Lecture 3

Introduction to OpAmp

Review

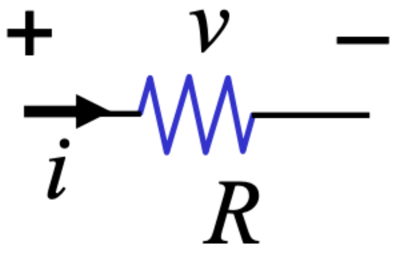
- Last class: alternative representation, KCL, KVL, nodal
- Today: **review** of dependent source, introduction to amplifiers, operational amplifiers

Dependent Source

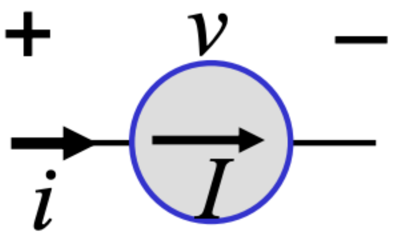
- Active sources – either voltage of current source
- Difference: voltage (or current) controlled by the voltage/current in a different branch
- Technically non-linear devices – because in real life, dependent sources are made using non-linear electronic devices (e.g. MOSFET)
- However, analysis are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

Major Difference

Independent devices:



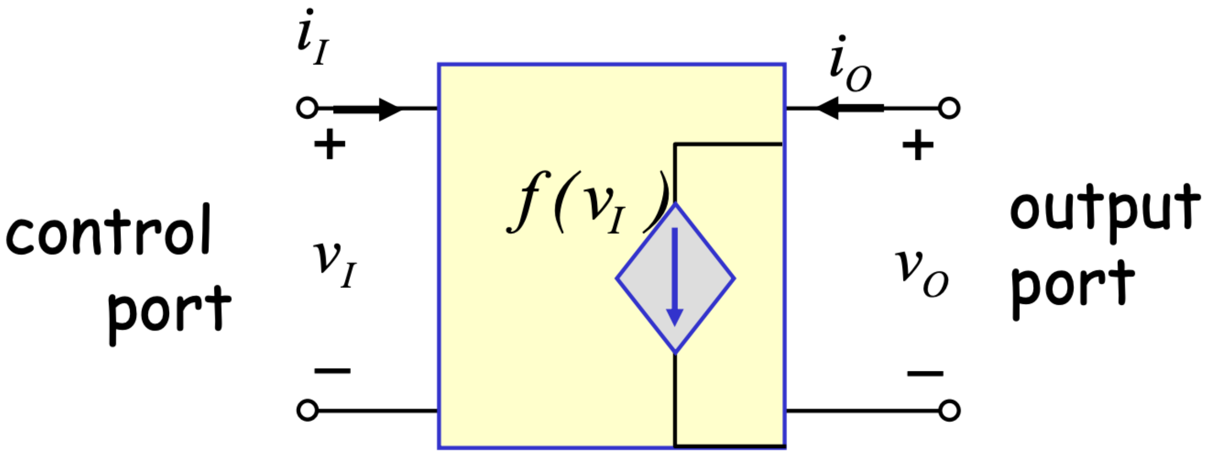
$$i = \frac{v}{R}$$



$$i = I$$

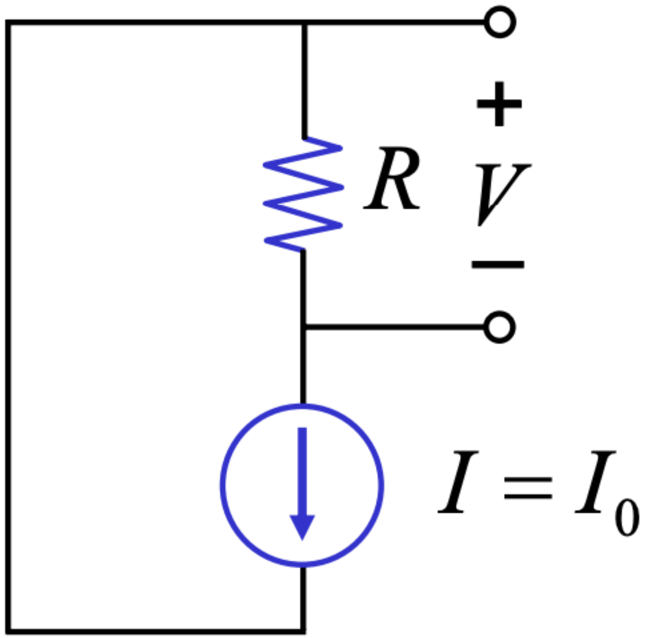
2 terminals, 1 port

Dependent devices:



2 terminals, 2 port

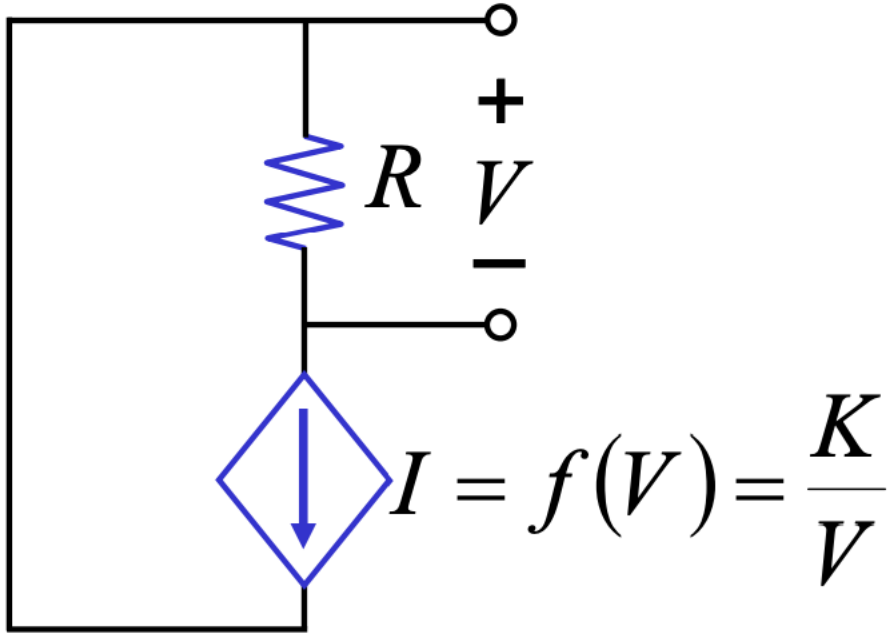
Example 1



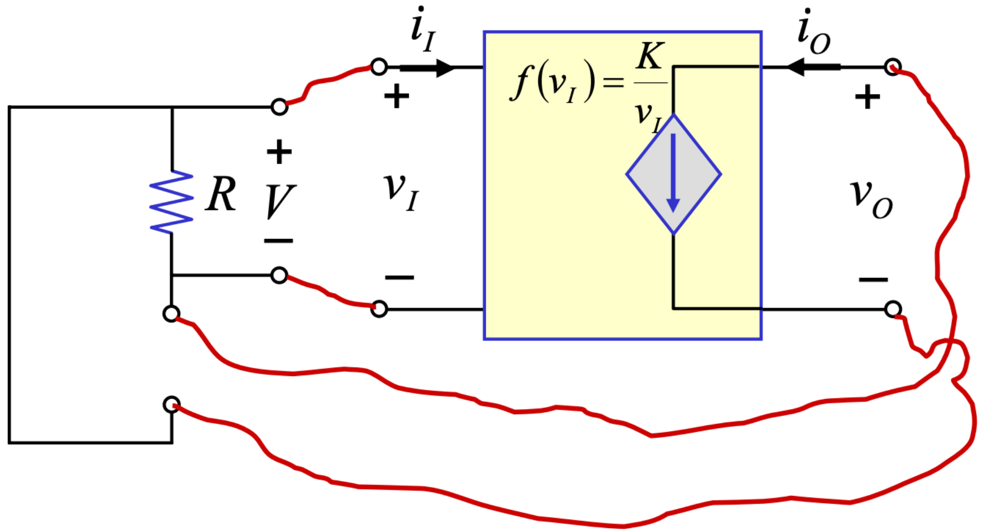
Find V

(Ans: $V = I_0 R$)

Example 2



Find V



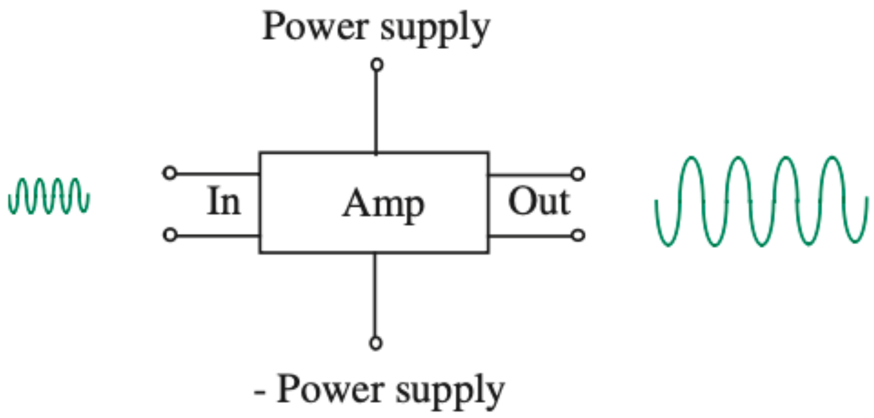
Ans: $V = IR \Rightarrow V = \left(\frac{K}{V}\right) R$

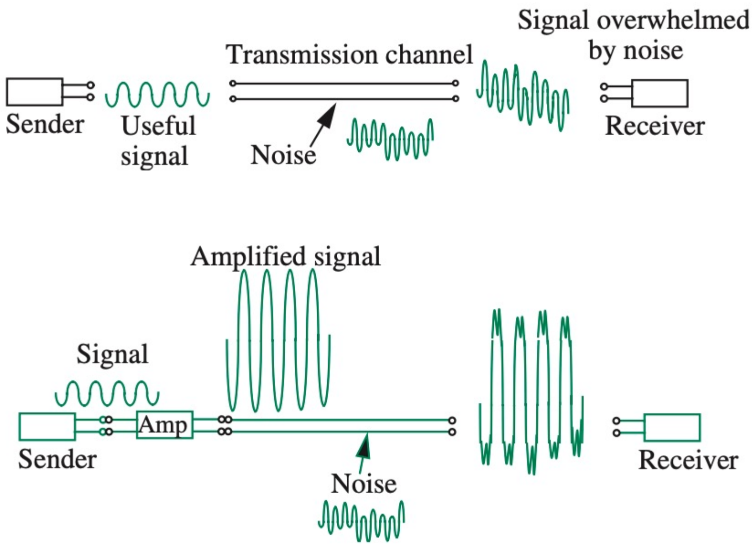
$\Rightarrow V^2 = KR \Rightarrow V = \sqrt{KR}$

Application of dependent sources: amplifiers!

Amplifier

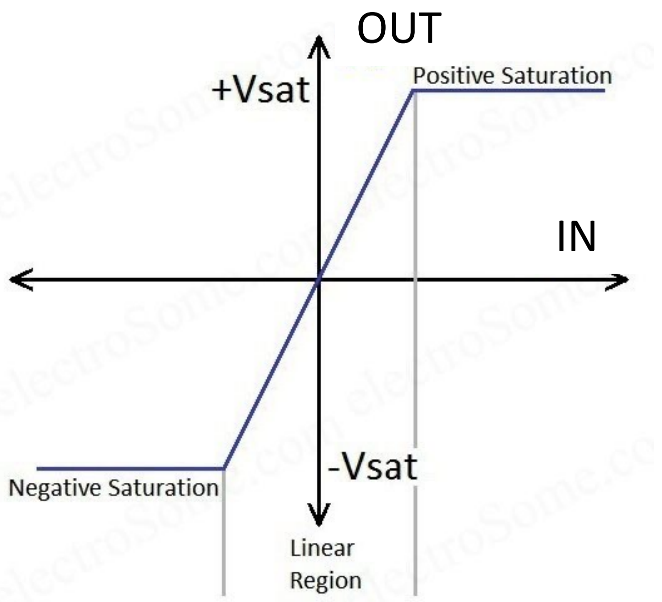
- Linear amplifier ⇒ $OUT = k \times IN$. k is called the **gain** of the amplifier
- OUT/IN can be voltage or current
- Amplifier must provide power gain ($P_{OUT} > P_{IN}$), hence need **power supply**
- Usage: communication

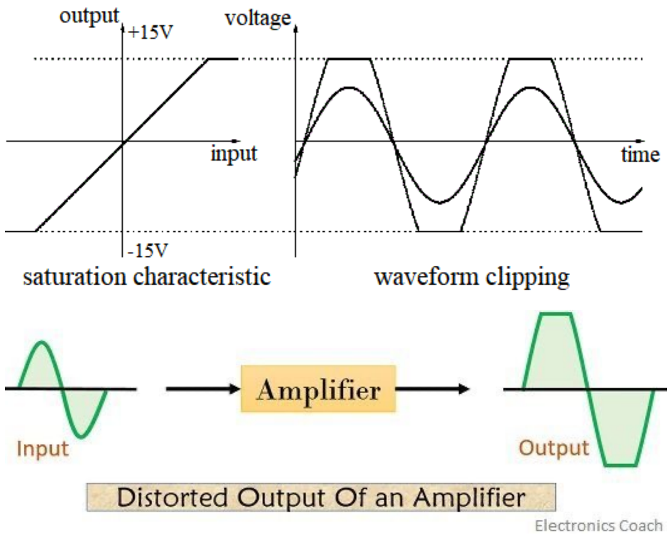




Transfer Characteristics of Amplifiers

- $y = mx$, hence straight line going through origin. Here, $m = k = \text{gain}$
- Saturation due to limited power supply. Output cannot be greater than P.S.
- Input must be within a **valid input range**, otherwise output will be distorted
- Amplifiers are <u>**non-linear devices**</u>, because they are made using dependent sources



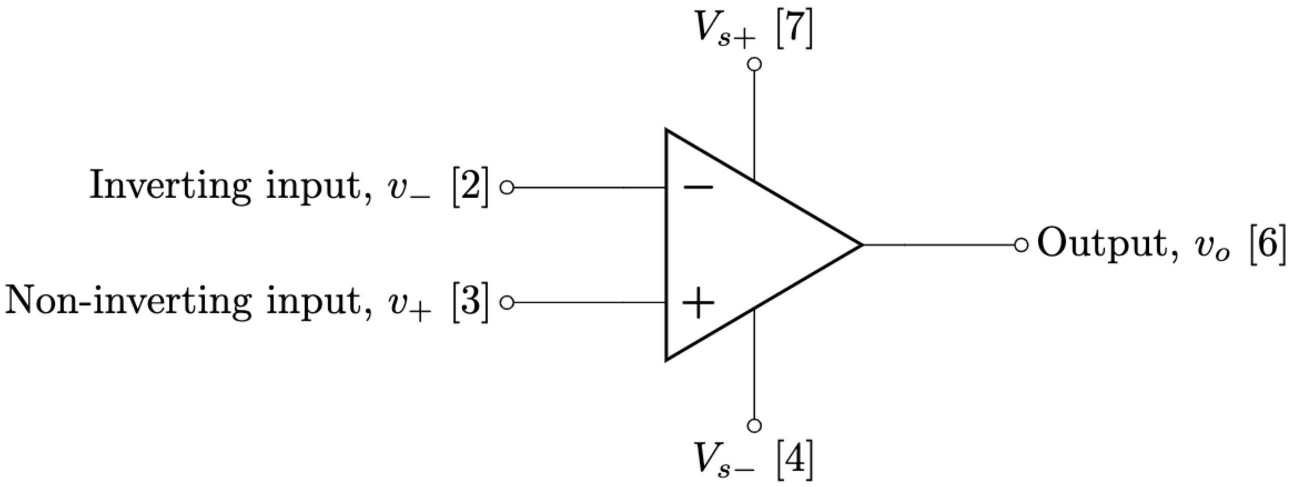


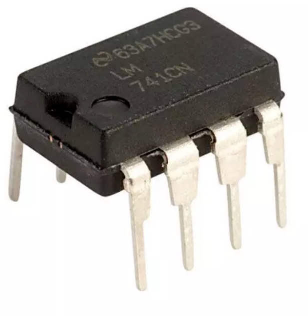
Operational Amplifiers

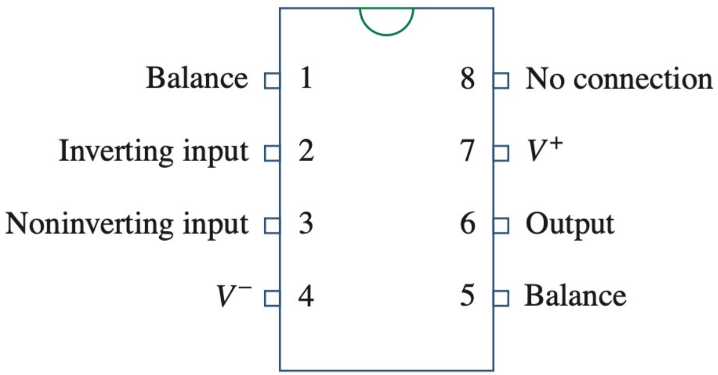
- An operational amplifier, or **op-amp** for short, is a versatile and powerful integrated circuit that is widely used in a variety of electronic applications.
- An Op-Amp is designed so that it performs some mathematical operations when external components, such as resistors and capacitors, are connected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

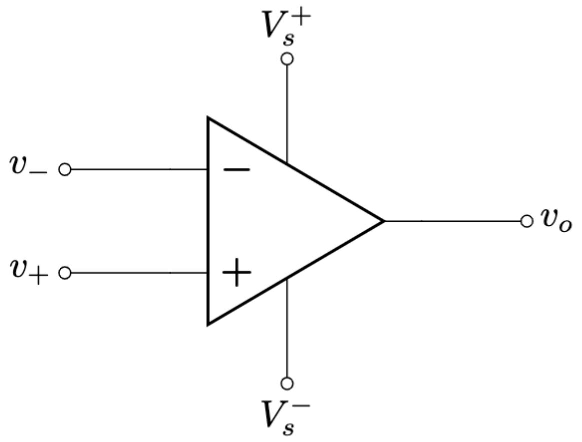


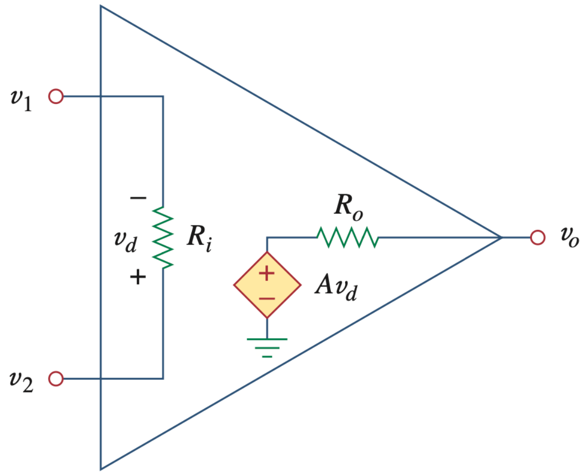




Equivalent Circuit

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

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

$A =$ 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

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

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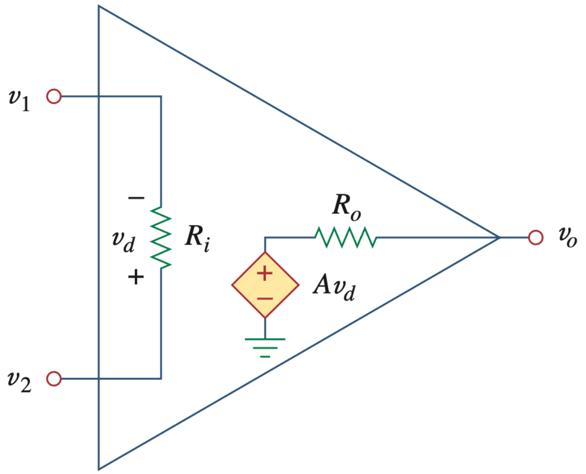

$v_1 = v_- =$ voltage of inverting terminal

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

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$R_i =$ Input resistance

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Parameter	Typical Range
A	$10^4 - 10^8$
R_i	$100\ k\Omega - 10^{10}\ k\Omega$
R_o	$0.01\ k\Omega - 0.1\ k\Omega$

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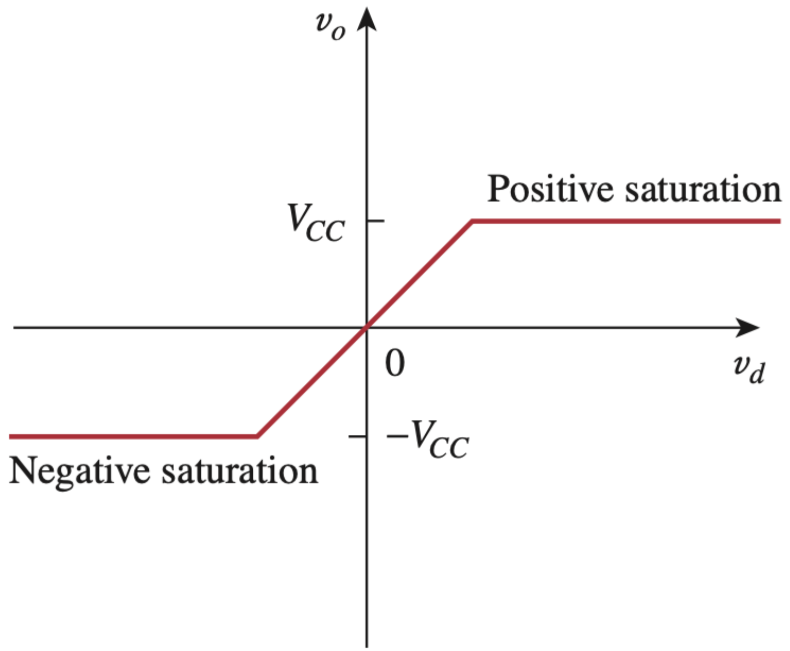
Practical Limitation - Saturation

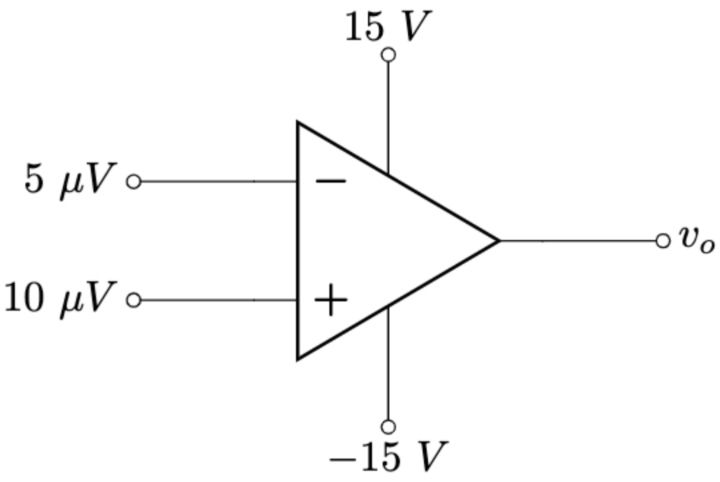
- Similar to amplifiers, the output of op-amp is limited by power supply (Saturation)
- Op-amp can operate in three modes, depending on v_d:
  - Positive saturation: $v_o = V_s^+ = V_{CC}$
  - Linear region: $-V_{CC} < v_o = Av_d < V_{CC}$ [Slope = A]
  - Negative saturation: $v_o = V_s^- = -V_{CC}$
- 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:

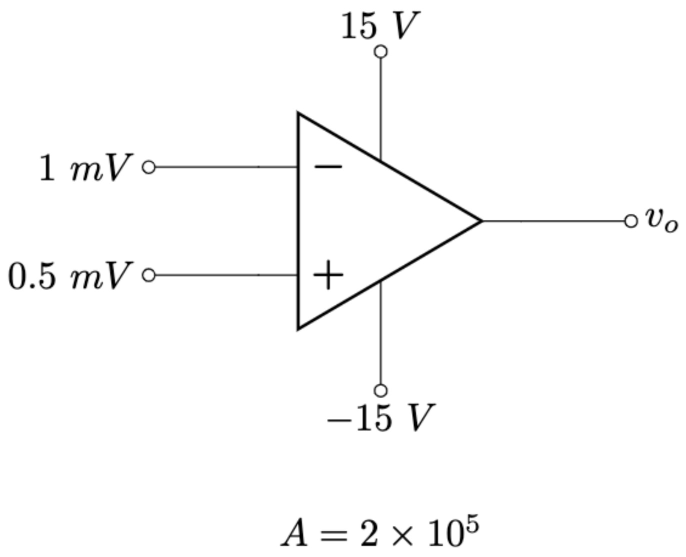
$v_d = v_+ - v_- = 10\ \mu V\ - 5\ \mu V = 5\ \mu V$

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

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

Example 4

- Find v_o



Solution:

$v_d = v_+ - v_- = 1\,mV\ - 0.5\,mV = 0.5\,mV$
$\Rightarrow v_o = Av_d = (2\times10^5)\times(0.5\times10^{-3}) = 100V$

However, the ouput must be limited between $-V_{CC}$ and V_{CC}. Therefore, the highest output voltage can be $V_{CC} = 15\,V$.

$\therefore v_o = 15\,V$

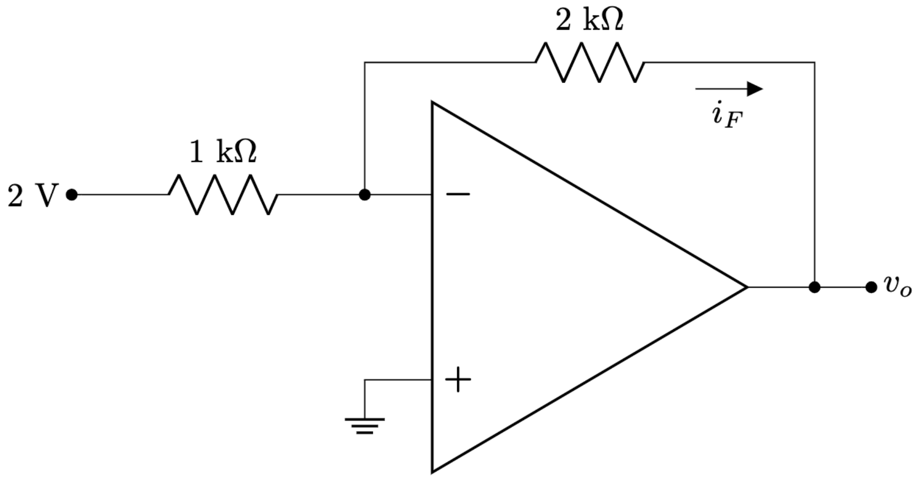
Solving Circuit with Op-Amp

- Don’t be scared! Circuit solving with op-amp is exactly same as the circuits you solved in CSE250

- Step 1: replace with equivalent circuit
- Step 2: solve using KCL & KVL, or nodal analysis (linear)
- In most cases, the power supply voltages are not mentioned. **Hence, we will assume the ouput is within the linear range in this case**

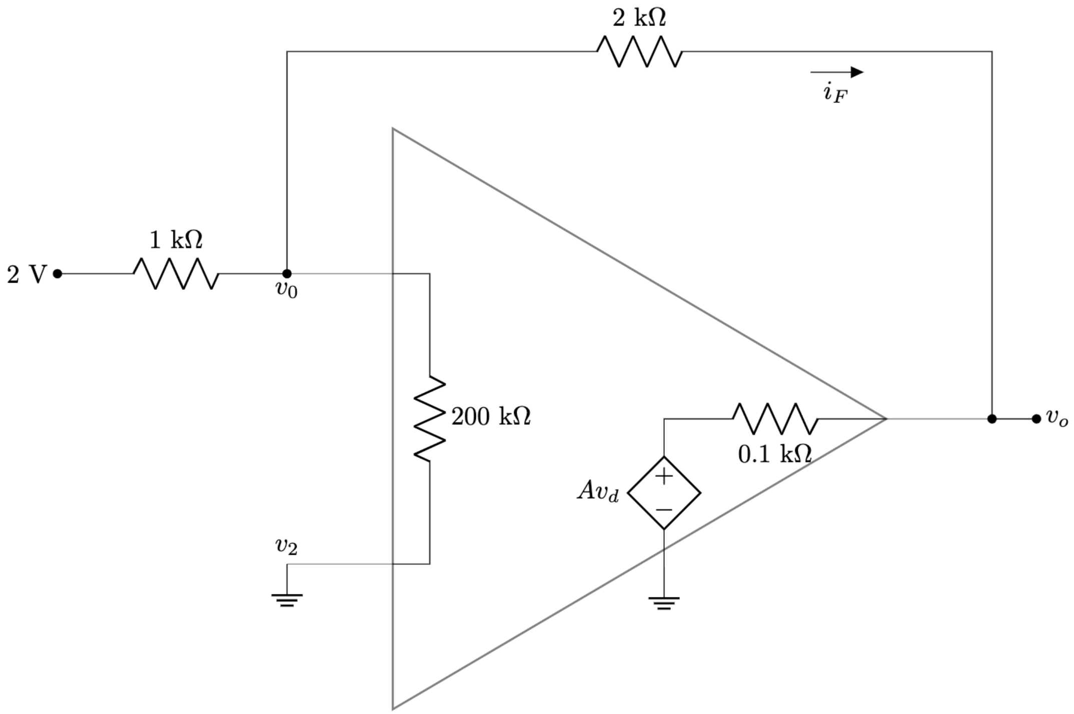
Example 5

Find i_F and v_o. Here, $R_i = 200\ k\Omega$, $R_o = 0.1\ k\Omega$, $A = 2\times10^5$



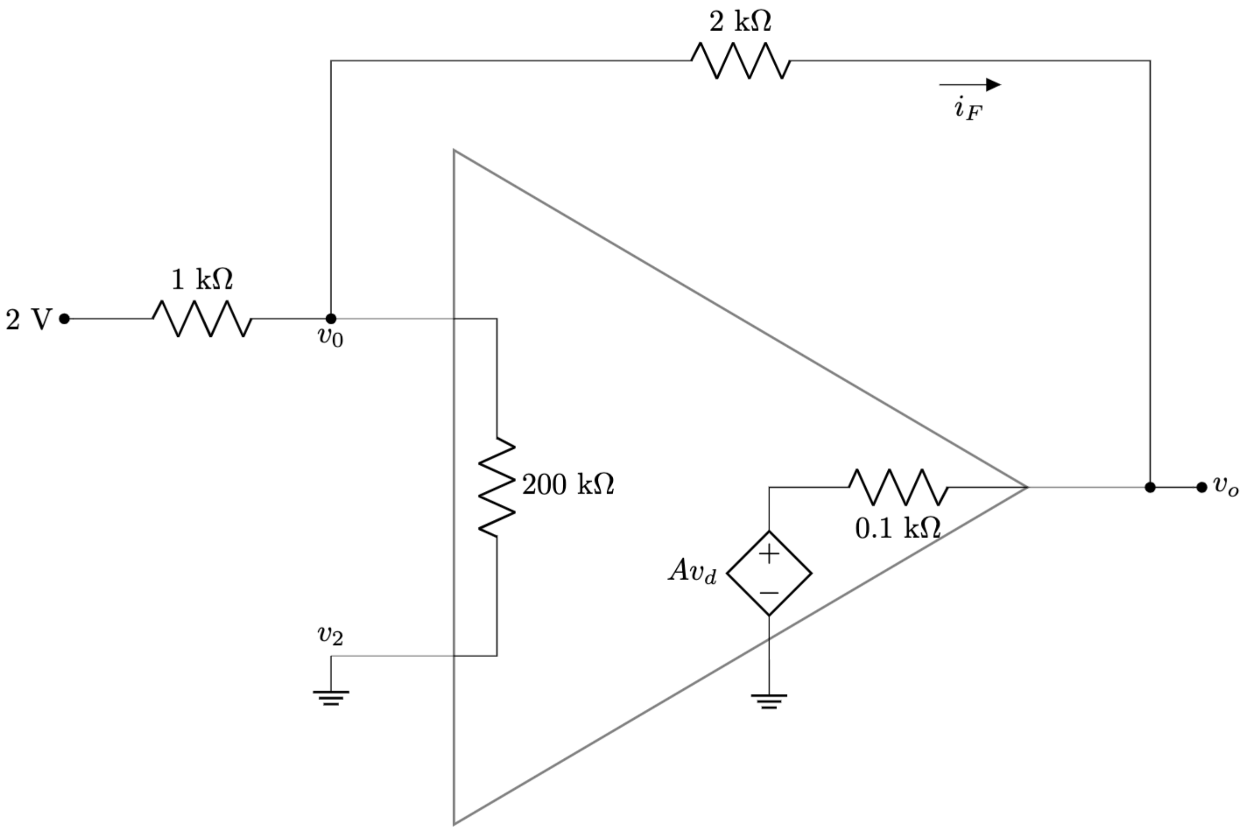
Solution:

Step 1: replace using equivalent circuit



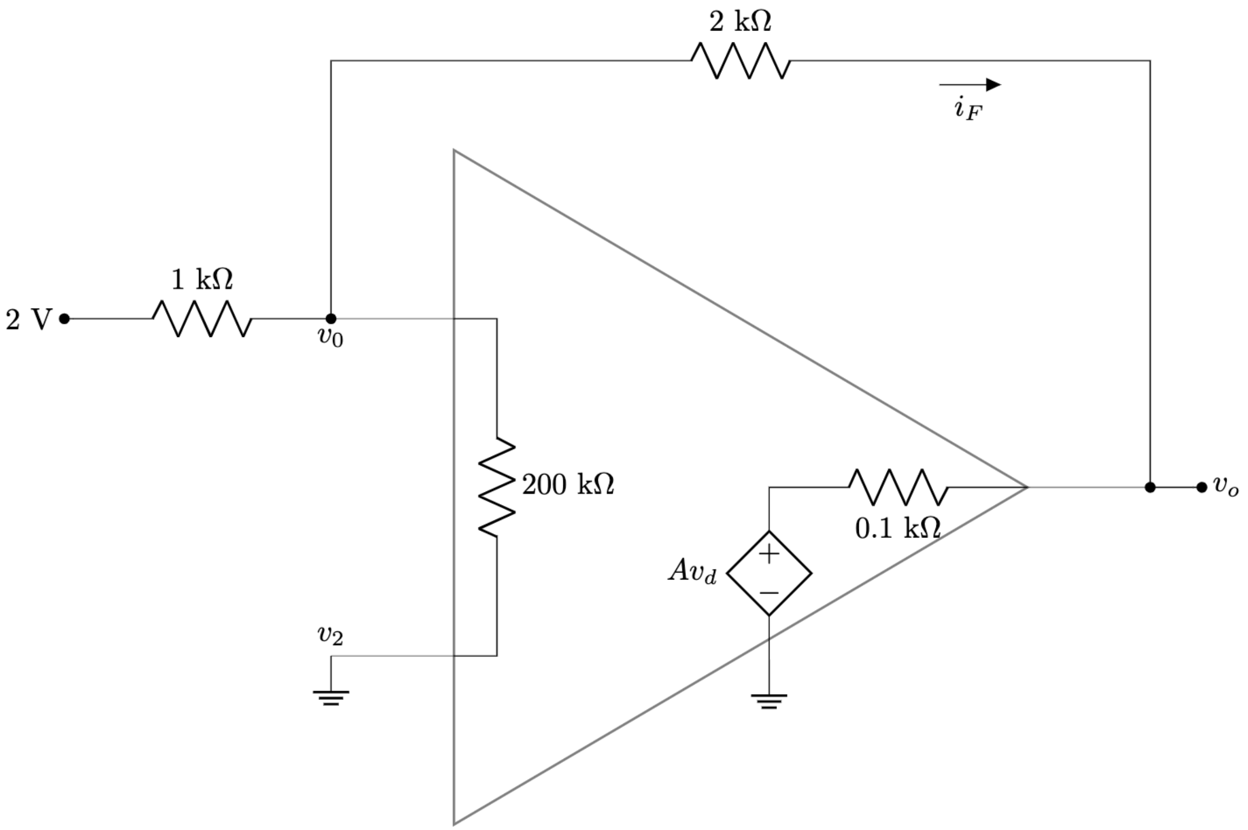
Example 5

Step 2: Solve using KCL & KVL or nodal



Example 5

Step 2: Solve using KCL & KVL or nodal



Example 6

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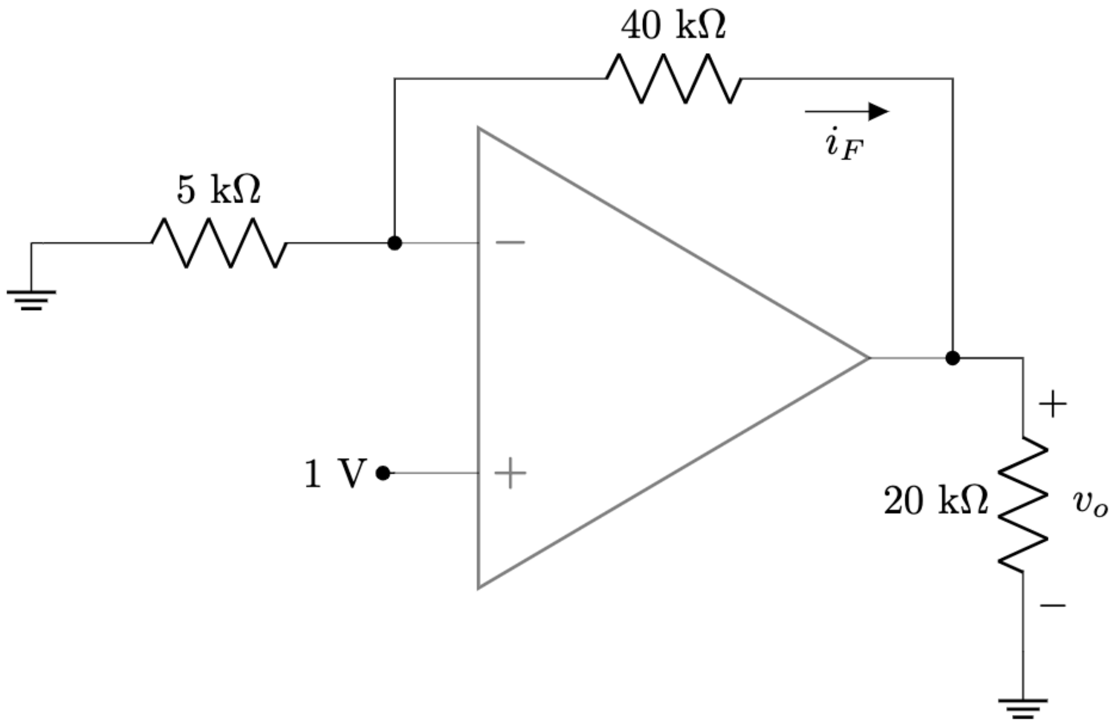
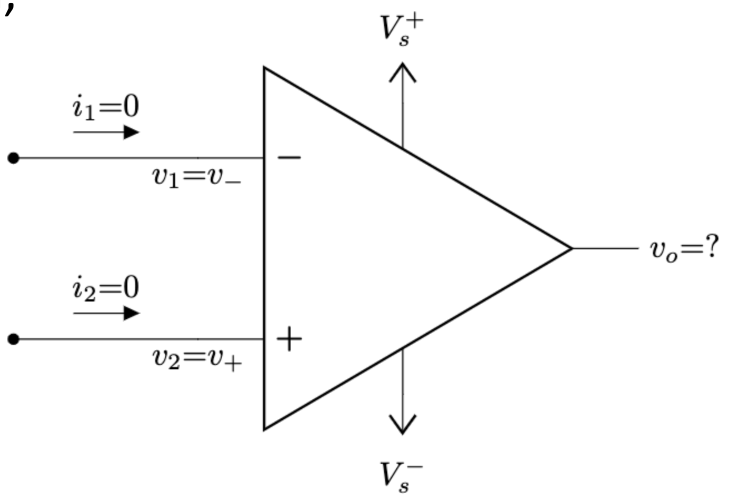


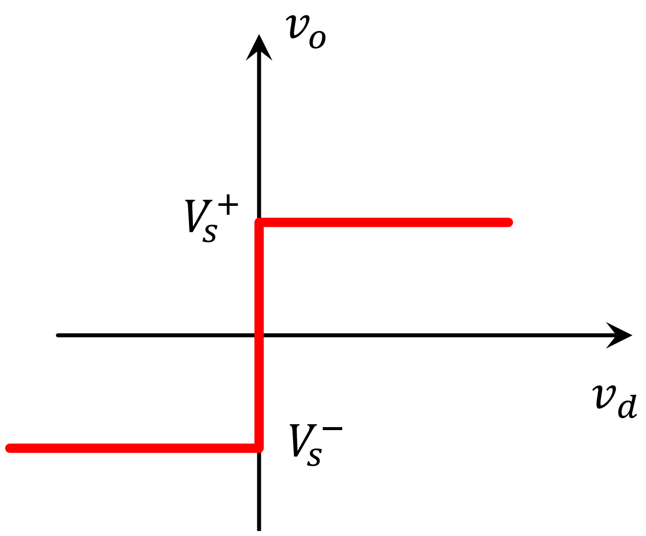
The Ideal Op-Amp

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





VTC of ideal op amp

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)

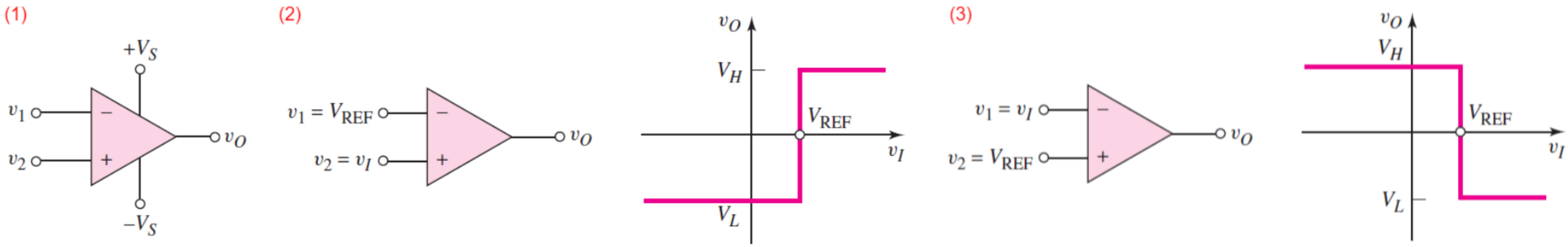


Figure 2: (1) Op-Amp Comparator (2) Noninverting Circuit (3) Inverting Circuit