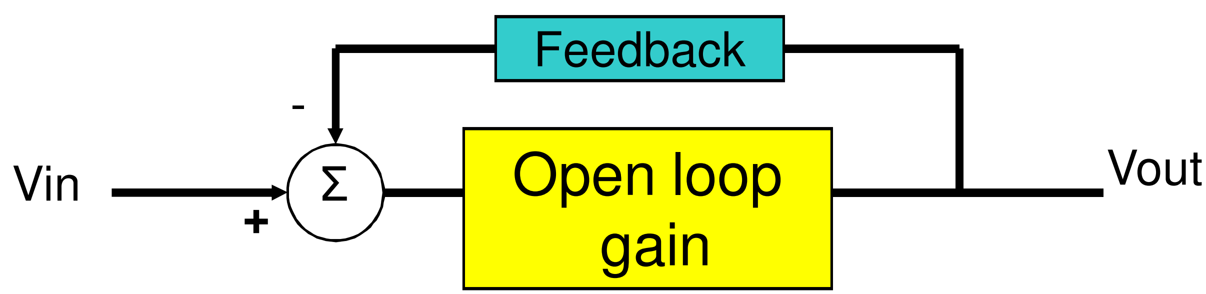
Open Loop , Close Loop, Feedback (Op-Amp)

Open Loop/Closed Loop and Feedback

- Open loop
  - Very high gain (intrinsic gain) **such high gain is not required in most applications**
  - Poor stability
  - Open loop gain assumed to be infinite for ideal op amps
- Closed loop
  - Uses feedback to add stability
  - Reduces gain of the amplifier
  - Output is applied back into the inverting (-) input
  - Most amplifiers are used in this configuration



Closed-loop/Feedback Op-Amp configurations

- In order to reduce gain, a part of output signal is fed back to the inverting input terminal (called negative feedback)
- Many other OPAMP characteristics are improvised with this
- A close loop amplifier can represent by using two block:

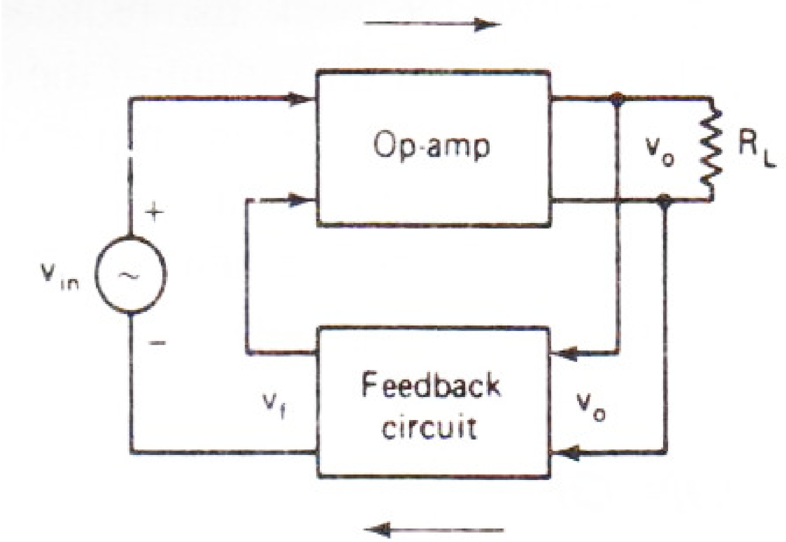
  A) Op-Amp B) Feedback circuit

Feedback

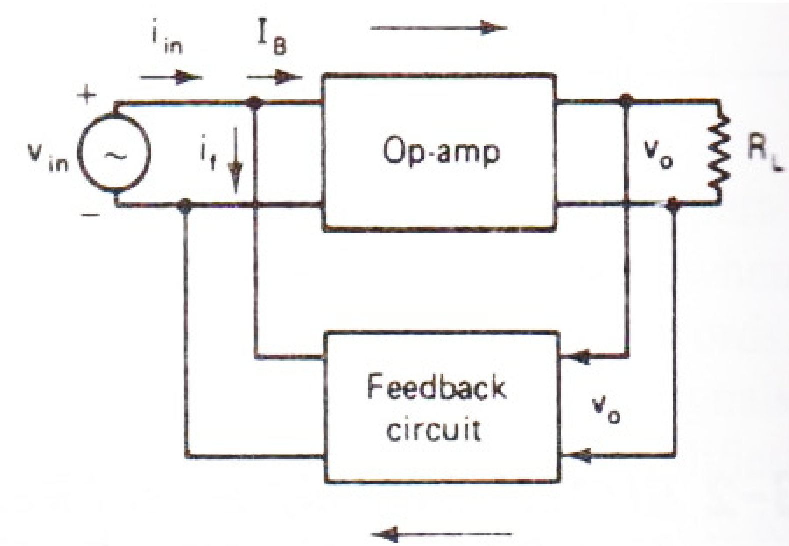
- Negative Feedback
  - Part of the output signal is returned to the input in opposition to the source signal
- Positive Feedback
  - The signal returned from the output to the input aids the original source signal

Classification of Feedback Op-Amp

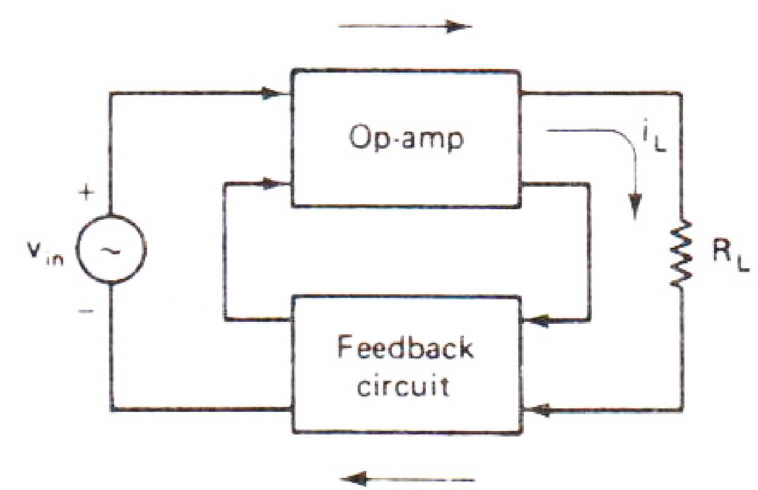
1. Voltage series feedback
2. Voltage shunt feedback
3. Current series feedback
4. Current shunt feedback



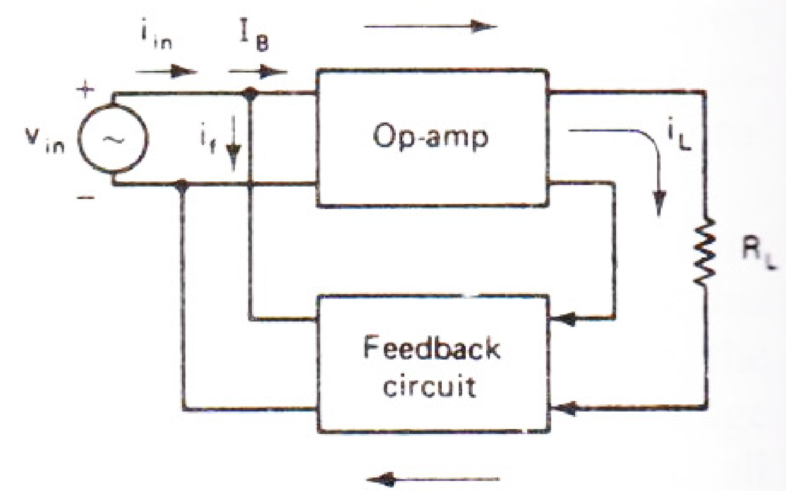
(a) Voltage series feedback



(b) Voltage shunt feedback



(c) Current series feedback



(d) Current shunt feedback

Golden Rules of Op-Amp Analysis

- **Rule 1: $V_A = V_B$**
  - The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
  - The op-amp “looks” at its input terminals and swings its output terminal around so that the external feedback network brings the input differential to zero.
- **Rule 2: $I_A = I_B = 0$**
  - The inputs draw no current
  - The inputs are connected to what is essentially an open circuit

Steps in Analyzing Op-Amp Circuits

Analysis Method :

Two ideal Op-Amp Properties:

(1) The voltage between V_+ and $V_–$ is zero $V_+ = V_–$

(2) The current into both V_+ and $V_–$ termainals is zero

For ideal Op-Amp circuit:

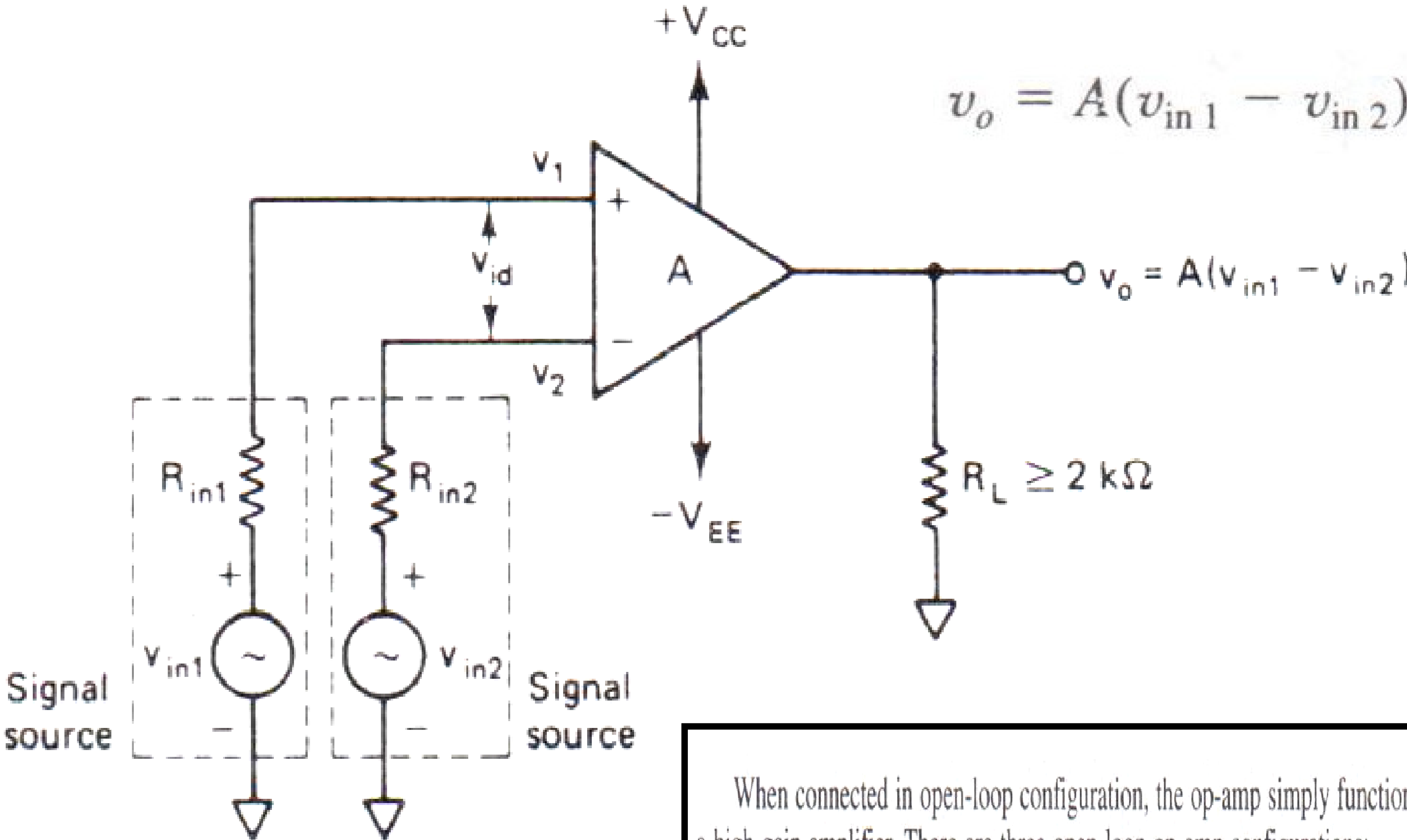
(1) Write the kirchhoff node equation at the noninverting terminal V_+

(2) Write the kirchhoff node eqaution at the inverting terminal $V_–$

(3) Set $V_+ = V_–$ and solve for the desired closed-loop gain

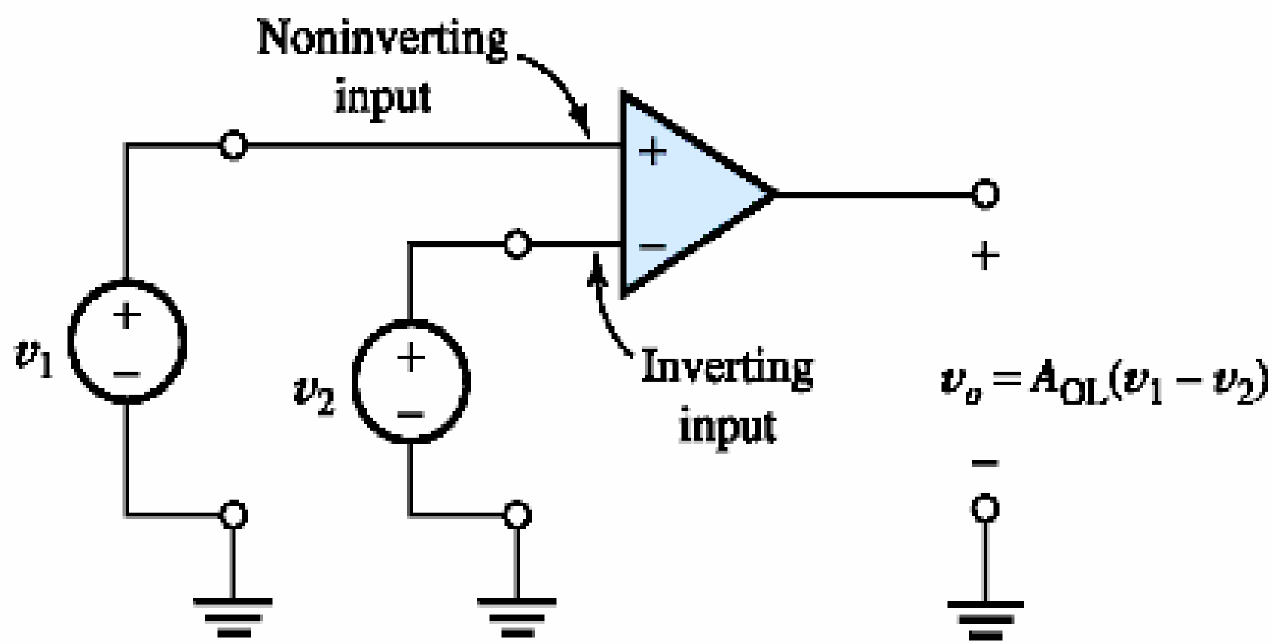
Open-loop Differential configuration

$$v_o = A(v_{\text{in }1} - v_{\text{in }2})$$



When connected in open-loop configuration, the op-amp simply functions a high-gain amplifier. There are three open-loop op-amp configurations:

Open-loop configuration



If $v_1 = 0$, then $v_o = -A_{OL}v_2$ **Inverting amplifier**

If $v_2 = 0$, then $v_o = A_{OL}v_1$ **Non inverting amp**

1. Differential amplifier
2. Inverting amplifier
3. Noninverting amplifier

Cont…

- A_{OL} **is the open-loop voltage gain of OPAMP**

❖ ***Its value is very high***

❖ ***Typical value is 0.5 million***

- **So, even if input is in micro volts, output will be in volts**

- **But output voltage cannot cross the value of power supply** V_{CC}

- **So, if input is in milli volts, output reaches saturation value**
  $V_{sat} = V_{CC}$ (or V_{EE})

Open-loop configuration

- If $v_1 = v_2$, then ideally output should be zero
- But in practical Op-Amp, output is

$$v_o = A_{cm}\left(\frac{v_1 + v_2}{2}\right)$$

Where, A_{CM} is the common-mode gain of Op-Amp

- So, final gain equation is:

$$v_o = A_d(v_1 - v_2) + A_{cm}\left(\frac{v_1 + v_2}{2}\right)$$

$$v_o = A_d v_{id} + A_{cm} v_{icm}$$

Cont…

- Common-mode rejection ratio
  - It is a measure of the ability of Op-Amp to reject the signals common to both input terminals (noise)
  - *Defined as*

$$CMRR = \frac{A_d}{A_{cm}}$$

$$(CMRR)_{dB} = 20\ log_{10}\left(\frac{A_d}{A_{cm}}\right)$$

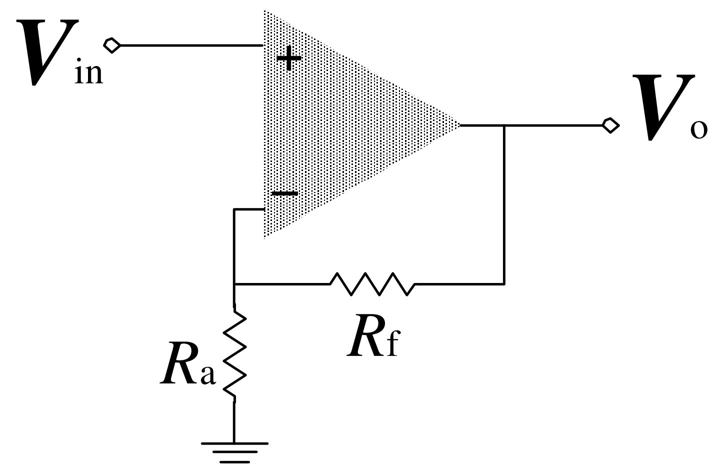
Noninverting Amplifier

(1) Kirchhoff node equation at V_+ yields, $V_+ = V_i$

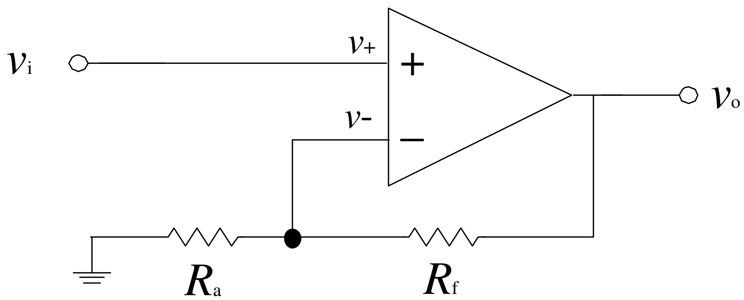
(2) Kirchhoff node equation at V_- yields, $\frac{V_- - 0}{R_a} + \frac{V_- - V_o}{R_f} = 0$

(3) Setting $V_+ = V_-$ yields

$$\frac{V_i}{R_a} + \frac{V_i - V_o}{R_f} = 0 \quad \text{or} \quad \frac{V_o}{V_i} = 1 + \frac{R_f}{R_a}$$

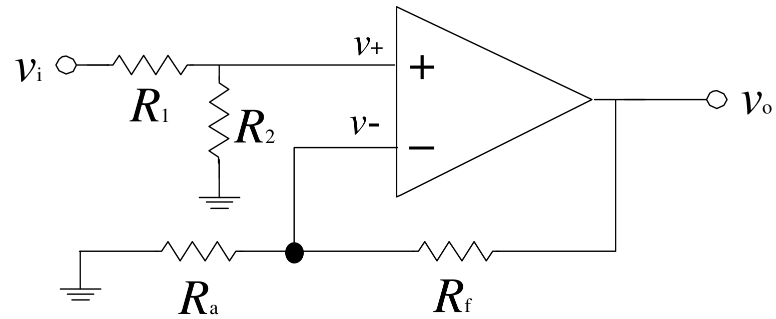


Various Configuration of Noninverting Amplifier



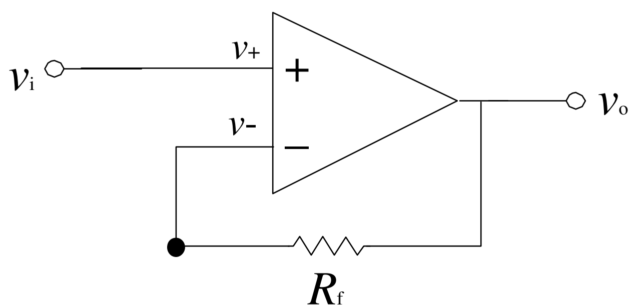
Noninverting amplifier

$$v_o = (1 + \frac{R_f}{R_a}) v_i$$



Noninverting input with voltage divider

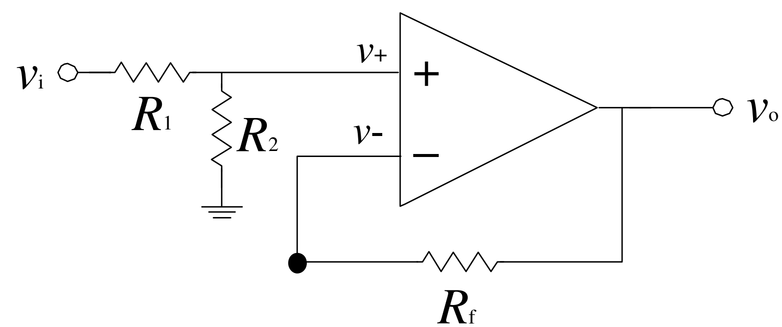
$$v_o = (1 + \frac{R_f}{R_a})(\frac{R_2}{R_1 + R_2}) v_i$$



Voltage follower

$$v_o = v_i \qquad A = \frac{V_{out}}{V_{in}} = 1$$

High input impedance Low output impedance Buffer circuit



Less than unity gain

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

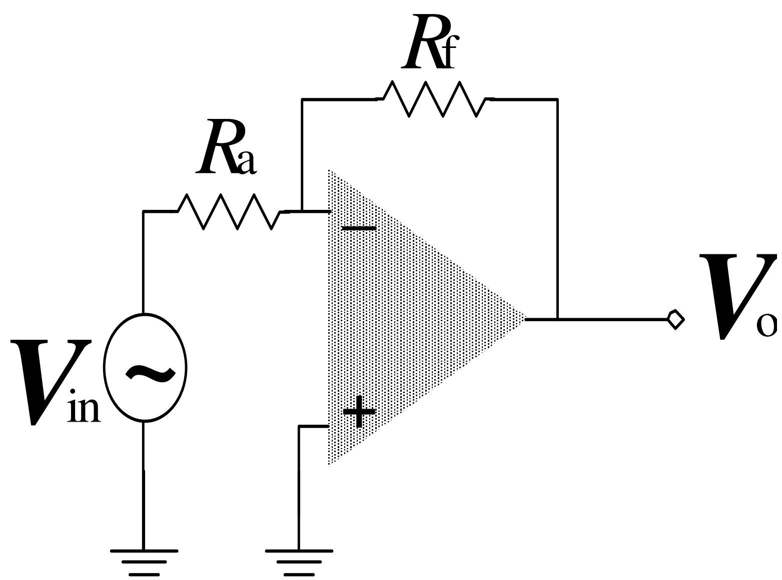
Inverting Amplifier

(1) Kirchhoff node equation at V_+ yields, $V_+ = 0$

(2) Kirchhoff node equation at V_- yields, $\frac{V_{in} - V_-}{R_a} + \frac{V_o - V_-}{R_f} = 0$

(3) Setting $V_+ = V_-$ yields

$$\frac{V_o}{V_{in}} = \frac{-R_f}{R_a}$$



Notice: The closed-loop gain V_o/V_{in} is dependent upon the ratio of two resistors, and is independent of the open-loop gain. This is caused by the use of feedback output voltage to subtract from the input voltage.

Integrator Op-Amp

- **Integrator is a circuit whose output voltage wave form is proportional to (negative) integral of the input voltage waveform with respect to time (known as integrator or integrator amplifier)**

- **It is basic inverting amplifier if the feedback resistor R_F is replaced by capacitor C_F.**

- **If input is sine wave output is cosine wave or input is square wave output by triangular wave.**

Integrator

Now replace resistors R_a and R_f by complex components Z_a and Z_f, respectively, therefore

$$V_o = \frac{-Z_f}{Z_a} V_{in}$$

Supposing

(i) The feedback component is a capacitor C, i.e.,

$$Z_f = \frac{1}{j\omega C}$$

(ii) The input component is a resistor R, $Z_a = R$

Therefore, the closed-loop gain (V_o/V_{in}) become:

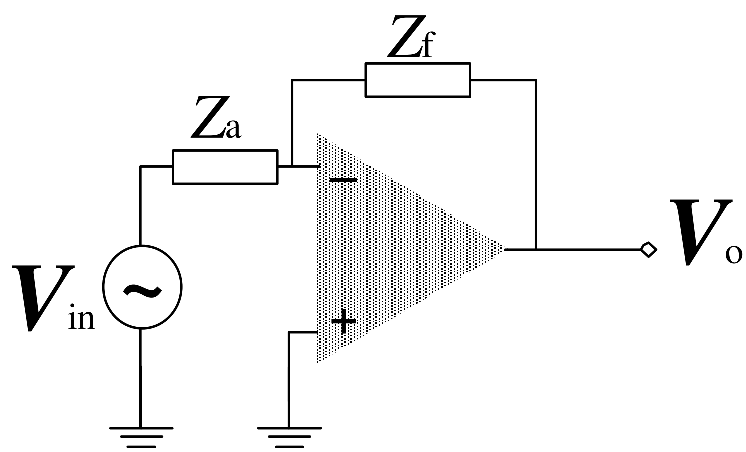
$$v_i(t) = V_i e^{j\omega t}$$

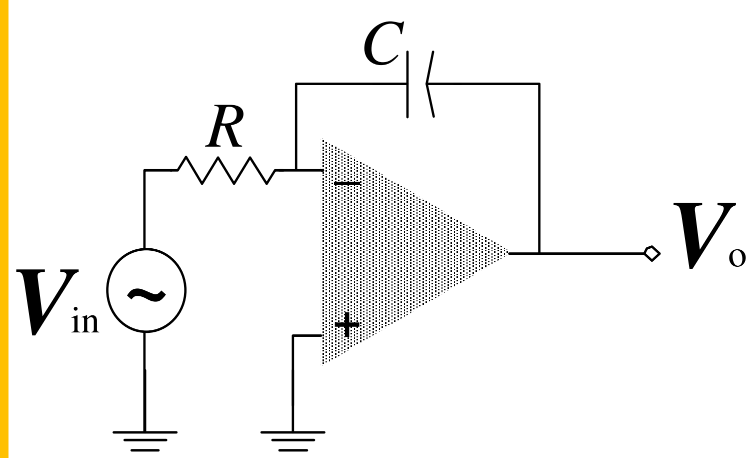
Where

$$v_o(t) = \frac{-1}{RC} \int v_i(t)\,dt$$

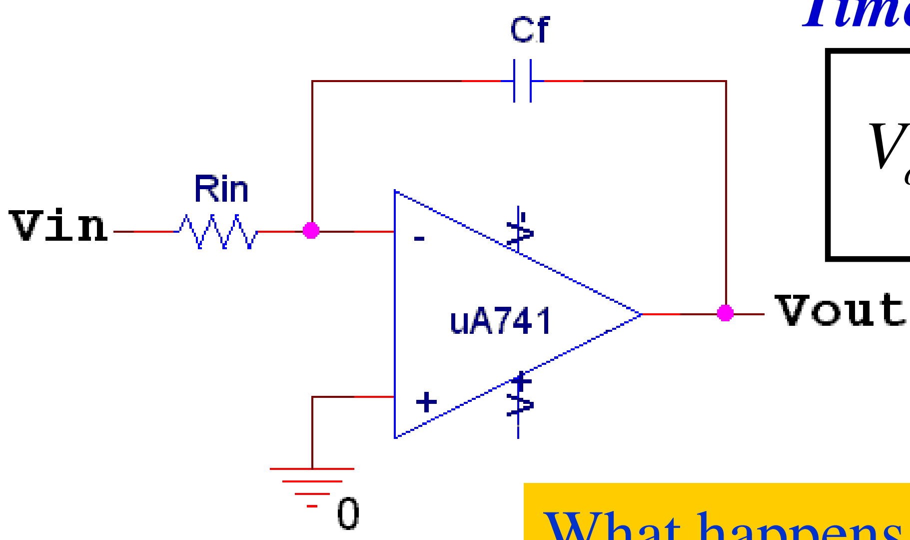
What happens if $Z_a = 1/j\omega C$ whereas, $Z_f = R$?

Inverting differentiator





Understanding of Integrator



Time domain (like oscilloscope)

$$\boxed{V_{out} = -\frac{1}{R_{in}C_f}\int V_{in}\,dt\ (+V_{DC})}$$

What happens to a capacitor at DC?

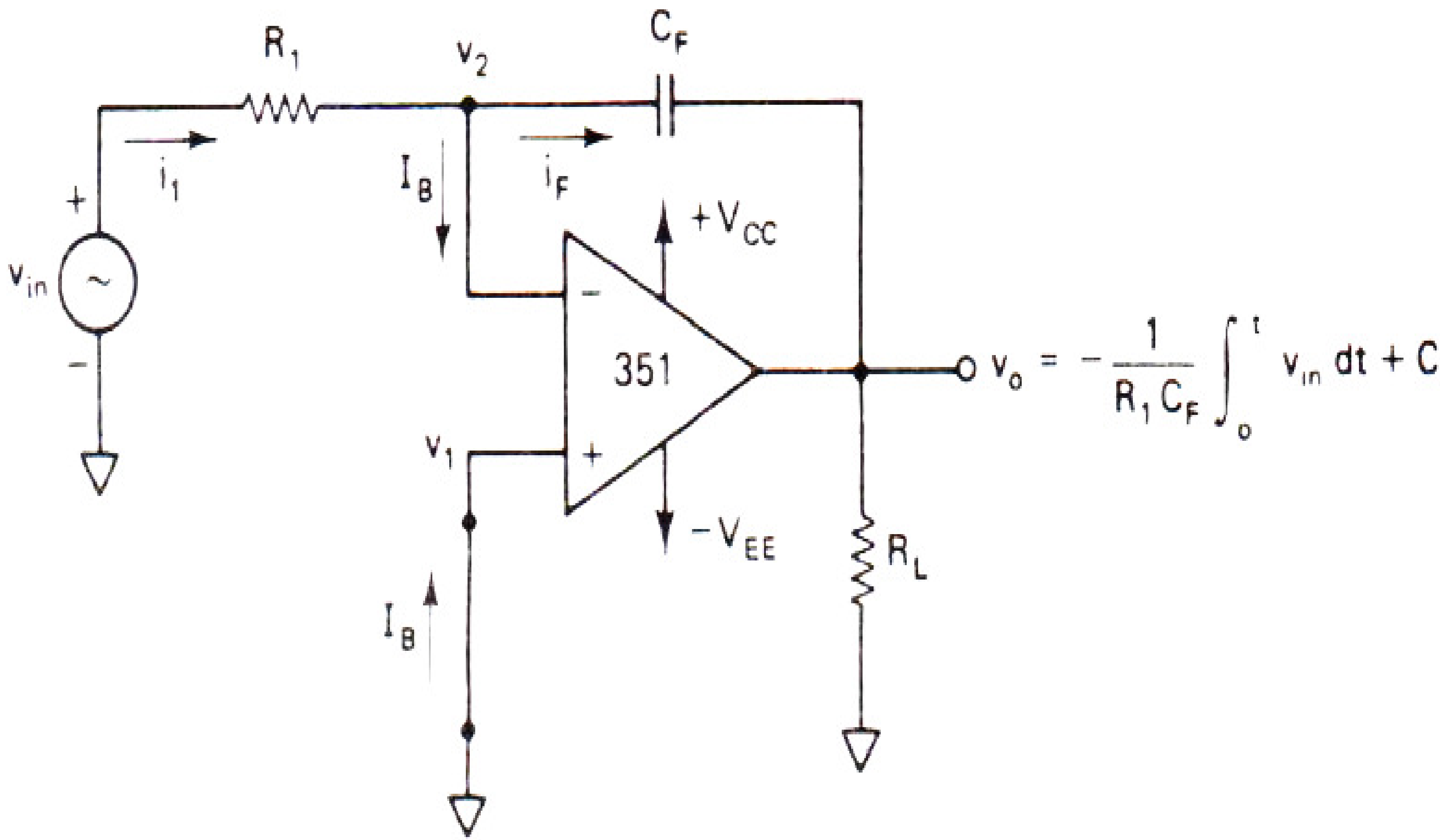
<u>Amplitude</u> changes by a factor of $1/\omega R_{in}C_f$

$$analysis:$$

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_{in}} = -\frac{1/j\omega C_f}{R_{in}} = -\frac{1}{j\omega R_{in}C_f}$$

Frequency domain (like AC sweep)

Integrator Circuits



Integrator Circuit

Integrator Circuit Analysis

The expression for the output voltage v_o can be obtained by writing Kirchhoff's current equation at node v_2:

$$i_1 = I_B + i_F$$

Since I_B is negligibly small,

$$i_1 \cong i_F$$

Recall that the relationship between current through and voltage across the capacitor is

$$i_c = C\frac{dv_c}{dt}$$

Therefore

$$\frac{v_{in} - v_2}{R_1} = C_F\left(\frac{d}{dt}\right)(v_2 - v_o)$$

However, $v_1 = v_2 \cong 0$ because A is very large. Therefore,

$$\frac{v_{in}}{R_1} = C_F\frac{d}{dt}(-v_o)$$

The output voltage can be obtained by integrating both sides with respect to time:

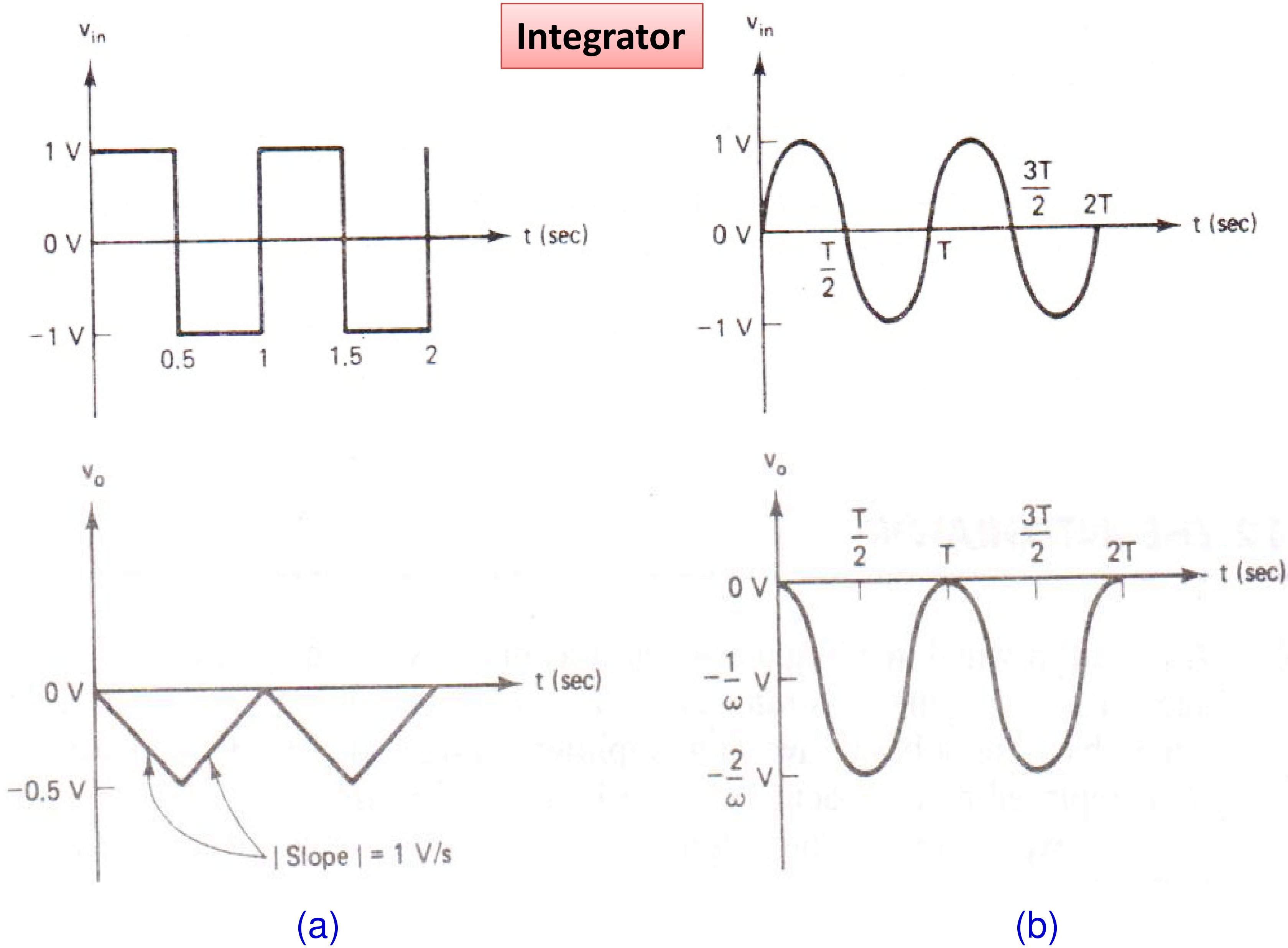
$$\int_0^t \frac{v_{in}}{R_1}\,dt = \int_0^t C_F\frac{d}{dt}(-v_o)\,dt$$
$$= C_F(-v_o) + v_o\big|_{t=0}$$

Therefore,

$$v_o = -\frac{1}{R_1C_F}\int_0^t v_{in}\,dt + C$$

where C is the integration constant and is proportional to the value of the output voltage v_o at time $t = 0$ seconds.

Integrator



(a) & (b) Input and Ideal output waveforms using a square wave & sine wave respectively

Differentiator

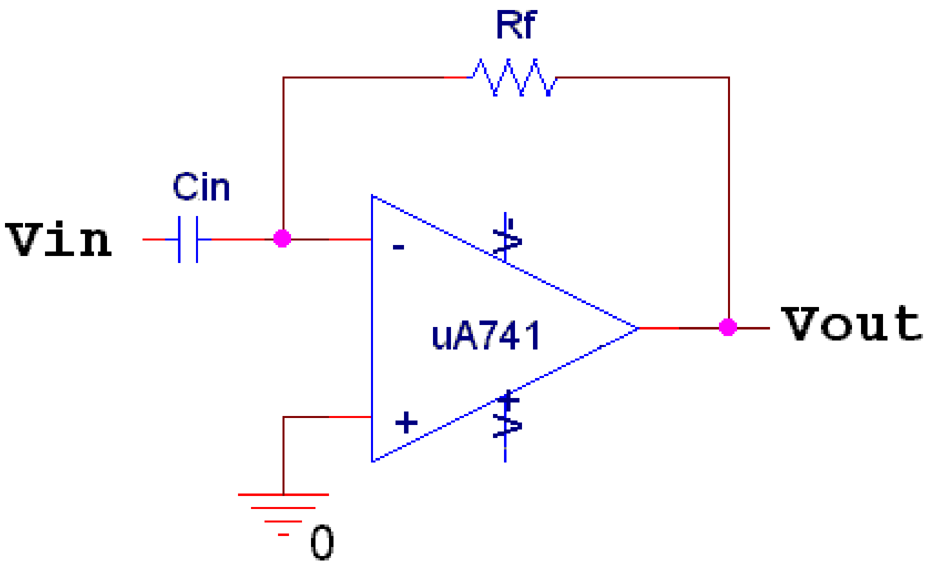
- Differentiator is circuit whose output is proportional to (negative) differential of input voltage with respect to time.

- Its application for mathematical operation of differentiation.

- The differentiator may be constructed from a basic inverting amplifier if an input resistance R_1 is replaced by a capacitor.

- If input is cosine wave output is sine wave or input is triangular wave output by square wave.

Differentiator



Time domain (like oscilloscope)

$$\boxed{V_{out} = -R_f C_{in} \frac{dV_{in}}{dt}}$$

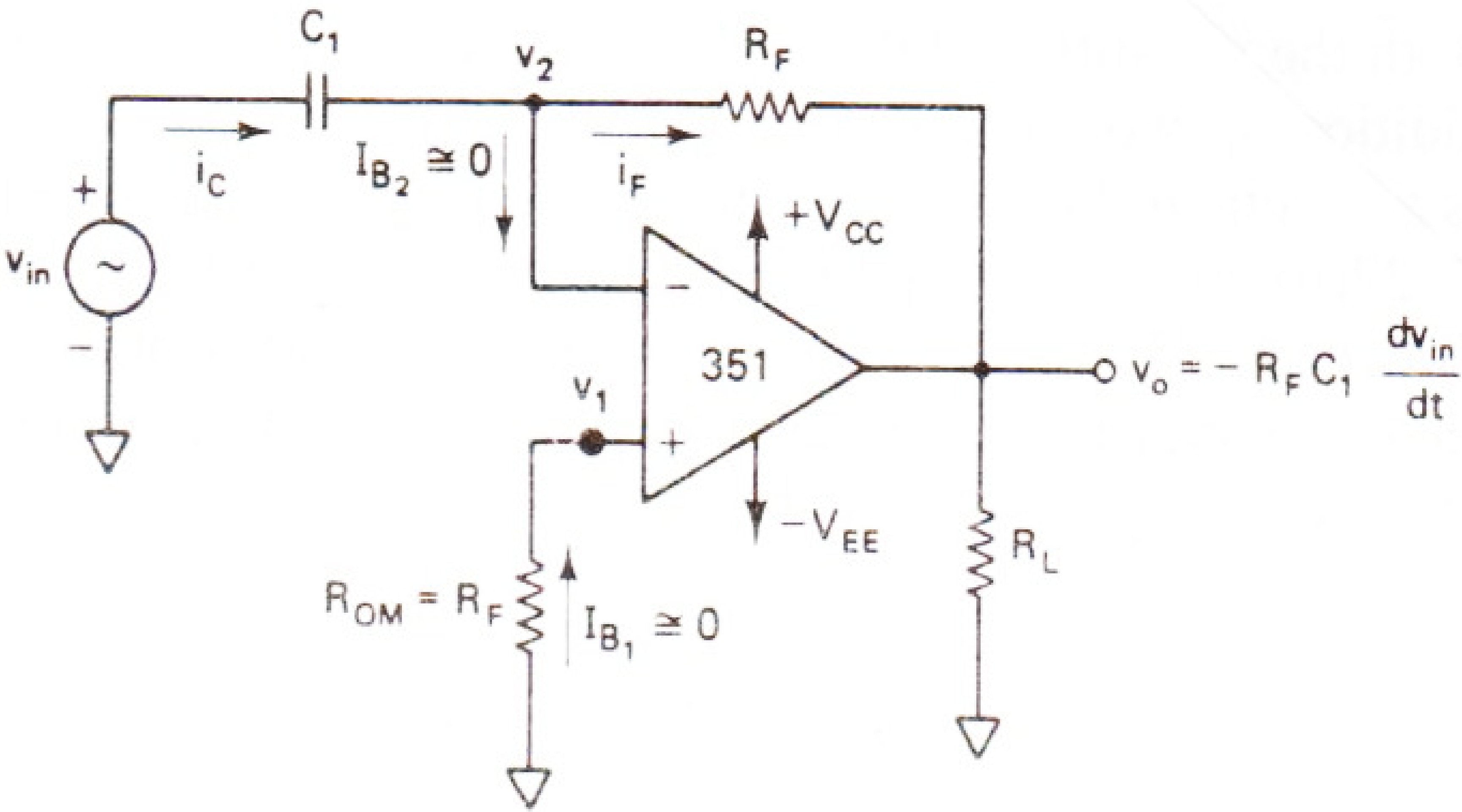
Amplitude changes by a factor of $\omega R_f C_{in}$

$analysis:$

$$\frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_{in}} = -\frac{R_f}{1/j\omega C_{in}} = -j\omega R_f C_{in}$$

Frequency domain (like AC sweep)

Differentiator Circuit



Differentiator

The expression for the output voltage can be derived from Kirchhoff's current equation written for node V_2 as follow :

$$i_C = I_B + i_F$$

Since $I_B \cong 0$,

$$i_C = i_F$$

$$C_1 \frac{d}{dt}(v_{in} - v_2) = \frac{v_2 - v_o}{R_F}$$

But $v_1 = v_2 \cong 0$ V, because A is very large. Therefore,

$$C_1 \frac{dv_{in}}{dt} = -\frac{v_o}{R_F}$$

or

$$v_o = -R_F C_1 \frac{dv_{in}}{dt}$$

Thus the output V_o is $R_F C_1$ times the negative instantaneous rate of change of input voltage V_{in} with time.

Comparison

	Differentiaion	Integration
original signal	$v(t)=A\sin(\omega t)$	$v(t)=A\sin(\omega t)$
mathematically	$dv(t)/dt = A\omega\cos(\omega t)$	$\int v(t)dt = -(A/\omega)\cos(\omega t)$
mathematical phase shift	+90 (sine to cosine)	-90 (sine to –cosine)
mathematical amplitude change	ω	$1/\omega$
$H(j\omega)$	$H(j\omega) = -j\omega RC$	$H(j\omega)= -1/j\omega RC = j/\omega RC$
electronic phase shift	-90 (-j)	+90 (+j)
electronic amplitude change	ωRC	$1/\omega RC$

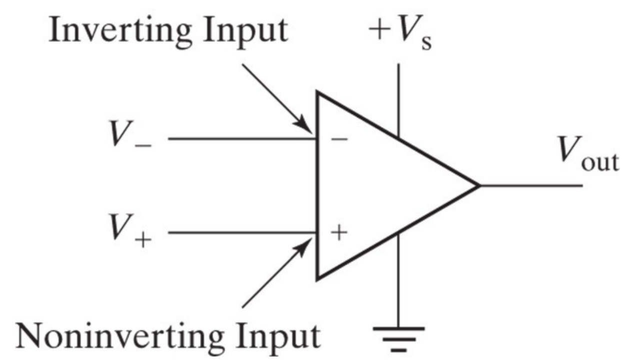
- **The op amp circuit will *invert* the signal and multiply the mathematical amplitude by RC (differentiator) or 1/RC (integrator)**

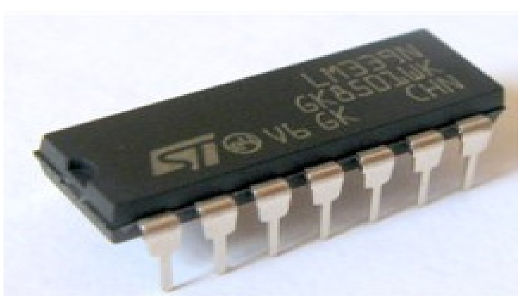
The Comparator

•A comparator, compares a signal voltage on one input of an Op-Amp with the a known voltage called reference voltage.

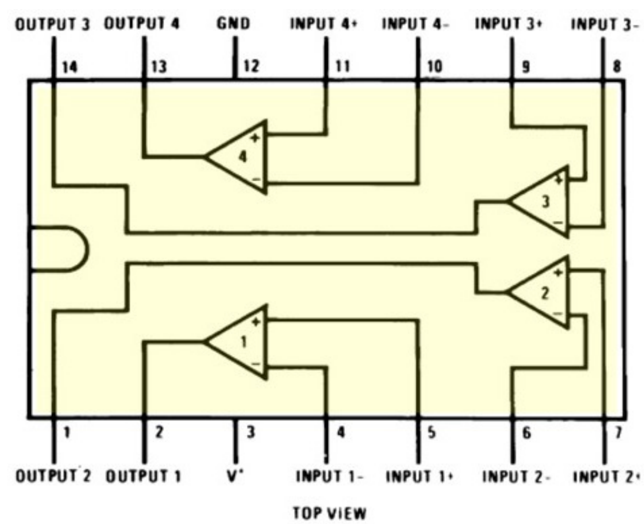
•It is used for digital interfacing of devices.

- **A specially designed op-amp, optimized to switch V_{out} *fast***
  - If V+ > V-, then $V_{out} \approx$ Vs
  - If V- > V+, then $V_{out} \approx$ 0 V
- **But usually output is '*open collector*'**
  - Can pull *low*, but…
  - Needs external resistor (pull-up) to go high

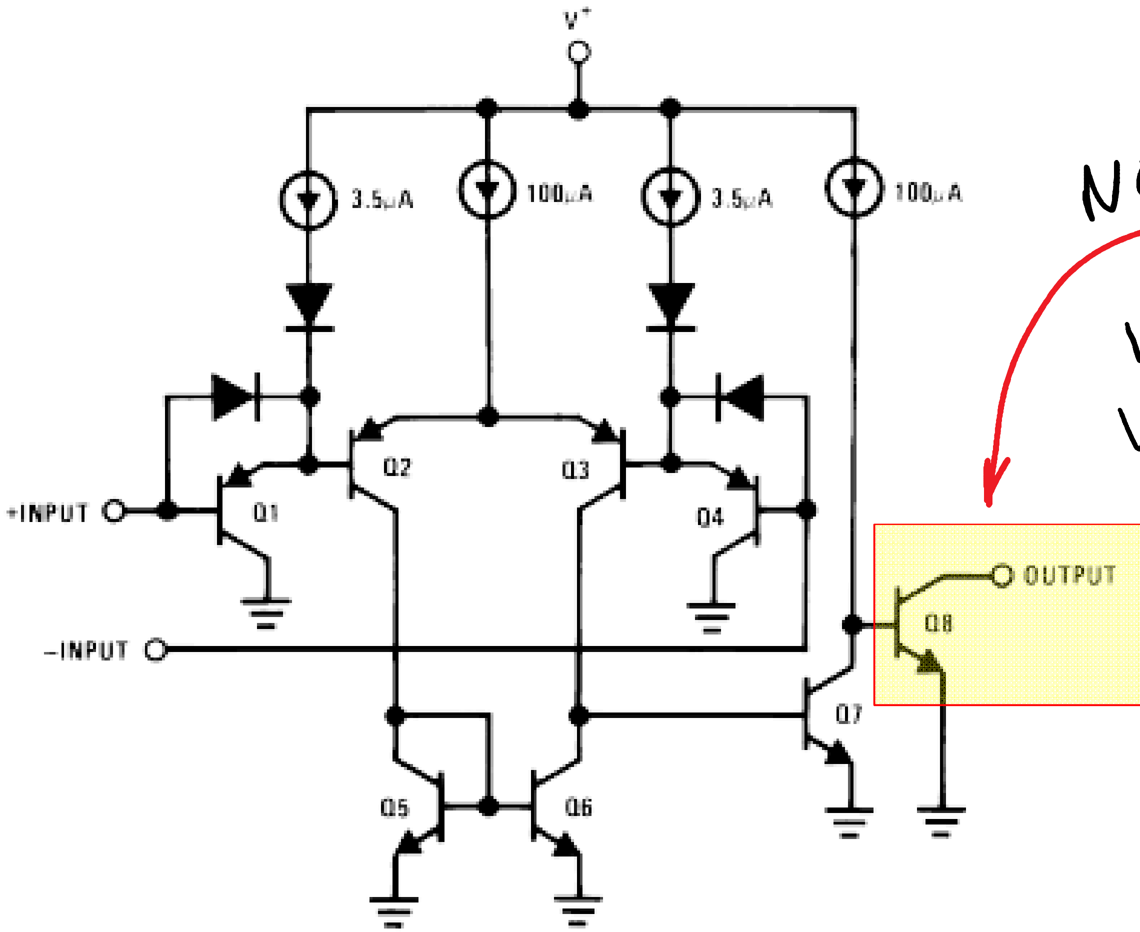




LM339 Quad IC



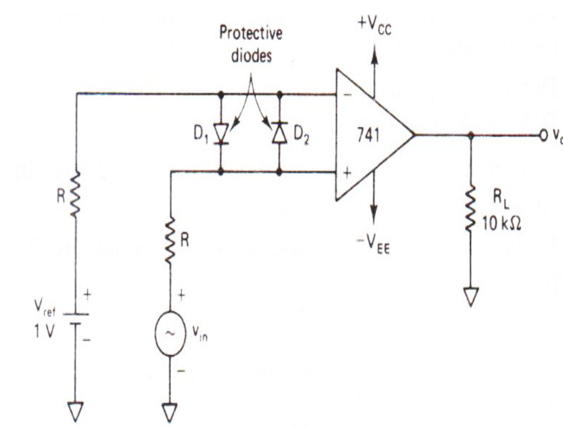
Inside the LM339 comparator



NOTE: OPEN COLLECTOR

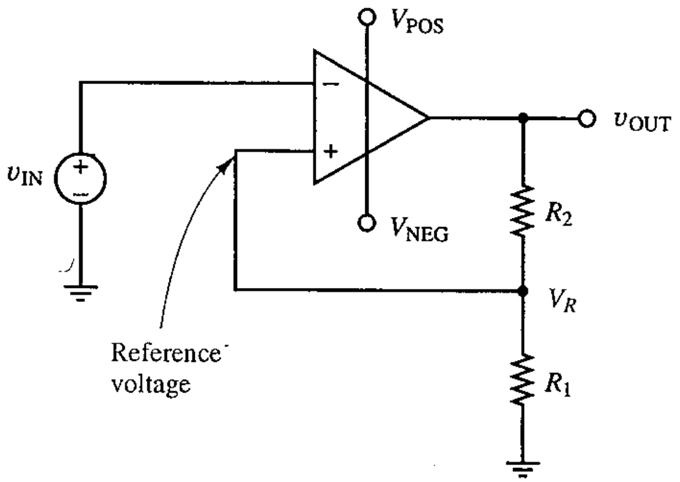
$V+ > V- \rightarrow Q_8$ OFF

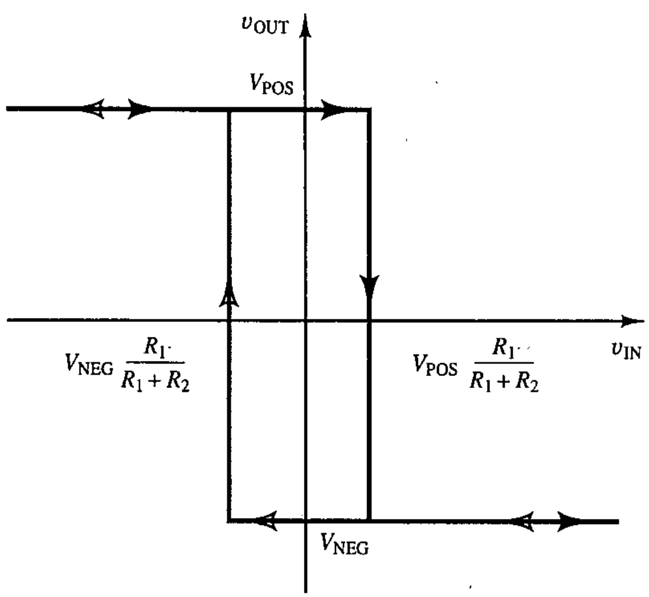
$V- > V+ \rightarrow Q_8$ ON



Non Inverting Comparator

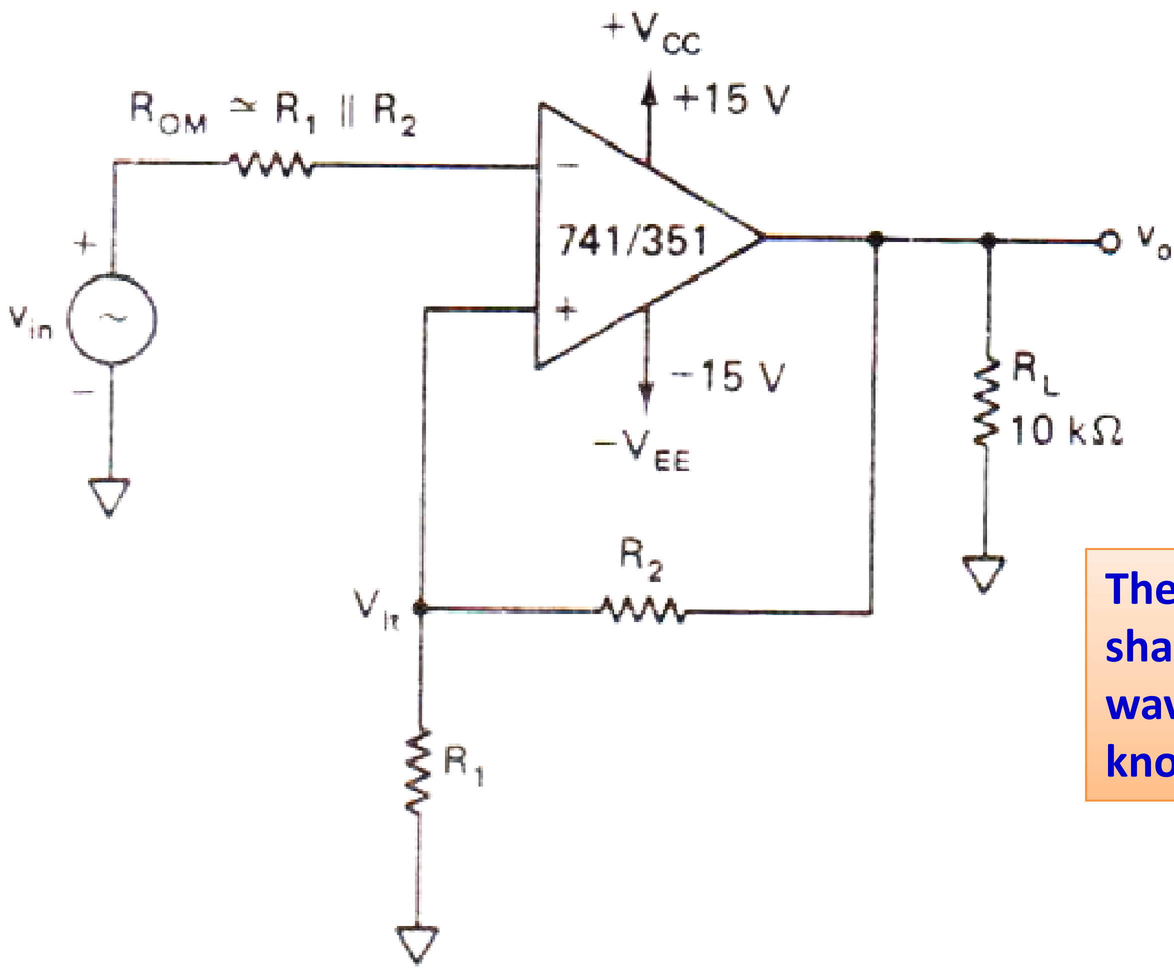
Schmitt Trigger Op-amp Circuit





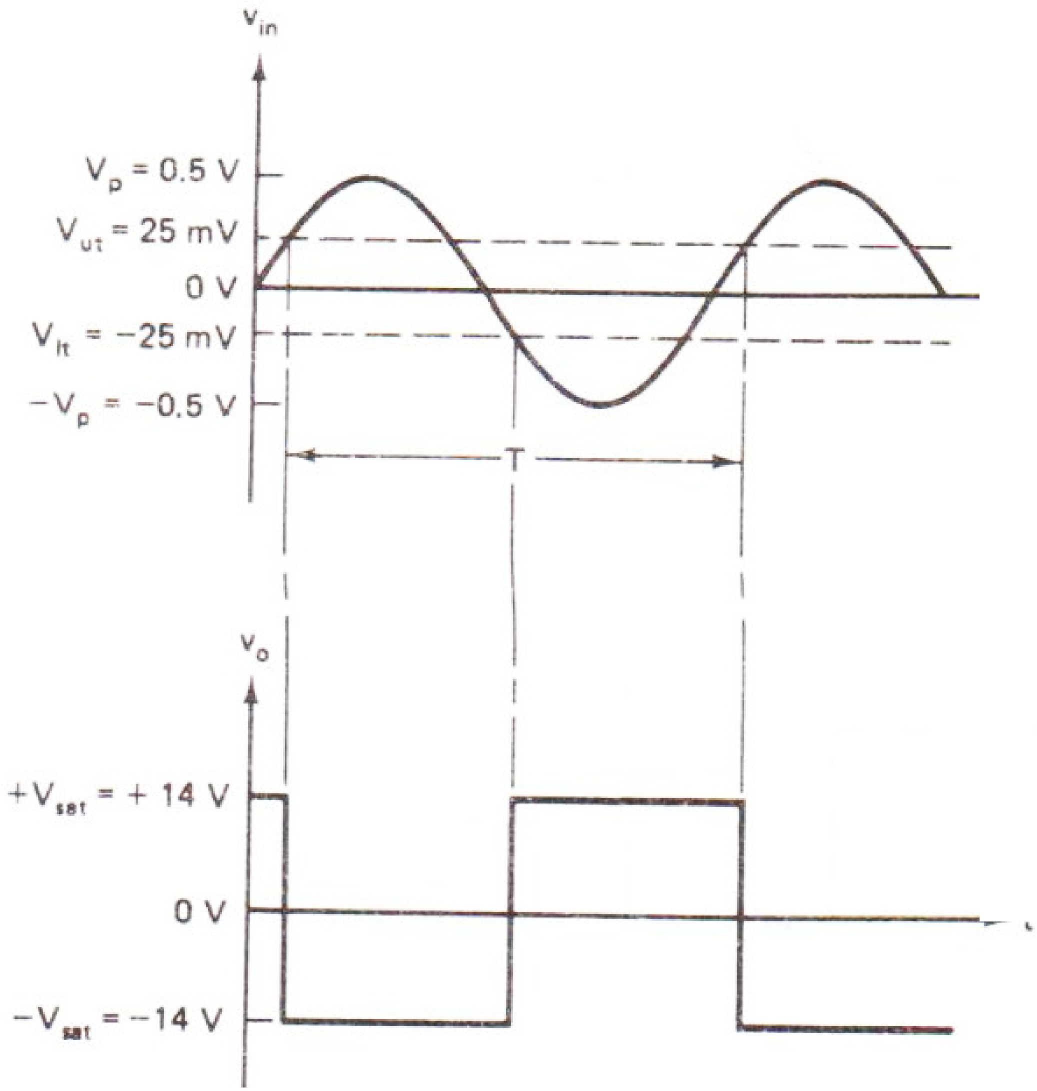
- The open-loop comparator from the previous slides is very susceptible to noise on the input
  - Noise may cause it to jump erratically from + rail to – rail voltages
- The Schmitt Trigger circuit (at the left) solves this problem by using positive feedback
  - It is a comparator circuit in which the reference voltage is derived from a divided fraction of the output voltage, and fed back as positive feedback.
  - The output is forced to either V_{POS} or V_{NEG} when the input exceeds the magnitude of the reference voltage
  - The circuit will remember its state even if the input comes back to zero (has memory)
- The transfer characteristic of the Schmitt Trigger is shown at the left
  - Note that the circuit functions as an inverter with hysteresis
  - Switches from + to – rail when $v_{IN} > V_{POS}(R1/(R1 + R2))$
  - Switches from – to + rail when $v_{IN} < V_{NEG}(R1/(R1 + R2))$

Schmitt Trigger Circuit

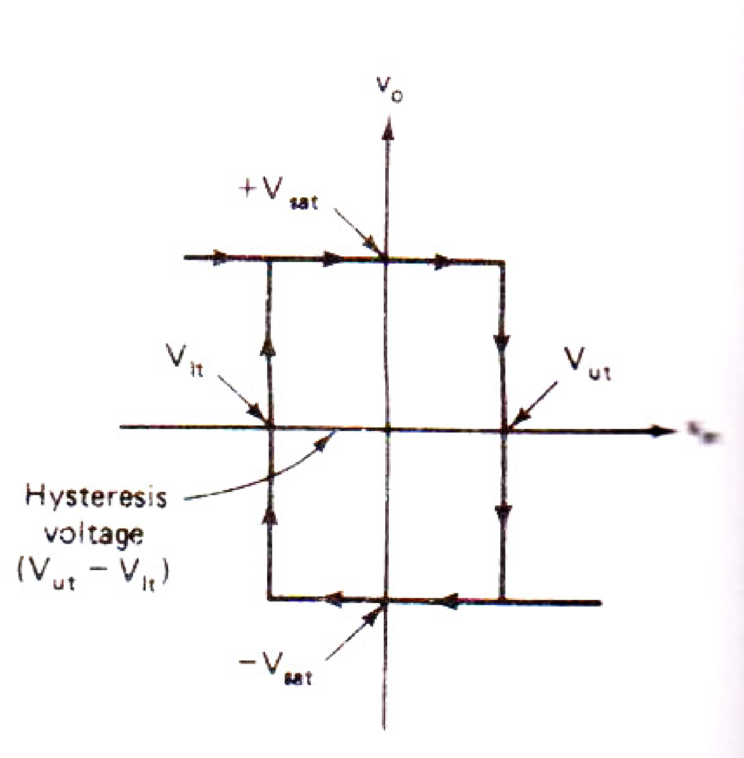


The circuit convert an irregular shape waveform to a square wave or pulse wave, the circuit known as Schmitt trigger.

Schmitt Trigger (Inverting Comparator)



(a)



(b)

(a) Input and Output Wave forms of Schmitt Trigger

(b) Vo versus Vin plot of the hysteresis voltage

Limitations of Op-Amp

Saturation

- Even with feedback,
  - any time the output tries to go above V+ the op-amp will saturate positive.
  - Any time the output tries to go below V- the op-amp will saturate negative.
- Ideally, the saturation points for an op-amp are equal to the power voltages, in reality they are 1-2 volts less.

$$-V \leq V_{out} \leq +V$$

Ideal: $-9V < V_{out} < +9V$

Real: $-8V < V_{out} < +8V$

- Current Limits → If the load on the op-amp is very small,
  - Most of the current goes through the load
  - Less current goes through the feedback path
  - Op-amp cannot supply current fast enough
  - Circuit operation starts to degrade
- Slew Rate
  - The op-amp has internal current limits and internal capacitance.
  - There is a maximum rate that the internal capacitance can charge, this results in a maximum rate of change of the output voltage.
  - This is called the slew rate.