



CSE 251

Electronic Devices and Circuits Lecture 3

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Outline

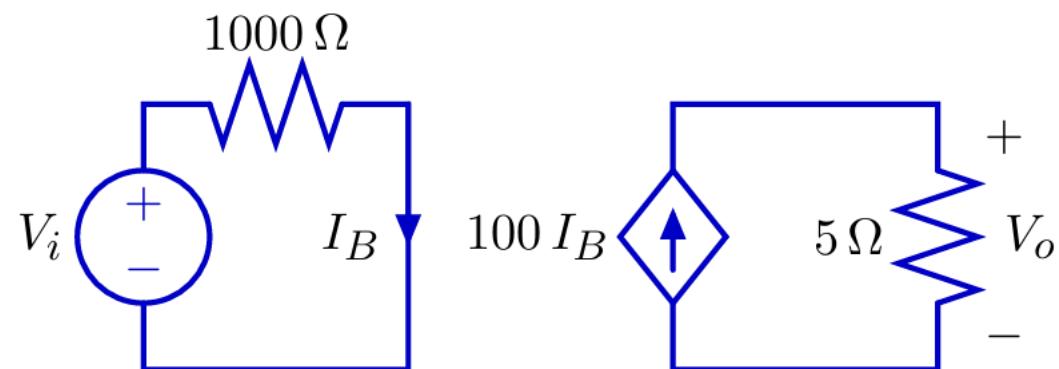
- **Operational Amplifier: Introduction**
 - Dependent Sources
 - Op-Amp: Circuit Symbols and terminal
 - Op-Amp: VTC (Voltage Transfer Characteristics)
 - Linear Amplification
 - (Positive and Negative) Saturation
 - Op-Amp: Examples
 - Op-Amp: Physical Entity

Dependent Sources

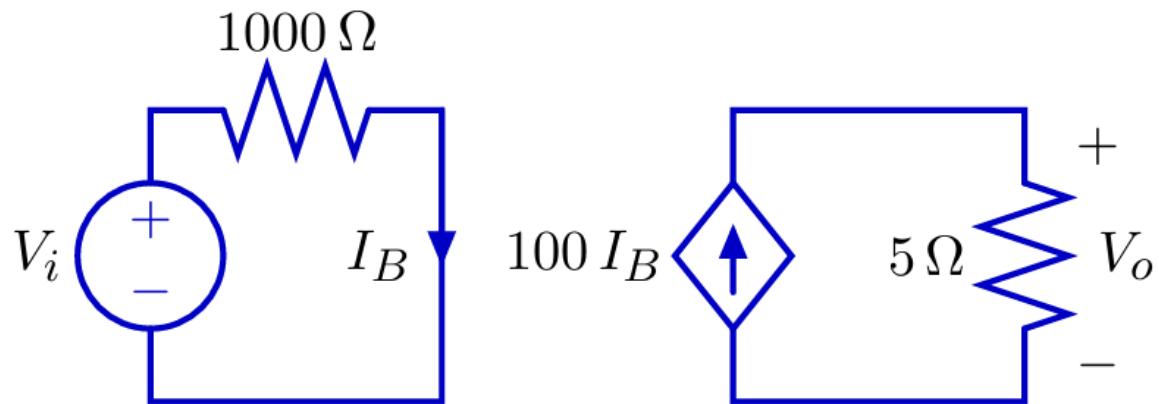
To analyze op-amps, we must understand **dependent source**.

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

Example: current-controlled current source



Dependent Sources



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

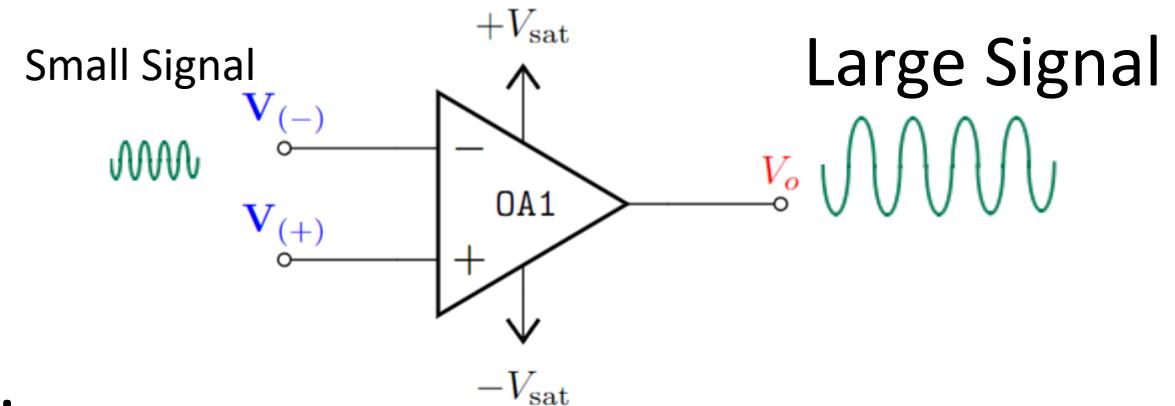
$$V_o = 100 I_B \times 5 \Omega$$

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

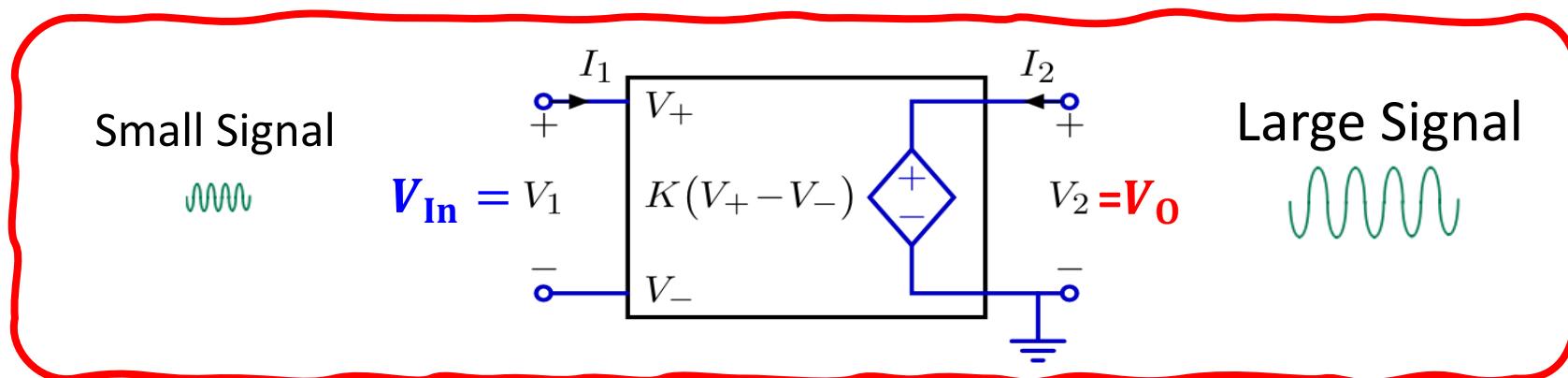
$$= 100 \frac{V_i}{1000 \Omega} \times 5 \Omega = \boxed{\frac{1}{2} V_i}$$

Operational Amplifier: Introduction

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

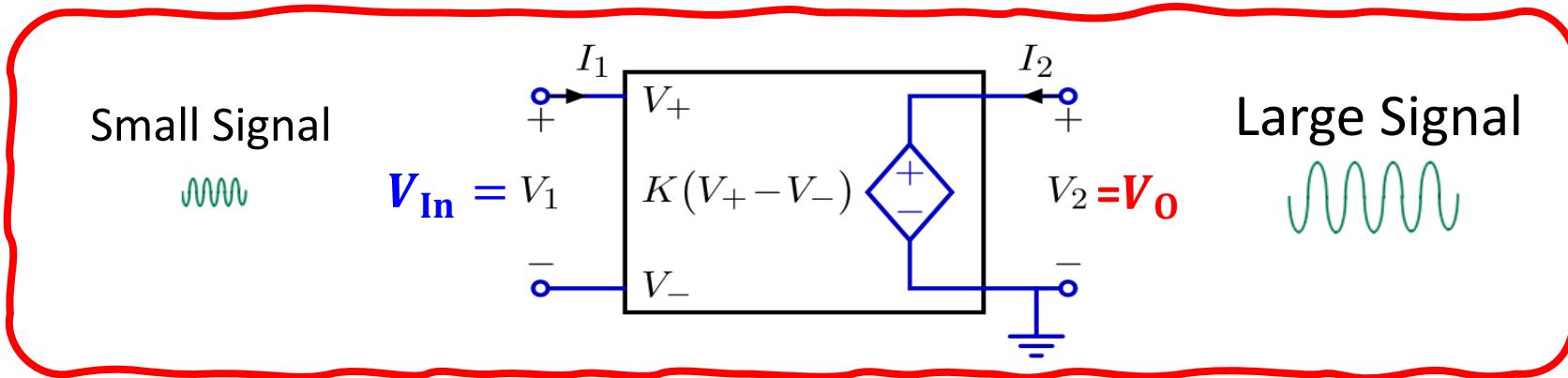


An **op-amp (operational amplifier)** can be modelled by a **voltage-controlled voltage source**.



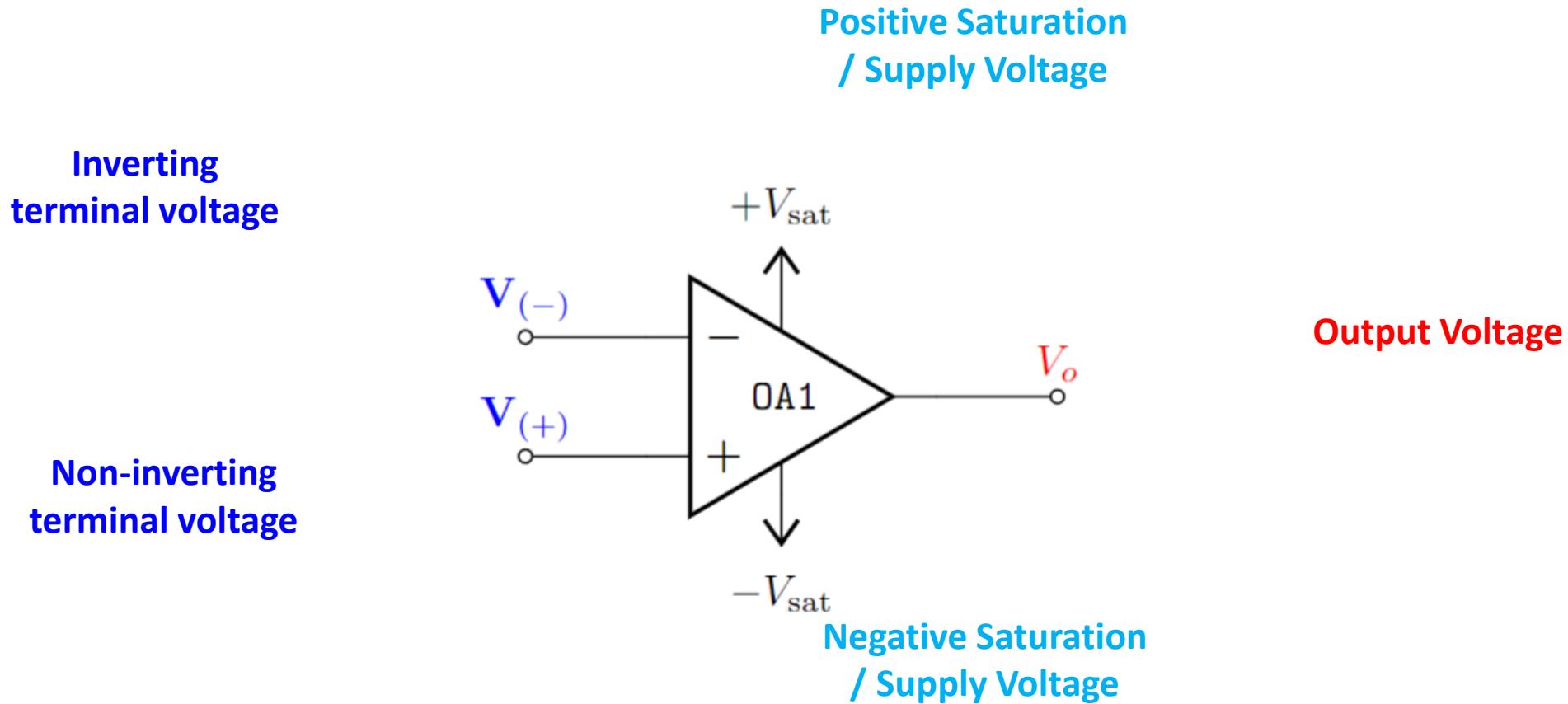
Operational Amplifier: Introduction

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



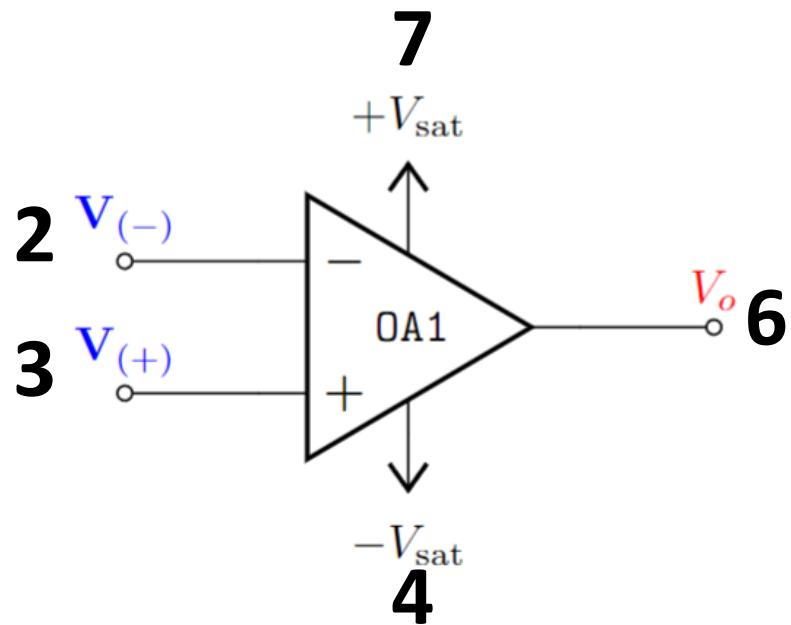
$I_1 = 0$ and $V_O = KV_{In}$ where K is large (typically $K > 10^5$).

Op-Amp: Circuit Symbols and terminal

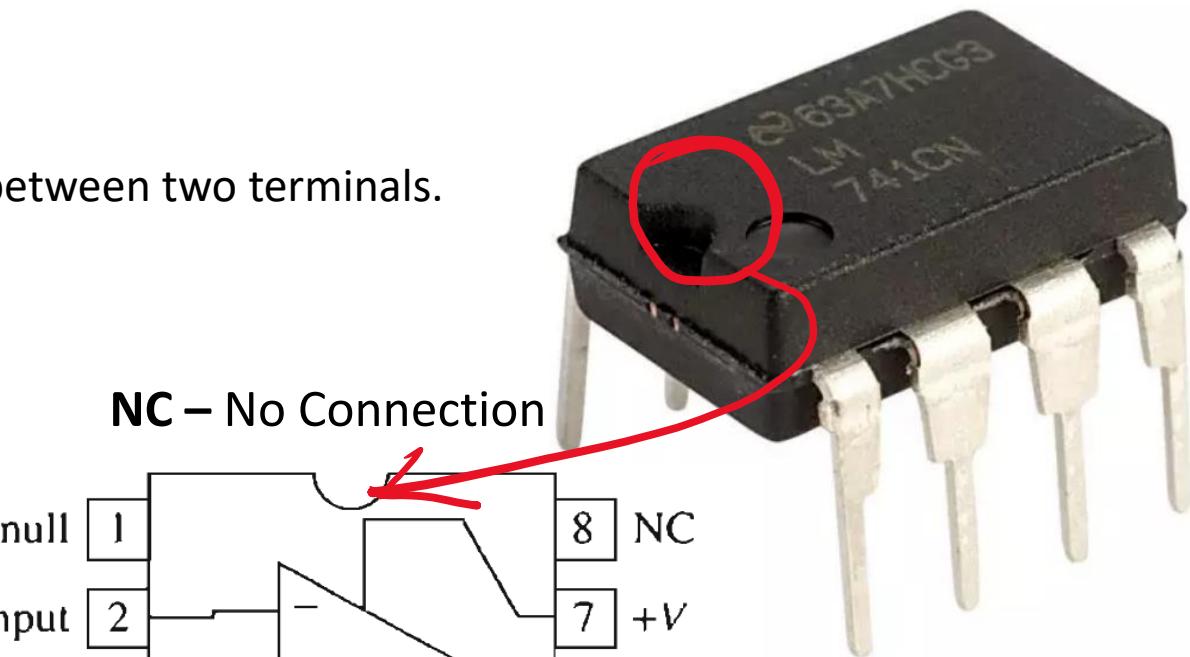
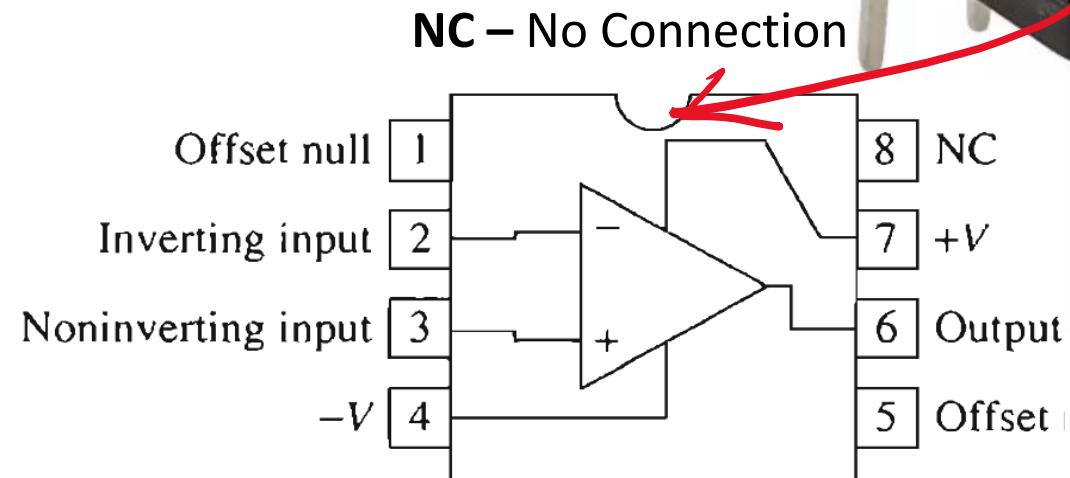


Op-Amp: Physical Entity

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**



μ A-741C →
Manufacturer ID
Part Identification Number (PIN)

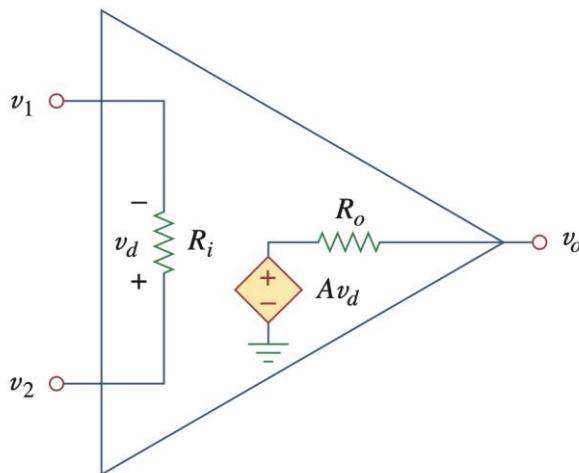
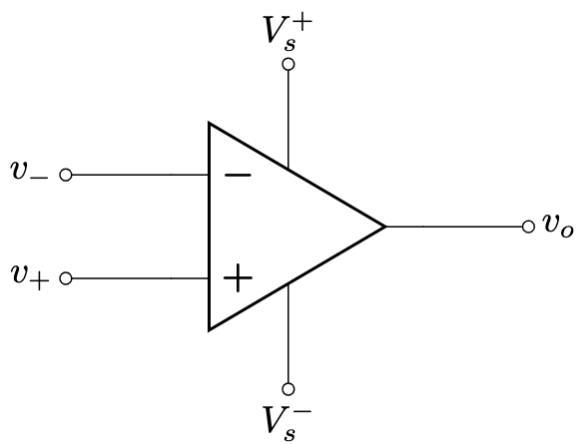
C: Commercial (0° – 70° C)
I: Industrial (-25° – 85° C)
M: Military (-55° – 125° C)

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

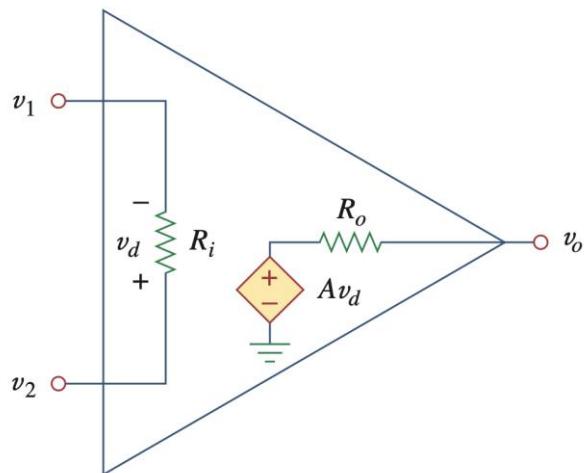
R_o = Output resistance

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

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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 $\rightarrow V_O$

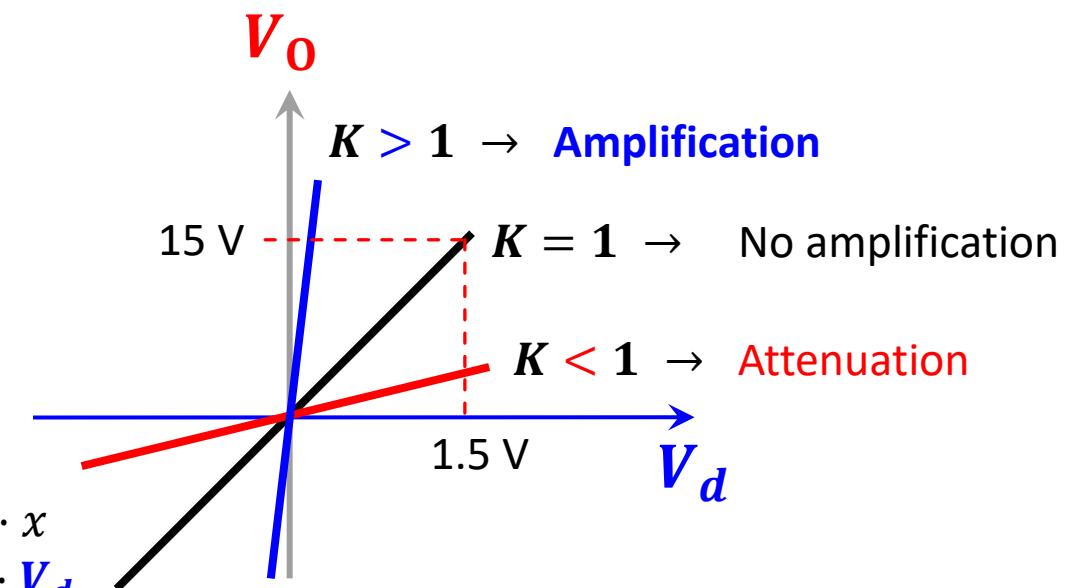
- x –axis $\rightarrow V_d$

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



If the line passes through origin:

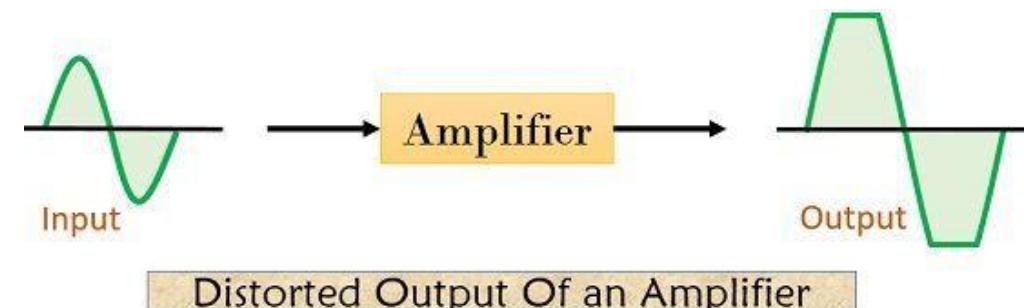
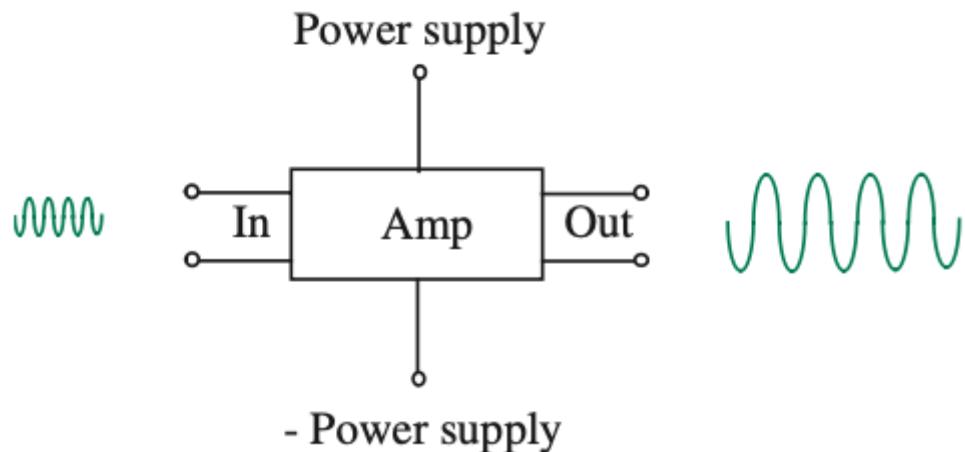
$$y = K \cdot x$$
$$V_O = K \cdot V_d$$



LINEAR AMPLIFICATION

Op-Amp: VTC – Linear Amplification

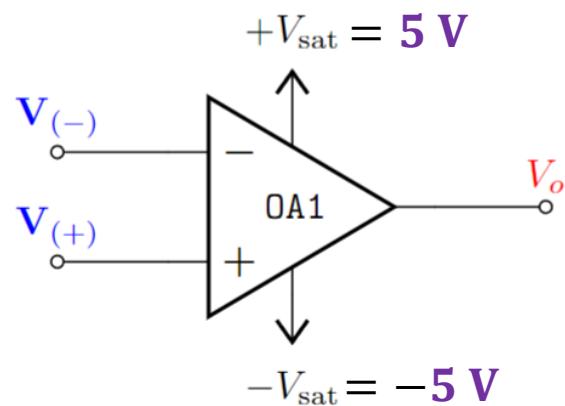
- **Linear Amplification** only takes place within a valid input range.
- Otherwise output will be distorted -- Saturation



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

Op-Amp: VTC - Saturation

VTC -> Voltage Transfer Characteristics



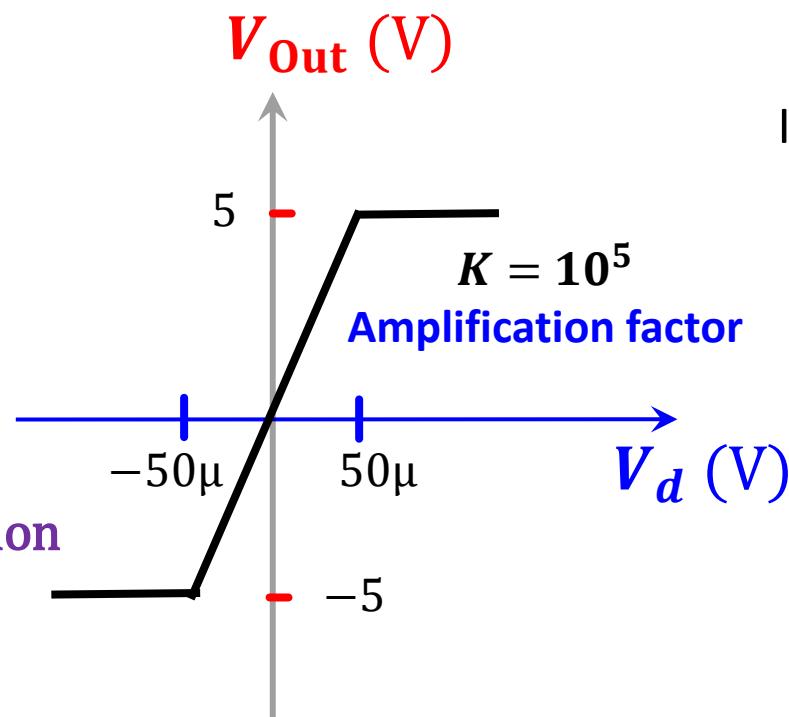
$$V_o = K \cdot V_{in} : \text{When } -5 \text{ V} < V_o < 5 \text{ V}$$

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

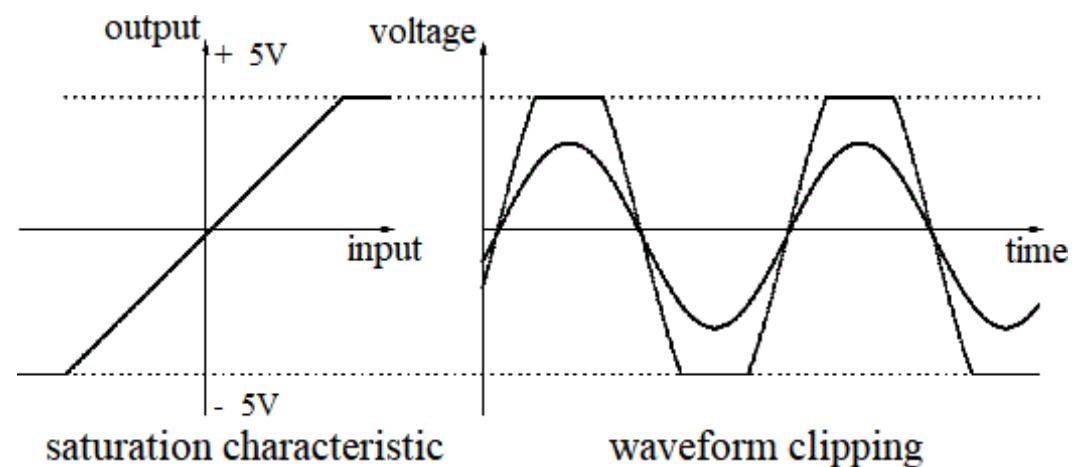
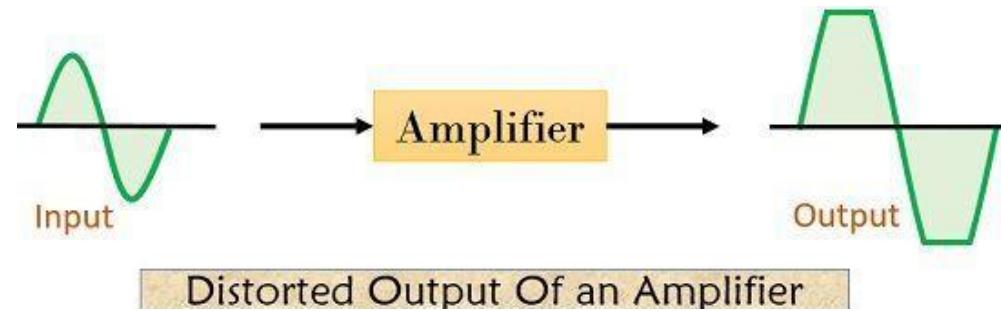
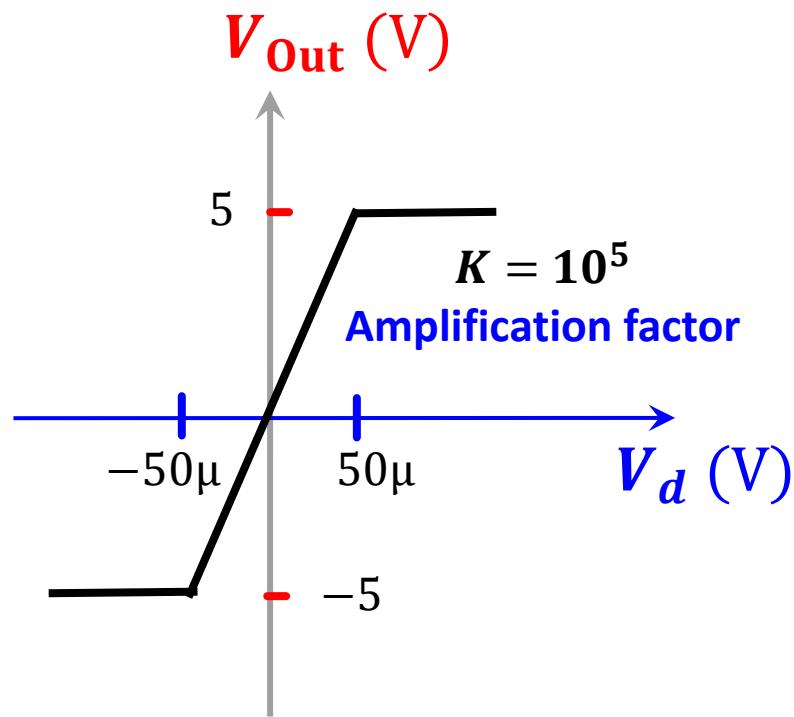
If $V_d < -50\mu$: Negative Saturation

$$\Rightarrow V_o = -5$$

If $V_d > 50\mu$: Positive Saturation
 $\Rightarrow V_o = 5$

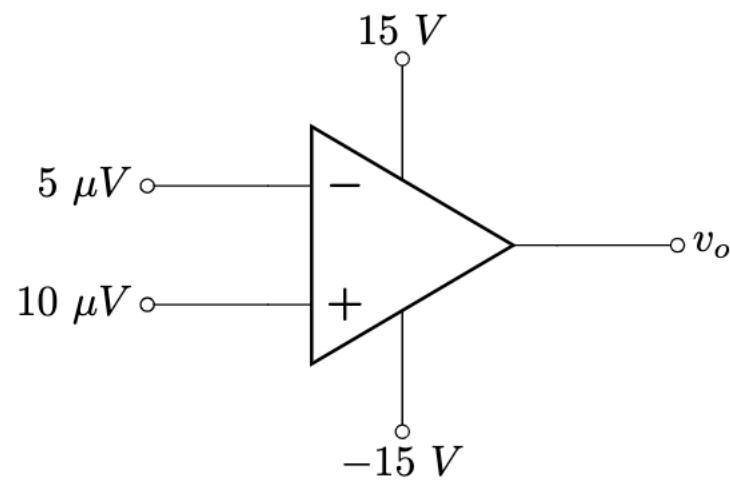


Op-Amp: VTC - Saturation

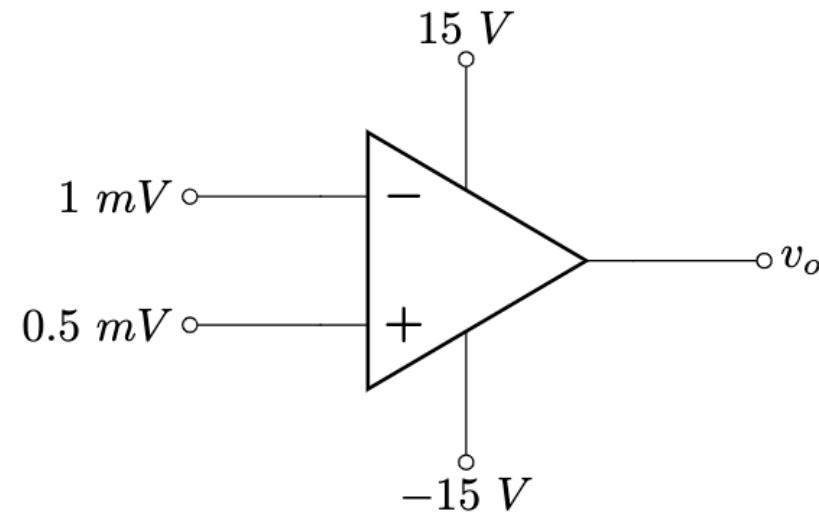


Op-Amp: Examples

Find v_o



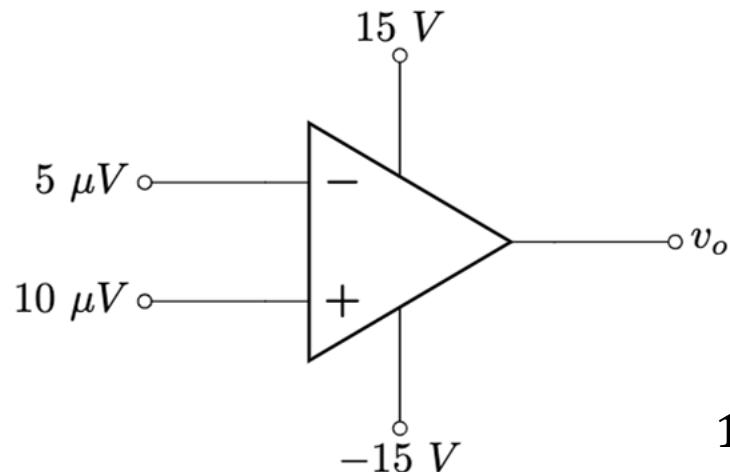
$$A = 2 \times 10^5$$



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

Example 1

- Find v_o



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

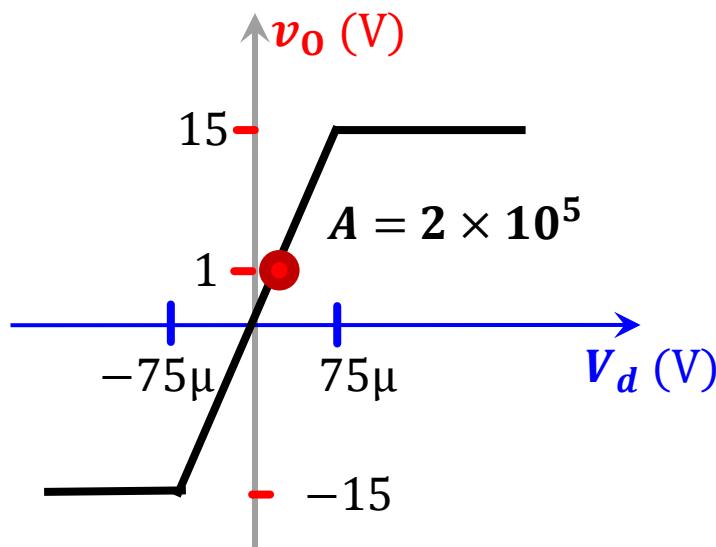
Solution:

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

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

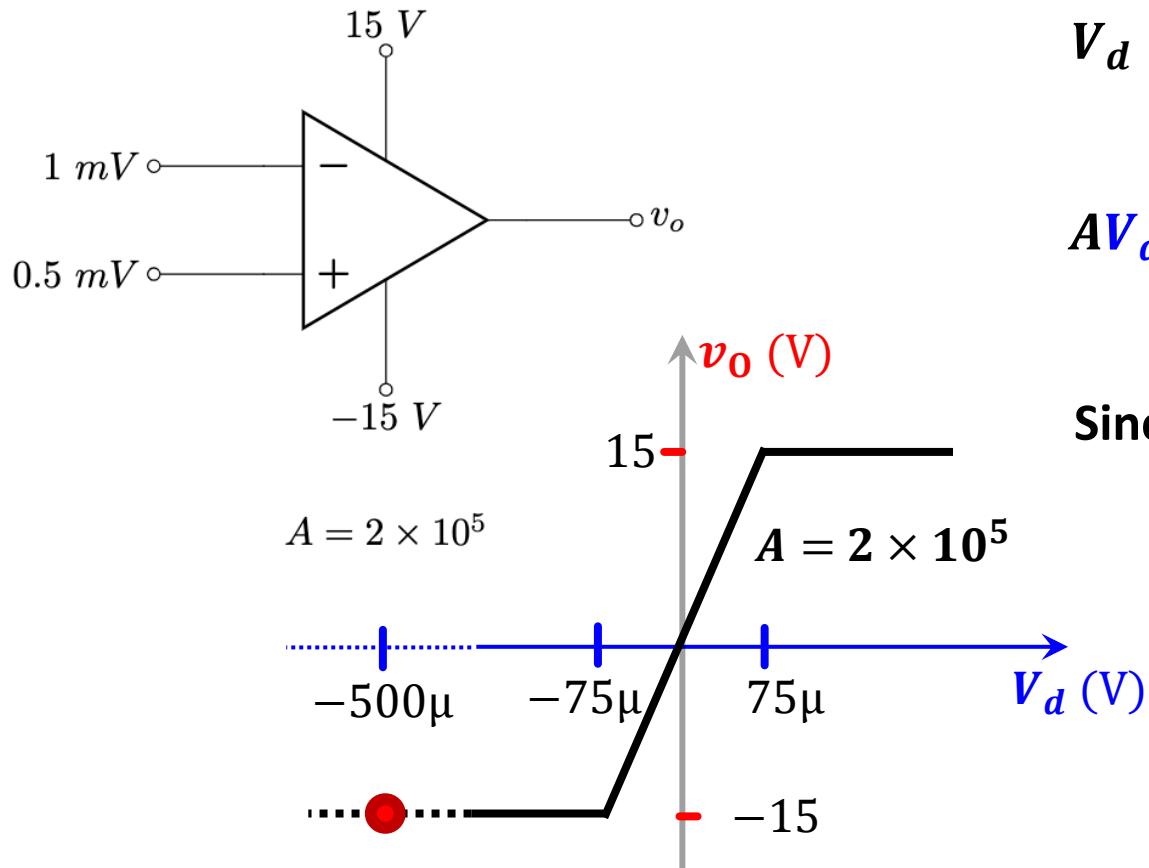
Since $-15 V < AV_d < +15 V$

$$v_o = AV_d = 1 V$$



Example 2

- Find v_o



Solution:

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

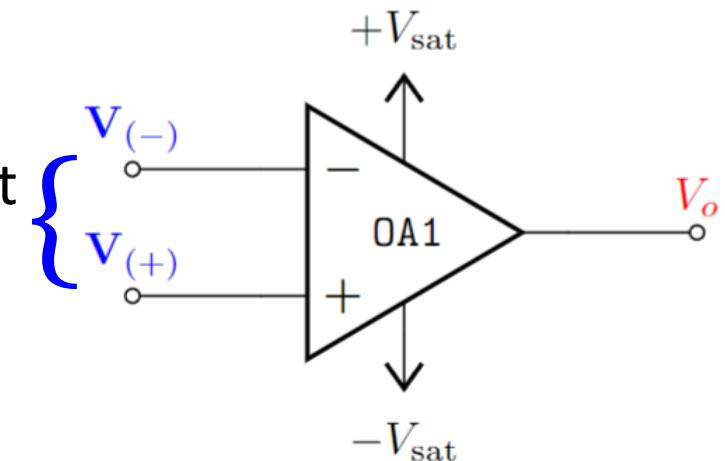
$$AV_d = (2 \times 10^5) \times (-0.5 \times 10^{-3}) \text{ V} = -100 \text{ V}$$

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

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

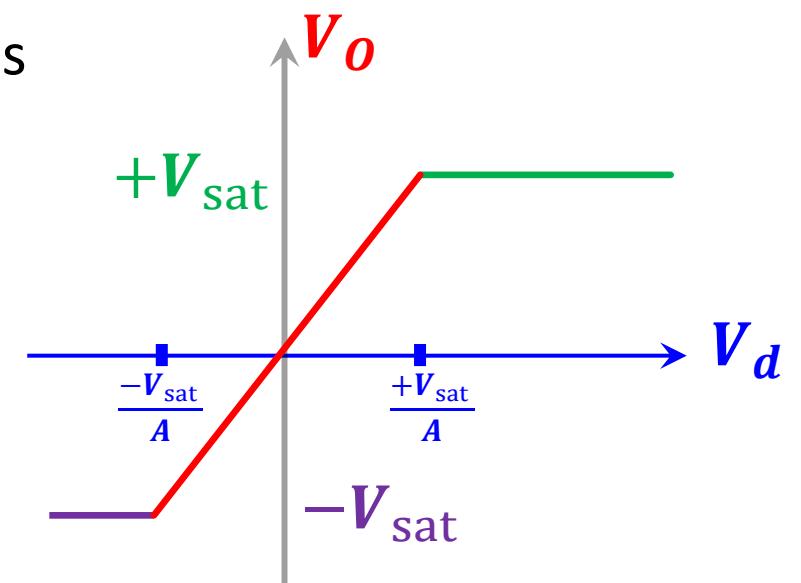
Op-Amp: Summary

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



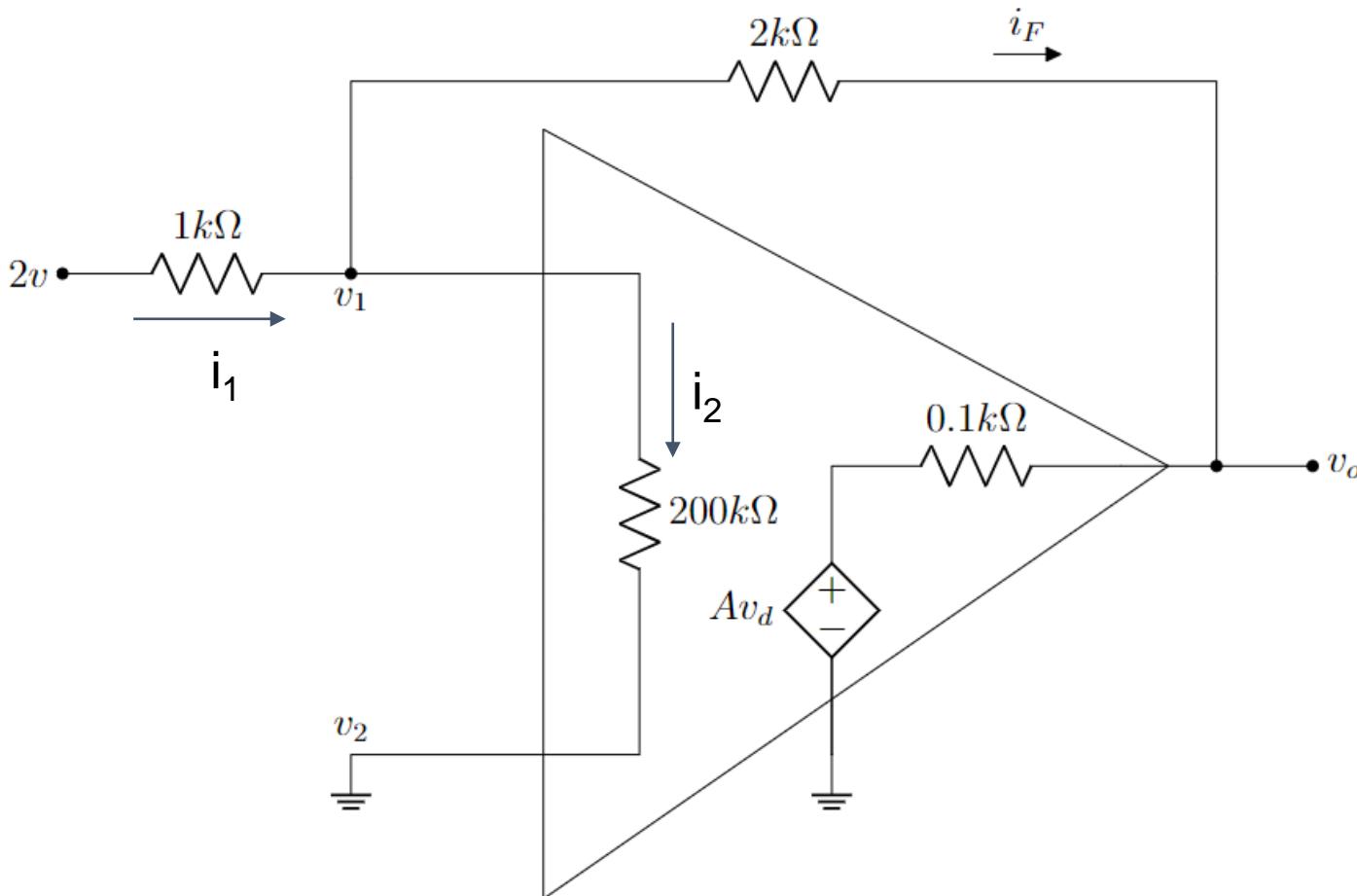
However, the **Amplification** is limited within voltage levels defined by the positive and negative saturation voltages $[-V_{sat}, +V_{sat}]$.

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,

$$i_{0.1k} = i_F$$

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

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

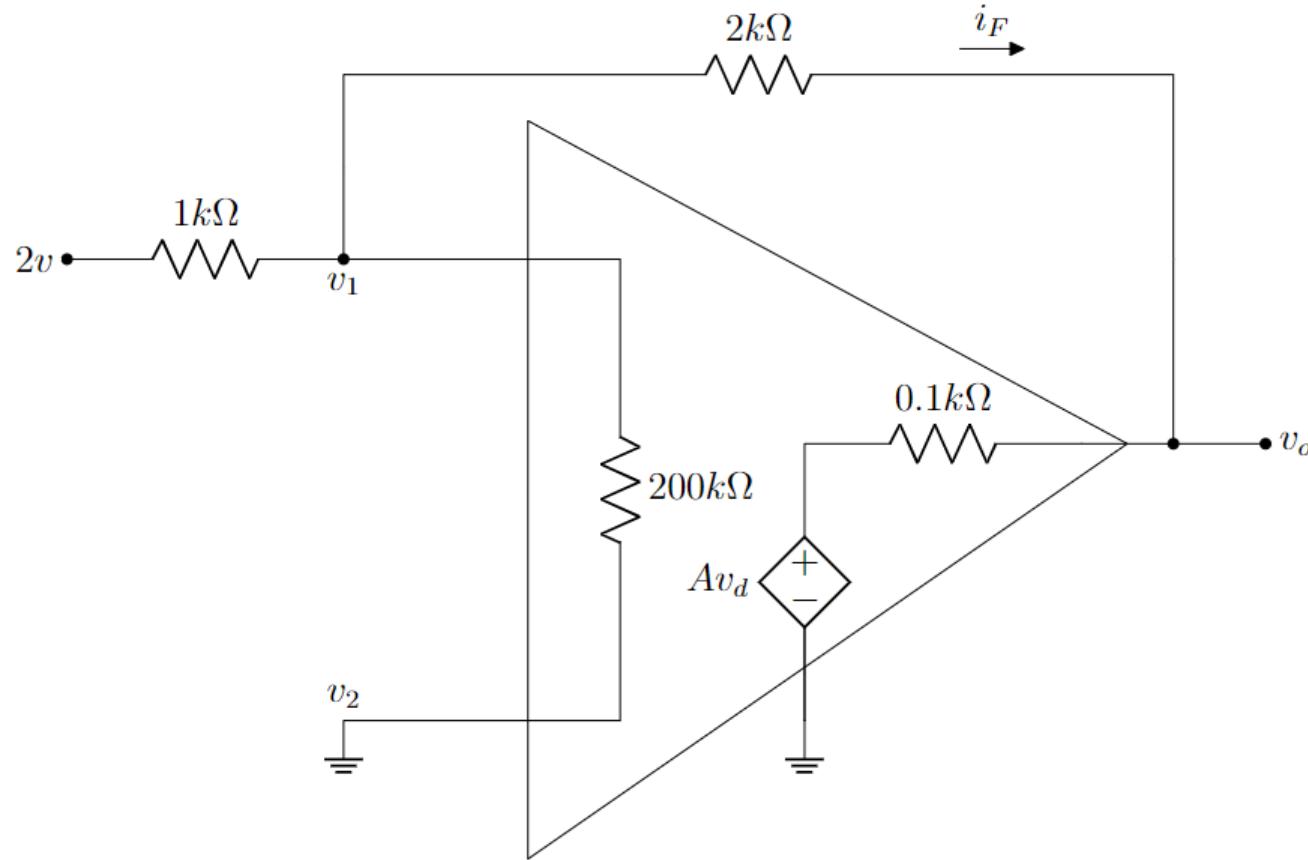
$$\rightarrow (v_o - (2 \times 10^5) \times (0 - v_1))/(0.1k) = (v_1-v_o)/(2k)$$

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

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

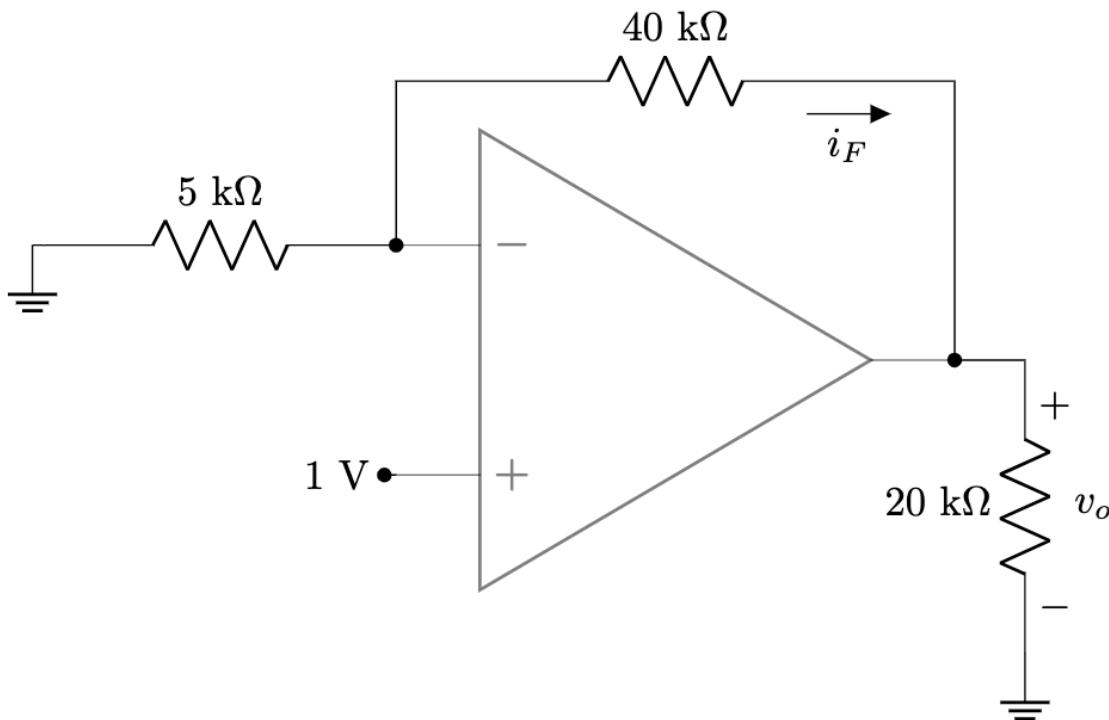
Example 5

Step 2: Solve using KCL & KVL or nodal



Example 6

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

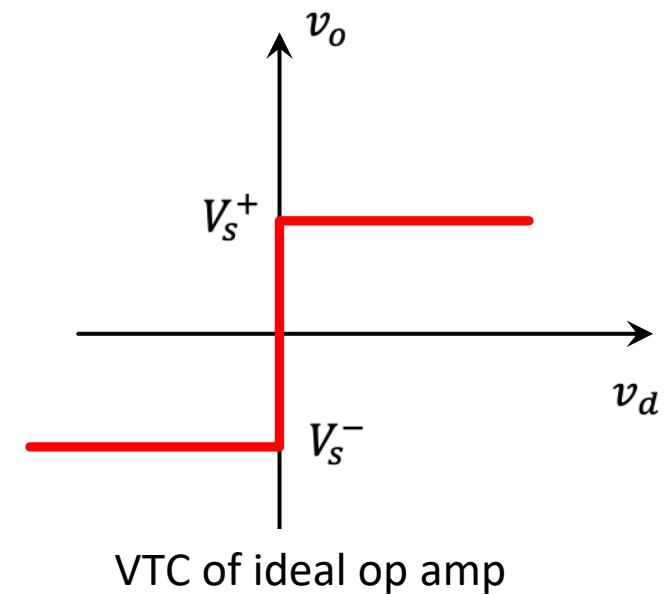
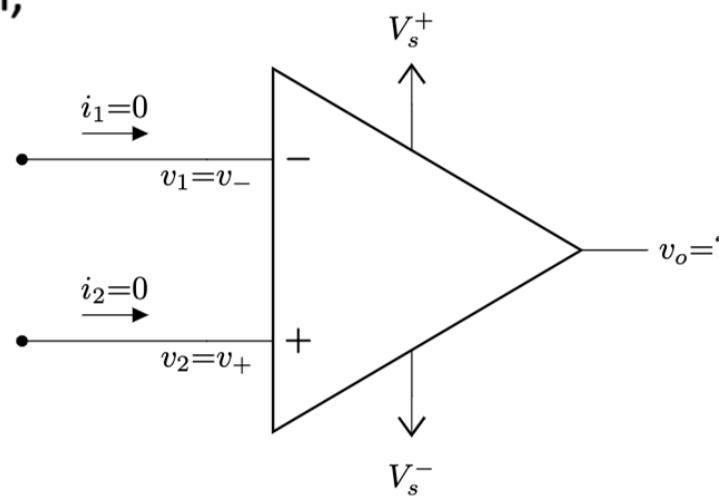


The Ideal Op-Amp

- To facilitate the understanding of op amp circuits, we will assume **ideal op amps**
 - Infinite open-loop gain, $A = \infty$
 - Infinite input resistance, $R_i = \infty =$ open circuit
 - Zero output resistance, $R_o = 0 =$ 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?)

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

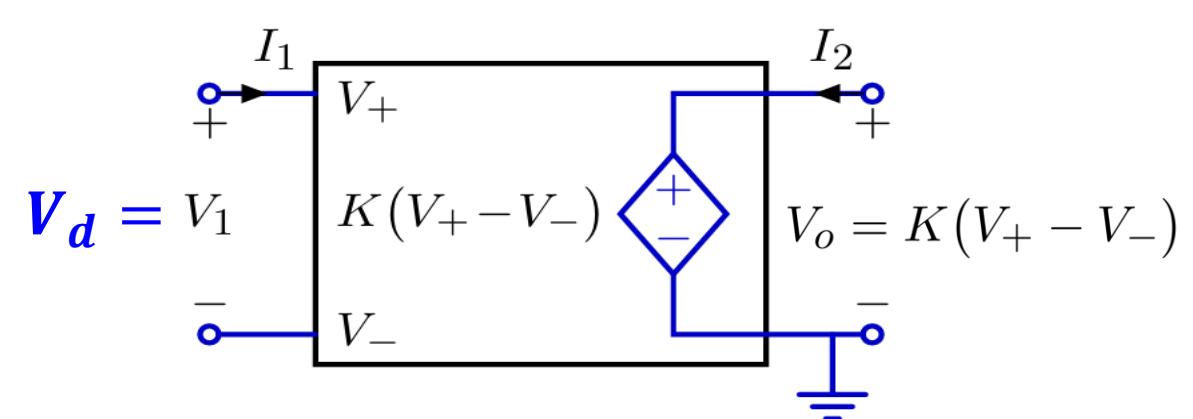
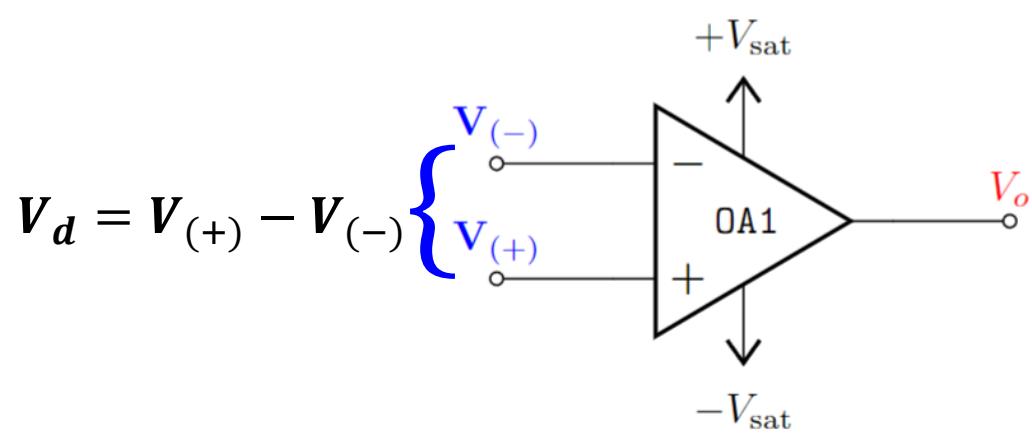
Reminder: $v_d = v_2 - v_1 = v_+ - v_-$



Op-Amp: Circuit Modelling

Voltage controlled voltage Source

“Ideal” op-amp approximation



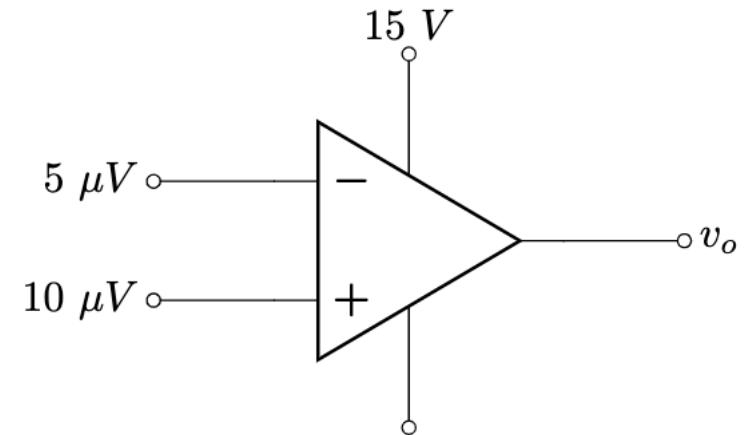
$$V_{(+)} \approx V_{(-)}$$

$$I_1 \approx 0$$

Types of Op-Amp configuration

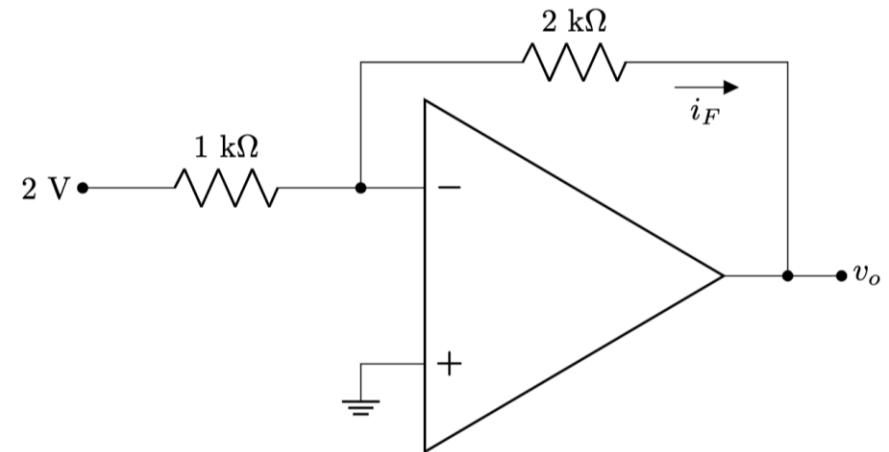
1. Open loop configuration:

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)

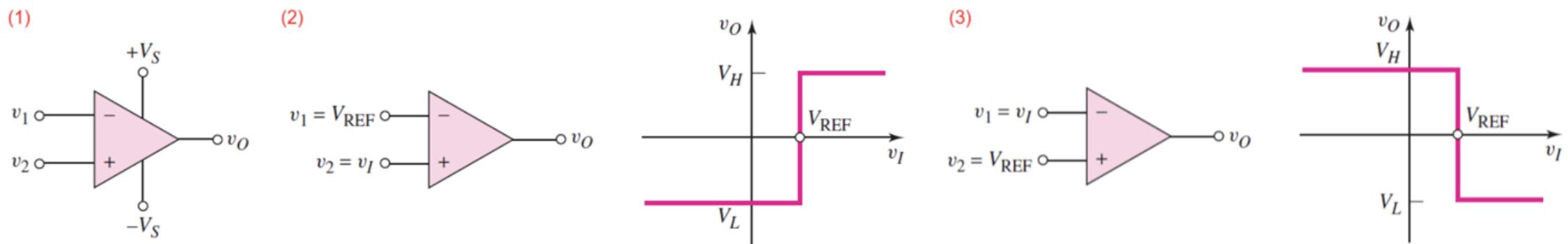
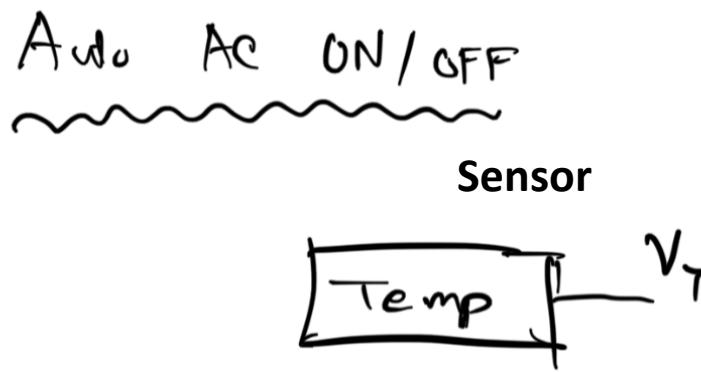


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

Comparator Application – Automatic AC



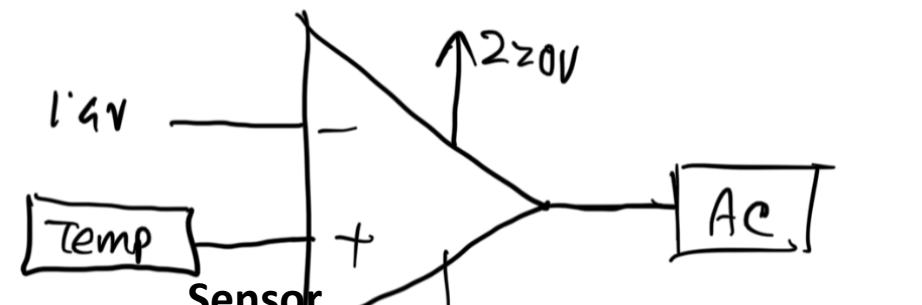
$$V_T \propto T$$

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

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

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

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



$$V_{THR} = 1.4V$$

$$V_T > V_{THR} \Rightarrow V_o = V_+$$
$$V_T < V_{THR} \Rightarrow V_o = V_-$$

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

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*), $\rho (= 1000\ kgm^{-3})$ is the density of water and g is the acceleration due to gravity (in 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 $h = 10 \text{ m}$: $P = h\rho g = 98000 \text{ Pa} = 0.967 \text{ atm}$

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

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

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

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

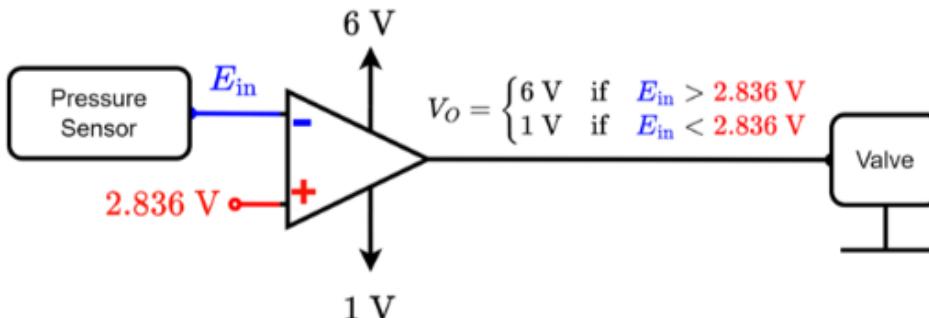
So, voltage at 0.967 atm pressure is $0.5 + 5 * 0.467 \text{ V} = 2.836 \text{ V}$

Active low logic:

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

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

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

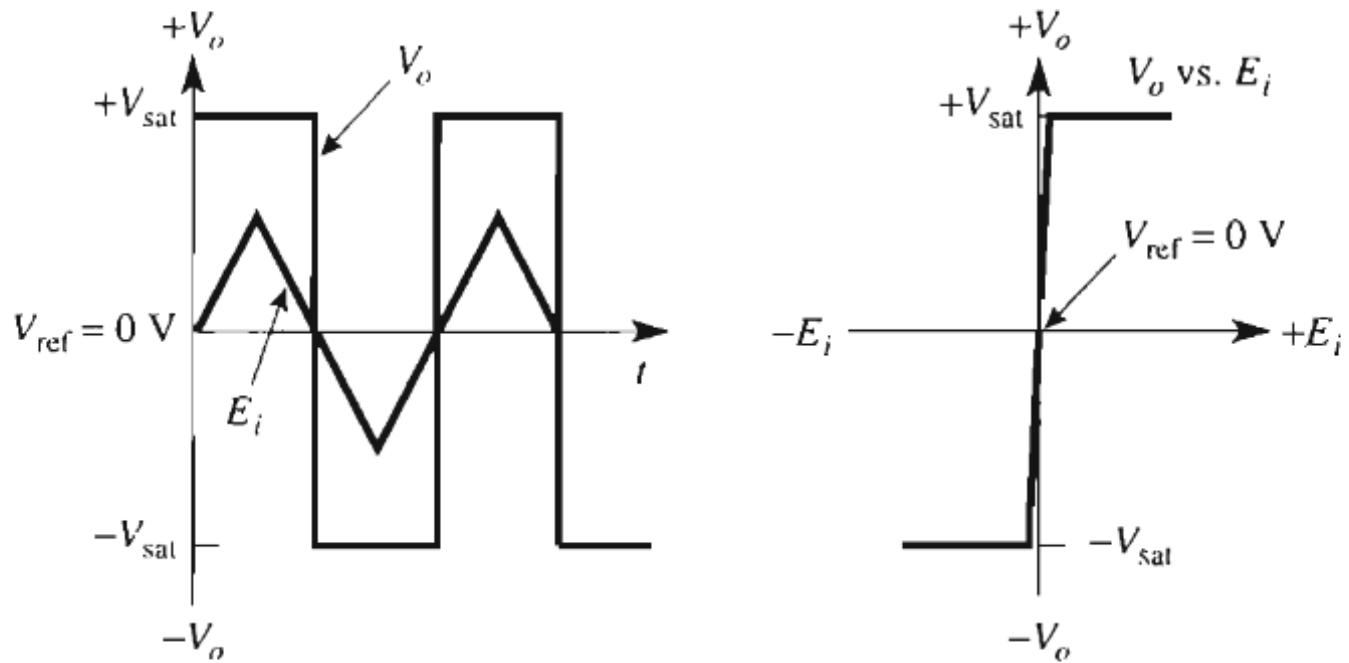
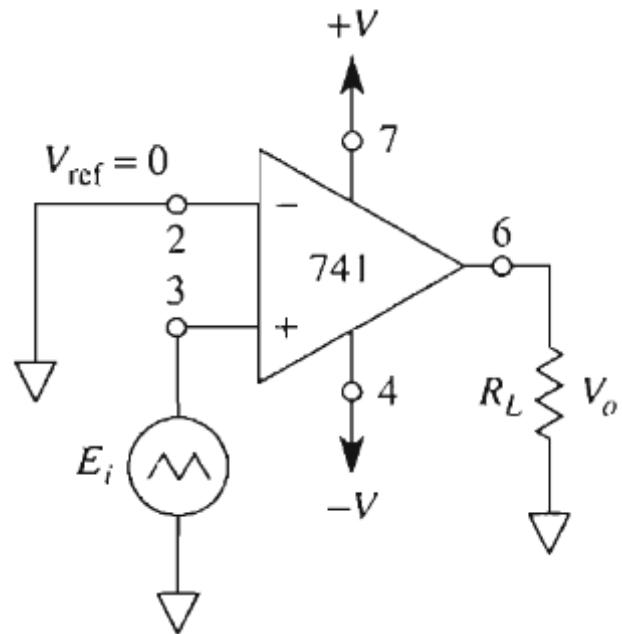


Open Loop Configuration: Comparator

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

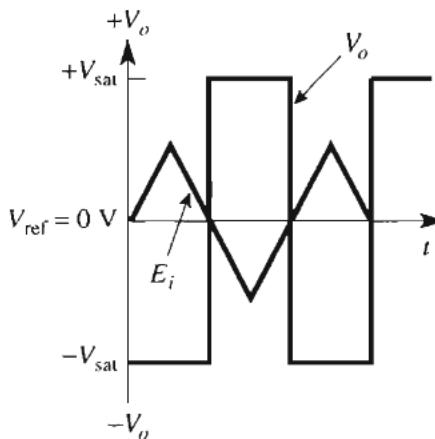
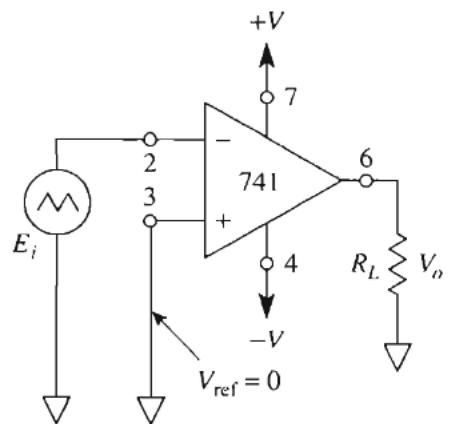


(a) Noninverting: When E_i is above V_{ref} , $V_o = +V_{sat}$.

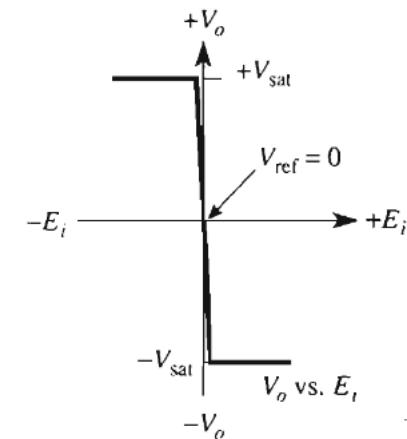
Open Loop Configuration: Comparator

Zero Crossing Detector

Inverting configuration

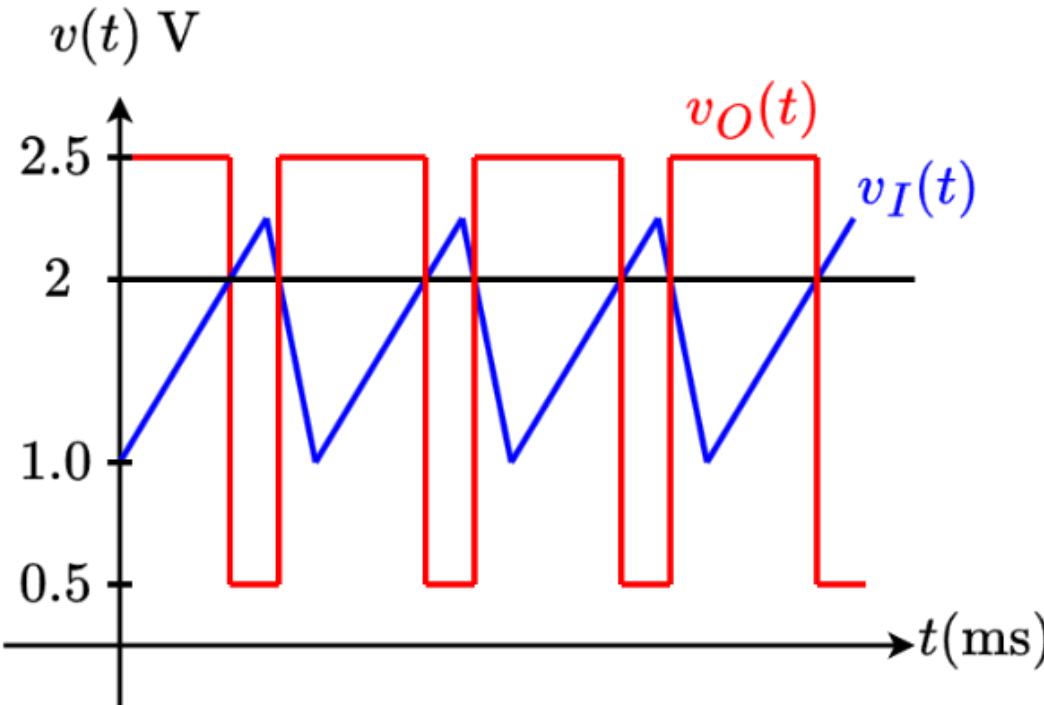


(b) Inverting: When E_i is above V_{ref} , $V_o = +V_{sat}$.



Open Loop Configuration: Example 2

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

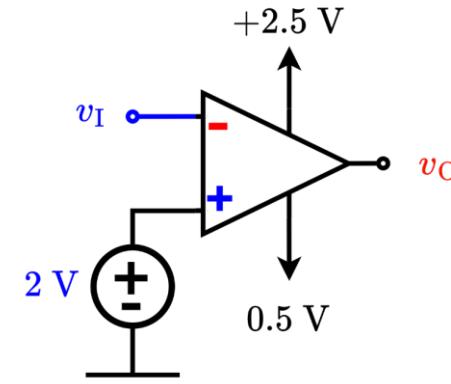


Solution:

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

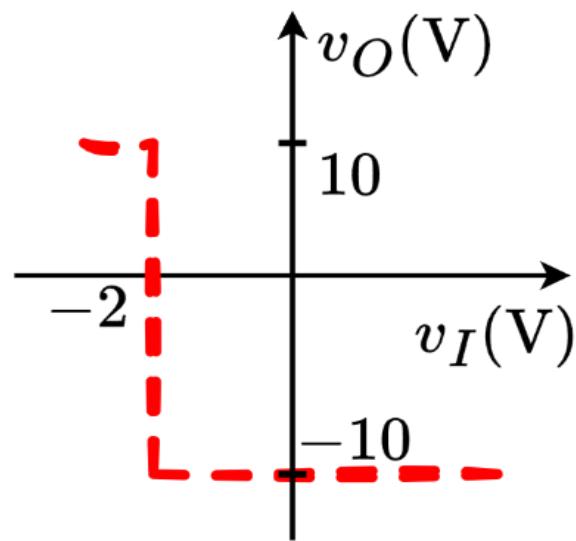
v_I larger than 2 V $\Rightarrow v_O = -2.5$ V \rightarrow Negative Saturation

INVERTING CONFIGURATION



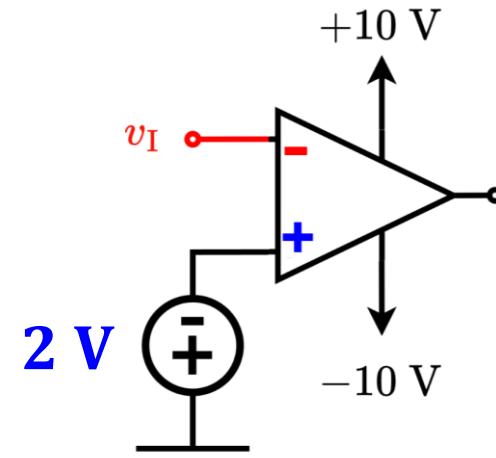
Open Loop Configuration: Example 1

- 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**.



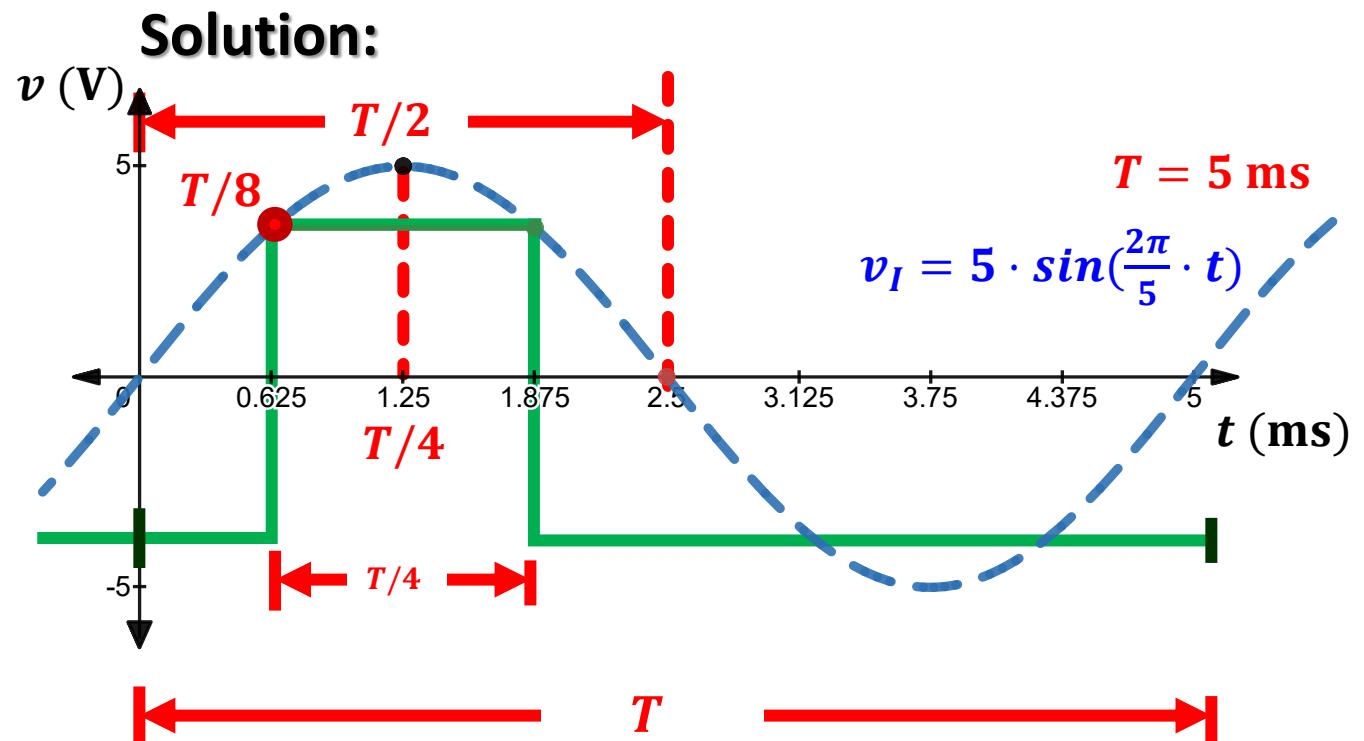
Solution:

Inverting comparator



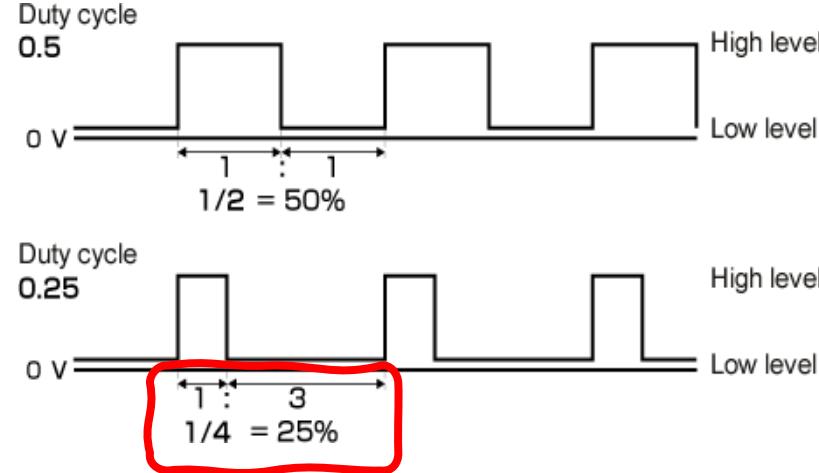
Open Loop Configuration: Example 3

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



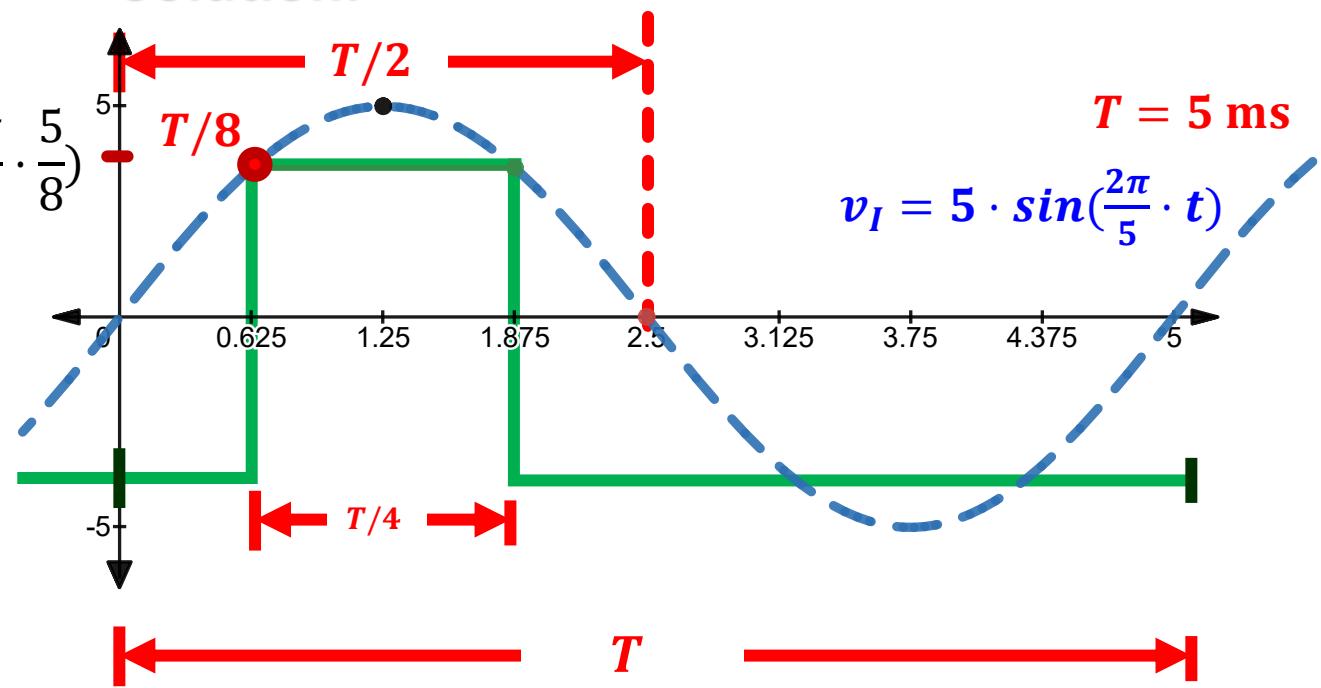
Open Loop Configuration: Example 3

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%.



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

Solution:



Open Loop Configuration: Example 3

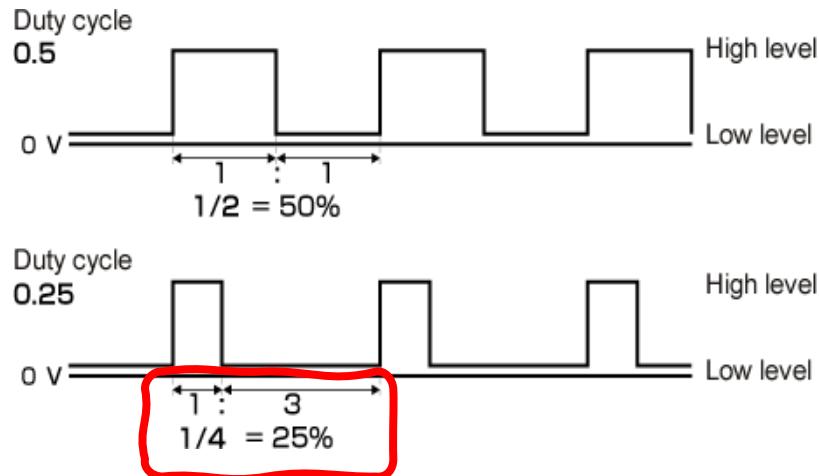
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Solution:

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

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

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



$v_I \geq 3.535 \text{ V} : v_o \rightarrow \text{Positive Saturation}$

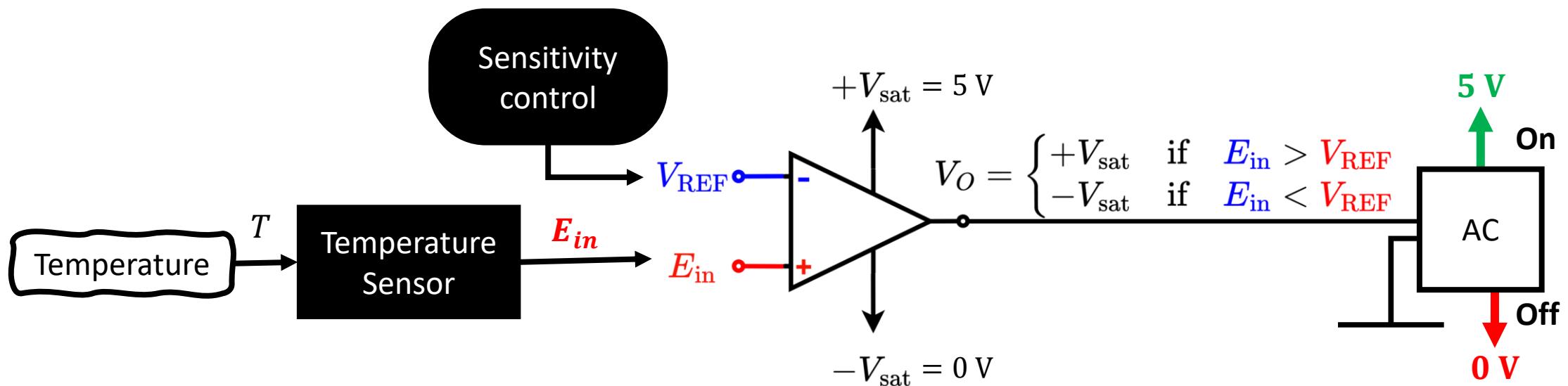


$v_I \leq 3.535 \text{ V} : v_o \rightarrow \text{Negative Saturation}$



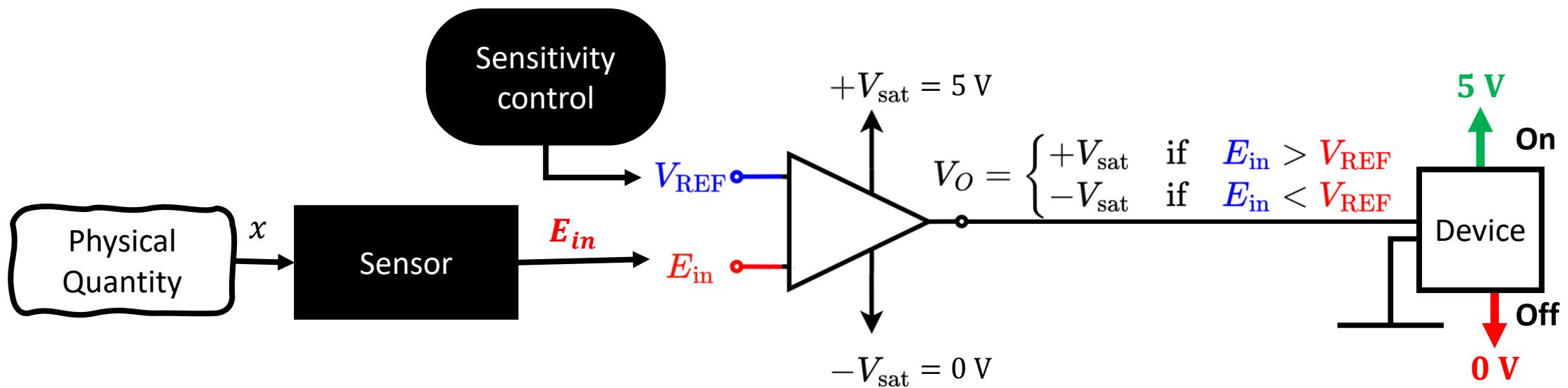
NON-INVERTING CONFIGURATION

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 $\uparrow \propto$ **$E_{in} \uparrow \rightarrow AC - ON$** → NON-INVERTING RELATIONSHIP: **NON INVERTING COMPARATOR**
- The sensitivity of **switching on the AC** is determined by V_{REF}

Comparator Application – Summary

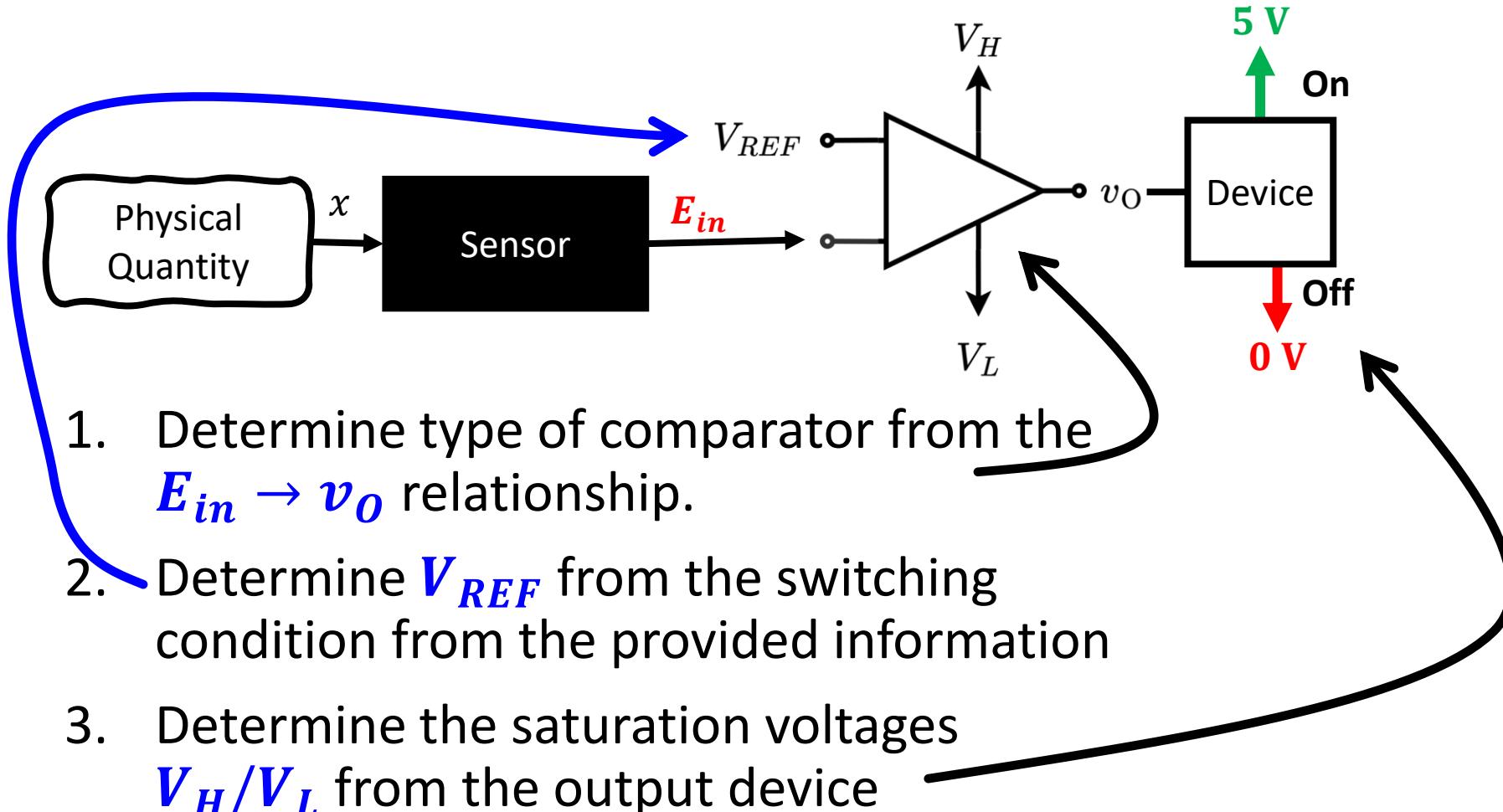


- Comparators can be used to switch on **any device** based on a **Physical Quantity**.
 - Phys. Qnty. \uparrow DEVICE – ON / OFF
 - Phys. Qnty. \downarrow DEVICE – OFF / ON
 - Phys. Qnty. $\rightarrow E_{in} \downarrow \uparrow \rightarrow$ DEVICE – ON/OFF
- The sensitivity of switching on the **AC** is determined by V_{REF}

This Relationship:

Determines the type of **Comparator**

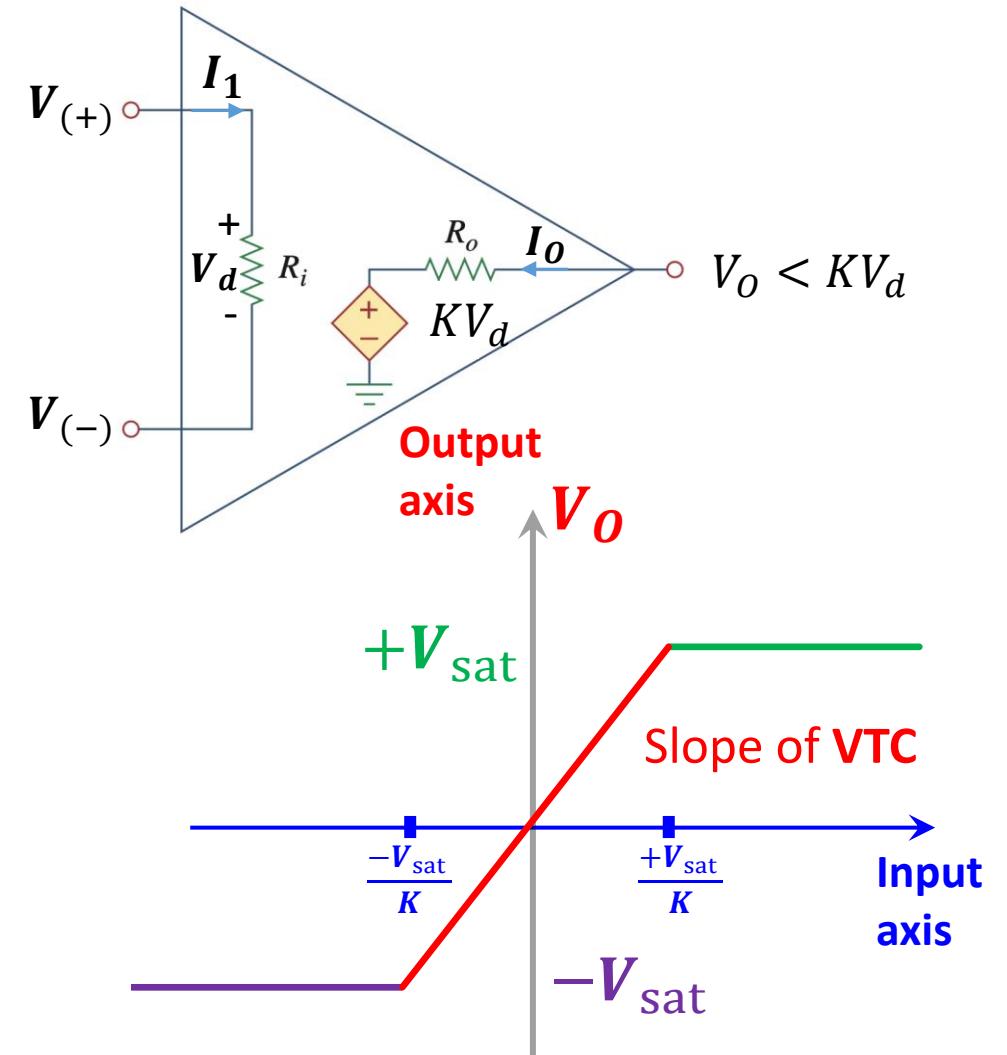
Solving Comparator Problems



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



Thank you!

Lecture 3 ends here