CSE 251:Electronic Devices & Circuits

3.Introduction to Op-Amp

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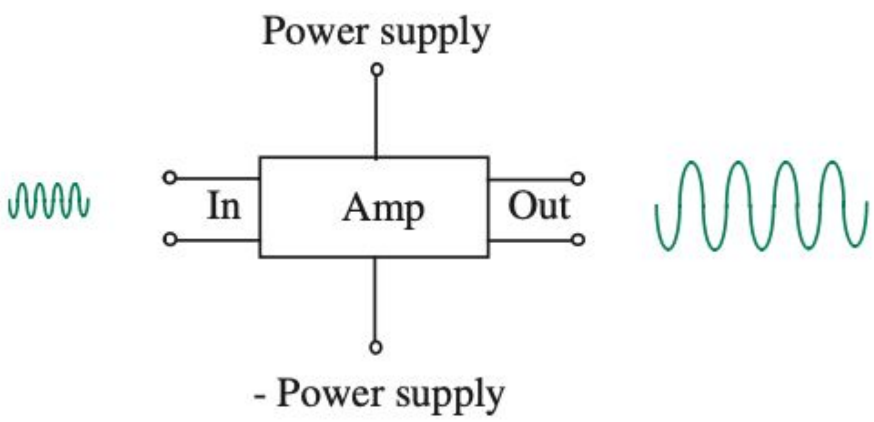
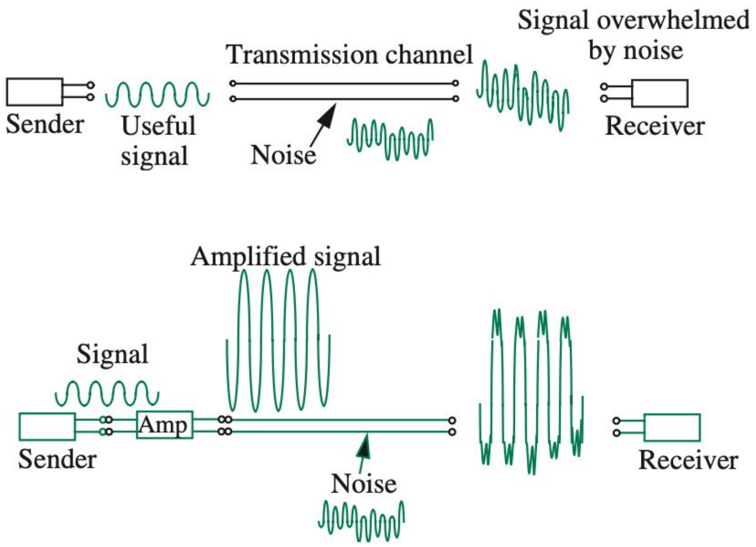
Review

- Last class: alternative representation, KCL, KVL, nodal
- Today: Operational amplifiers (Op-amp)

Amplifier

- Linear amplifier ⇒ $OUT = k \times IN$. k is called the **gain** of the amplifier
- OUT/IN can be voltage or current
- Amplifier must provide power gain ($P_{OUT} > P_{IN}$), hence need **power supply**
- Usage: communication



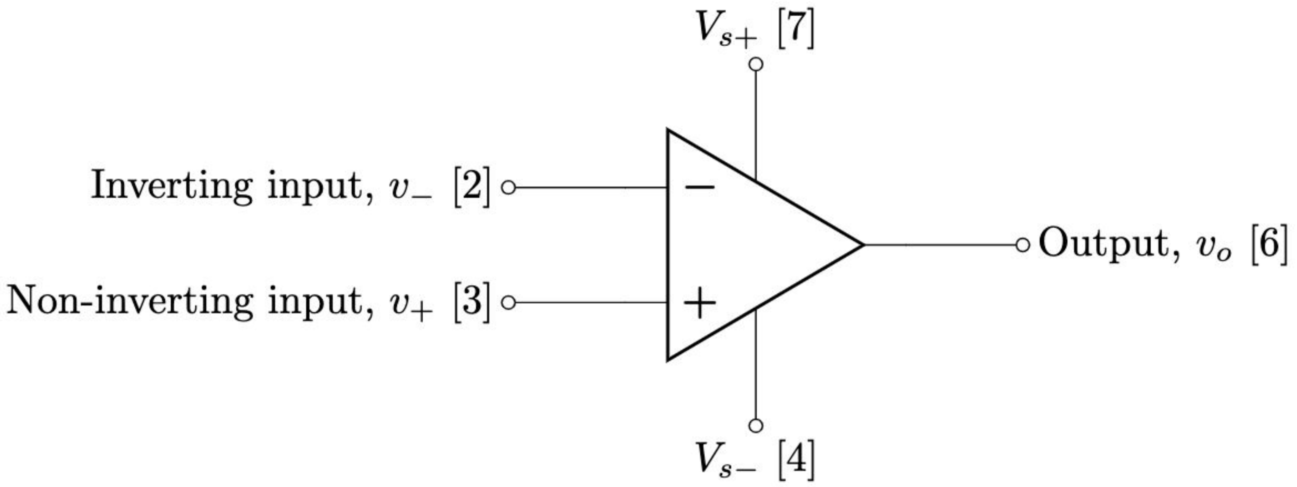


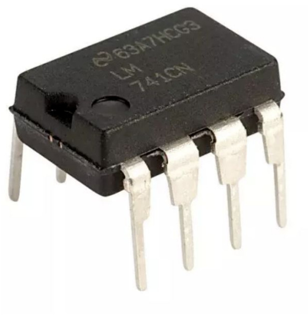
Operational Amplifiers

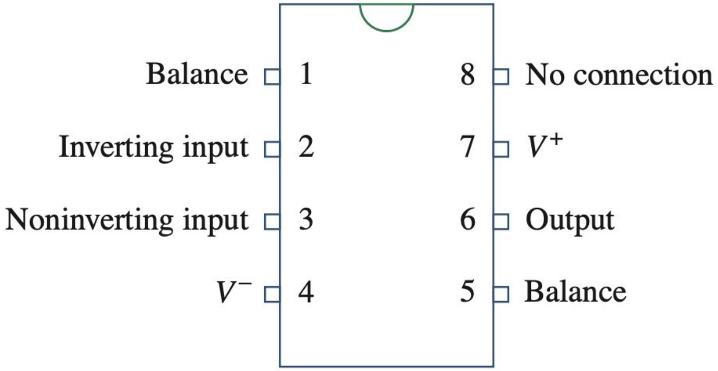
- An operational amplifier, or **op-amp** for short, is a versatile and powerful integrated circuit that is widely used in a variety of electronic applications.
- An Op-Amp is designed so that it performs some mathematical operations when external components, such as resistors and capacitors, are connected 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.

Terminals and Circuit Symbol

- Op-amps are **differential amplifiers** – meaning it amplifies the voltage difference between two terminals. Therefore, it has two inputs
- Since this is an amplifier, there are two terminals for **power supply**



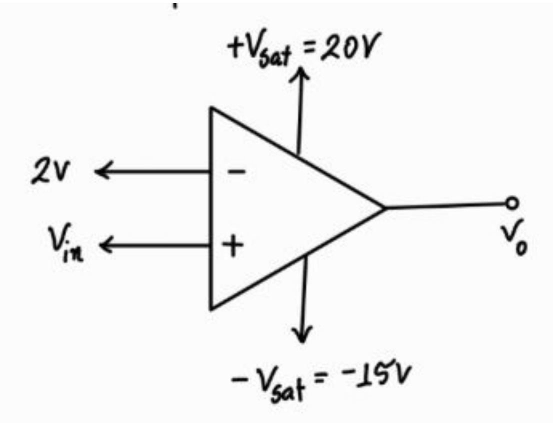




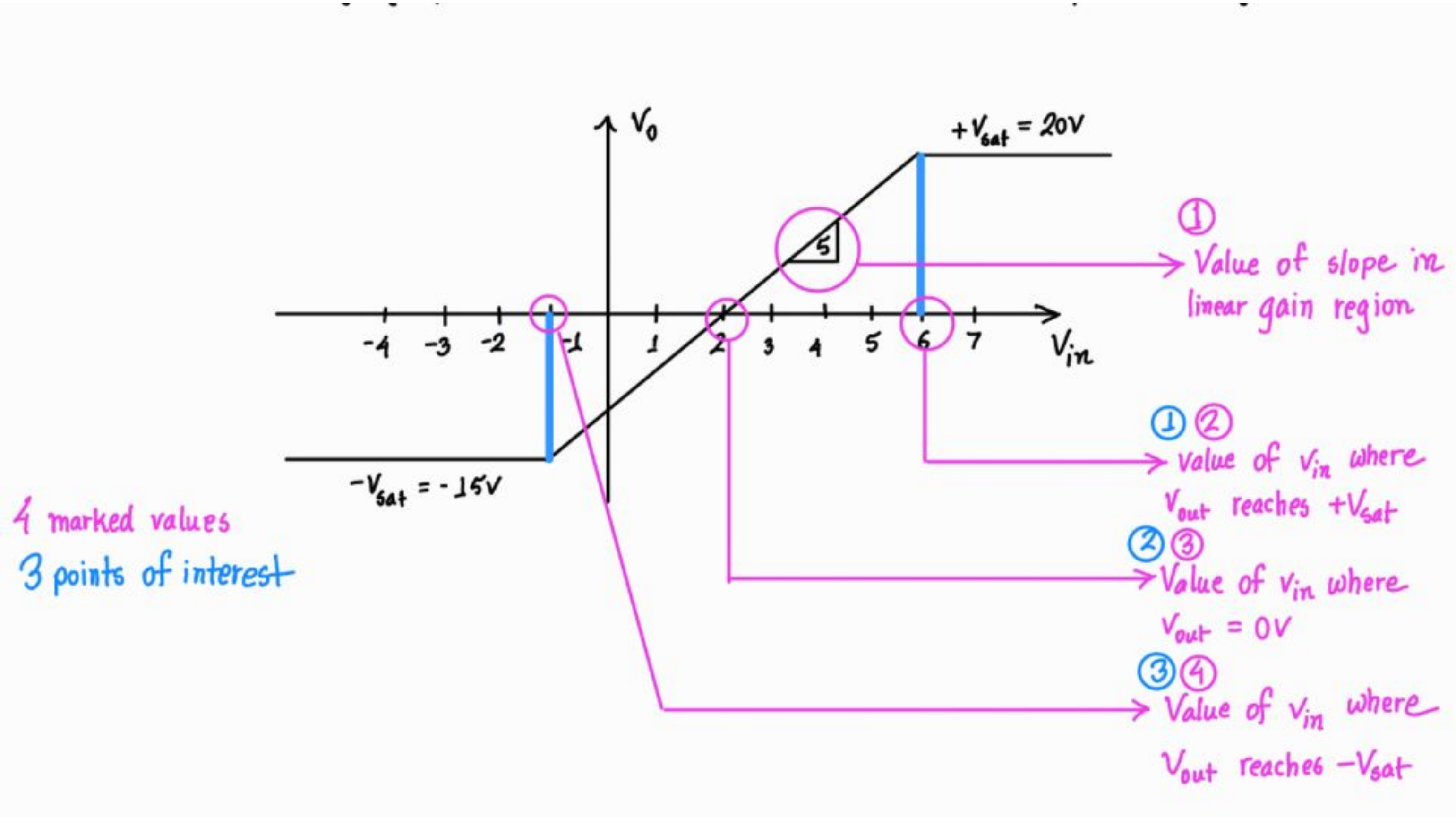
Why Vs needed?

Example

- Consider A=5. Calculate V_o for different values of V_{in}



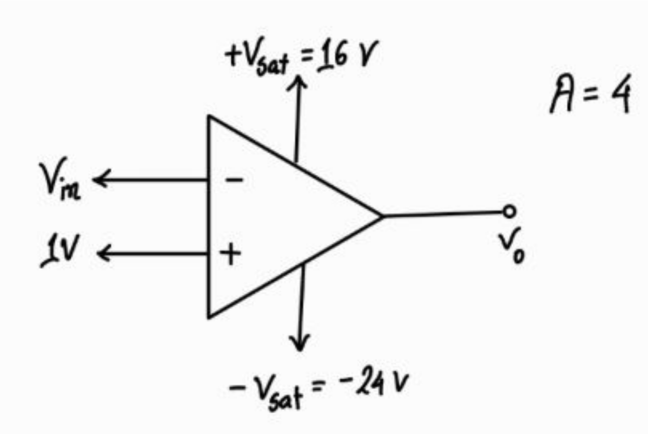
Example(VTC)



V_o
$+V_{sat} = 20V$
5
-4 -3 -2 -1 1 2 3 4 5 6 7
V_{in}
$-V_{sat} = -15V$
① Value of slope in linear gain region
① ② Value of V_{in} where V_{out} reaches $+V_{sat}$
② ③ Value of V_{in} where V_{out} = 0V
③ ④ Value of V_{in} where V_{out} reaches $-V_{sat}$
4 marked values
3 points of interest

Example

- Plot the VTC



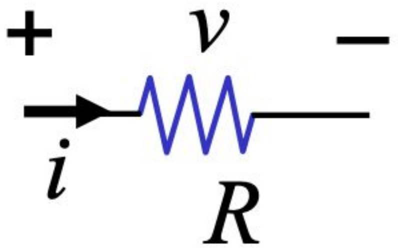
- The technique is only applicable for finite gain

Dependent Source

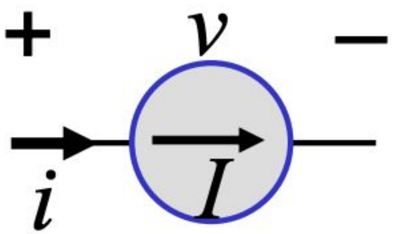
- Active sources – either voltage of current source
- Difference: voltage (or current) controlled by the voltage/current in a different branch
- Technically non-linear devices – because in real life, dependent sources are made using non-linear electronic devices (e.g. MOSFET)
- However, analysis are similar to linear circuits (CSE250), hence we will start with this

Major Difference

Independent devices:



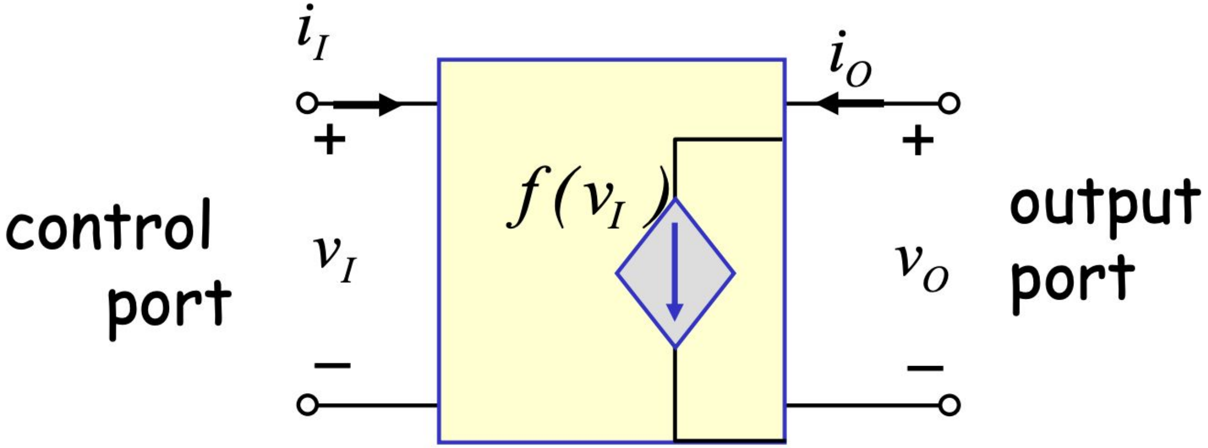
$$i = \frac{v}{R}$$



$$i = I$$

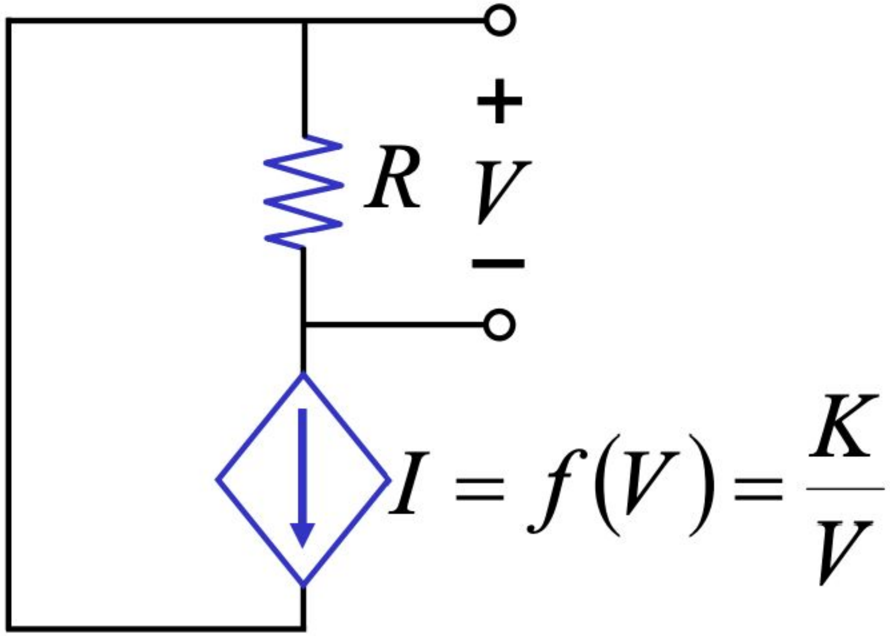
2 terminals, 1 port

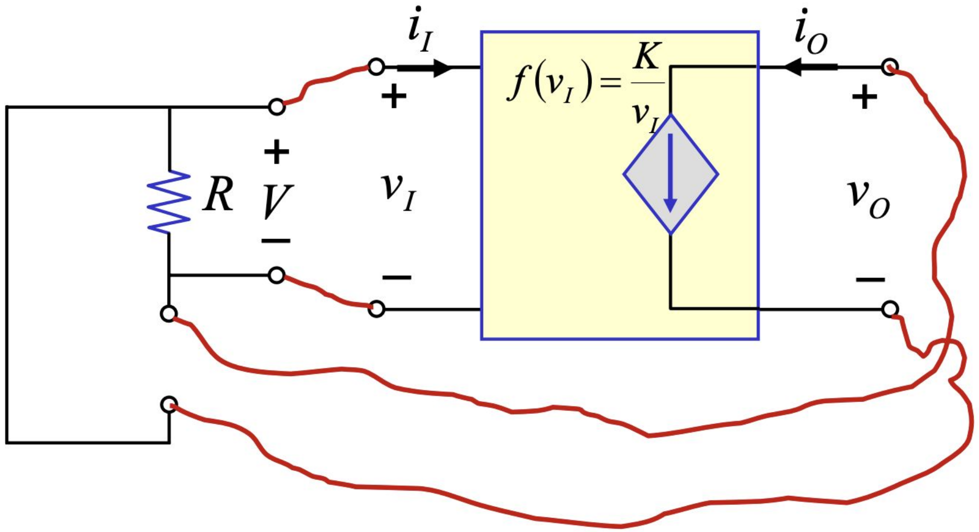
Dependent devices:



2 terminals, 2 port

Example 2





Find V

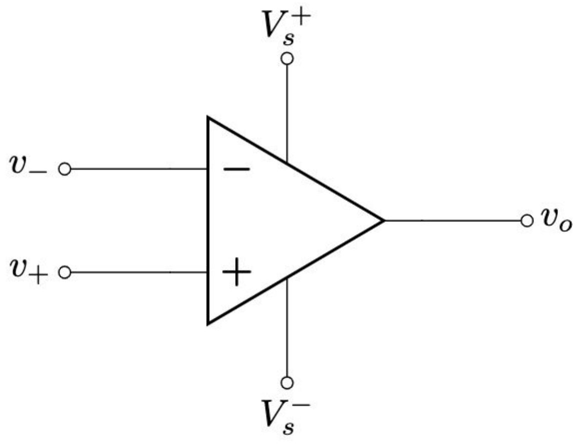
Ans: $V = IR \Rightarrow V = \left(\frac{K}{V}\right) R$

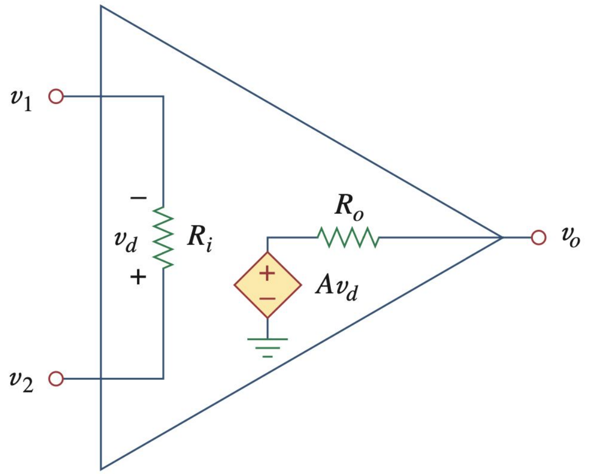
$\Rightarrow V^2 = KR \Rightarrow V = \sqrt{KR}$

Application of dependent sources: amplifiers!

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

$$v_d = v_+ - v_- = v_2 - v_1$$
$= \text{differential input voltage for VCVS}$

$A =$ Open loop gain

$R_i =$ Input resistance

$R_o =$ Output resistance

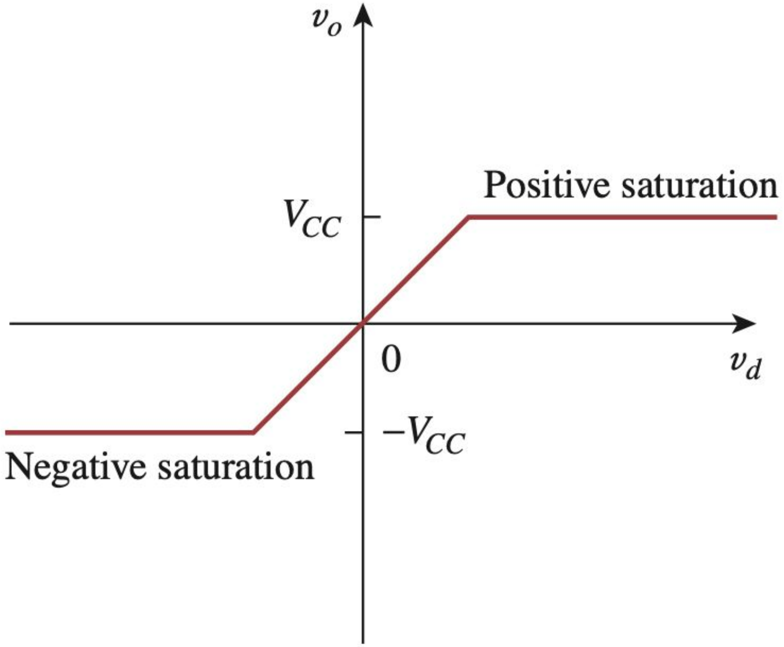
The op amp senses the difference between the two inputs, multiplies it by the gain A, and causes the resulting voltage to appear at the output. Thus, the output v_o is given by

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

Practical Limitation - Saturation

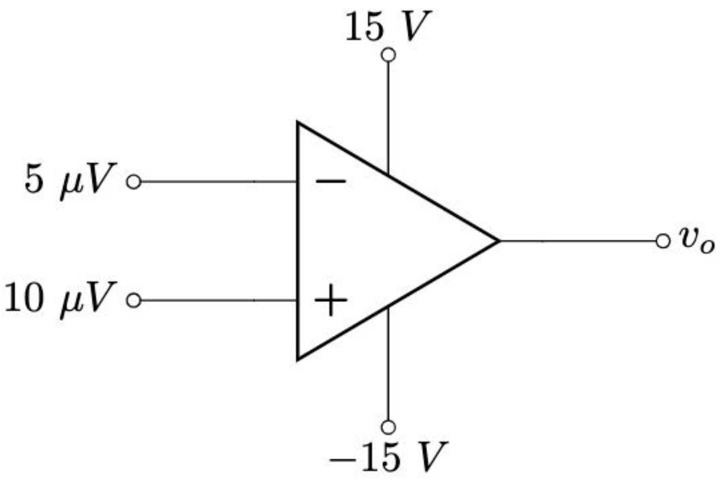
- Similar to amplifiers, the output of op-amp is limited by power supply (Saturation)
- Op-amp can operate in three modes, depending on v_d:
  - Positive saturation: $v_o = V_s^+ = V_{CC}$
  - Linear region: $-V_{CC} < v_o = Av_d < V_{CC}$ [Slope = A]
  - Negative saturation: $v_o = V_s^- = -V_{CC}$
- If we attempt to increase v_d beyond the linear range, the op-amp becomes saturated and yields $v_o = V_{CC}$ or $v_o = -V_{CC}$. That is the output voltage is restricted by

$$-V_{CC} \leq v_o \leq V_{CC}$$



Example 3

- Find v_o



$A = 2 \times 10^5$

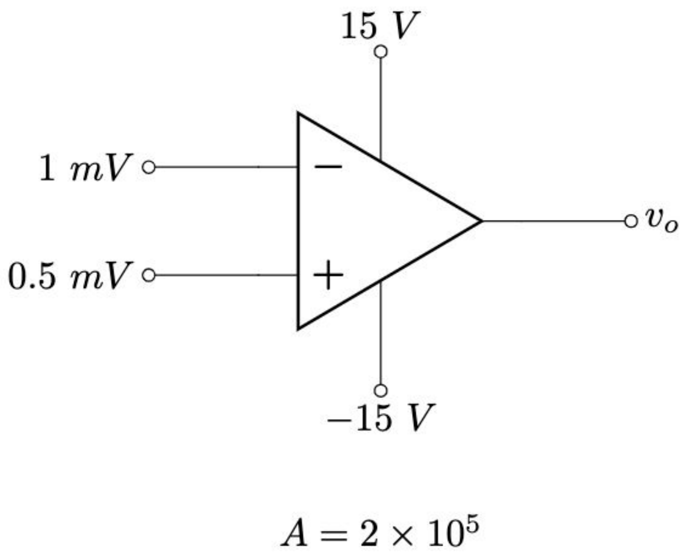
Solution:

$v_d = v_+ - v_- = 10\ \mu V\ - 5\ \mu V = 5\ \mu V$
$\Rightarrow v_o = Av_d = (2\times10^5)\times(5\times10^{-6}) = 1V$

Since this is in between $-V_{CC}$ and V_{CC}, output valid

Example 4

- Find v_o



Solution:

$v_d = v^+ - v^- = 0.5\ mV - 1\ mV = -0.5\ mV$
➞ $v_o = Av_d = (2x10^5)x(-0.5x10^{-3}) = -100V$

However, the output must be limited within the range of $-V_{CC}$ to $+V_{CC}$. Therefore, the highest output voltage can be -15V.

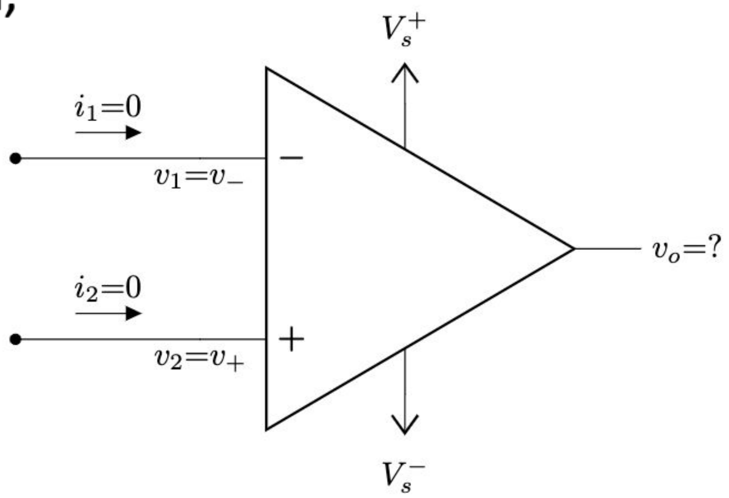
∴ $v_o = -15V$

The Ideal Op-Amp

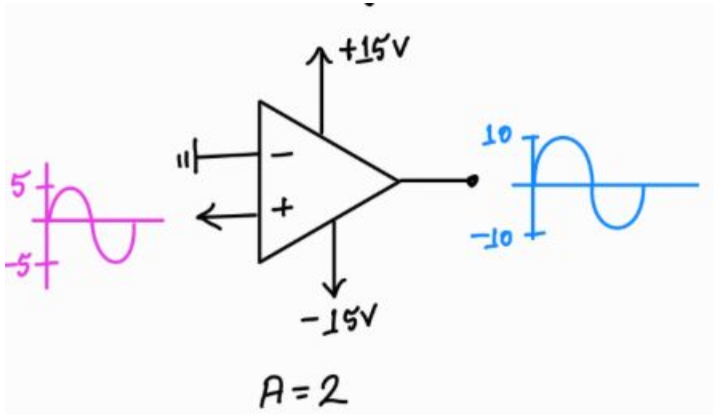
- To facilitate the understanding of op amp circuits, we will assume **ideal op amps**
  - Infinite open-loop gain, $A = \infty$
  - Infinite input resistance, $R_i = \infty = \text{open circuit}$
  - Zero output resistance, $R_o = 0 = \text{short circuit}$
- Although an ideal op amp provides only an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

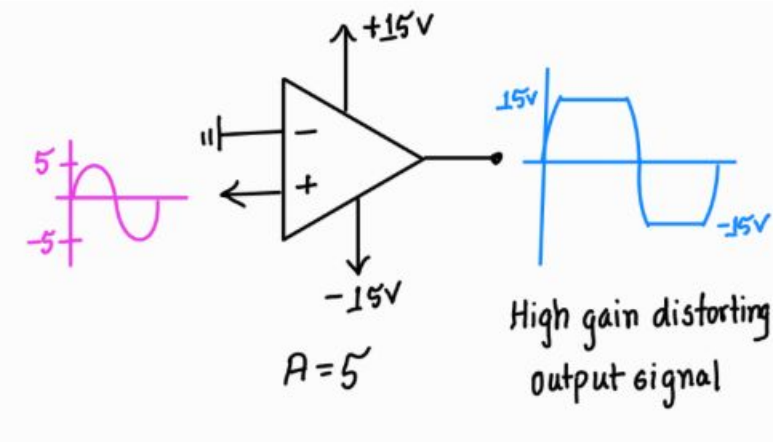
$$v_o = \begin{cases} V_s^+ \; if \; v_d > 0 \Rightarrow v_2 > v_1 \\ V_s^- \; if \; v_d < 0 \Rightarrow v_2 < v_1 \end{cases}$$

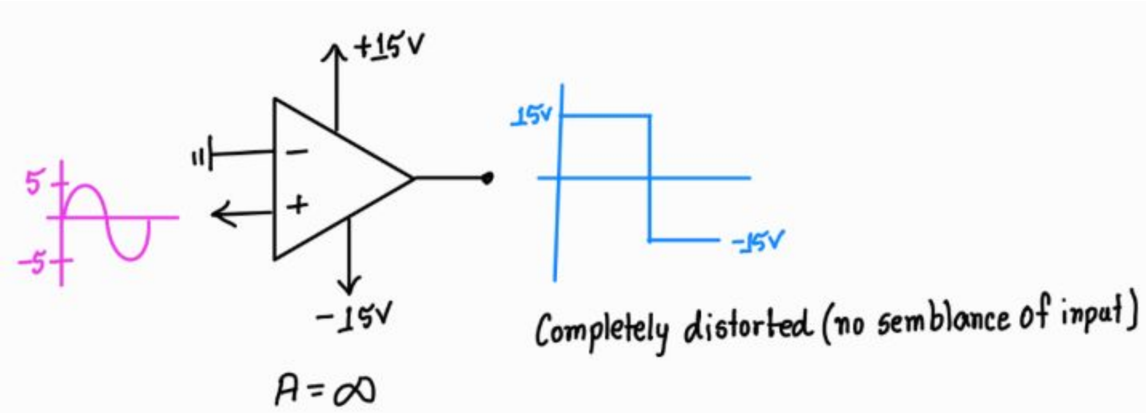
Reminder: $v_d = v_2 - v_1 = v_+ - v_-$



Problem with infinite gain







Why use open loop then? - 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

Bonus Task: VTC of (2) & (3)

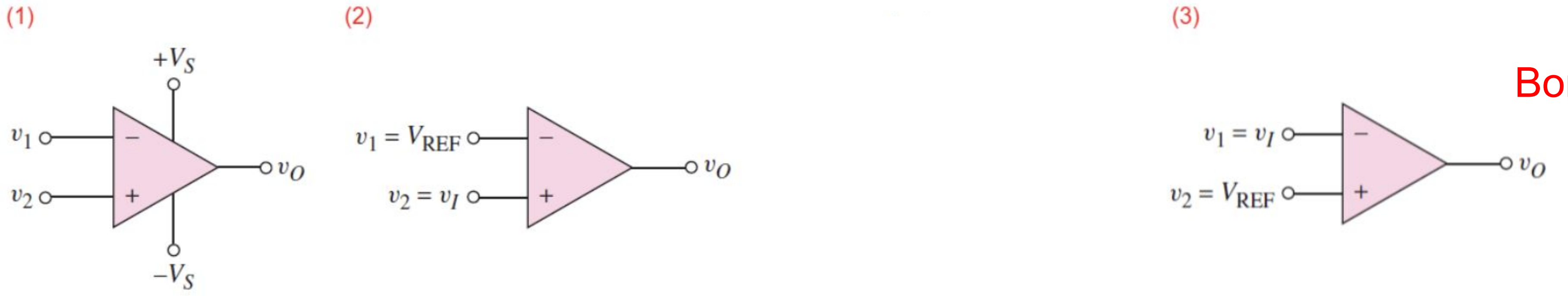
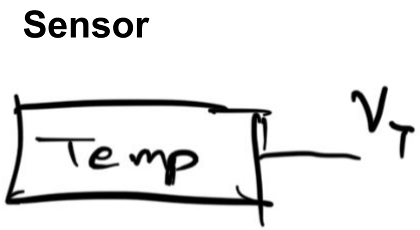


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit

Comparator Application – Automatic AC

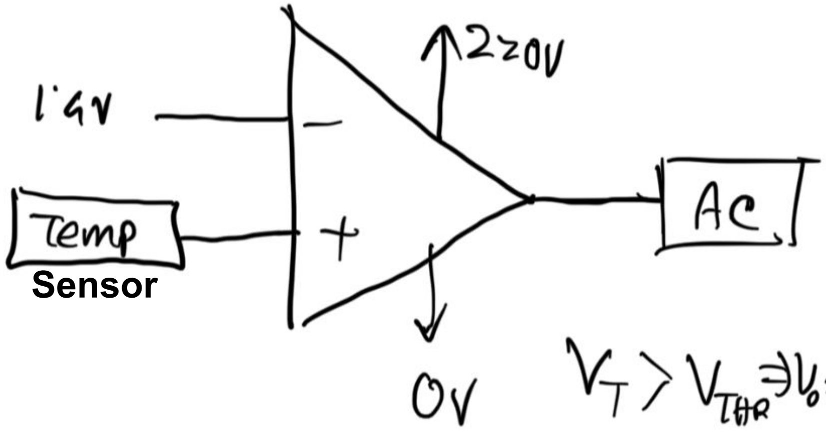
Auto AC ON/OFF



AC should be on if

$T > 24^\circ C$

$V_T \propto T$



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

$\boxed{24^\circ, \quad V_T = 1.4V}$

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

$V_T > V_{THR} \Rightarrow V_0 = V_S^+$

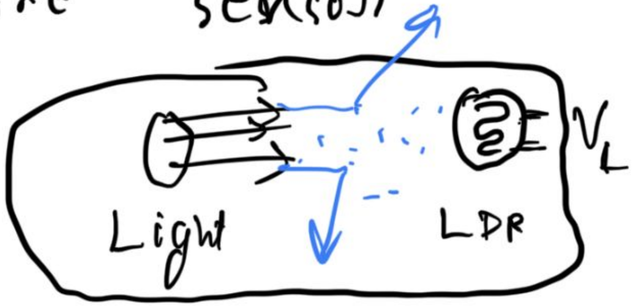
$V_{THR} = 1.4V$

$V_T < V_{THR} \Rightarrow V_S^-$

Smoke Detector

③ Smoke Detector

Smoke sensor



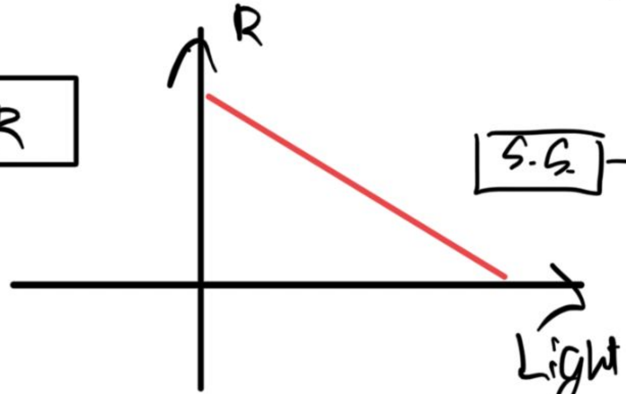
No smoke, V_L = small = 2V

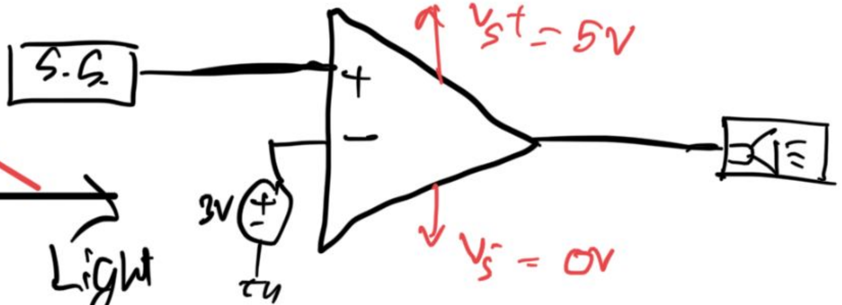
Smoke, V_L = high = 4V

$V_L > 3V \Rightarrow$ Alarm ON

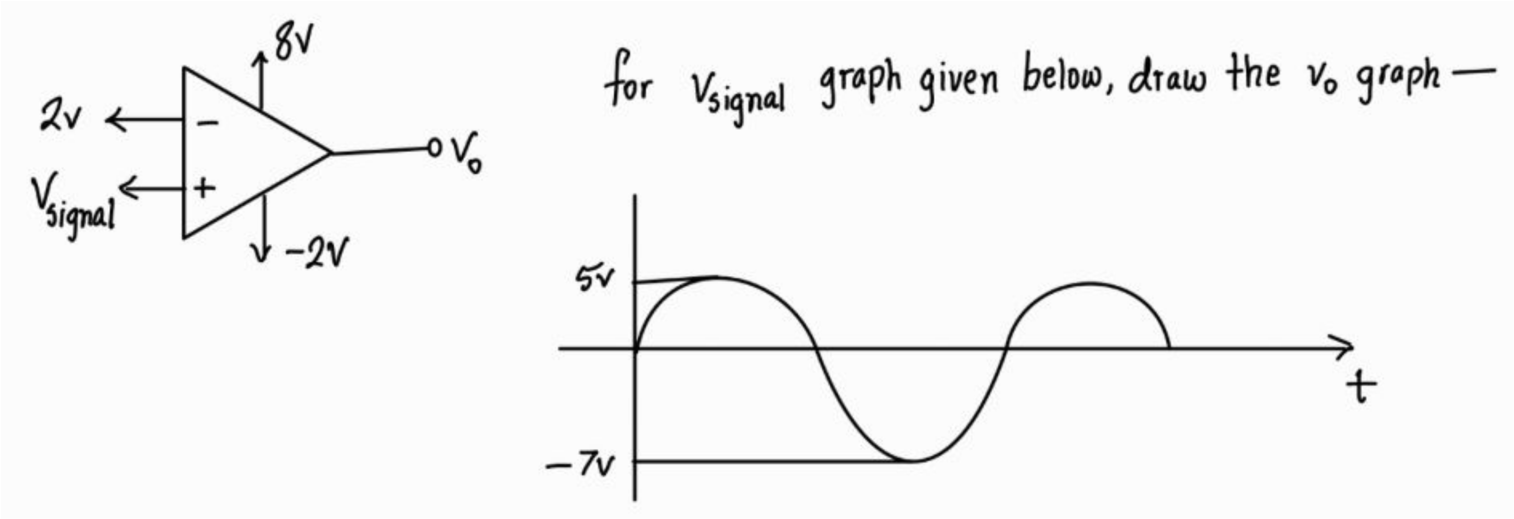
$V_L < 3V \Rightarrow$ " OFF

$\boxed{V_L \propto R}$





Comparator Example



Comparator Example