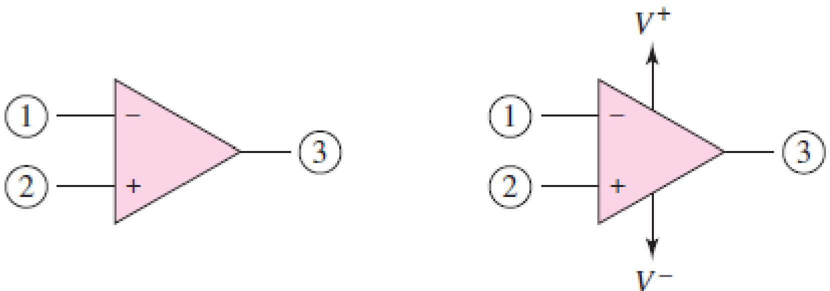
Electronic Circuits
Chapter 1: Op-Amp

Dr. Dung Trinh

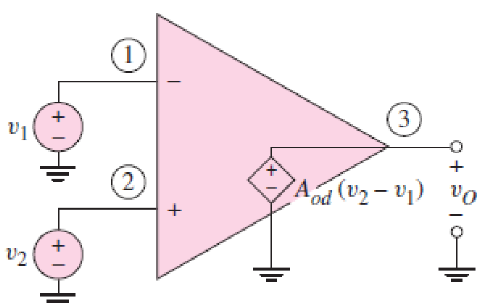
Content

Introduction

- The integrated circuit operational amplifier evolved soon after development of the first bipolar integrated circuit.
- The μA-709 was introduced by Fairchild Semiconductor in 1965 and was one of the first widely used general-purpose op-amps. The new classic μA-741, also by Fairchild, was introduced in the late 1960s.



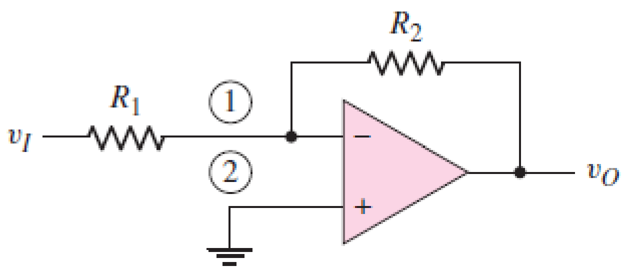
Circuit symbol of Op-Amp



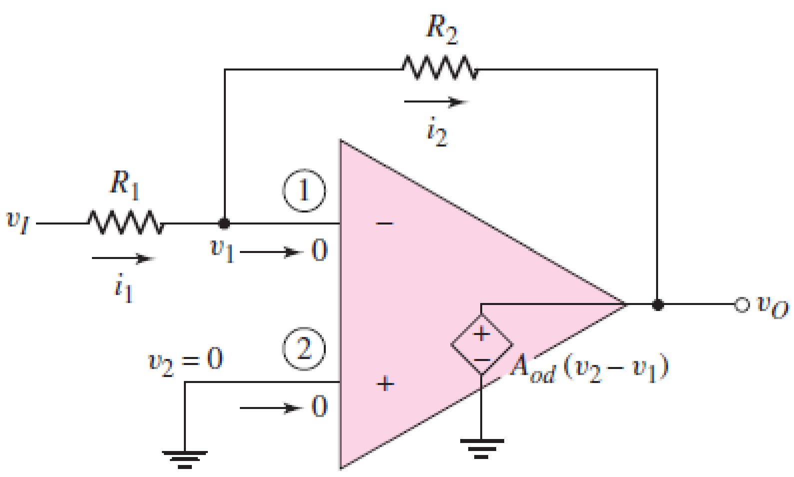
- In the ideal op-amp:
  - The open-loop gain A_{od} approaches infinity
  - The common-mode output signal is zero.
  - Input resistance R_i is infinite.
  - Output resistance R_o is zero.

Inverting Amplifier

❖ One of the most widely used op-amp circuits is the **inverting amplifier**



Inverting op-amp circuit



Inverting op-amp equivalent circuit

- The closed-loop gain:

$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

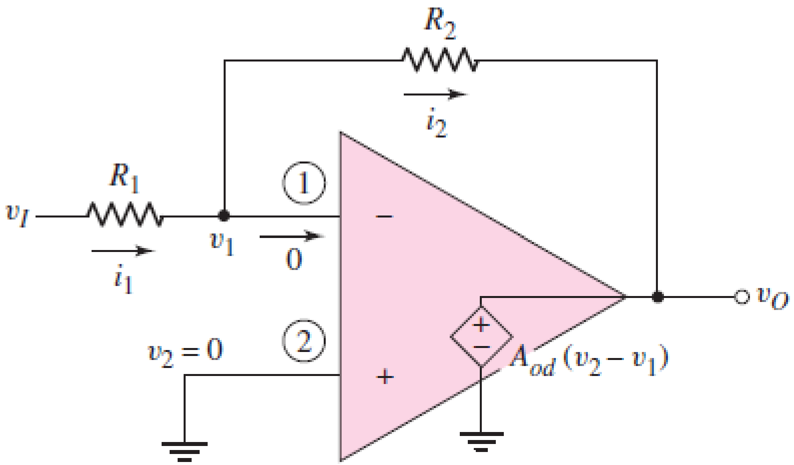
- The input resistance:

$$R_i = R_1$$

Example 1: Using the inverting Op-amp amplifier to design the circuit such that the voltage gain is $A_v = -5$. Assume the op-amp is driven by an ideal sinusoidal source, $v_s = 0.1\sin\omega t\ (V)$, that can supply a maximum current of $5\mu A$.

$R_1 = 20k\Omega$ $\quad\quad$ $R_2 = 100k\Omega$

Inverting Amplifier – Finite Gain



- We have:

$$i_1 = \frac{v_I - v_1}{R_1} \qquad i_2 = \frac{v_I - v_O}{R_2}$$

- The output voltage is: $v_O = -A_{od} v_1$

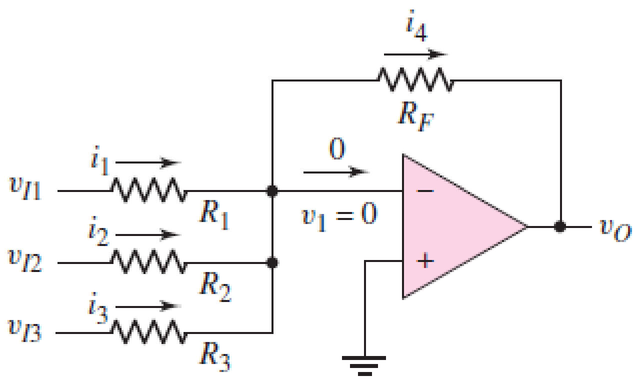
- We obtain: $$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I + \frac{v_I}{A_{od}}}{R_1} = i_2 = -\frac{v_O + \frac{v_O}{A_{od}}}{R_2}$$

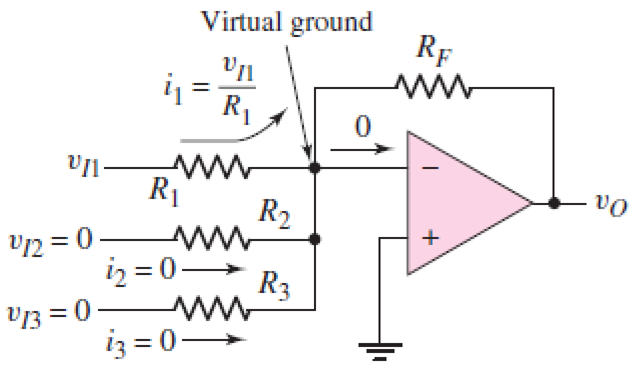
- Then: $$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}\frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)\right]}$$

A_{od}	A_v	Deviation (%)
10^2	−9.01	9.9
10^3	−9.89	1.1
10^4	−9.989	0.11
10^5	−9.999	0.01
10^6	−9.9999	0.001

Example 2: Consider an inverting op-amp with $R_1 = 10k\Omega$ and $R_2 = 100k\Omega$. Determine the closed-loop gain for: $A_{od} = 10^2, 10^3, 10^4, 10^5$, and 10^6. Calculate the percent deviation from the ideal gain.

Summing Amplifier





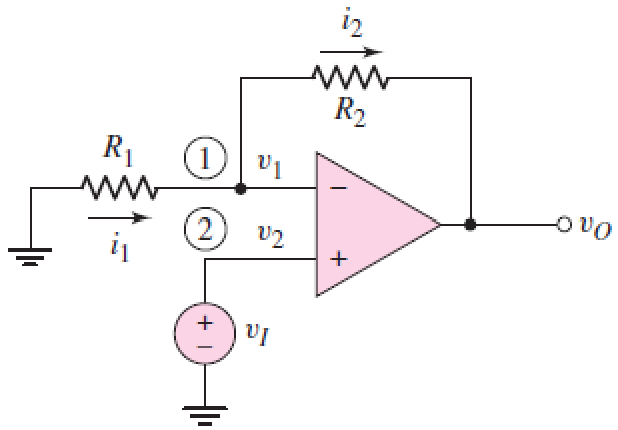
- Using superposition theorem to analysis the summing amplifier, we obtain:

$$v_O = -\left(\frac{R_F}{R_1}v_{I1} + \frac{R_F}{R_2}v_{I2} + \frac{R_F}{R_3}v_{I3}\right)$$

- If $R_1 = R_2 = R_3$, then:

$$v_O = -\frac{R_F}{R_1}(v_{I1} + v_{I2} + v_{I3})$$

Non-Inverting Amplifier

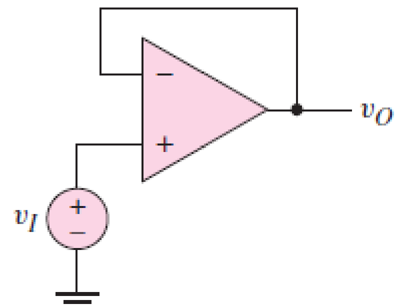


Non-inverting op-amp circuit

- We have:

$$i_1 = \frac{0 - v_I}{R_1} \qquad i_2 = \frac{v_I - v_O}{R_2}$$

- Because $i_1 = i_2$, then: $A_v = \frac{v_o}{v_i} = 1 + \frac{R_2}{R_1}$



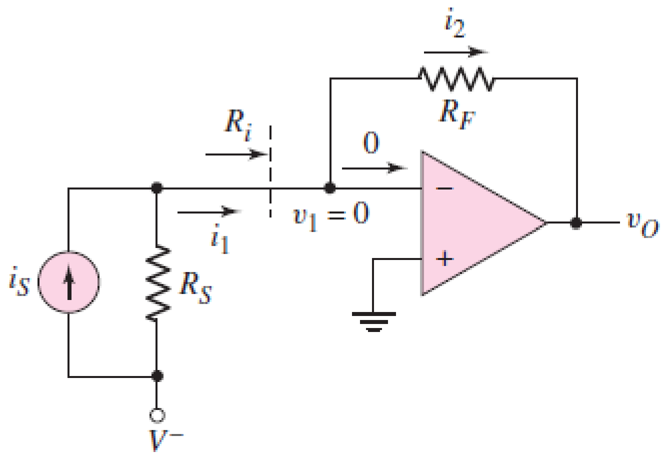
Voltage follower op-amp

- In voltage follower circuit: $R_2 = 0$

$$A_v = 1 \qquad R_i = \infty \qquad R_o = 0$$

Example 3: Derive the closed-loop gain of non-inverting amplifier which has a finite differential gain of A_{od}.

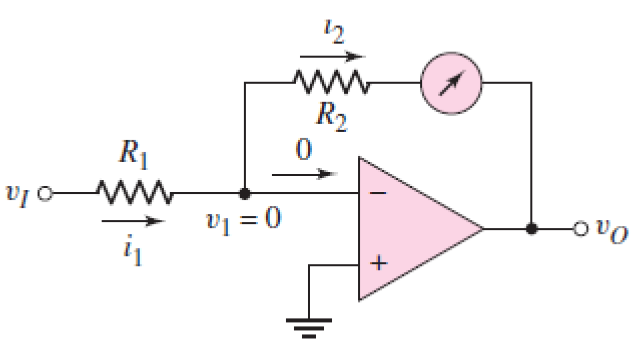
Current-to-Voltage Converter



Current-to-voltage converter

❖ In some situations, the output of a device or circuit is a current. An example is the output of a photodiode or photo-detector. We may need to convert this output current to an output voltage.

$$v_O = -i_2 R_F = -i_S R_F$$

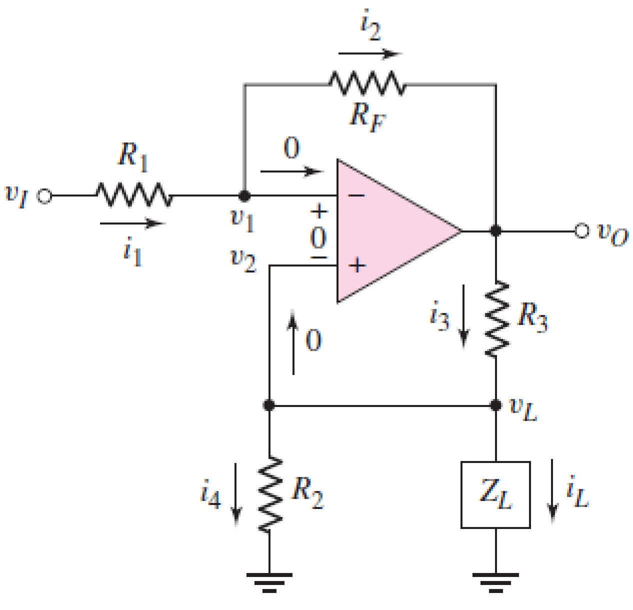


Simple voltage-to-current converter

❖ Voltage-to-current converter: $i_2 = i_1 = \dfrac{v_I}{R_1}$

- Current i_2 is independent of the load impedance or resistance R_2.
- NOT practical as the load need to be at ground potential.

Voltage-to-Current Converter



Voltage-to-current converter

- At the inverting terminal: $$\frac{v_I - i_L Z_L}{R_1} = \frac{i_L Z_L - v_O}{R_F}$$

- At the non-inverting terminal: $$\frac{v_O - i_L Z_L}{R_3} = i_L + \frac{i_L Z_L}{R_2}$$

- From these two equations, we obtain:

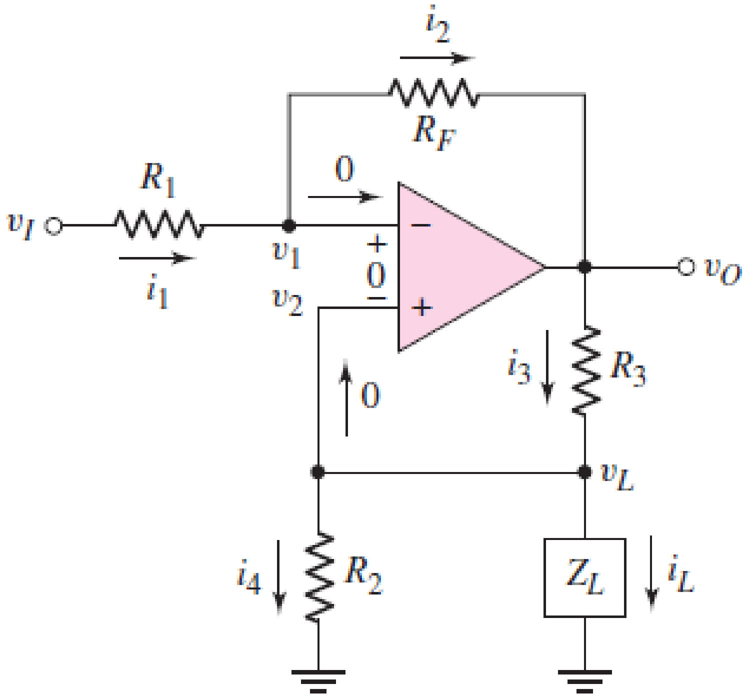
$$\frac{R_F}{R_1}\frac{i_L Z_L - v_I}{R_3} = i_L + \frac{i_L Z_L}{R_2}$$

- Then: $$i_L\left(\frac{R_F Z_L}{R_1 R_3} - 1 - \frac{Z_L}{R_2}\right) = v_I\left(\frac{R_F}{R_1 R_3}\right)$$

- If $\frac{R_F}{R_1 R_3} = \frac{1}{R_2}$: $i_L = -v_I\left(\frac{R_F}{R_1 R_3}\right) = -\frac{v_I}{R_2}$

Voltage-to-Current Converter

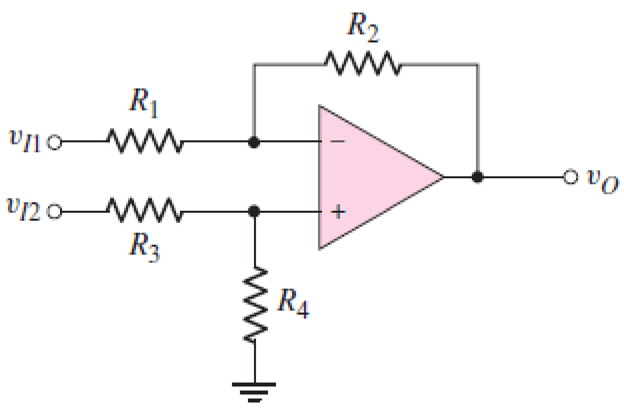
Example 4: Let $Z_L = 100\Omega$, $R_1 = 10k\Omega$, $R_2 = 1k\Omega$, $R_3 = 1k\Omega$, and $R_F = 10k\Omega$. If $v_I = -5V$, determine the load current i_L and the output voltage v_O.



$i_L = 5mA$

$v_o = 6V$

Difference Amplifier

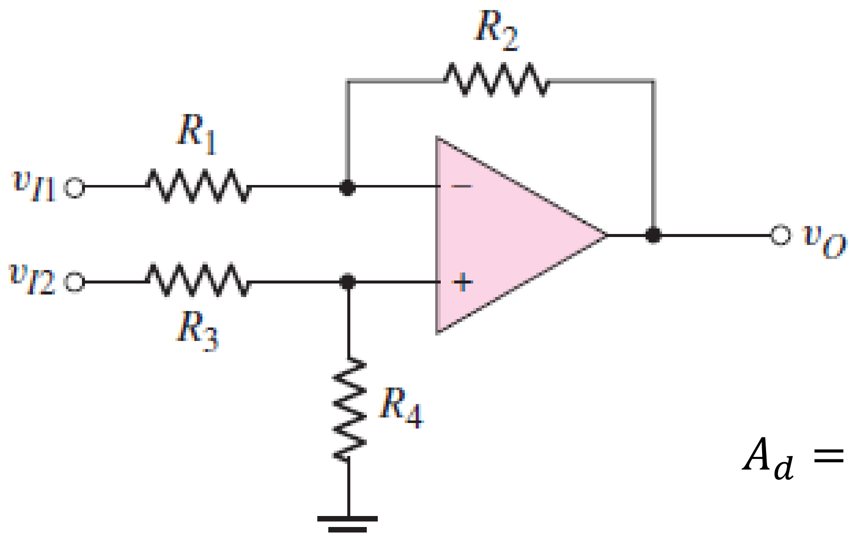


Op-amp difference amplifier

- An ideal difference amplifier amplifies only the difference between two signals. It rejects any common signals to the two input terminals.
- For example, a microphone system amplifies an audio signal applied to one terminal of a difference amplifier, and rejects any 60 Hz noise signal or "hum" existing on both terminals
- The output voltage: $$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$
- If $\frac{R_2}{R_1} = \frac{R_4}{R_3}$: $$v_O = \frac{R_2}{R_1}(v_{I2} - v_{I1})$$
- If $\frac{R_2}{R_1} \neq \frac{R_4}{R_3}$: $$v_{cm} = \frac{1}{2}(v_{I2} + v_{I1}) \qquad A_{cm} = \frac{v_O}{v_{cm}} \qquad CMRR = \left|\frac{A_d}{A_{cm}}\right|$$

Difference Amplifier

Example 5: Consider the difference amplifier. Let $R_2/R_1 = 10$ and $R_4/R_3 = 11$. Determine CMRR(dB).

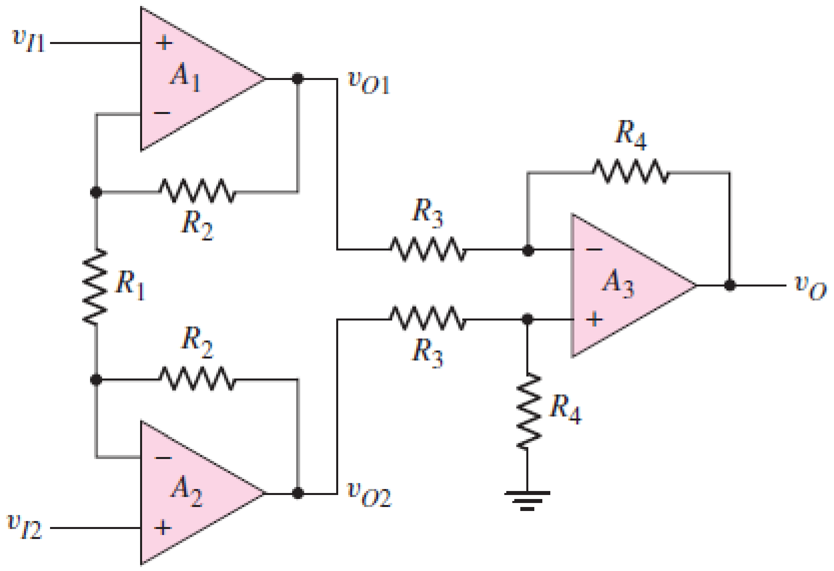


$$A_d = 10.042$$

$$A_{cm} = 0.0833$$

$$CMRR = 41.6dB$$

Instrumentation Amplifier



Instrumentation amplifier

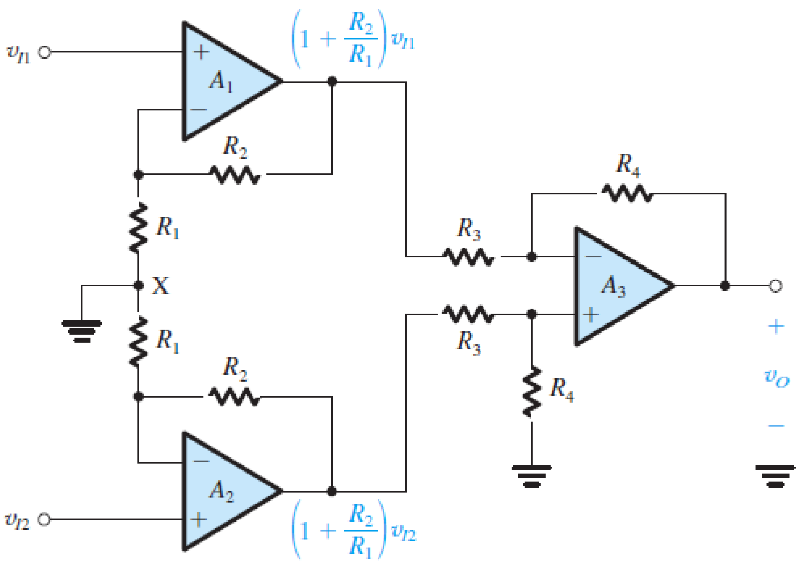
- Obtain a *high input impedance* and a *high gain* in a difference amplifier with reasonable resistor values: ***DIFFICULT***.

- **SOLUTION**: insert a voltage follower

→ Problem: GAIN is not easily to change.

- **INSTRUMENTATION AMPLIFIER** allows us to change the gain by changing only a single resistance value.

Instrumentation Amplifier



Instrumentation amplifier

- The output of difference amplifier is:

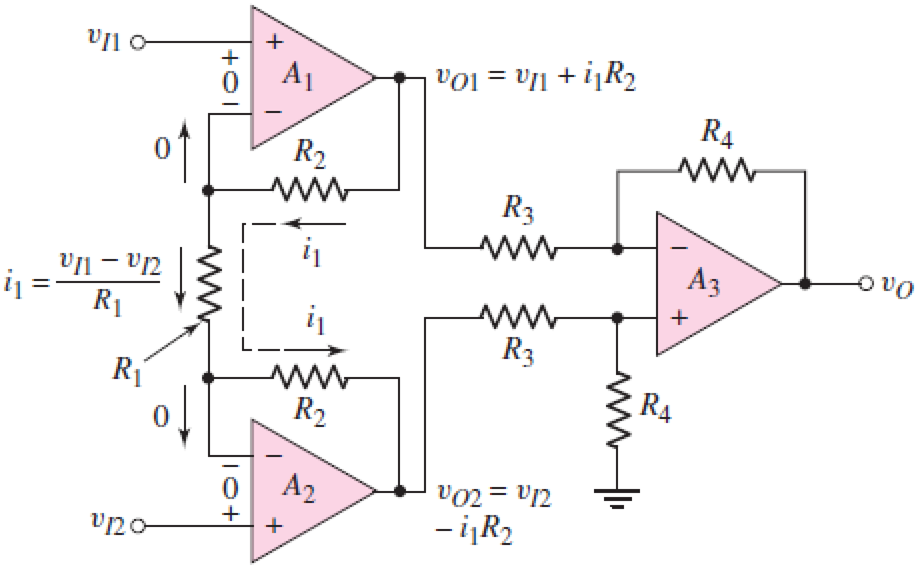
$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1}) = \frac{R_4}{R_3}\left(1 + 2\frac{R_2}{R_1}\right)(v_{I2} - v_{I1})$$

❖ **Problems:**

1. The common mode gain A_{cm} and the differential gain A_{id} of the first stage are equal. This means the common mode signal will be amplified and the overall CMRR will be reduced.
2. In order to change the overall gain, we need to vary the values of two resistance. This is not an easy task.

Solution: Disconnect point X to the ground.

Instrumentation Amplifier



Voltages and currents in instrumentation amplifier

- The current in resistor R_1 and R_2 is

$$i_1 = \frac{v_{I1} - v_{I2}}{R_1}$$

- The output voltages of op-amps are:

$$v_{O1} = v_{I1} + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I1} - \frac{R_2}{R_1} v_{I2}$$

$$v_{O2} = v_{I2} - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

- The output of difference amplifier is:

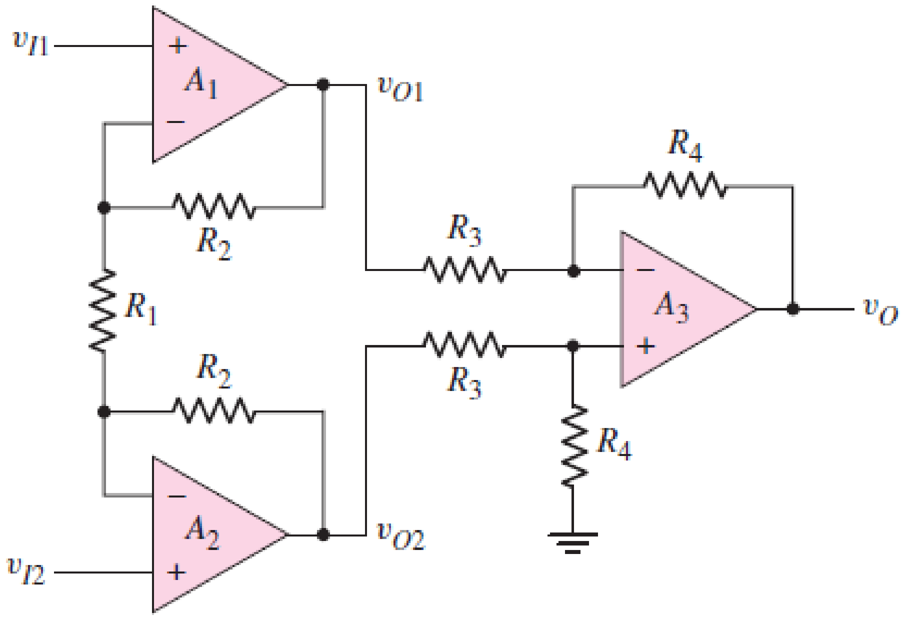
$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1}) = \frac{R_4}{R_3}\left(1 + 2\frac{R_2}{R_1}\right)(v_{I2} - v_{I1})$$

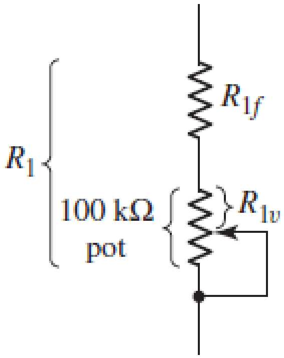
❖ **The overall gain does not depend on the matching between the two resistors.**

❖ **v_{01} and v_{O2} are equal if equal voltages appear at the negative terminal of A_1 and A_2**

Instrumentation Amplifier

Example 6: Consider the instrumentation amplifier circuit. Assume that $R_4 = 2R_3$ so that the difference amplifier gain is 2. Determine the range required for resistor R_1 to realize a differential gain adjustable from 5 to 500. Assume that R_1 is a variable resistor varying from R_{1f} to $R_{1f} + 100k\Omega$

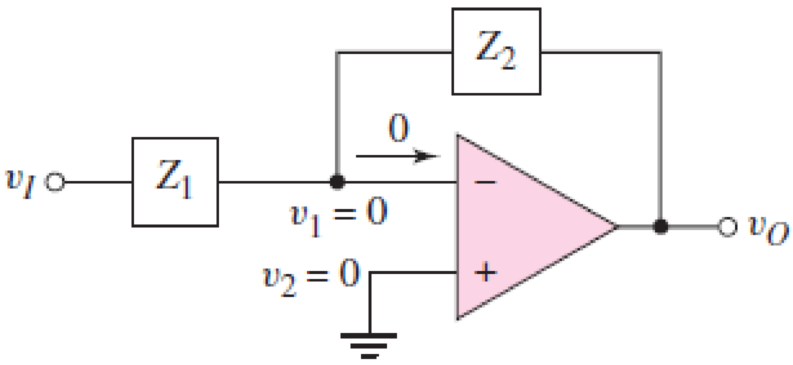




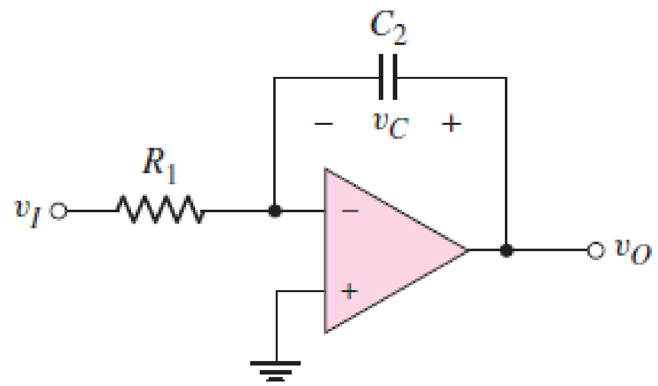
$$R_{1f} = 0.606k\Omega$$

$$R_2 = 75.5k\Omega$$

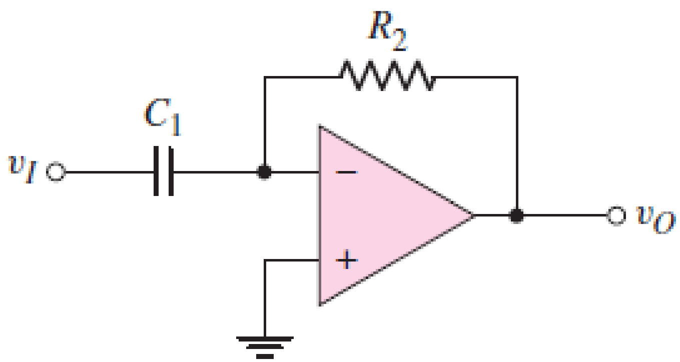
Integrator and Differentiator



Generalized inverting amplifier



Op-amp integrator



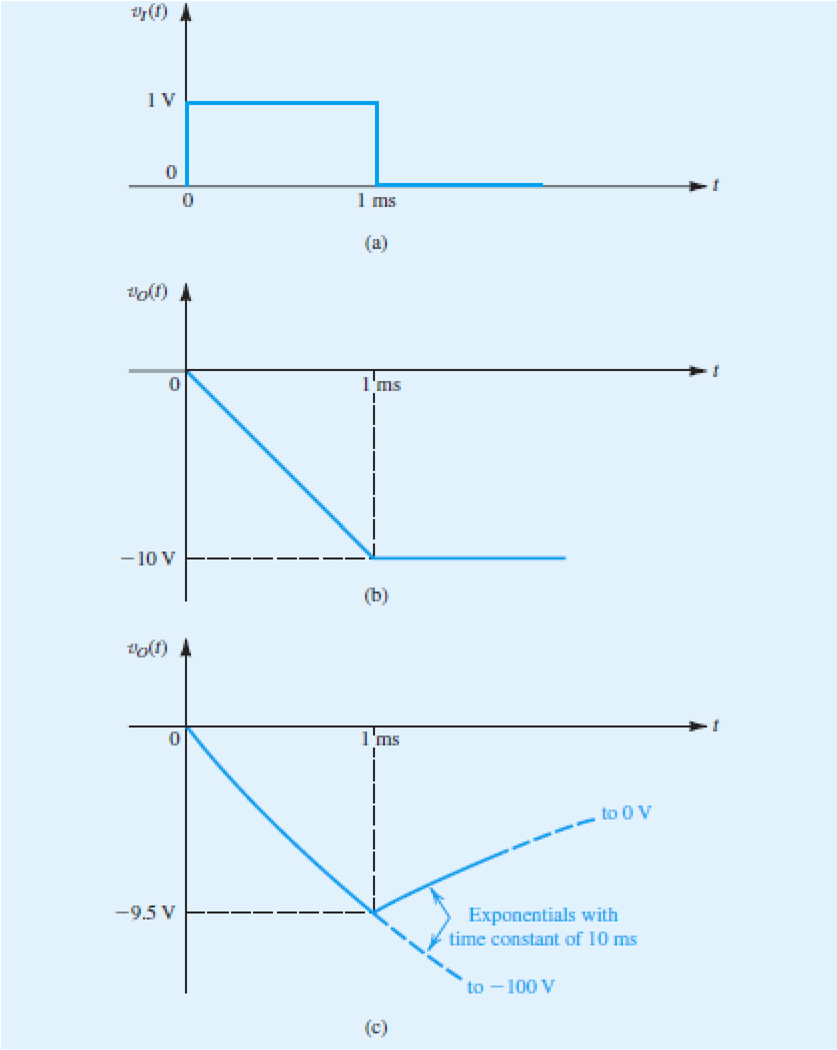
Op-amp differentiator

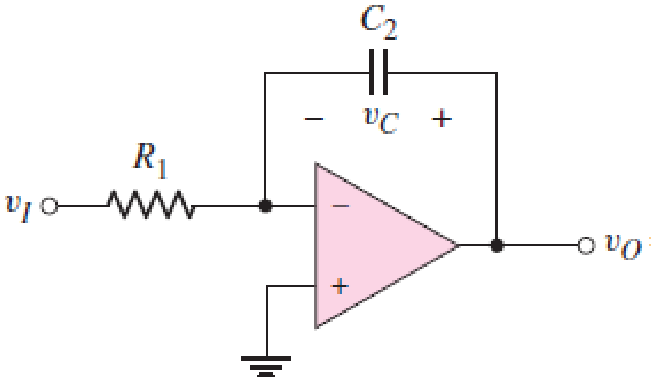
- Op-amp integrator: $$v_O = -\frac{v_I}{sR_1C_2}$$
- Op-amp differentiator: $$v_O = -v_I sR_2C_1$$

Reading: Microelectronics, Circuit Analysis and Design, D.A. Neamen, 4th edition, p621-670

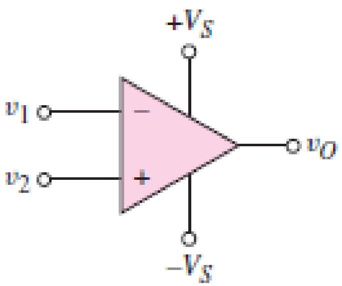
Integrator and Differentiator

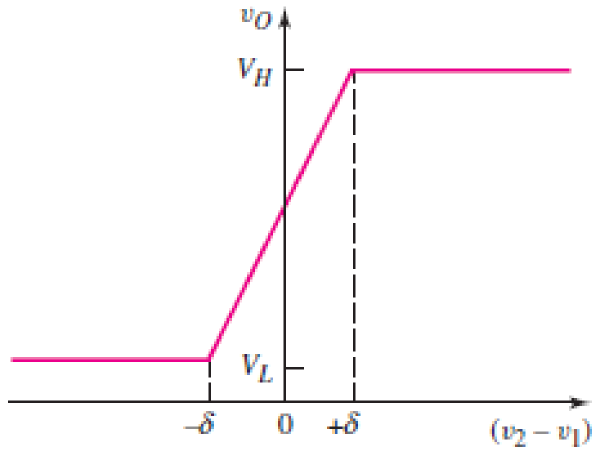
Example 7: Find the output produced by an integrator in response to an input pulse of 1V height and 1ms width. Let $\mathrm{R} = 10k\Omega$ and $\mathrm{C} = 10nF$. If the integrator is shunted by a $1M\Omega$ resistor. How will the response be modified.





Comparator





❖ When v_2 is slightly greater than v_1:

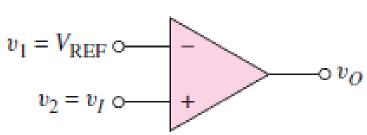
The output is driven to a high saturated state V_H

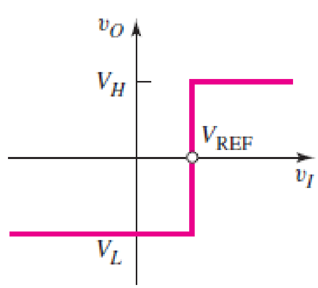
❖ When v_2 is slightly less than v_1:

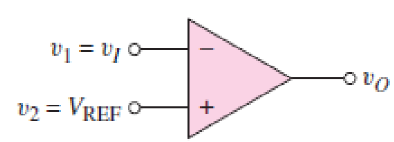
The output is driven to a low saturated state V_L

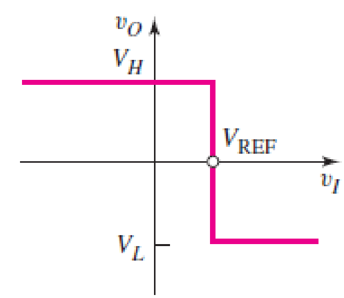
❖ The transition region occurs when the difference input voltage in the range $[-\delta, \delta]$

Example: if the open-loop voltage gain is 10^5 and the difference between the two stage is $(V_H - V_L) = 10V$ then $2\delta = \frac{(V_H - V_L)}{G} = \frac{10}{10^5} = 10^{-4}(V)$.



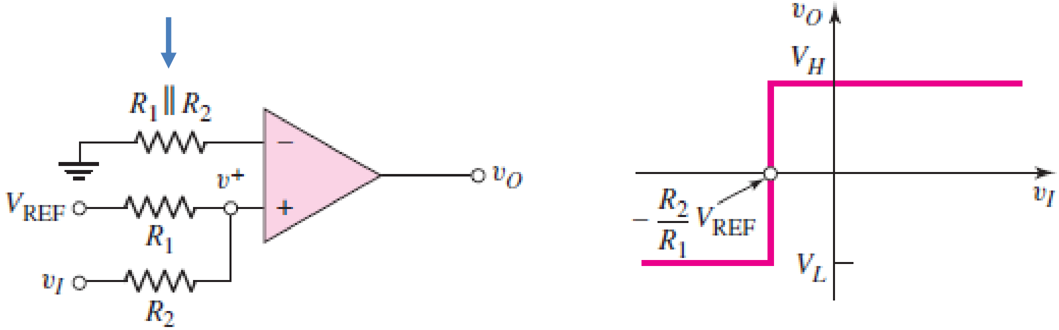






Comparator

For input bias current compensation

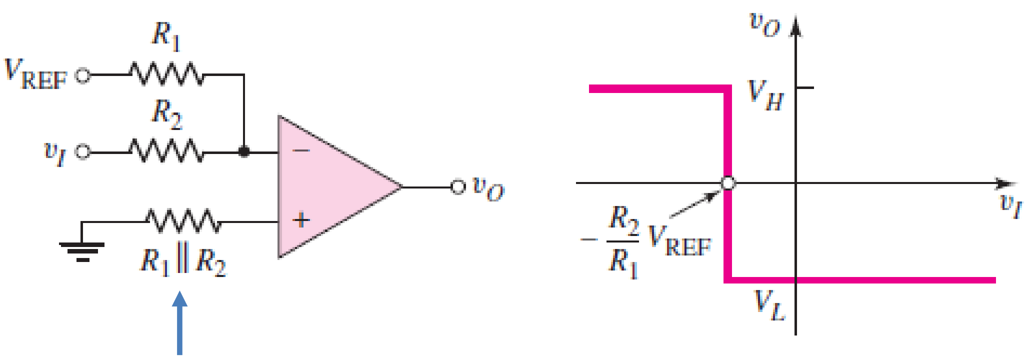


- Using the superposition, we obtain:

$$v_+ = \frac{R_1}{R_1 + R_2} V_{REF} + \frac{R_2}{R_1 + R_2} v_I$$

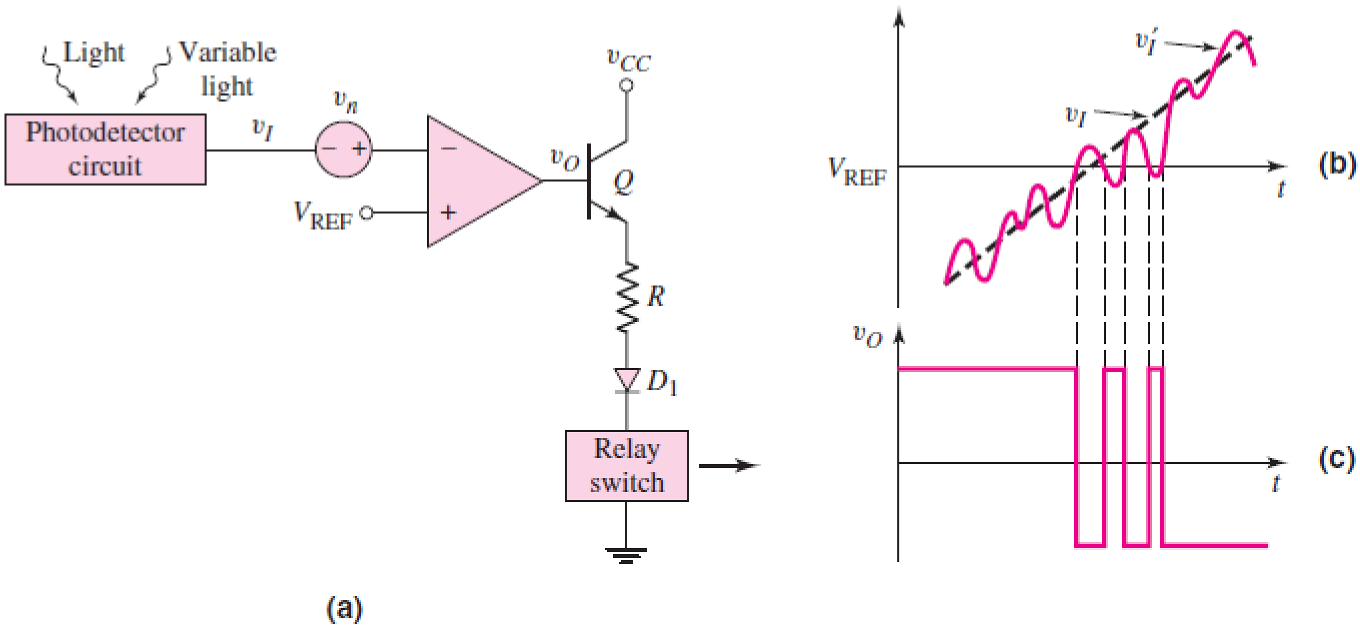
- The ideal crossover voltage occur:

$$v_+ = 0 \leftrightarrow v_I = -\frac{R_1}{R_2} V_{REF}$$



For input bias current compensation

Comparator



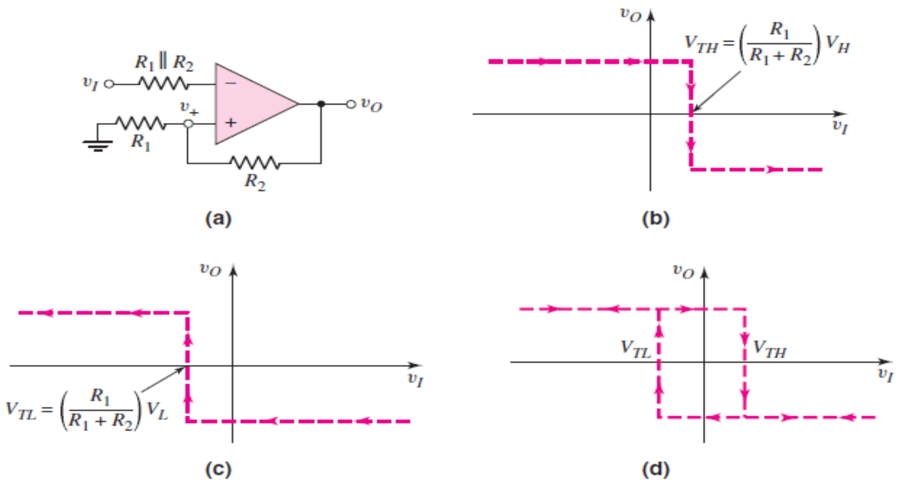
❖ Figure above shows a comparator circuit for street lights control applications.

❖ During night, $v_I < V_{REF}$: v_o to a high saturated state V_S, transistor turns on.

❖ During day, $v_I > V_{REF}$: v_o to a low saturated state $-V_S$, transistor turns off.

❖ With a variable light source, such as clouds causing the light fluctuate over a short period of time → This causes the light off and on for a short period of time. **Solution: Schmitt trigger.**

Inverting Schmitt Trigger



❖ Using the positive feedback, we obtain:

$$v_+ = \frac{R_1}{R_1 + R_2} v_o$$

❖ v_+ is NOT a constant, rather, it is a function of v_o.

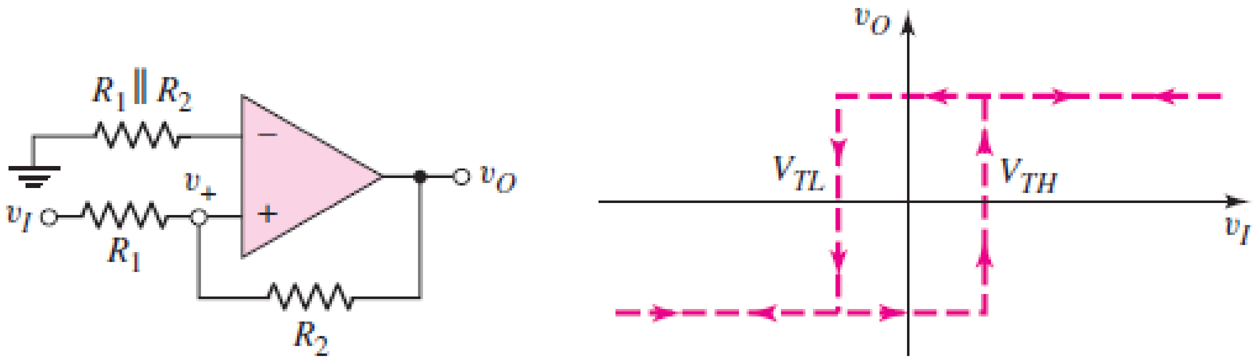
❖ Assume that the output of the comparator is in one state, namely $v_o = V_H$. Then:

$$v_+ = V_{TH} = \frac{R_1}{R_1 + R_2} V_H$$

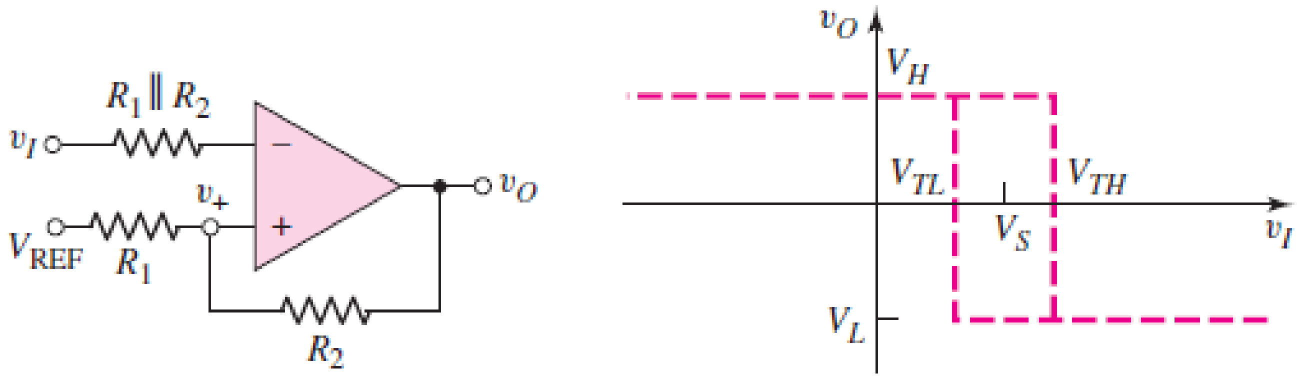
❖ When v_I is less than v_+, the output remain the high state. When v_I is greater than V_{TH} . Then: $v_o = V_L$ and:

$$v_+ = V_{TL} = \frac{R_1}{R_1 + R_2} V_L$$

Other Schmitt Trigger Configurations



Non-Inverting Schmitt Trigger



Schmitt Trigger circuit with Applied reference voltage

Q&A