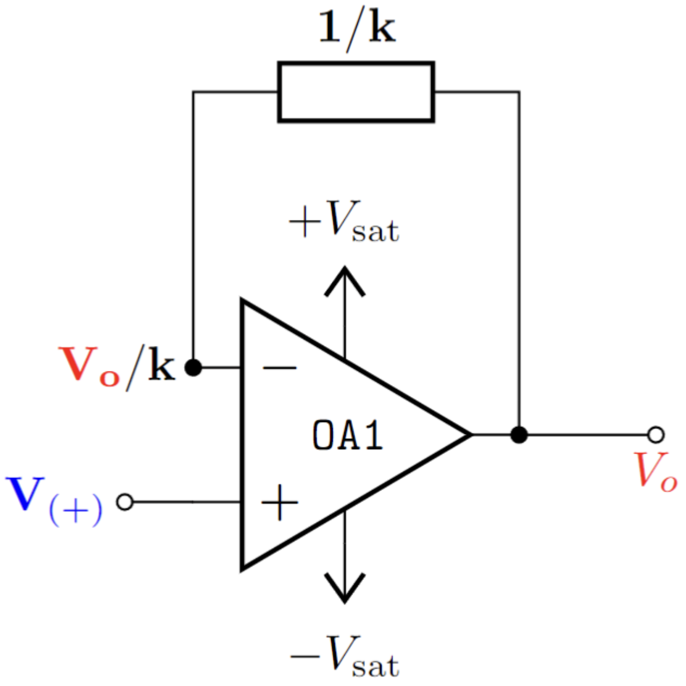
$$\boldsymbol{V_{(-)}} = \frac{\mathbf{1}}{\boldsymbol{k}} \cdot \boldsymbol{V_O}$$

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



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

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

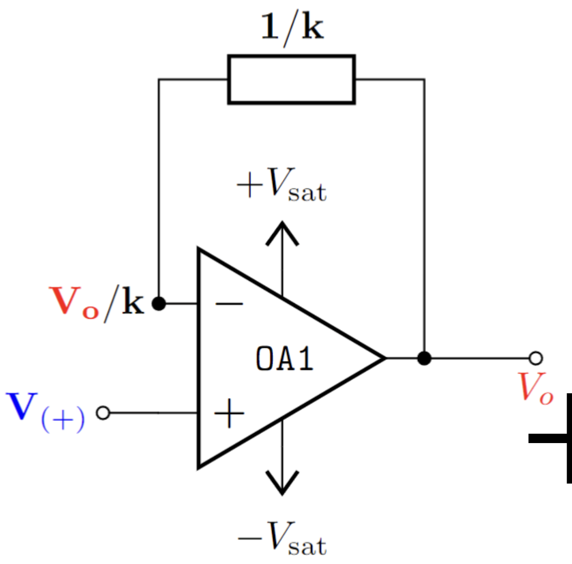


A voltage divider can act as a **multiplier/factor** in the **feedback** branch

Negative Feedback in Op-Amp circuit

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

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



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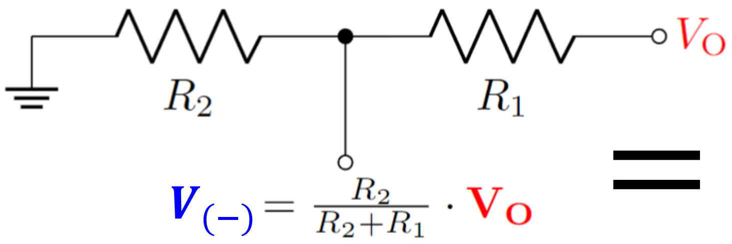

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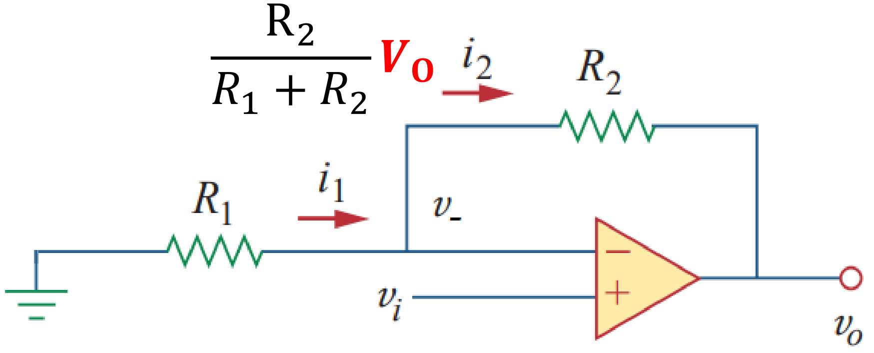
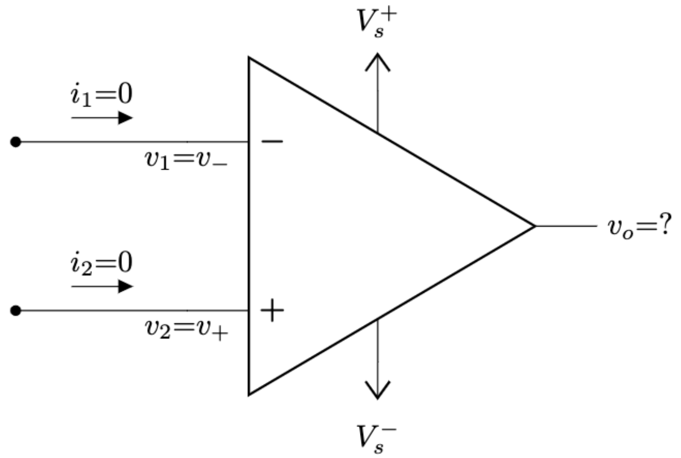


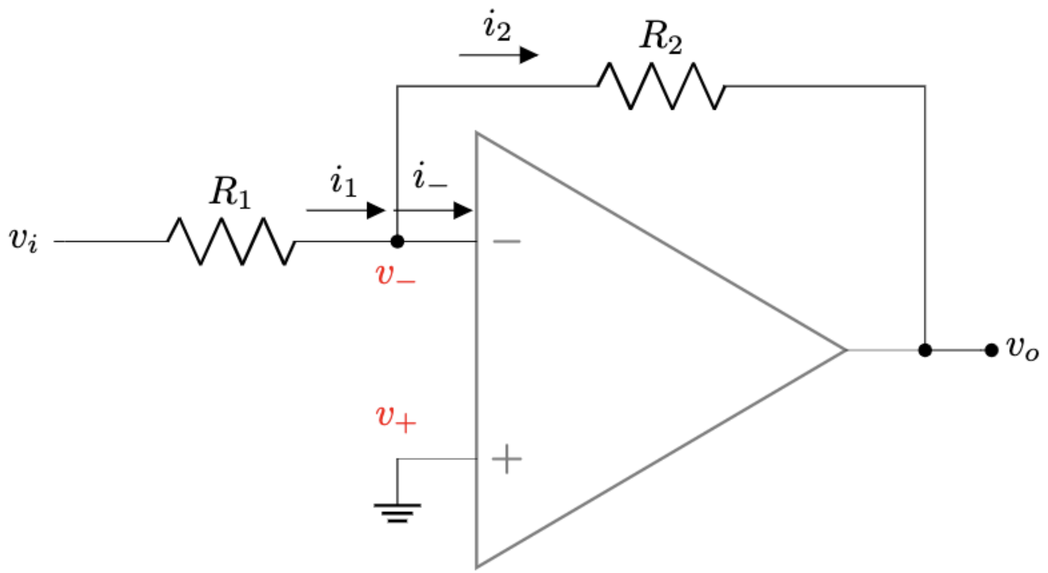
If $\boldsymbol{k}$ = 10 (meaning we feed back one tenth of the output to negative input), we will get $\boldsymbol{v_o}$=10*$\boldsymbol{v_i}$. that is 10-fold gain.

Solving Closed Loop Op-Amp Circuit

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



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 $R_1 \Rightarrow i_1 = \frac{v_i - 0}{R_1} = \frac{v_i}{R_1}$

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]