



Inspiring Excellence

# **CSE 251**

# **Electronic Devices and Circuits**

## **Lecture 3**

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# Outline

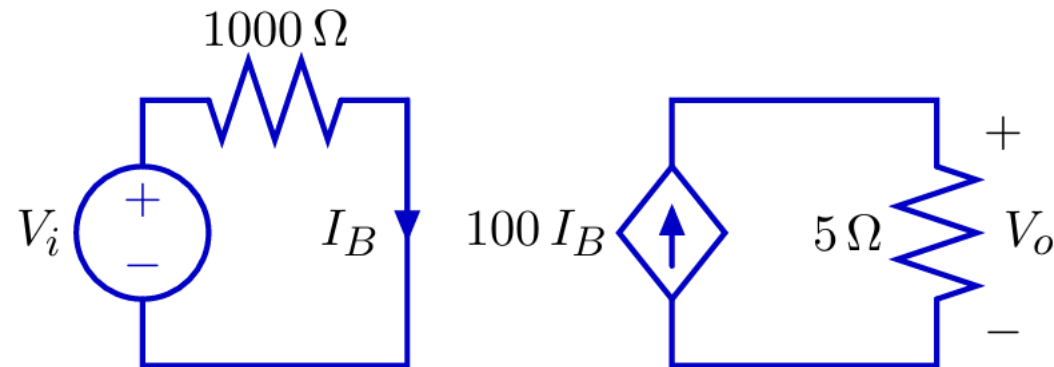
- **Operational Amplifier: Introduction**
  - Dependent Sources
  - Op-Amp: Circuit Symbols and terminal
  - Op-Amp: VTC (Voltage Transfer Characteristics)
    - Linear Amplification
    - (Positive and Negative) Saturation
  - Op-Amp: Examples
  - Op-Amp: Physical Entity

# Dependent Sources

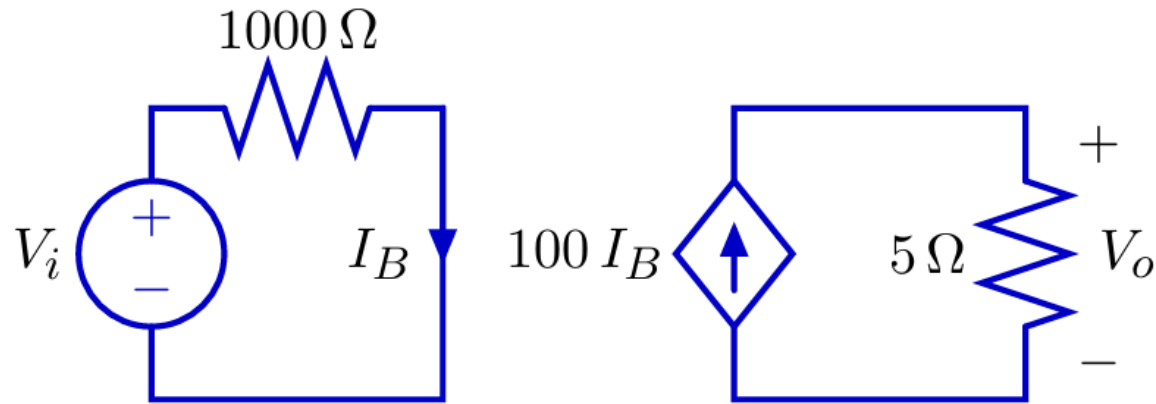
To analyze op-amps, we must understand **dependent source**.

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

Example: current-controlled current source



# Dependent Sources



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

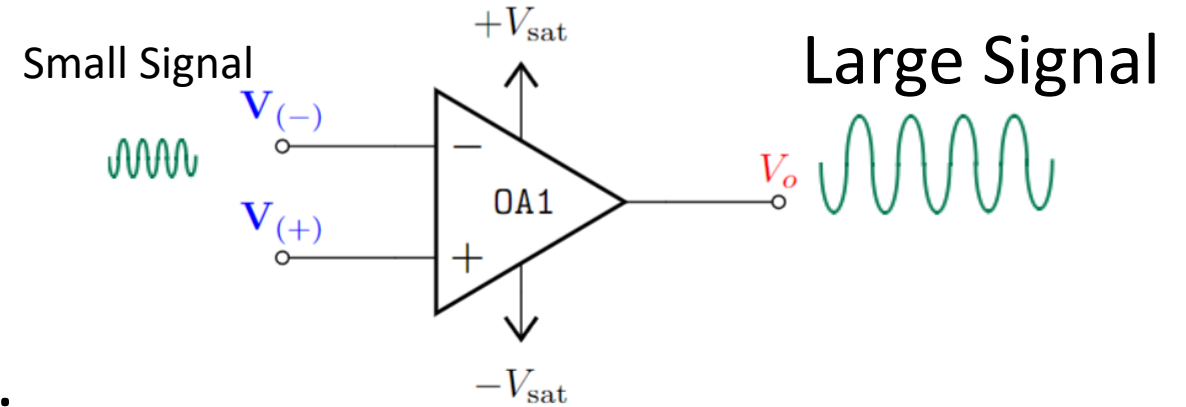
$$V_o = 100 I_B \times 5\ \Omega$$

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

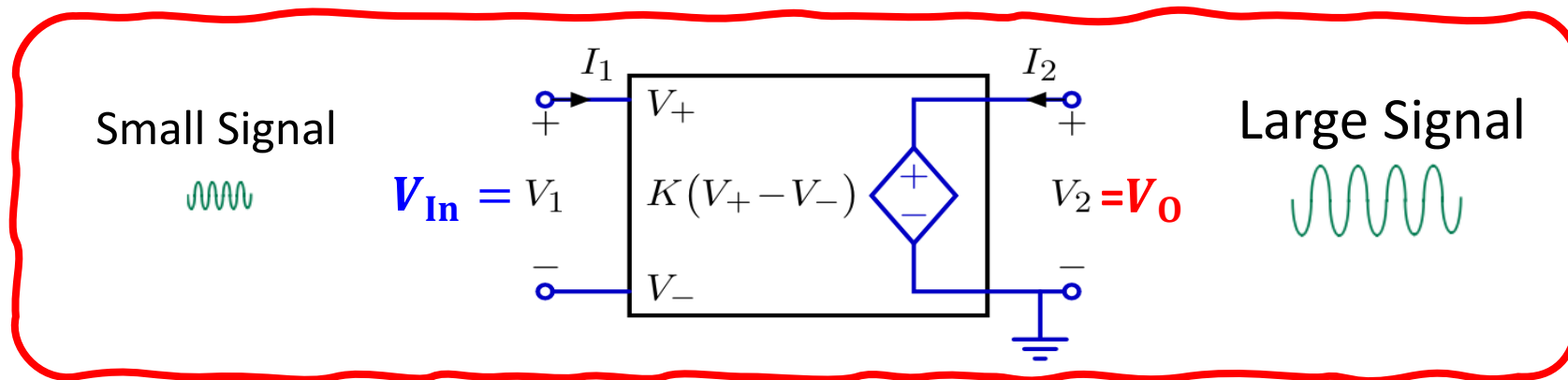
$$= 100 \frac{V_i}{1000\ \Omega} \times 5\ \Omega = \frac{1}{2} V_i$$

# Operational Amplifier: Introduction

- **Operational:**  
Mathematical Operations
- **Amplifier:**  
Amplifies input signal/voltage.

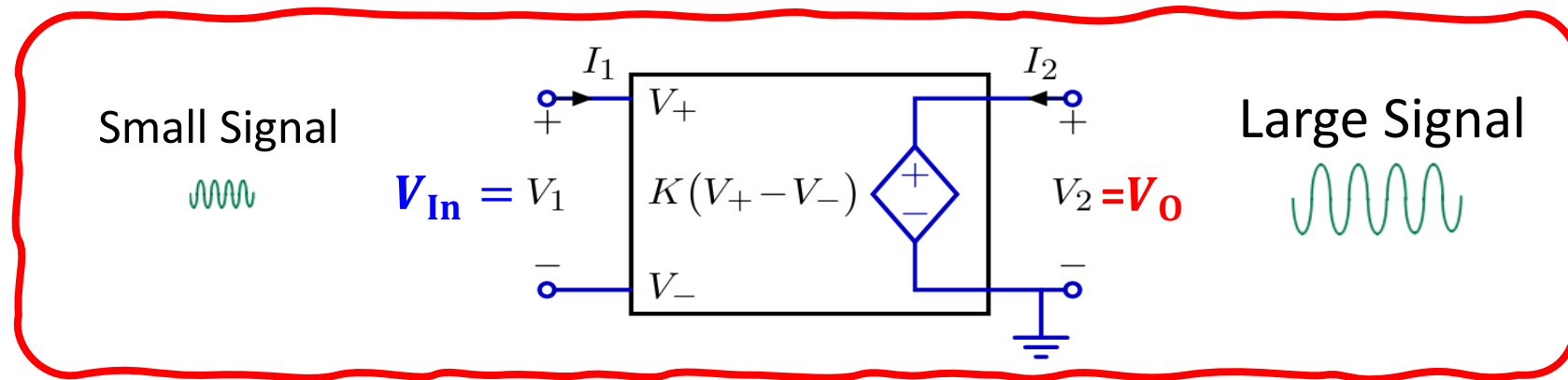


An **op-amp (operational amplifier)** can be modelled by a **voltage- controlled voltage source**.



# Operational Amplifier: Introduction

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

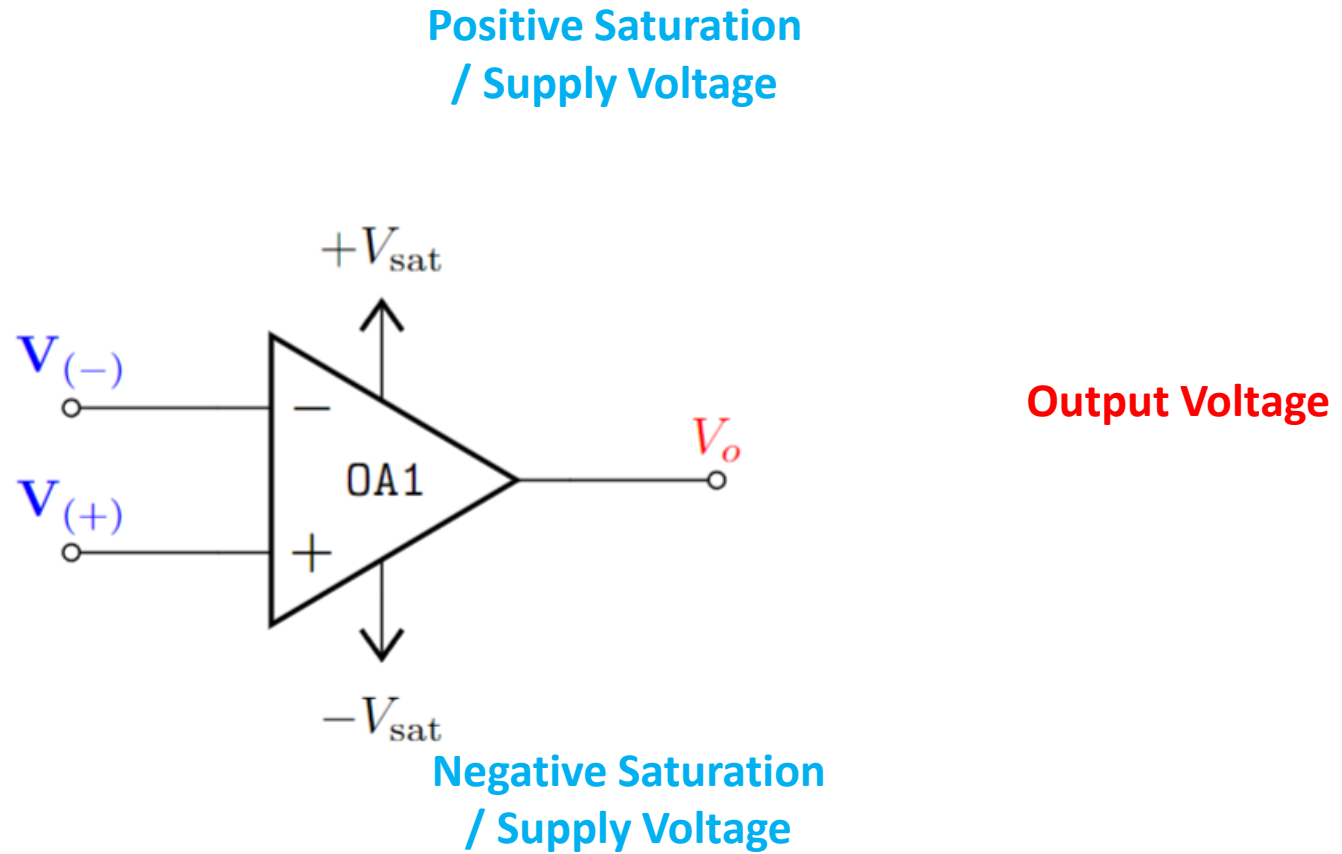


$I_1 = 0$  and  $V_O = K V_{In}$  where  $K$  is large (typically  $K > 10^5$ ).

# Op-Amp: Circuit Symbols and terminal

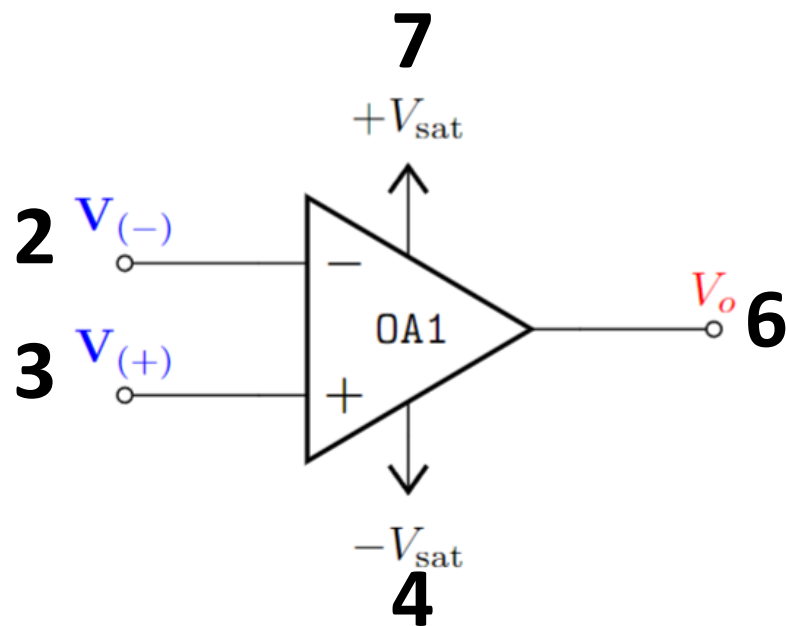
Inverting  
terminal voltage

Non-inverting  
terminal voltage

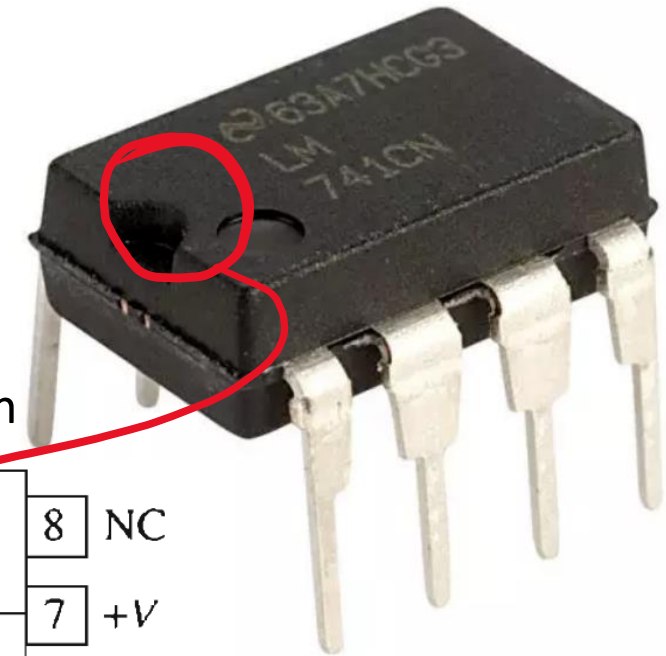
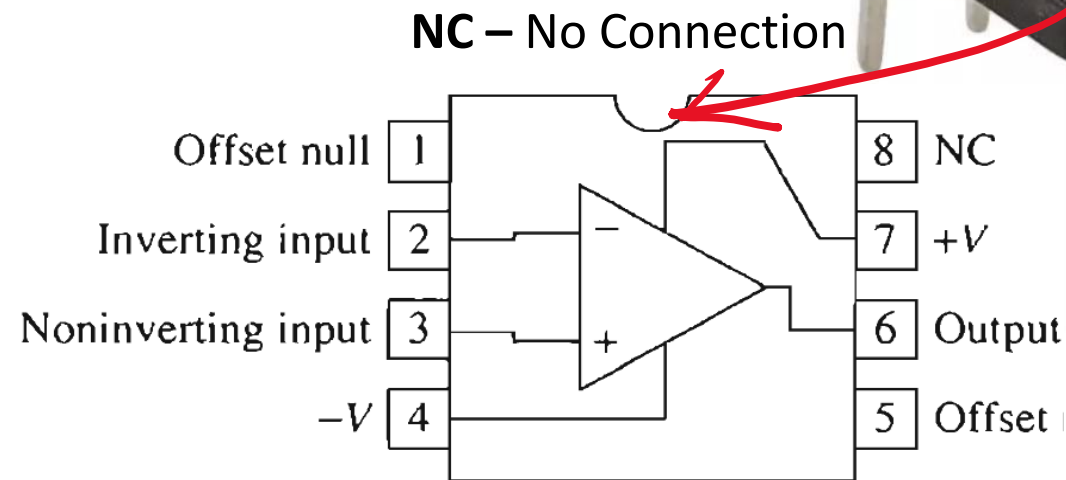


# Op-Amp: Physical Entity

**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**



**$\mu$ A-741C**

Manufacturer ID

Part Identification Number (PIN)

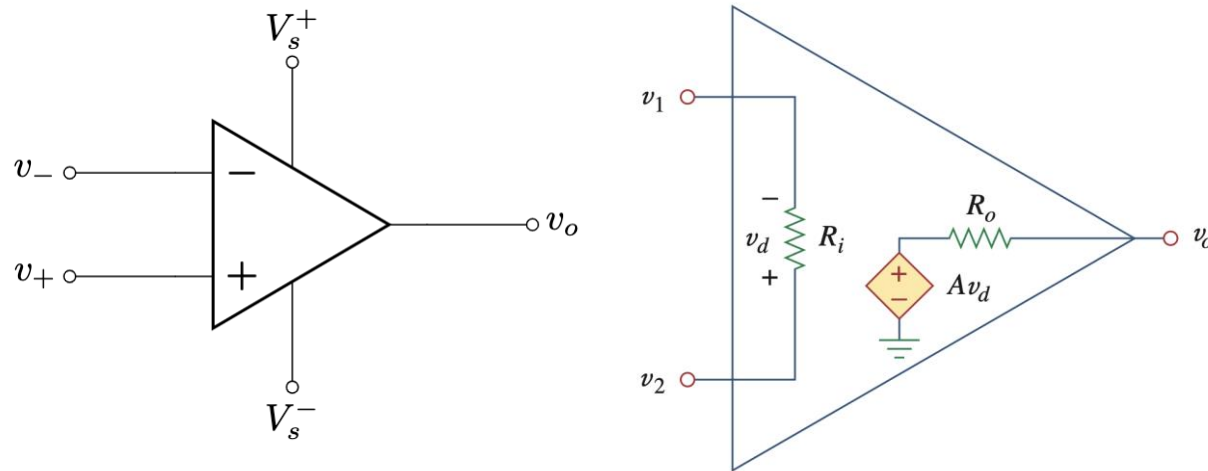
**C:** Commercial ( $0^{\circ} - 70^{\circ}\text{C}$ )  
**I:** Industrial ( $-25^{\circ} - 85^{\circ}\text{C}$ )  
**M:** Military ( $-55^{\circ} - 125^{\circ}\text{C}$ )

# Operational Amplifiers

- An operational amplifier, or **op-amp** for short, is a versatile and powerful integrated circuit that is widely used in a variety of electronic applications.
- An Op-Amp is designed so that it performs some mathematical operations when external components, such as resistors and capacitors, are connected to its terminals.
- The op amp is an electronic device consisting of a complex arrangement of resistors, transistors, capacitors, and diodes. A full discussion of what is inside the op amp is beyond the scope of this course. For now, it will suffice to treat the op amp as a circuit building block and simply study what takes place at its terminals.

# Equivalent Circuit

Since op amp is an amplifier, the internal circuit can be modeled using a **voltage controlled voltage source** (VCVS)! (actual circuit is complicated)



$v_1 = v_- =$  voltage of inverting terminal  
 $v_2 = v_+ =$  voltage of noninverting terminal

$v_d = v_+ - v_- = v_2 - v_1$   
= differential input voltage for VCVS

$A =$  Open loop gain

$R_i =$  Input resistance

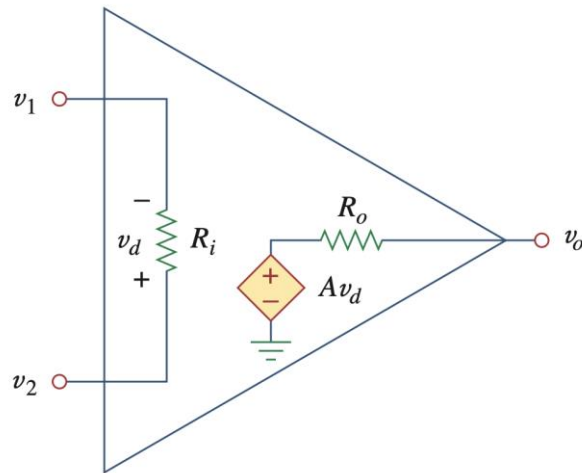
$R_o =$  Output resistance

The op amp senses the difference between the two inputs, multiplies it by the gain  $A$ , and causes the resulting voltage to appear at the output. Thus, the output  $v_o$  is given by

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

# Equivalent Circuit

Since op amp is an amplifier, the internal circuit can be modeled using a **voltage controlled voltage source** (VCVS)! (actual circuit is complicated)



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$R_i$  = Input resistance

$R_o$  = Output resistance

Parameter	Typical Range

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# Op-Amp: VTC – Linear Amplification

## Voltage Transfer Characteristics (VTC)

- Shows how the **output voltage** varies with the **input voltage**  $V_O(V_d)$

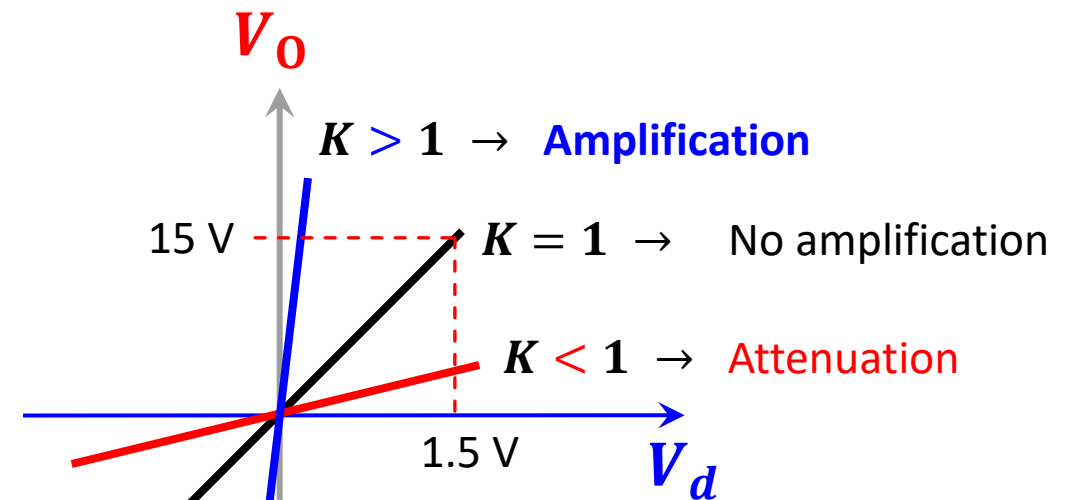
- $y$  –axis  $\rightarrow V_O$

- $x$  –axis  $\rightarrow V_d$

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

If the line passes through origin:

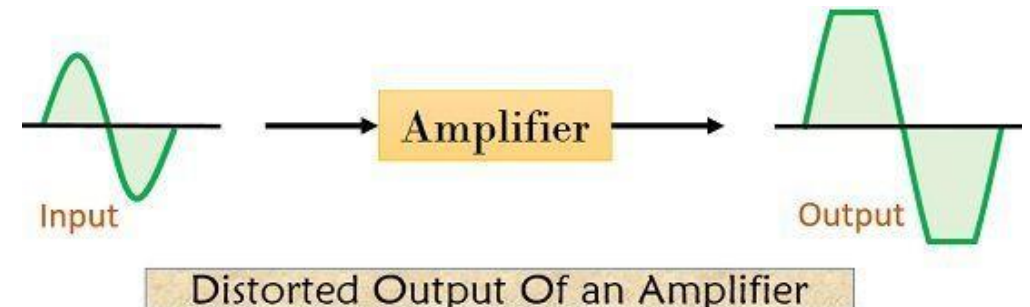
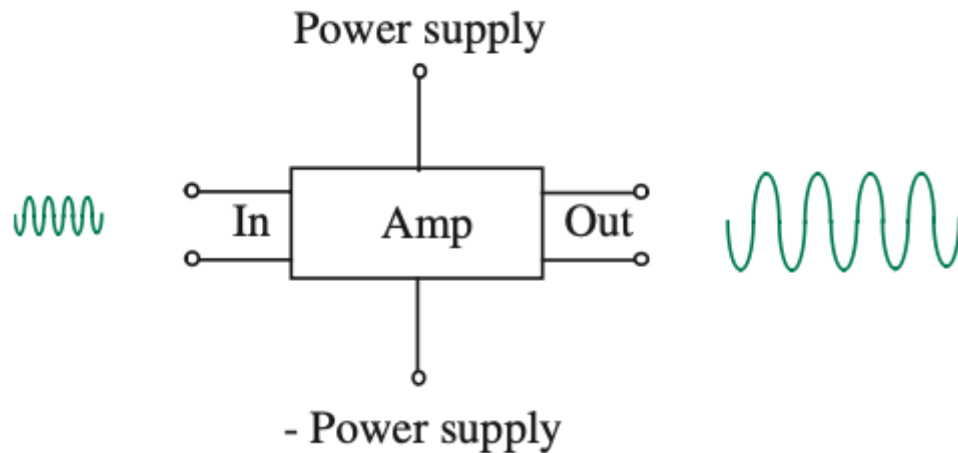
$$y = K \cdot x$$
$$V_O = K \cdot V_d$$



## LINEAR AMPLIFICATION

# Op-Amp: VTC – Linear Amplification

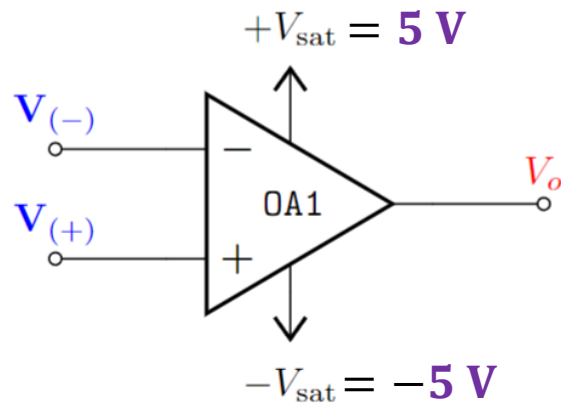
- **Linear Amplification** only takes place within a [valid input range](#).
- Otherwise output will be distorted - - Saturation



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

# Op-Amp: VTC - Saturation

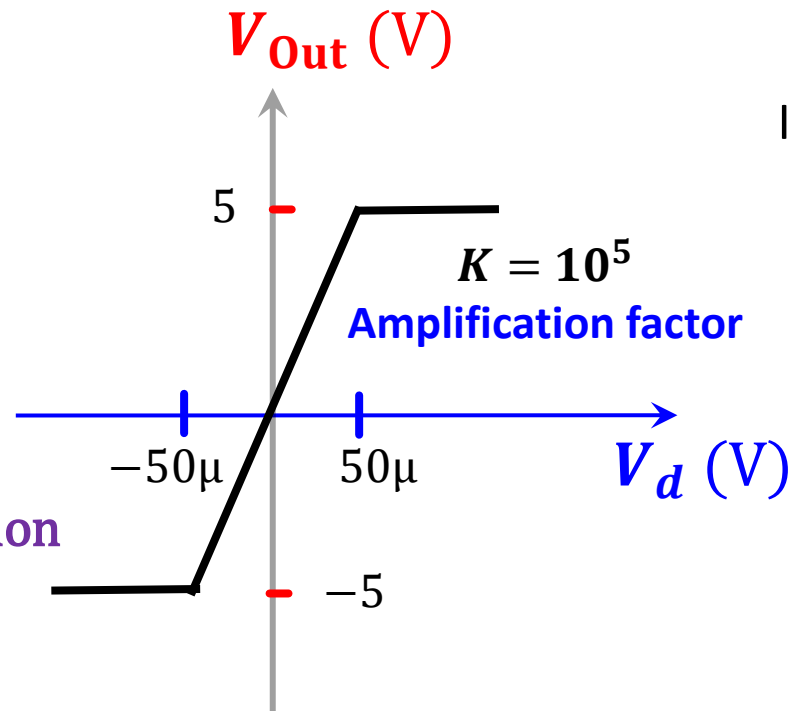
VTC -> Voltage Transfer Characteristics



$$V_o = K \cdot V_{in} : \text{When } -5\text{ V} < V_o < 5\text{ V}$$

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

Non-Linear characteristics



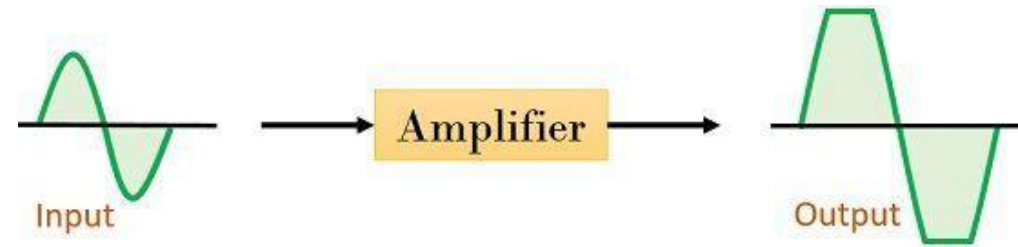
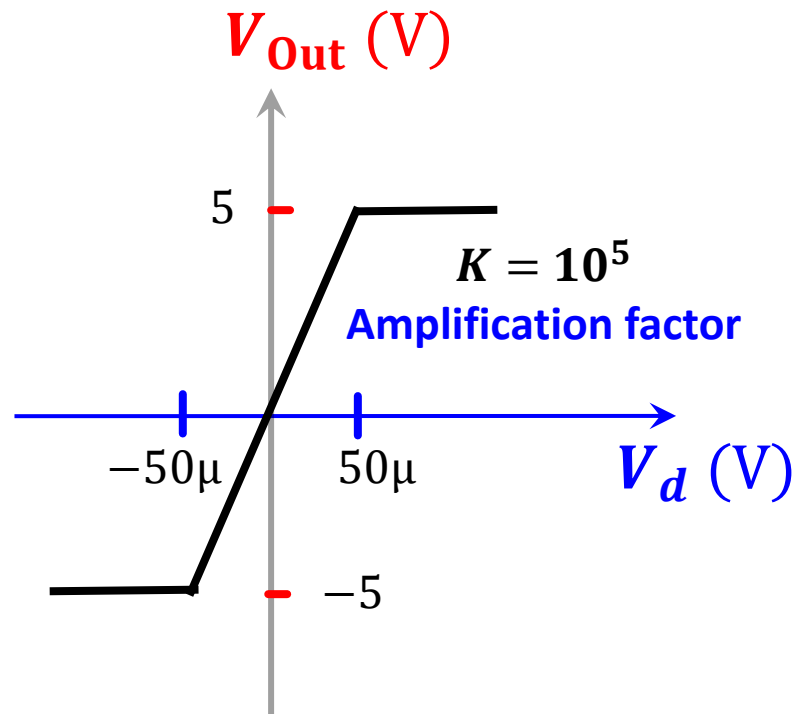
If  $V_d > 50\mu$ : Positive Saturation

$$\Rightarrow V_o = 5$$

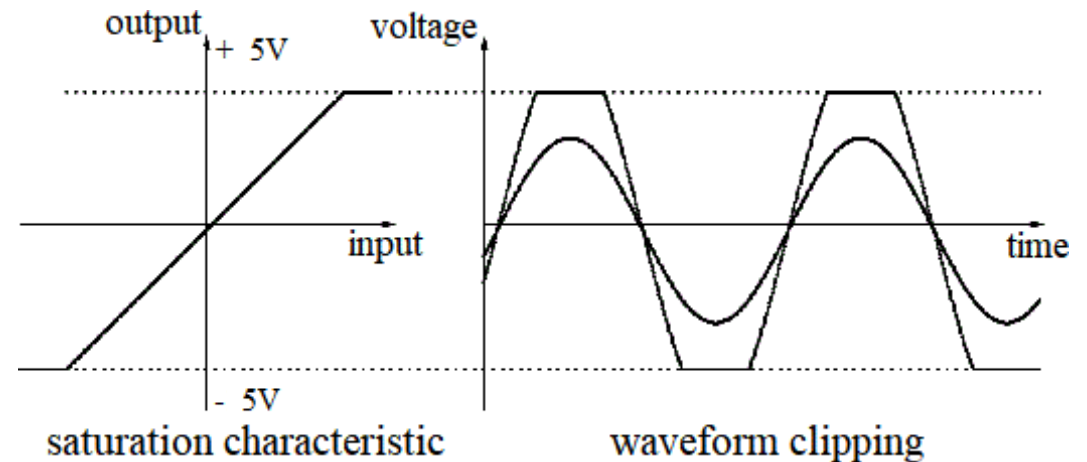
If  $V_d < -50\mu$ : Negative Saturation

$$\Rightarrow V_o = -5$$

# Op-Amp: VTC - Saturation

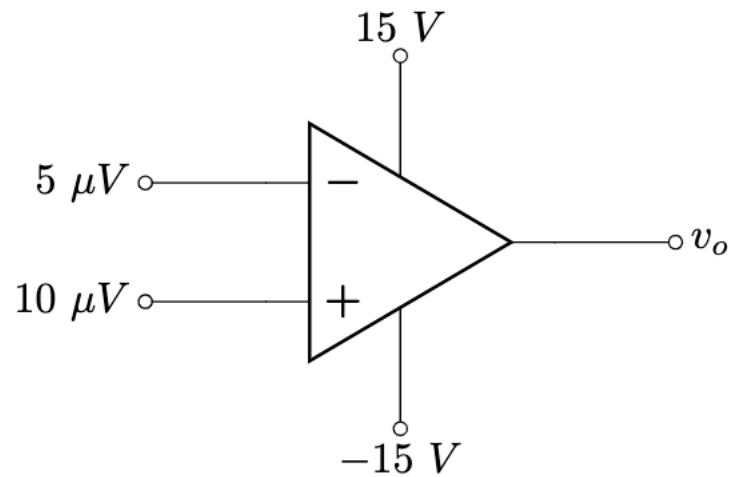


Distorted Output Of an Amplifier

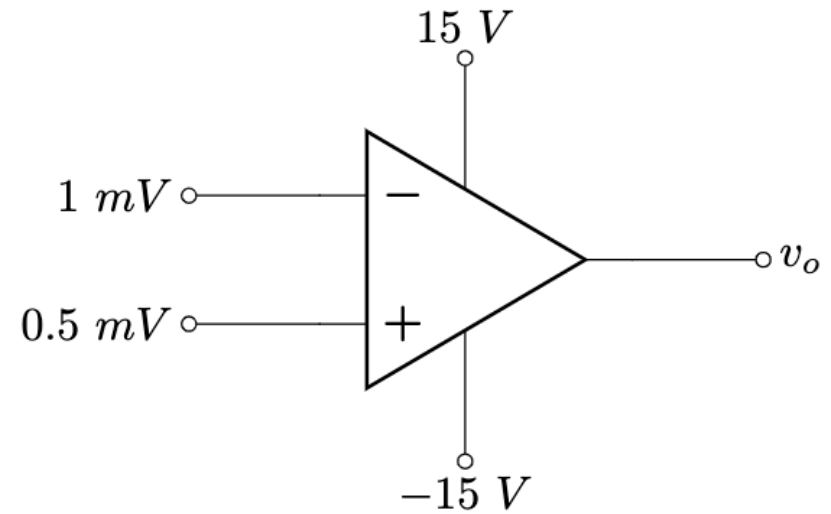


# Op-Amp: Examples

Find  $v_o$



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

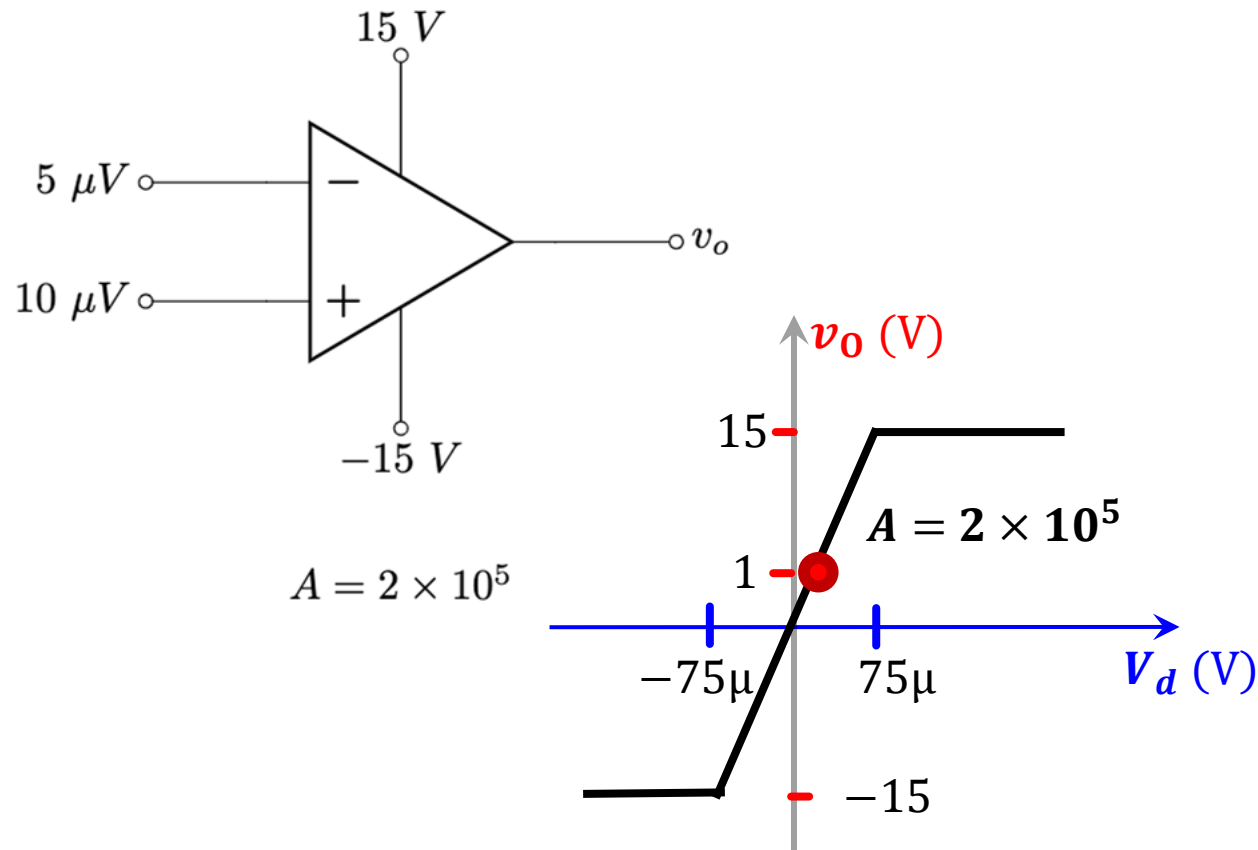


$$A = 2 \times 10^5$$

# Example 1

- Find  $v_o$

**Solution:**



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

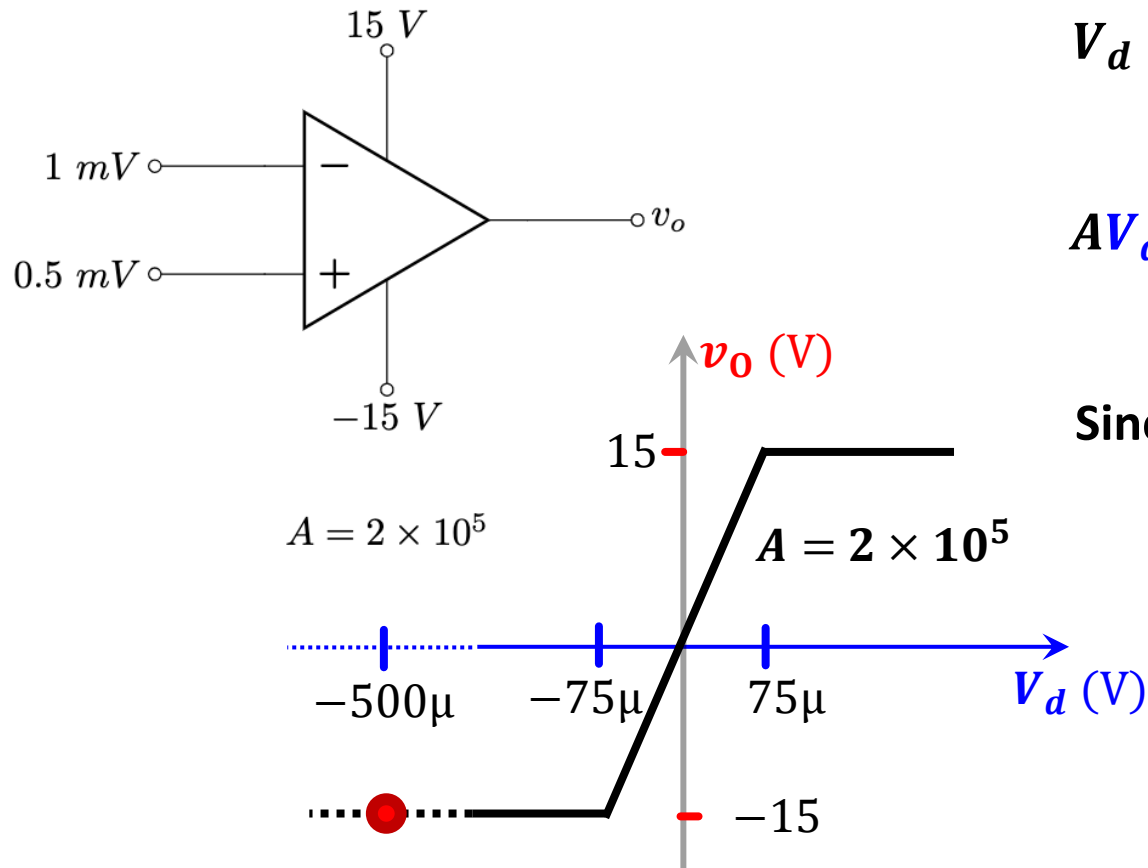
$$AV_d = (2 \times 10^5) \times (5 \times 10^{-6})\ \text{V} = 1\ \text{V}$$

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

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

## Example 2

- Find  $v_o$



**Solution:**

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

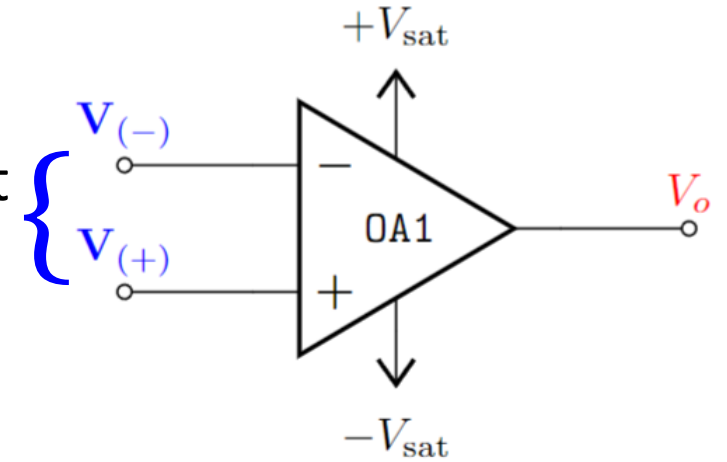
$$AV_d = (2 \times 10^5) \times (-0.5 \times 10^{-3}) \text{ V} = -100 \text{ V}$$

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

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

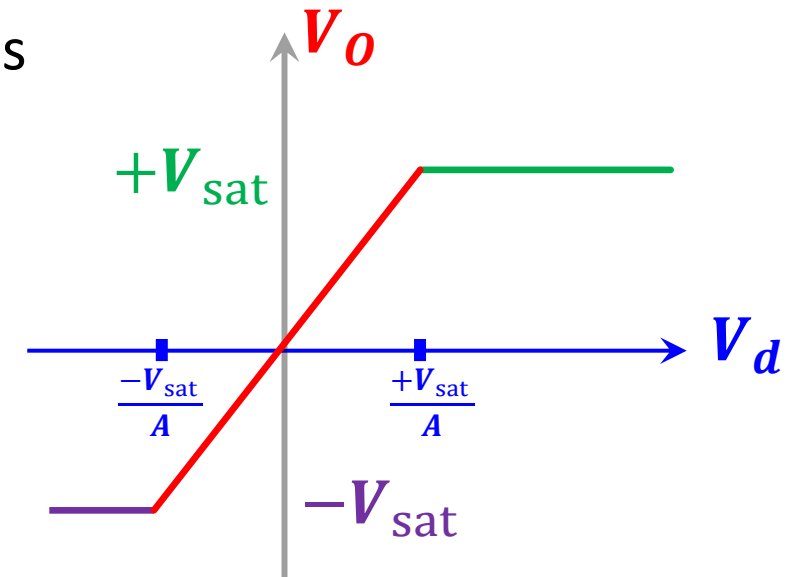
# Op-Amp: Summary

Op-Amp **Amplifies** the difference between the voltages at its two input terminals -  $V_d$



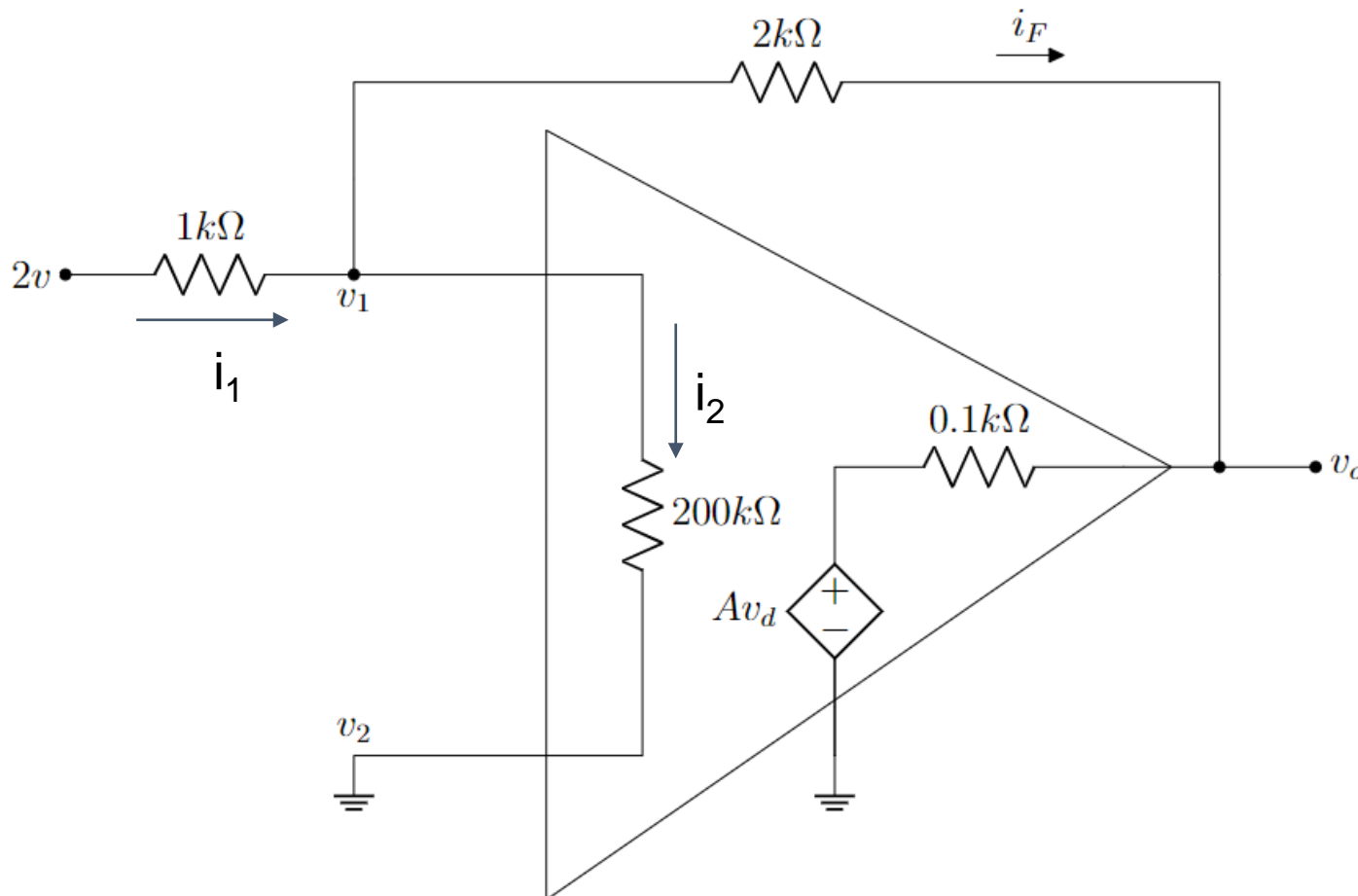
However, the **Amplification** is limited within voltage levels defined by the positive and negative saturation voltages  $[-V_{sat}, +V_{sat}]$ .

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



# Example 5

Step 2: Solve using KCL & KVL or nodal



Applying KCL we get,

$$i_1 = i_2 + i_F$$

$$\rightarrow (2 - v_1)/(1k) = (v_1 - v_2)/(200k) + (v_1 - v_o)/(2k)$$

$$\rightarrow (2 - v_1)/(1k) = (v_1 - 0)/(200k) + (v_1 - v_o)/(2k)$$

$$\rightarrow (2 - v_1)/(1k) = v_1/(200k) + (v_1 - v_o)/(2k) \dots \dots (i)$$

Again, from the figure,

$$i_{0.1k} = i_F$$

$$\rightarrow (v_o - Av_d)/(0.1k) = (v_1 - v_o)/(2k)$$

$$\rightarrow (v_o - (2 \times 10^5) \times (v_2 - v_1))/(0.1k) = (v_1 - v_o)/(2k)$$

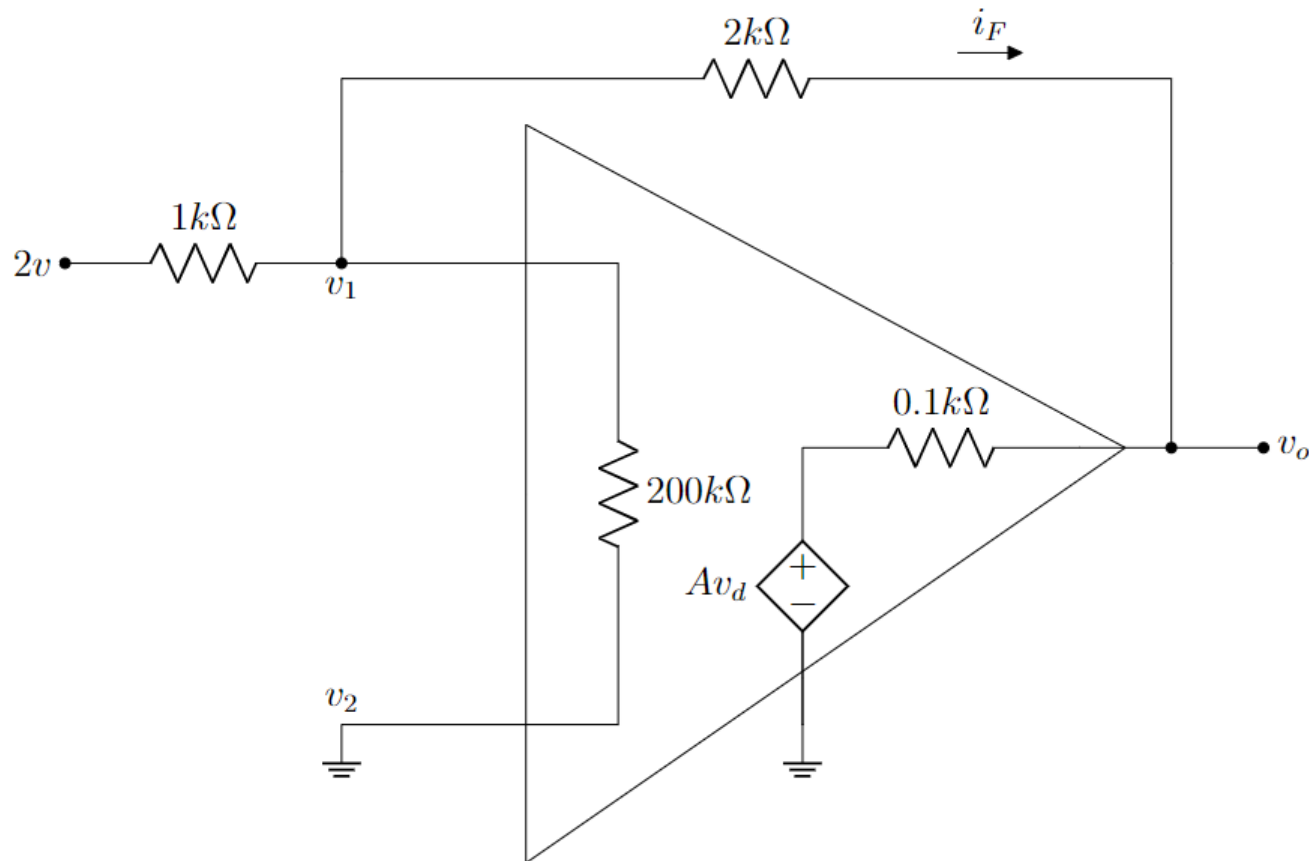
$$\rightarrow (v_o - (2 \times 10^5) \times (0 - v_1))/(0.1k) = (v_1 - v_o)/(2k)$$

$$\rightarrow (v_o - (2 \times 10^5) \times (-v_1))/(0.1k) = (v_1 - v_o)/(2k) \dots (ii)$$

We can get  $v_1$  and  $v_o$  by solving equation (i) and (ii)

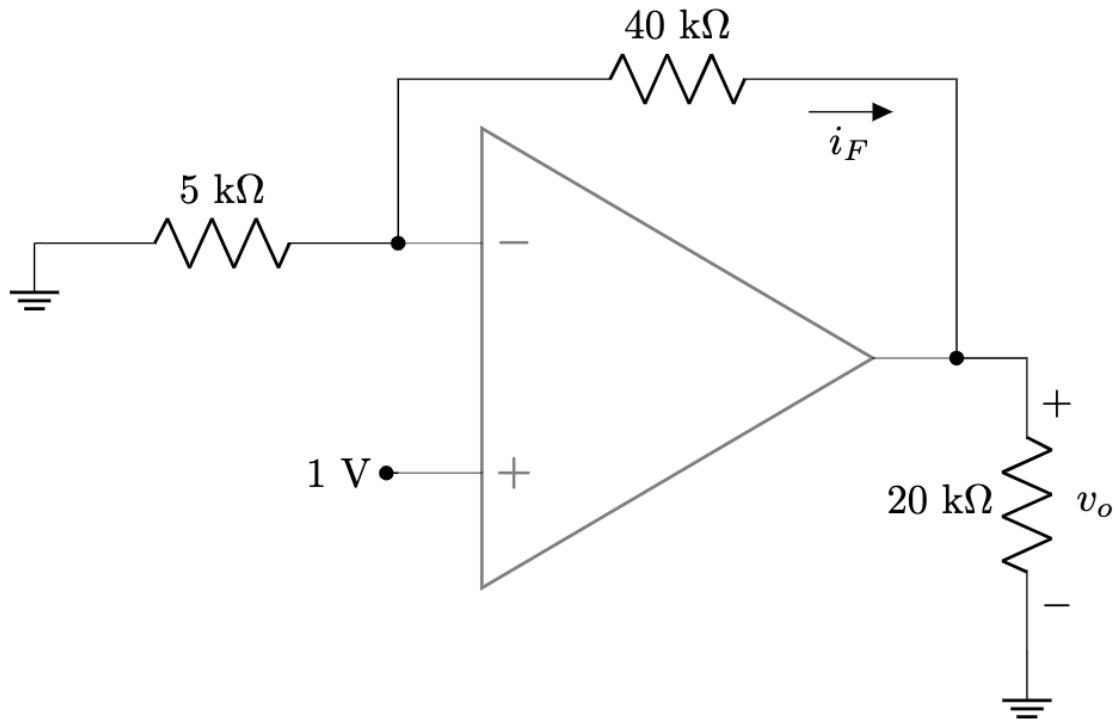
# Example 5

Step 2: Solve using KCL & KVL or nodal



## Example 6

Find  $i_F$  and  $v_o$ . Here,  $R_i = 200\text{ k}\Omega$ ,  $R_o = 0.1\text{ k}\Omega$ ,  $A = 2 \times 10^5$

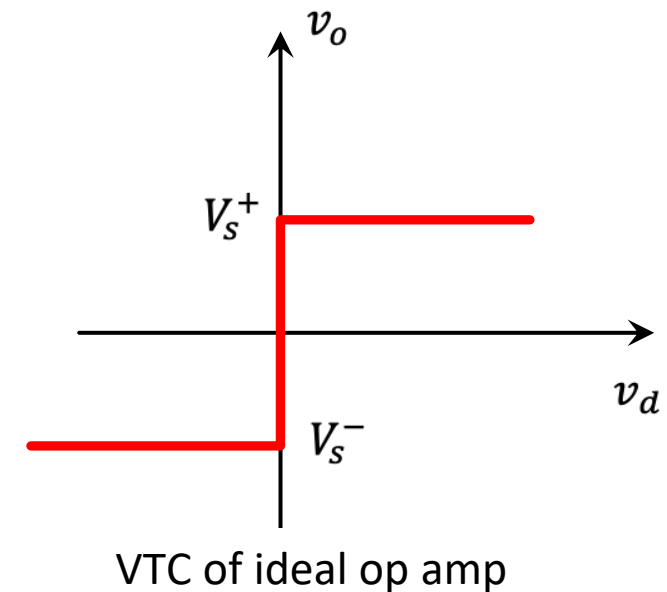
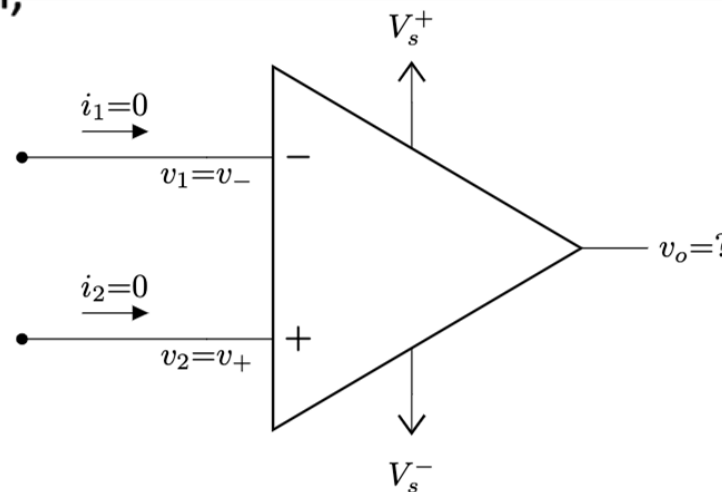


# The Ideal Op-Amp

- To facilitate the understanding of op amp circuits, we will assume **ideal op amps**
  - Infinite open-loop gain,  $A = \infty$
  - Infinite input resistance,  $R_i = \infty = \text{open circuit}$
  - Zero output resistance,  $R_o = 0 = \text{short circuit}$
- Although an ideal op amp provides only an approximate analysis, most modern amplifiers have such large gains and input impedances that the approximate analysis is a good one.
- **Circuit solving become much simpler.** As  $R_i = \infty, i_1 = i_2 = 0$
- Since  $A = \infty$ , in open-loop configuration,  $v_o$  will either be positive saturated or negative saturated (why?)

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

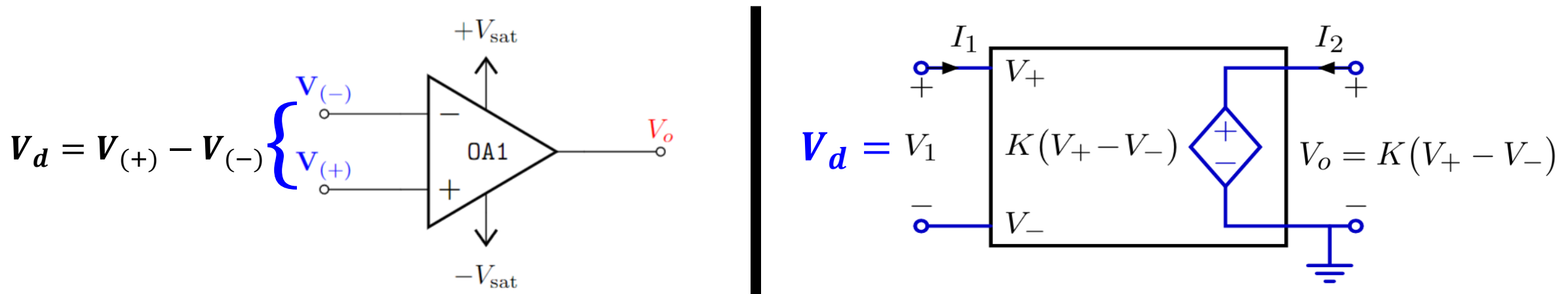
**Reminder:**  $v_d = v_2 - v_1 = v_+ - v_-$



# Op-Amp: Circuit Modelling

## Voltage controlled voltage Source

“Ideal” op-amp approximation



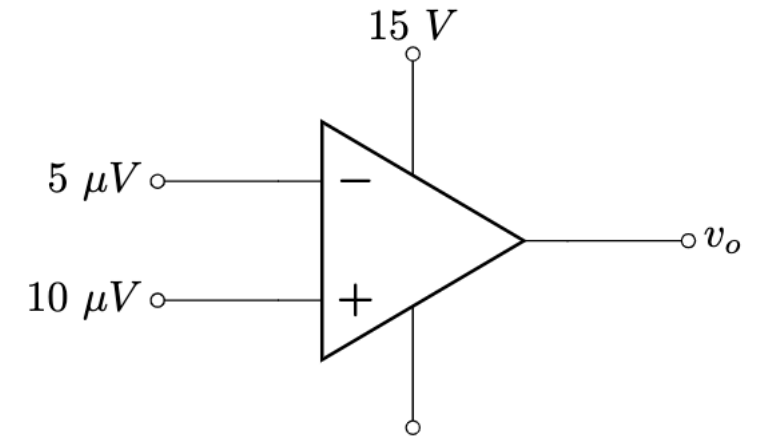
$$V_{(+)} \approx V_{(-)}$$

$$I_1 \approx 0$$

# Types of Op-Amp configuration

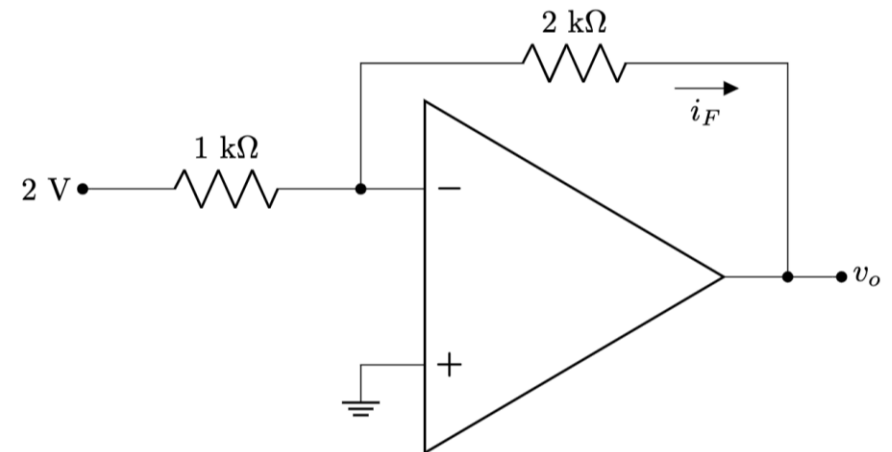
## 1. Open loop configuration:

No physical connection between input and output



## 2. Closed loop configuration:

Feedback from output terminal



# Application - Comparator

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

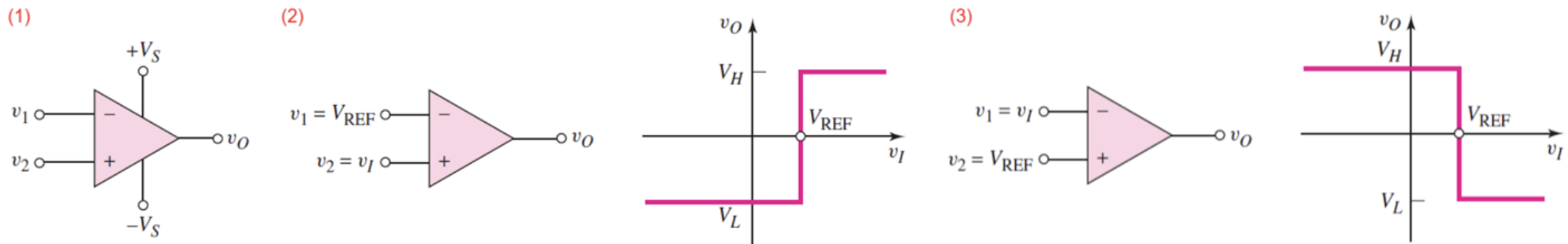


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

# Comparator Application – Automatic AC

Auto AC ON/OFF

Sensor



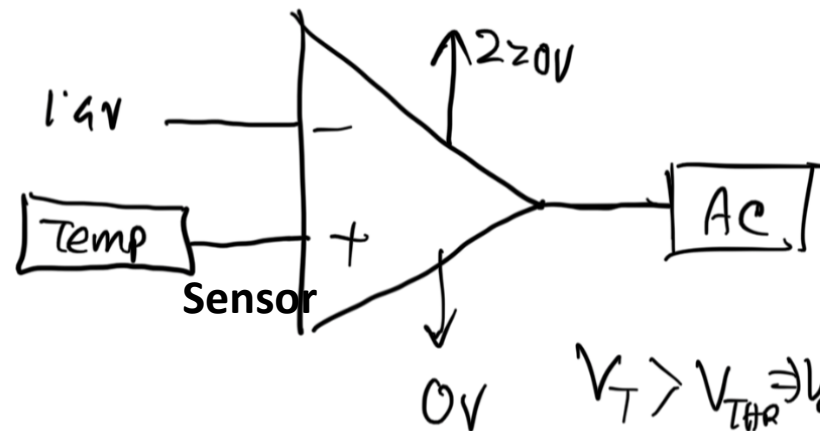
$$V_T \propto T$$

$$23^\circ, V_T = 1.2V$$

$$24^\circ, V_T = 1.4V$$

$$25^\circ, V_T = 1.6V$$

AC should be on if  
 $T > 24^\circ C$



$$V_{THR} = 1.4V$$

$$V_T > V_{THR} \Rightarrow V_o = V_H$$

$$V_T < V_{THR} \Rightarrow V_o = V_L$$

## Example 1

A valve is used to release (when valve is OPEN,) or maintain (when valve is CLOSED,) water pressure in a water tank. The valve operates on **ACTIVE LOW** logic. (i.e., the valve is OPENED when given a LOW voltage of 1 V, but remains CLOSED when provided a HIGH voltage of 6 V.)

A pressure sensor is installed in the water tank that outputs a voltage linearly proportional to pressure, as shown in the table below.

At 0.5 atm pressure	At 1 atm pressure	At 1.5 atm pressure
$v_{0.5 \text{ atm}} = 0.5 \text{ V}$	$v_{1 \text{ atm}} = 3 \text{ V}$	$v_{1.5 \text{ atm}} = 5.5 \text{ V}$

The pressure in the water tank can be measured by the formula  $P = h\rho g$ , where  $P$ , (in **Pascals (Pa)** unit) is the water pressure,  $h$  is the height of water in the tank (in *metres*),  $\rho (= 1000 \text{ kgm}^{-3})$  is the density of water and  $g$  is the acceleration due to gravity (in  $\text{ms}^{-2}$ ).

**[1 atm = 101325 Pa]**

- i. **Design** a circuit using Op-Amp comparator to automatically turn OPEN the valve if water level exceeds **10 m**.

## Solution:

When  $h = 10$  m:  $P = h\rho g = 98000$  Pa = 0.967 atm

**From the table we can interpolate and find the exact voltage at this pressure.**

For  $1 - 0.5 = 0.5$  atm pressure change, the voltage changes by 2.5 V

For 1 atm pressure change, the voltage changes by  $2.5/0.5$  V = 5 V

So, for  $0.967 - 0.5 = 0.467$  atm pressure change, the voltage changes by  $5 * 0.467$  V

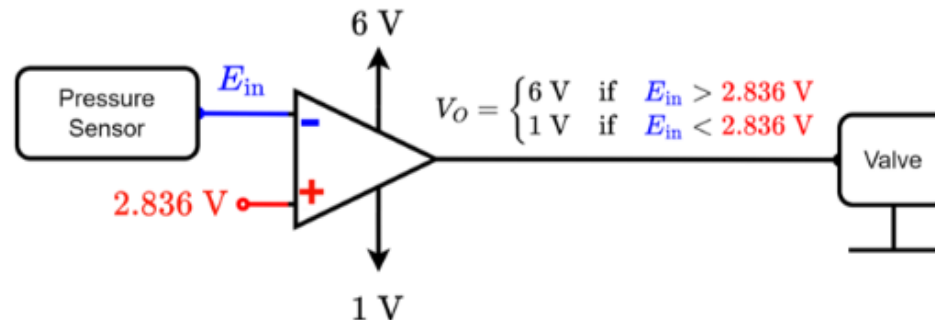
So, voltage at 0.967 atm pressure is  $0.5 + 5 * 0.467$  V = 2.836 V

### Active low logic:

High water level  $\rightarrow$  High pressure  $\rightarrow$  **High input voltage**  $\rightarrow$  Valve Open  $-1$  V =  $V_L$

Low water level  $\rightarrow$  Low pressure  $\rightarrow$  **Low input voltage**  $\rightarrow$  Valve Closed  $-6$  V =  $V_H$

So the comparator is in inverting configuration. As shown below:

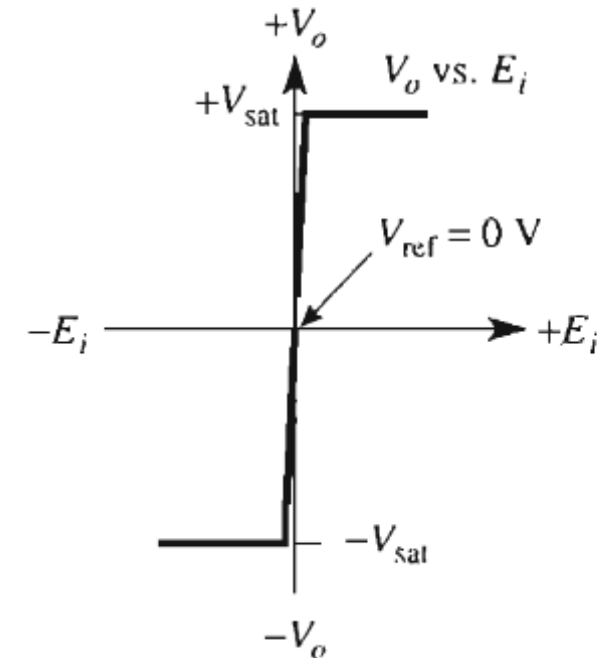
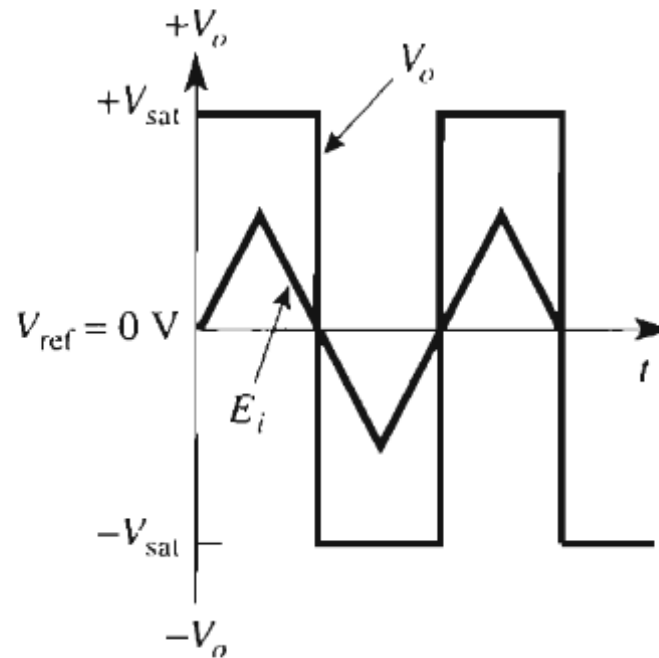
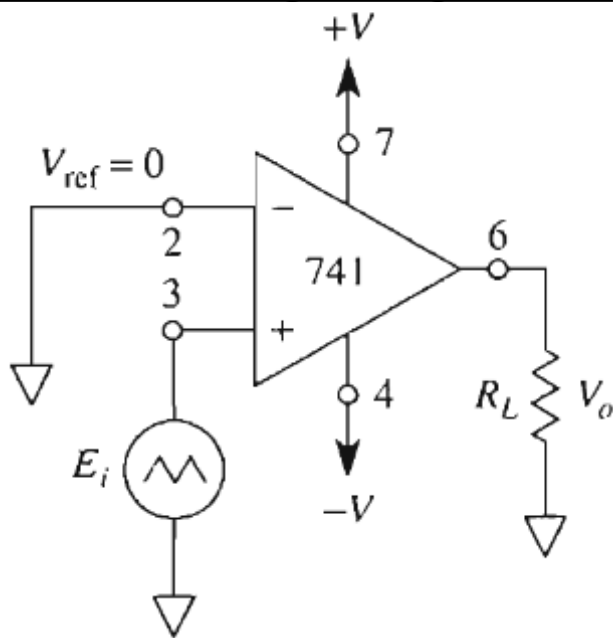


# Open Loop Configuration: Comparator

## Zero Crossing Detector

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

### Non-inverting configuration

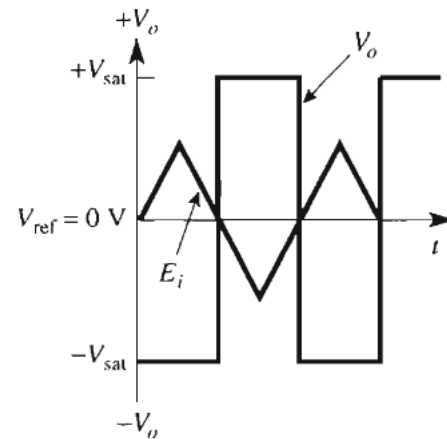
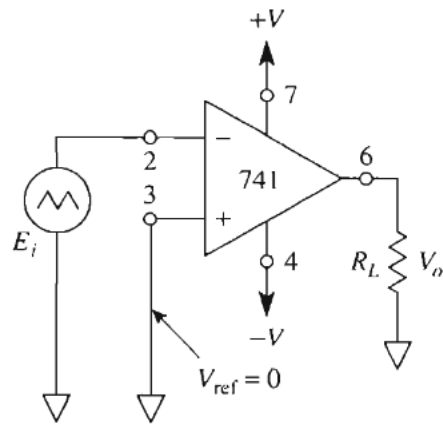


(a) Noninverting: When  $E_i$  is above  $V_{ref}$ ,  $V_o = +V_{sat}$ .

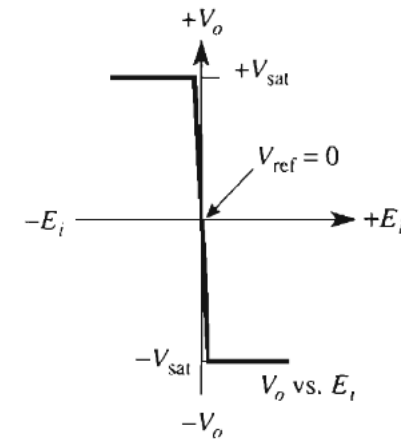
# Open Loop Configuration: Comparator

Zero Crossing Detector

## Inverting configuration

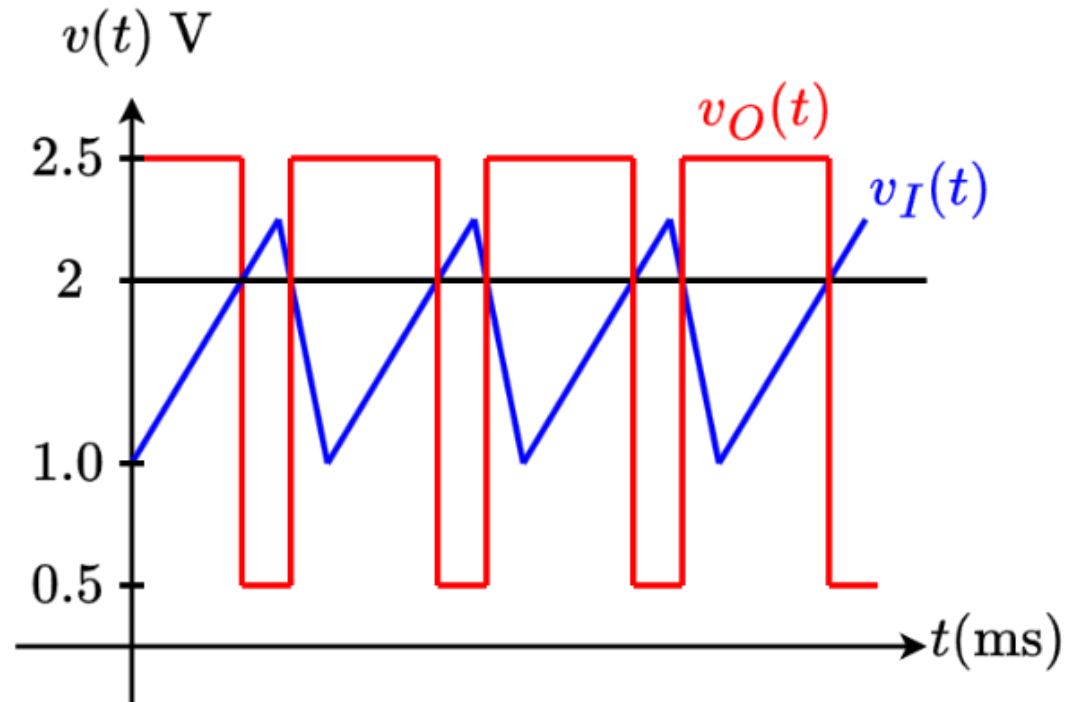


(b) Inverting: When  $E_i$  is above  $V_{ref}$ ,  $V_o = -V_{sat}$ .



# Open Loop Configuration: Example 2

- Design a circuit using OP Amp from the waveform graph.

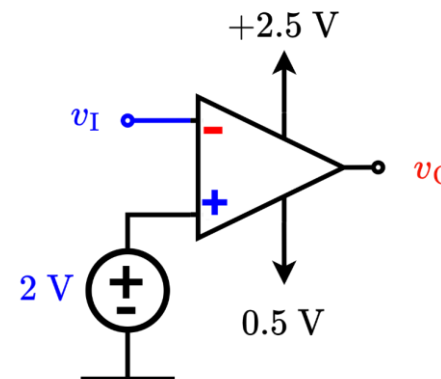


## Solution:

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

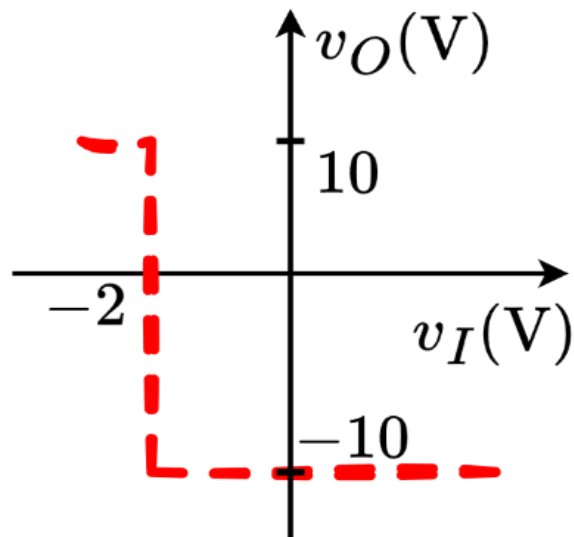
$v_I$  larger than 2 V  $\Rightarrow v_O = -2.5$  V  $\rightarrow$  **Negative Saturation**

## INVERTING CONFIGURATION



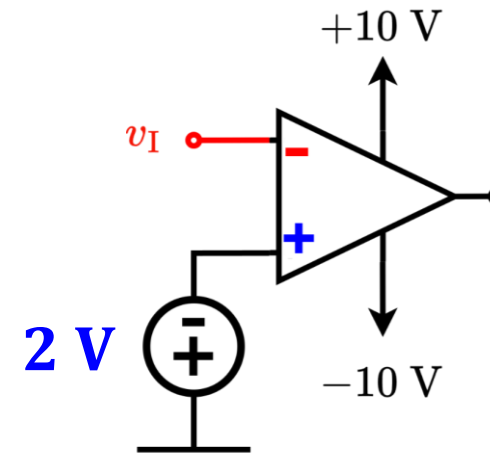
# Open Loop Configuration: Example 1

- 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:**

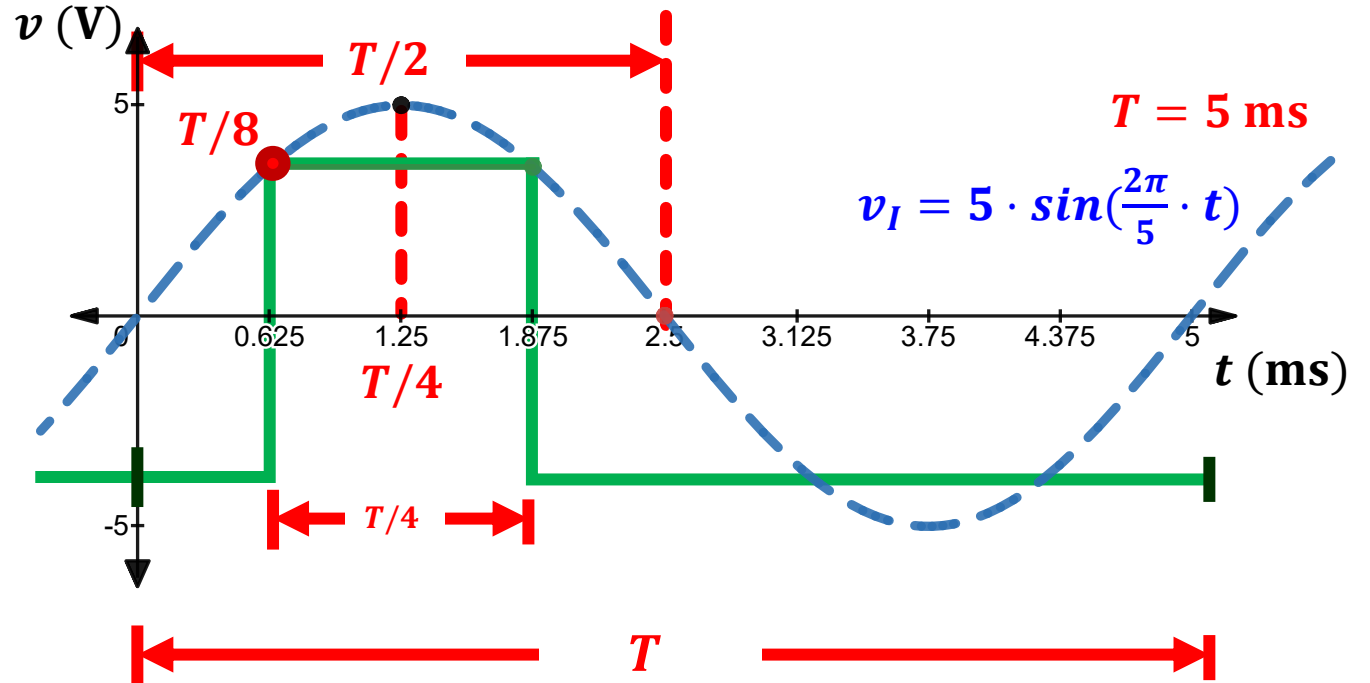
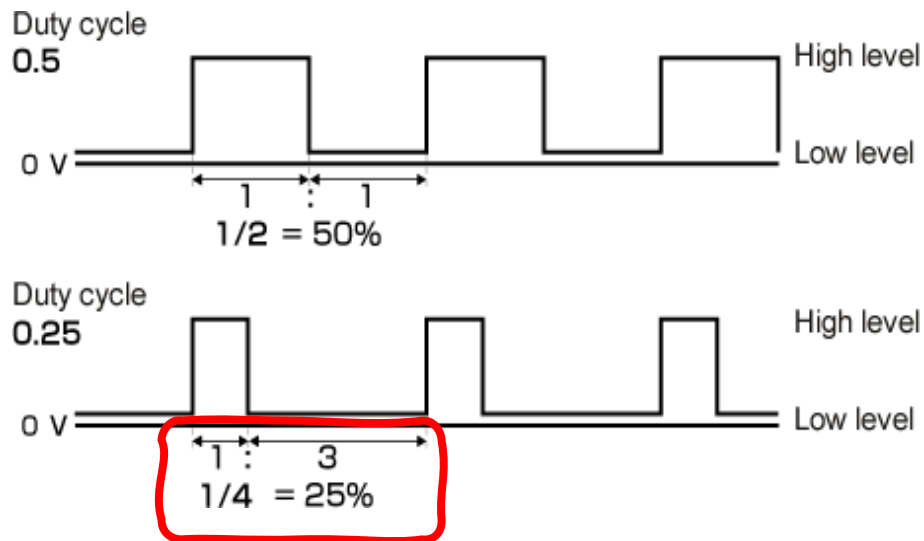
Inverting comparator



# Open Loop Configuration: Example 3

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

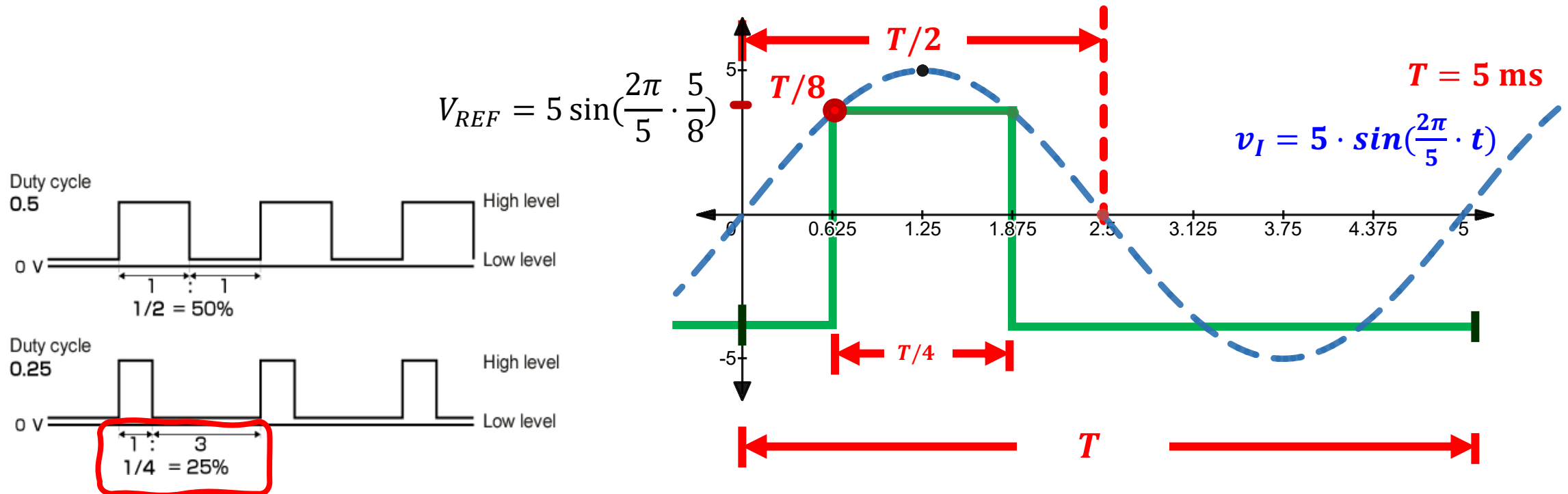
**Solution:**



# Open Loop Configuration: Example 3

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

**Solution:**

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

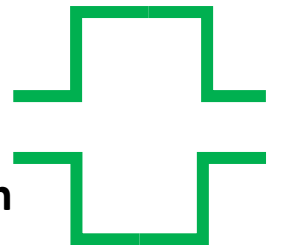
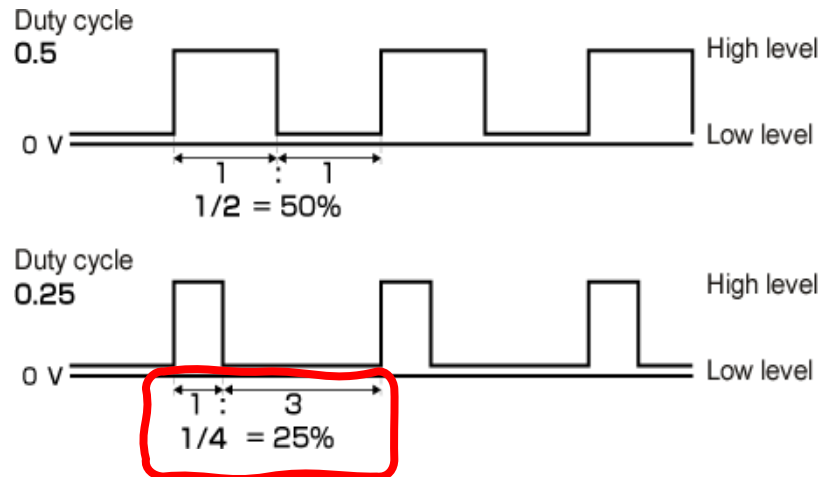
$$V_{REF} = 5 \cdot \frac{1}{\sqrt{2}}\ V$$

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

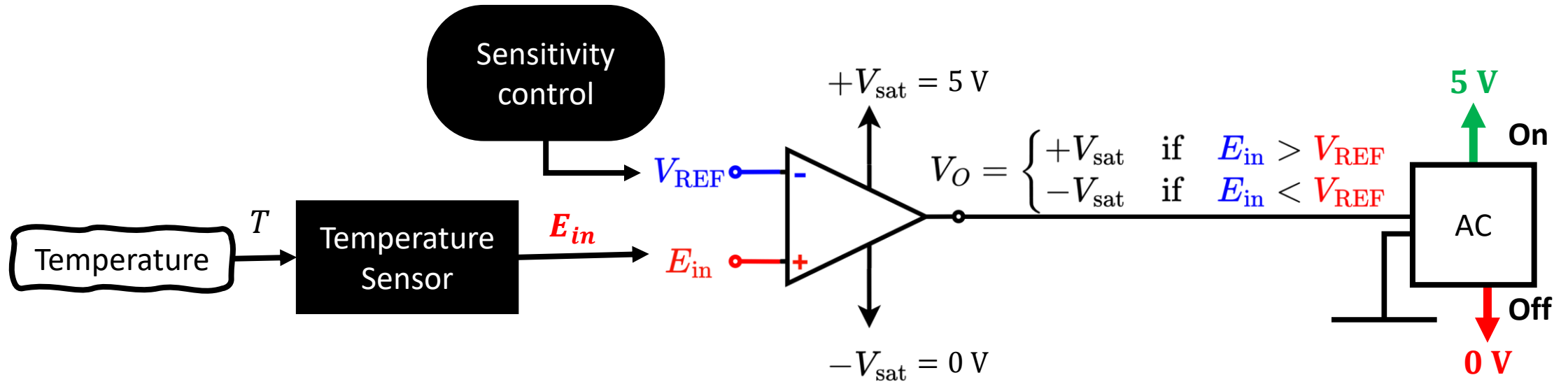
$v_I \geq 3.535\ V : v_o \rightarrow$  **Positive Saturation**

$v_I \leq 3.535\ V : v_o \rightarrow$  **Negative Saturation**

**NON-INVERTING CONFIGURATION**

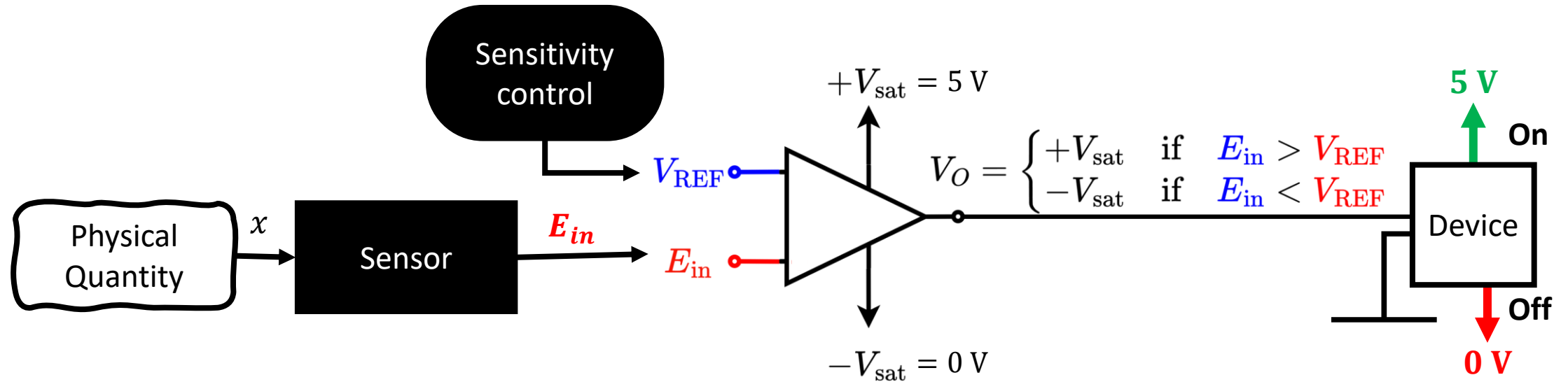


# Comparator Application – Automatic AC



- Comparators can be used to switch on an **AC** based on a **Temperature**.
  - Temp.  $\uparrow$  **AC** - ON
  - Temp.  $\downarrow$  **AC** - OFF
  - Temp  $\uparrow \propto E_{in} \uparrow \rightarrow$  **AC** - ON  $\rightarrow$  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.  $\uparrow$  **DEVICE** – ON / OFF

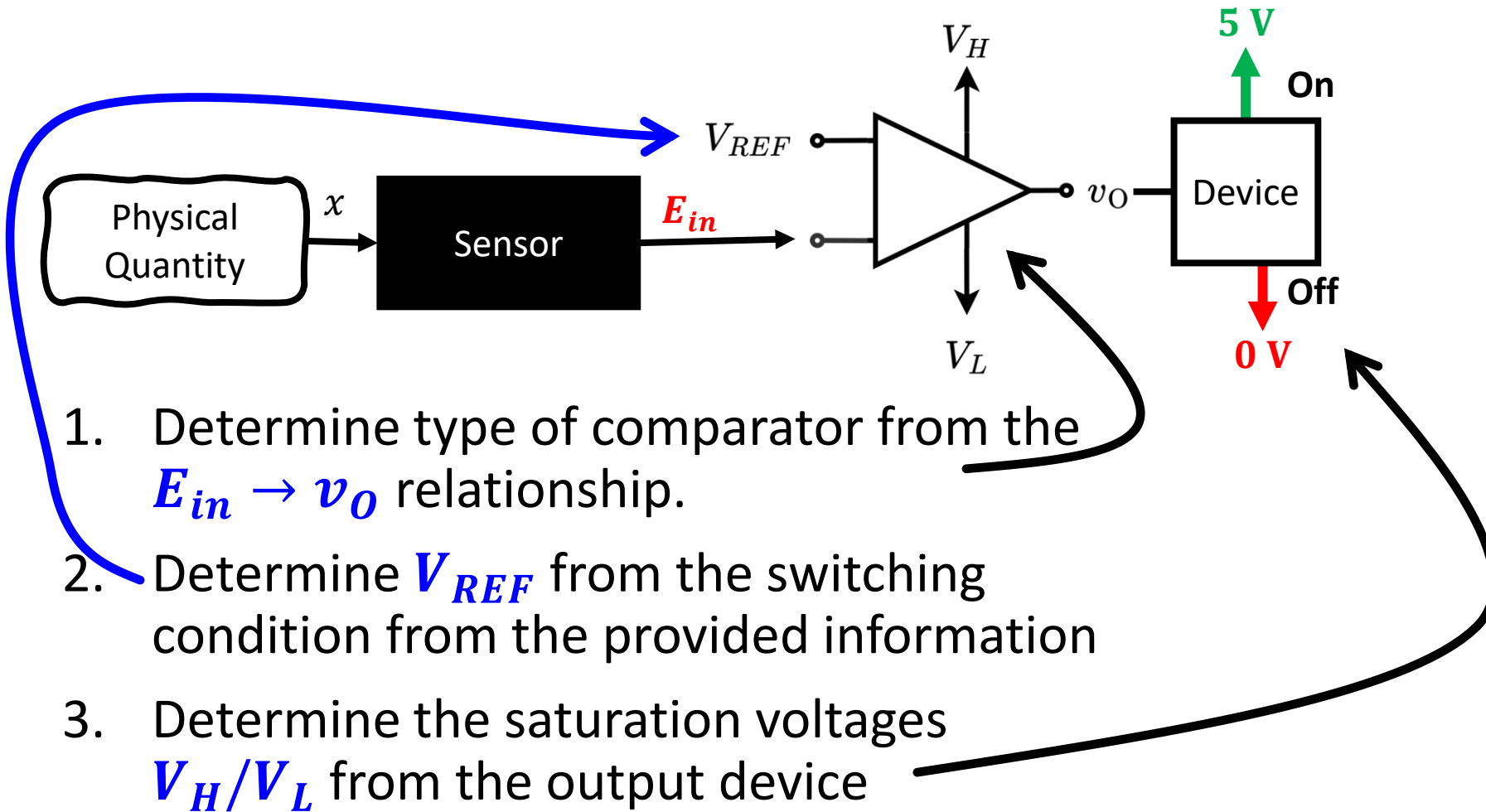
Phys. Qnty.  $\downarrow$  **DEVICE** – OFF / ON

Phys. Qnty.  $\rightarrow$   $E_{in} \downarrow \uparrow \rightarrow$  **DEVICE** – ON/OFF

This Relationship:  
Determines the type of **Comparator**

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

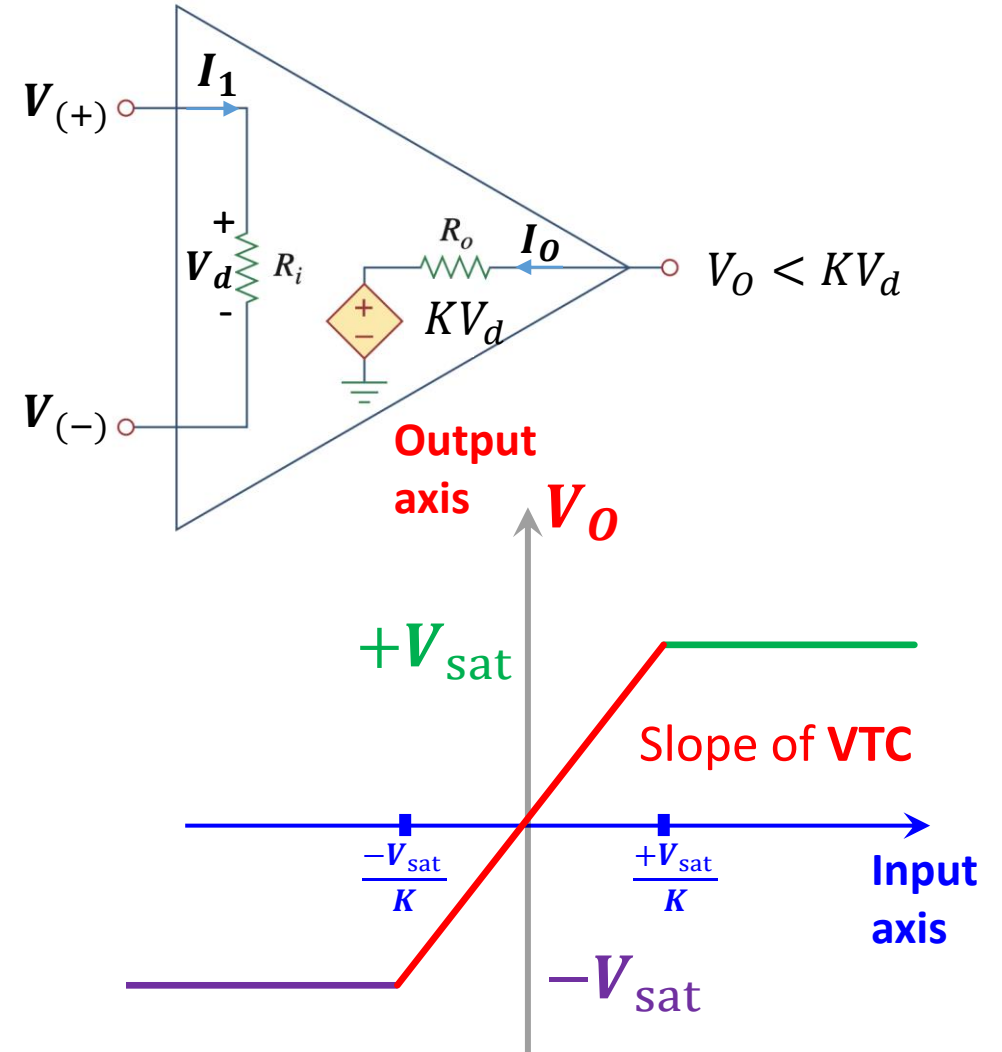
# Solving Comparator Problems



# 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 $K$	$10^4 - 10^8$	$\infty$
$R_i$	$100\text{ k}\Omega - 10^{10}\text{ k}\Omega$	$\infty$
$R_o$	$0.01\text{ k}\Omega - 0.1\text{ k}\Omega$	$0$



# Thank you!

Lecture 3 ends here