SEE 2253: ELECTRONIC CIRCUITS

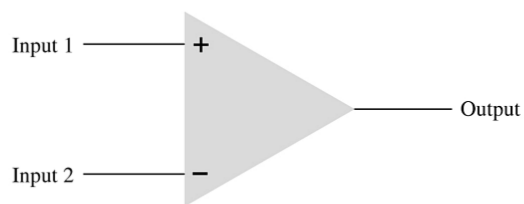
Chapter 5: Operational Amplifiers

5.0 The Operational Amplifiers

- Usually Called Op-Amps.
- An amplifier is a device that accepts a varying input signal and produces a similar output signal with a larger amplitude.
- Usually connected so part of the output is fed back to the input (Feedback Loop).
- Most Op-Amps behave like voltage.
- They are the basic components used to build analog circuits.
- The name “operational amplifier” comes from the fact that they were originally used to perform mathematical operations such as integration and differentiation.

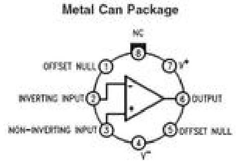
The Operational Amplifiers (continue…)

- Integrated circuit fabrication techniques have made high-performance operational amplifiers very inexpensive in comparison to older discrete devices.
- Op-Amp is a very high gain differential amplifier with a high input impedance (typically a few mega-Ohms) and low output impedance (less than 100 Ohms).
- Note the op-amp has two inputs and one output.

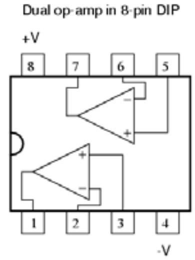


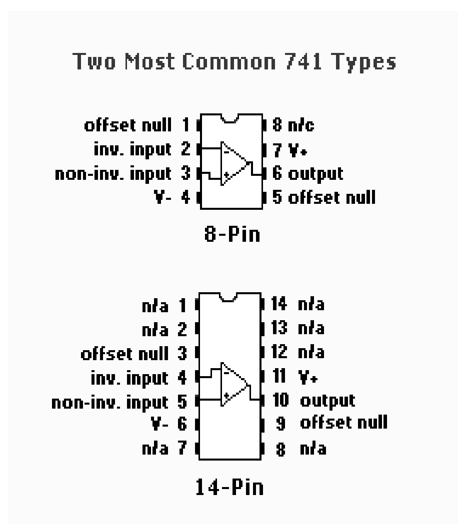
5.1 Typical Op-Amps

Metal Can Package



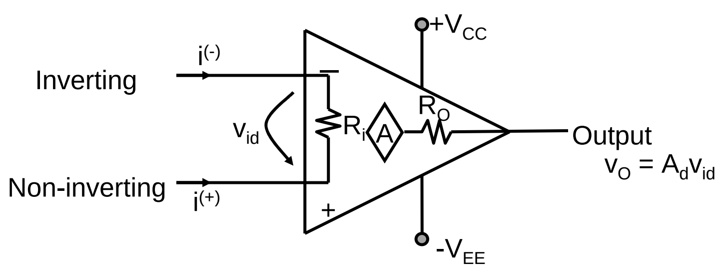
Dual op-amp in 8-pin DIP





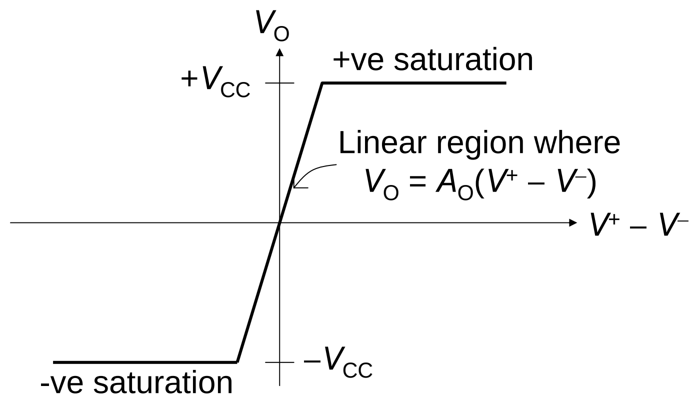
5.2 The Op-Amp Gain

- Op-Amps have a very high gain.
- They can be connected open-loop or closed-loop.
  - **Open-loop** refers to a configuration where there is no feedback from output back to the input. In the open-loop configuration the gain can exceed 10,000.
  - **Closed-loop** configuration reduces the gain. In order to control the gain of an op-amp it must have feedback. This feedback is a negative feedback. A negative feedback reduces the gain and improves many characteristics of the op-amp.



- $i^{(+)}$, $i^{(-)}$: Currents into the amplifier on the inverting and non-inverting lines respectively.
- v_{id} : The input voltage from inverting to non-inverting inputs.
- $+V_{CC}$, $-V_{EE}$: DC source voltages, usually +15V and –15V.
- R_i : The input impedance. Ideally infinity.
- A : The gain of the amplifier. Ideally infinity.
- R_O: The output impedance. Ideally zero.
- v_O: The output voltage, $v_O = A_{OL}v_{id}$ where A_{OL} is the open-loop voltage gain.

5.3 The Op-Amp Transfer Curve



5.4 Ideal Op-Amp Characteristics

- High open-loop gain, ($A_{OL}= \infty$).
- High input impedance, ($R_i = \infty$).
- Low output impedance, ($R_o = 0$).
- Output saturation voltage, $\pm V_{o(sat)}$ is equal to input supply voltage, $\pm V_{CC}$.
- High CMRR (∞).
- High bandwidth, (BW = ∞).

5.5 Op-Amp Specifications —DC Offset Parameters

Even when the input voltage is zero, there will be an output called **offset**. The following can cause this offset:

- Input offset voltage
- Output offset voltage due to input offset current
- Total offset voltage due to input offset voltage and input offset current
- Input bias current

Input Offset Voltage (V_{IO})

The specification sheet for an op-amp indicate an input offset voltage (V_{IO}).

The effect of this input offset voltage on the output can be calculated with:

$$V_{o(offset)} = V_{IO} \times \frac{R_1 + R_f}{R_1}$$

Output Offset Voltage Due to Input Offset Current (I_{IO})

If there is a difference between the dc bias currents for the same applied input, then this also causes an output offset voltage:

- The input offset Current (I_{IO}) is specified in the specifications for the op-amp.
- The effect on the output can be calculated with

$$V_{o(\text{offset due to } I_{IO})} = I_{IO} R_f$$

Total Offset Due to V_{IO} and I_{IO}

Op-amps may have an output offset voltage due to both factors V_{IO} and I_{IO}. The total output offset voltage will be the sum of the effects of both:

$$V_{O(\text{offset})} = V_{O(\text{offset due to } V_{IO})} + V_{O(\text{offset due to } I_{IO})}$$

Input Bias Current (I_{IB})

A parameter that is related to input offset current (I_{IO}) is called **input bias current** (I_{IB})

The separate input bias currents are:

$$I_{IB}^{-} = I_{IB} - \frac{I_{IO}}{2} \qquad I_{IB}^{+} = I_{IB} + \frac{I_{IO}}{2}$$

The total input bias current is the average:

$$I_{IB} = \frac{I_{IB}^{-} + I_{IB}^{+}}{2}$$

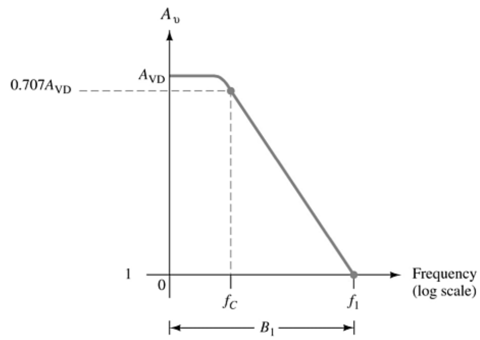
Op-Amp Specifications —Frequency Parameters

An op-amp is a wide-bandwidth amplifier. The following affect the bandwidth of the op-amp:

- Gain
- Slew rate

Gain and Bandwidth

The op-amp's high frequency response is limited by internal circuitry. The plot shown is for an open loop gain (A_{OL}or A_{VD}). This means that the op-amp is operating at the highest possible gain with no feedback resistor.



In the open loop, the op-amp has a narrow bandwidth. The bandwidth widens in closed-loop operation, but the gain is lower.

SEE 2253 OPERATIONAL AMPLIFIERS

Slew Rate (SR)

Is the maximum rate at which an op-amp can change output without distortion.

OR

A limitation of the maximum possible rate of change of the output of an op-amp.

Slew Rate is independent of the closed-loop gain of the op-amp.

$$SR = \frac{\Delta V_o}{\Delta t} \quad V/\mu s$$

The SR rating is given in the specification sheets as V/μs rating.

Example:

An op-amp has SR = 2V/μs. Determine A_{CL} if v_i changes by 0.5V/10μs?.

$$V_O = A_{CL} V_i$$

$$\frac{\Delta V_o}{\Delta t} = A_{CL} \frac{\Delta V_i}{\Delta t}$$

$$\therefore A_{CL} = \frac{\Delta V_o / \Delta t}{\Delta V_i / \Delta t} = \frac{SR}{\Delta V_i / \Delta t} = \frac{2V / \mu s}{0.5V / 10\mu s} = 40$$

This means that for A_{CL} greater than 40 will cause a distortion at the output.

Maximum Signal Frequency

The slew rate determines the highest frequency of the op-amp without distortion.

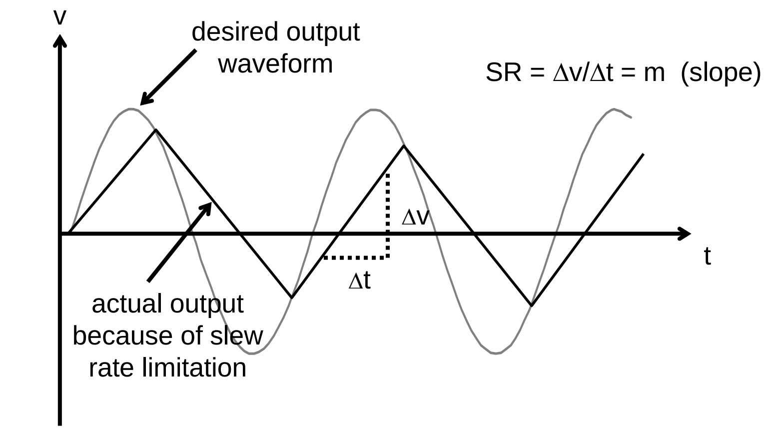
$$f \le \frac{SR}{2\pi V_P}$$

where V_P is the peak voltage

Example:

An op-amp has SR = 0.5V/μs and a supply voltage ±15V. What is the maximum frequency before distortion occur?

$$f \le \frac{SR}{2\pi V_P} \le \frac{0.5V/\mu s}{2\pi(15)} = 5.3\text{kHz}$$



The picture above shows exactly what happens when the slew rate limitations are not met and the output of the operational amplifier is distorted.

19

Absolute Ratings

These are commonly the maximum ratings for the op-amp.

Absolute Maximum Ratings	
Supply voltage	6 22 V
Internal power dissipation	500 mW
Differential input voltage	6 30 V
Input voltage	6 15 V

20

Electrical Characteristics

TABLE 13.2 mA741 Electrical Characteristics: $V_{CC} = \pm 15$ V, $T_A = 25°C$

Characteristic	MIN	TYP	MAX	Unit
V_{IO} Input offset voltage		1	6	mV
I_{IO} Input offset current		20	200	nA
I_{IB} Input bias current		80	500	nA
V_{ICR} Common-mode input voltage range	±12	±13		V
V_{OM} Maximum peak output voltage swing	±12	±14		V
A_{VD} Large-signal differential voltage amplification	20	200		V/mV
r_i Input resistance	0.3	2		MΩ
r_o Output resistance		75		Ω
C_i Input capacitance		1.4		pF
CMRR Common-mode rejection ratio	70	90		dB
I_{CC} Supply current		1.7	2.8	mA
P_D Total power dissipation		50	85	mW

Note these ratings are for specific circuit conditions, and they often include minimum, maximum and typical values.

CMRR

One rating worth mentioning that is unique to op-amps is CMRR or **common-mode rejection ratio**.

Because the op-amp has two inputs that are opposite in phase (inverting input and the non-inverting input) any signal that is common to both inputs will be cancelled.

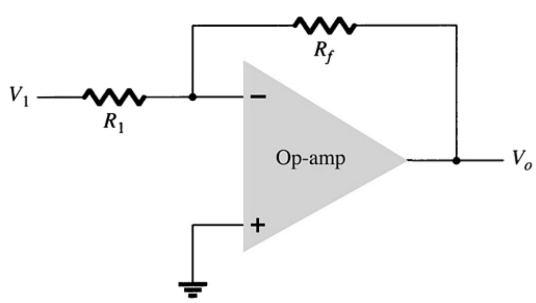
A measure of the ability to cancel out common signals is called CMRR.

5.6 Op-Amp Advantages

- No external element is needed for stability.
- Gain value varies with feedback to one of the inputs.
- AC signal can be amplified without biasing.
- Output nearly zero when input is zero.
- Output can be in phase or 180º out of phase with input.

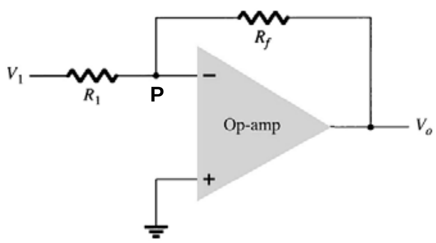
5.7 Op-Amp Linear Applications
- Inverting Amplifier

- The signal input is applied to the **inverting (–) input**.
- The **non-inverting input (+)** is grounded.
- The resistor R_f is the **feedback resistor**.
- It is connected from the output to the negative (inverting) input. This is ***negative feedback***.



Inverting Op-Amp Gain

- Gain can be determined from external resistors: R_f and R_1.



$$V^- = \frac{R_f}{R_1 + R_f} V_1 + \frac{R_1}{R_1 + R_f} V_O$$

$$V^+ = 0$$

$$\therefore V^+ = V^- = 0$$

$$\therefore \frac{R_f}{R_1 + R_f} V_S + \frac{R_1}{R_1 + R_f} V_O = 0$$

$$R_f V_1 = -R_1 V_O$$

$$\therefore A_V = \frac{V_O}{V_1} = -\frac{R_f}{R_1}$$

•The negative sign denotes a 180° phase shift between input and output.

•***Point* P** is known as virtual ground.

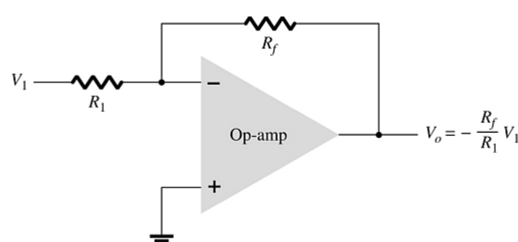
25

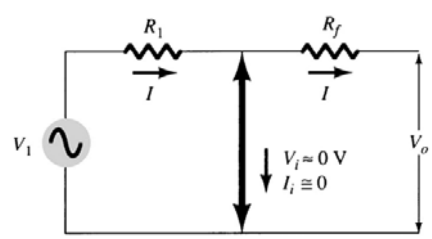
5.8 Virtual Ground And Virtual Short Circuit

An understanding of the concept of ***virtual ground*** provides a better understanding of how an op-amp operates.

Virtual ground refers to one of op-amp input terminals that is virtually connected to ground due to the other input terminal that is physically connected to ground.

The *non-inverting input* pin is at ground. *The inverting input* pin is also at 0V for an AC signal.





26

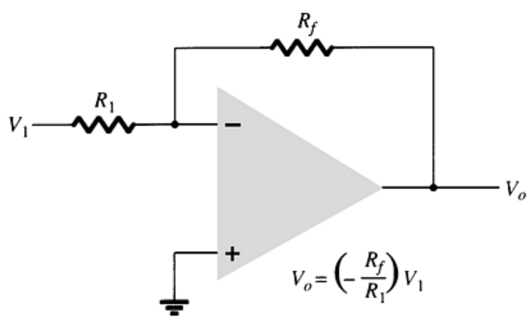
- The op-amp has such high input impedance that even with a high gain there is no current from inverting input pin, therefore there is no voltage from inverting pin to ground—all of the current is through R_f.
- ***Virtual short circuit*** means that whatever voltage that appears at the non-inverting input terminal will automatically appear at the inverting input terminal because of the very large open-loop gain.

5.9 Practical Op-Amp Circuits

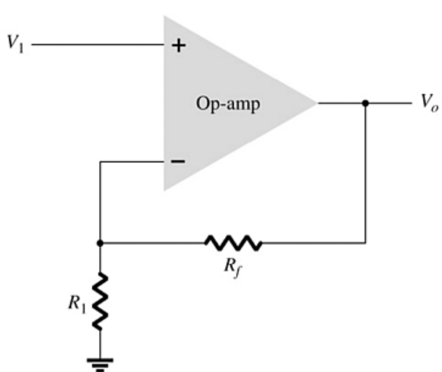
- These op-amp circuits are commonly used:
  - Inverting amplifier
  - Non-inverting amplifier
  - Unity follower
  - Summing amplifier
  - Integrator
  - Differentiator

Inverting Amplifier

- The output voltage is the gain times the input voltage.
- What makes an op-amp different from other amplifiers is its impedance characteristics and gain calculations that depend solely on external resistors.



Non-Inverting Amplifier



$$V^- = \frac{R_1}{R_1 + R_f} V_O$$

$$V^+ = V_1$$

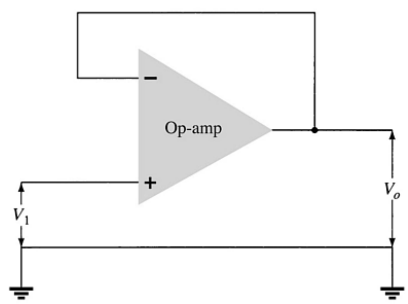
$$V^- = V^+$$

$$\frac{R_1}{R_1 + R_f} V_O = V_1$$

$$\therefore A_V = \frac{V_O}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

Unity Follower

- Any amplifier with no gain or loss is called a unity gain amplifier.
- The advantages of using a unity gain amplifier:
  - Very high input impedance
  - Very low output impedance



$$V^- = V_o$$

$$V^+ = V_1$$

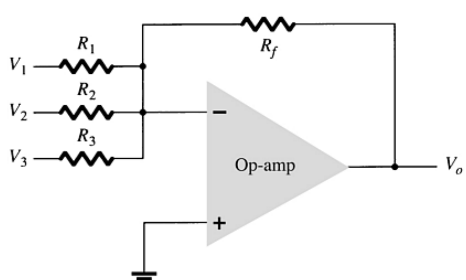
$$\therefore V^- = V^+$$

$$V_O = V_1$$

$$\therefore \frac{V_O}{V_1} = 1$$

Inverting Summing Amplifier

- The output is the sum of individual signals times the gain:



$$I_1 = \frac{V_1 - V^-}{R_1} = \frac{V_1 - 0}{R_1} = \frac{V_1}{R_1}$$

$$I_2 = \frac{V_2 - V^-}{R_2} = \frac{V_2 - 0}{R_2} = \frac{V_2}{R_2}$$

$$I_3 = \frac{V_3 - V^-}{R_3} = \frac{V_3 - 0}{R_3} = \frac{V_3}{R_3}$$

$$V^- = V^+ = 0$$

$$I_1 + I_2 + I_3 = I_f$$

$$I_f = \frac{V^- - V_O}{R_f} = \frac{0 - V_O}{R_f}$$

$$\therefore \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_O}{R_f}$$

$$\therefore V_O = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

If $R_1 = R_2 = R_3 = R_f$

$$V_O = -(V_1 + V_2 + V_3)$$

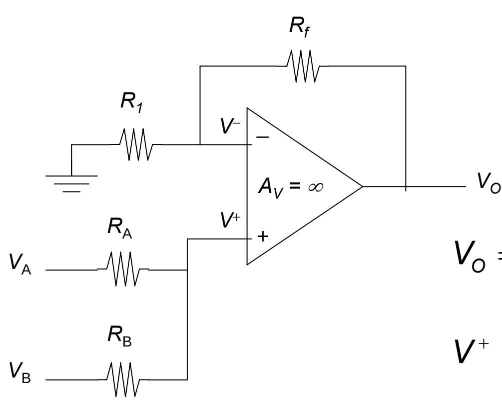
For N numbers of input:

$$V_O = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + ... + \frac{R_f}{R_N}V_N\right)$$

And if $R_1 = R_2 = R_3 = R_f = \ldots\ldots = R_N$

$$V_O = -(V_1 + V_2 + V_3 + ... + V_N)$$

Non-Inverting Summing Amplifier

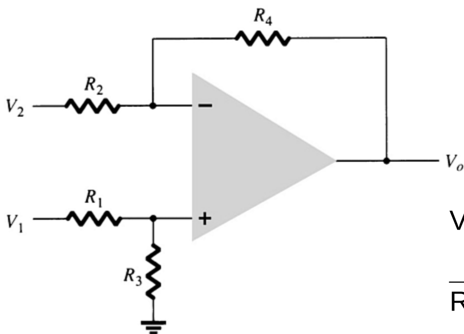


$$V_O = \left(1 + \frac{R_f}{R_I}\right)V^+$$

$$V^+ = \frac{R_B}{R_B + R_A}V_A + \frac{R_A}{R_A + R_B}V_B$$

$$V_O = \left(1 + \frac{R_f}{R_I}\right)\left[\frac{R_B}{R_B + R_A}V_A + \frac{R_A}{R_A + R_B}V_B\right]$$

Subtracting Amplifier



$$V^- = \frac{R_2}{R_2+R_4}V_O + \frac{R_4}{R_2+R_4}V_2$$

$$V^+ = \frac{R_3}{R_1+R_3}V_1$$

$$V^- = V^+$$

$$\frac{R_2}{R_2+R_4}V_O + \frac{R_4}{R_2+R_4}V_2 = \frac{R_3}{R_1+R_3}V_1$$

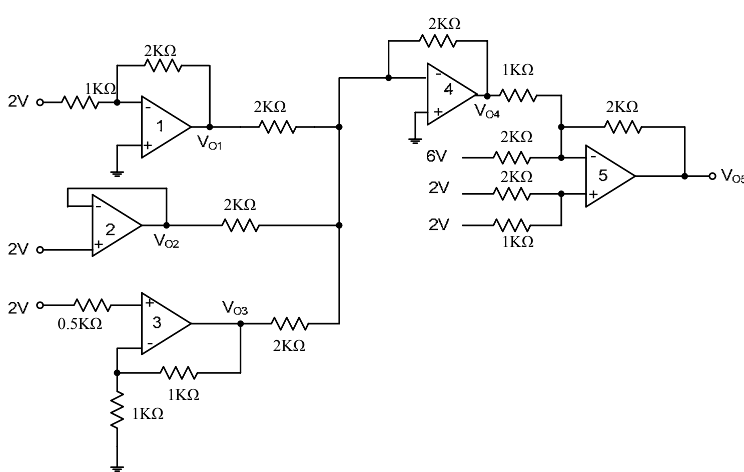
$$V_O = \left(1+\frac{R_4}{R_2}\right)\left[\frac{R_3}{R_1+R_3}V_1 - \frac{R_4}{R_2+R_4}V_2\right]$$

If $R_1 = R_2 = R_3 = R_4$

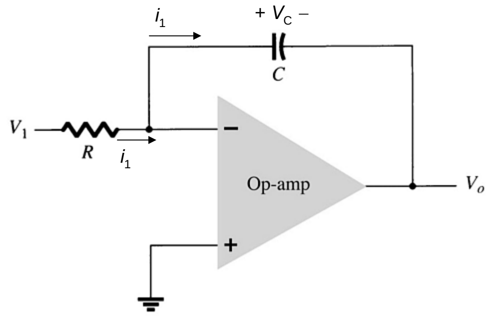
$V_O = V_1 - V_2$

Exercise:

- Name the function of each op-amp.
- Determine v_{o1}, v_{o2}, v_{o3}, v_{o4} and v_{o5}.



Integrator



$$i_1 = \frac{V_1 - V^-}{R} \equiv \frac{V_1}{R}$$

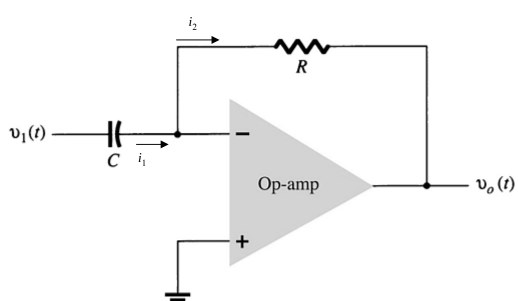
$$\frac{dV_C}{dt} = \frac{i_1}{C}$$

$$\frac{dV_o}{dt} = -\frac{dV_C}{dt}$$

$$\frac{dV_o}{dt} = -\frac{i_1}{C} = -\frac{V_1}{RC}$$

$$\therefore V_o(t) = -\frac{1}{CR}\int V_1 dt$$

Differentiator



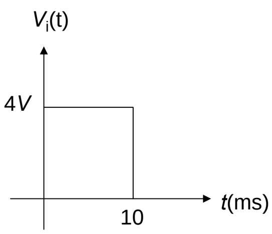
$$i_1 = C\frac{dV_1}{dt}$$

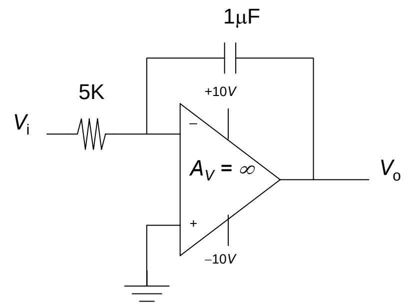
$$V_o = -i_2 R$$

$$i_1 = i_2$$

$$\therefore V_o = -i_1 R = -RC\frac{dV_1}{dt}$$

Example : Plot $V_O(t)$ and $V_C(t)$ versus t.





If capacitor initially uncharge,

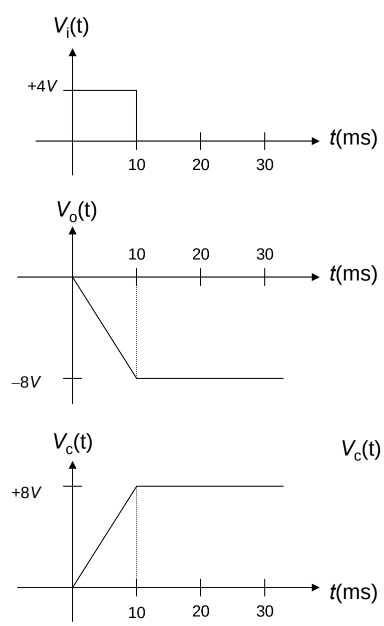
V_{out} = 0 at t = 0.

$$V_o(t) = -\frac{1}{CR}\int_0^t V_i dt$$

$$V_O(t) = -\frac{1}{(5\times10^3)(1\times10^{-6})}\int_0^t 4dt$$

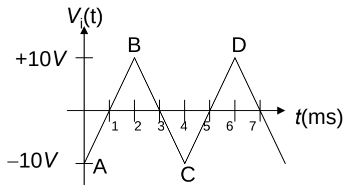
$$= -0.2(4t-0) = -0.8t$$

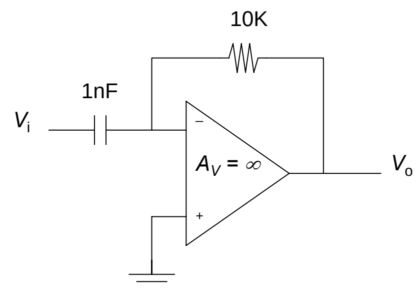
$$V_o\Big|_{t=10ms} = (-0.8)(10) = -8V$$



$V_c(t) = -V_o(t)$

Example : Determine $V_o(t)$.





From A - B

$$\frac{dV_i}{dt} = \frac{10-(-10)}{2ms} = 10^4\ V/s$$

$$V_O = -RC\frac{dV_i}{dt}$$

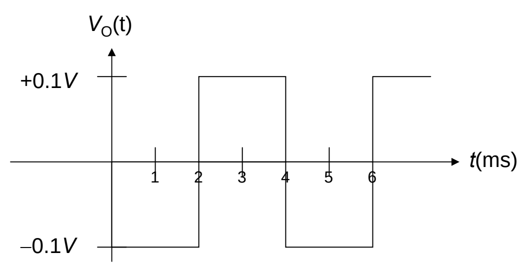
$$= -(10^4)(0.001\mu F)(10^4\ V/s) = -0.1V$$

From B - C

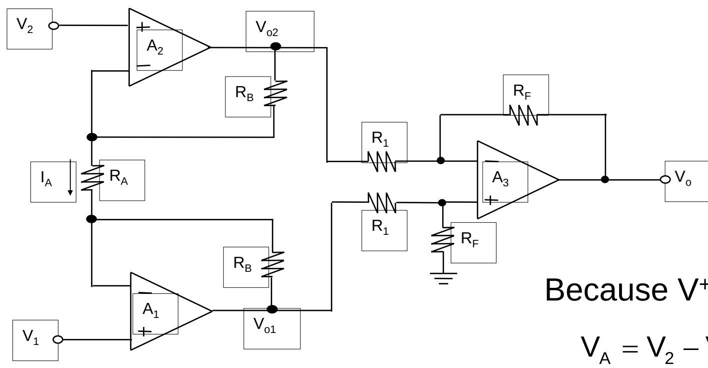
$$\frac{dV_i}{dt} = \frac{(-10)-10}{2ms} = -10^4\ V/s$$

$$V_O = -RC\frac{dV_i}{dt}$$

$$= -(10^4)(0.001\mu F)(-10^4\ V/s) = +0.1V$$



Instrumentation Amplifier



Because $V^+ = V^-$,

$$V_A = V_2 - V_1$$

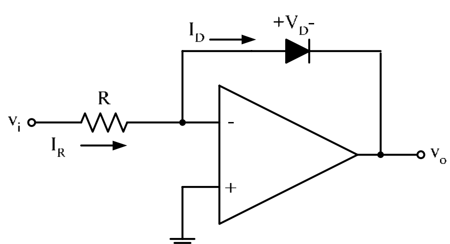
$$I_A = \frac{V_A}{R_A} = \frac{V_2 - V_1}{R_A}$$

$$V_{o2} - V_{o1} = I_A\left(R_B + R_A + R_B\right)$$

$$= \frac{V_2 - V_1}{R_A}\left(R_A + 2R_B\right)$$

$$V_o = \frac{R_F}{R_1}\left(1 + \frac{2R_B}{R_A}\right)\left(V_1 - V_2\right)$$

Log Amplifier



$$I_D = I_S(e^{\frac{V_D}{V_T}} - 1)$$

$$\approx I_S e^{\frac{V_D}{V_T}}$$

$$I_R = \frac{V_i}{R}, V_O = -V_D$$

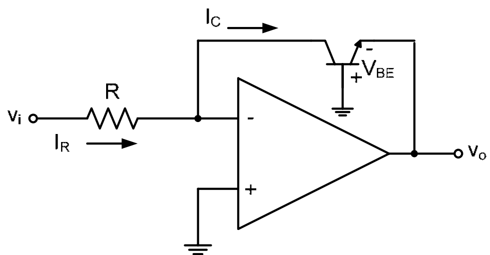
$$I_R = I_D$$

$$\frac{V_i}{R} = I_S e^{-\frac{V_D}{V_T}}$$

$$\ln(\frac{V_i}{I_S R}) = -\frac{V_O}{V_T}$$

$$V_O = -V_T \ln(\frac{V_i}{I_S R})$$

I_S is a function of temperature and its value defer between diodes. In order to overcome this problem, replace the diode with a transistor.

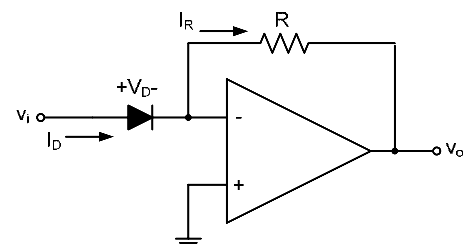


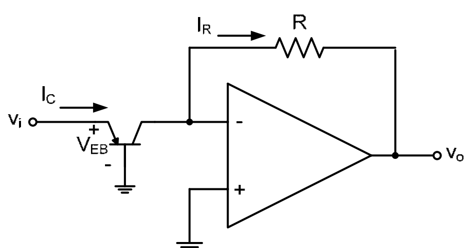
$$I_C = I_O(e^{\frac{V_{BE}}{V_T}} - 1)$$

$$V_{BE} = -V_O$$

$$\therefore V_O = -V_T \ln(\frac{V_i}{I_O R})$$

Antilog Amplifier





$$I_D = I_R$$

$$I_S(e^{\frac{V_D}{V_T}} - 1) = -\frac{V_O}{R}$$

$$V_D = V_i$$

$$I_S e^{\frac{V_i}{V_T}} = -\frac{V_O}{R}$$

$$V_O = -I_S R(e^{\frac{V_i}{V_T}})$$

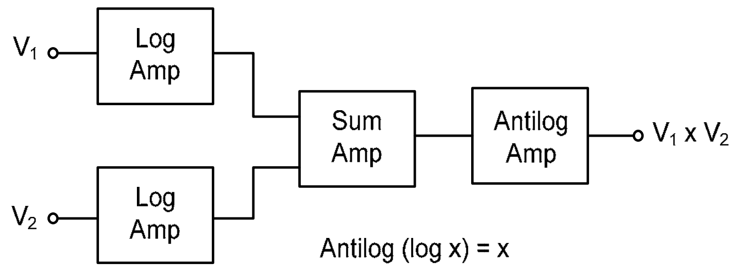
$$V_i = V_{EB}$$

$$V_O = -I_O R(e^{\frac{V_i}{V_T}})$$

Log And Antilog Amplifiers Application

Example : $V_1 \times V_2$

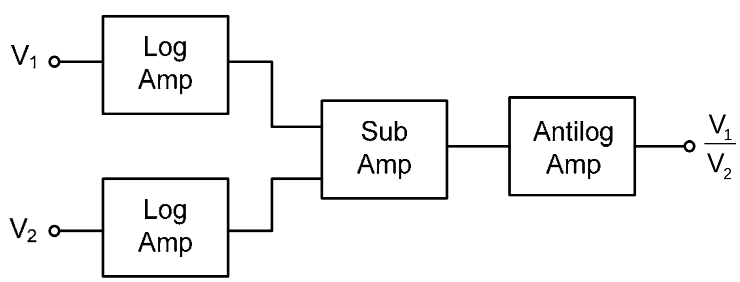
$\text{Log}(V_1 \times V_2) = \log V_1 + \log V_2$



Antilog (log x) = x

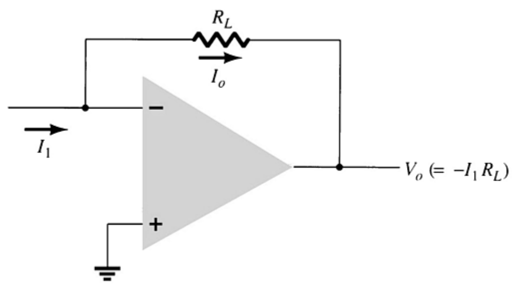
Example : $\frac{V_1}{V_2}$

$\text{Log} \left(\frac{V_1}{V_2}\right) = \log V_1 - \log V_2$



Current to Voltage Converter

- This is simply another way of applying the op-amp operation.
- Whether the input is a current determined by V_{in}/R_1 or as I_1:
- For example output from photodiode or photodetector.



$$V_o = \frac{-R_f}{R_1}$$

$$or \quad V_o = -I_1R_L$$

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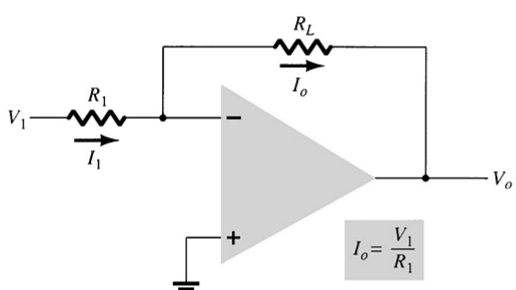
Voltage to Current Converter

- This is opposite to current to voltage converter.
- For example to drive magnetic coil.

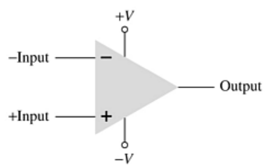


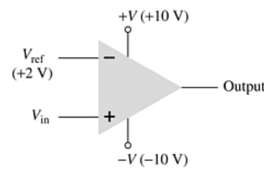
The output current is:

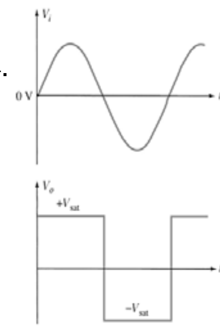
$$I_o = \frac{V_1}{R_1} = kV_1$$

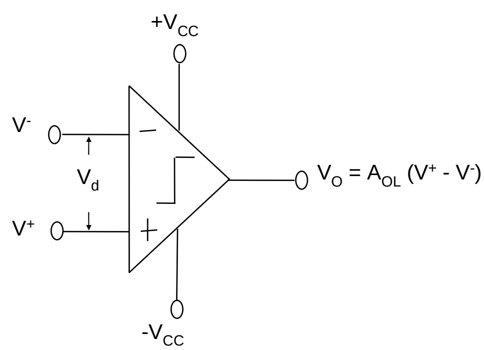
5.10 Op-Amp Non-Linear Applications
- Comparator Circuit

- Comparators have two inputs and one output.
- The operation is a basic comparison.
- The output swings between its maximum and minimum voltage, depending upon whether one input (V_{in}) is greater or less than the other (V_{ref}).
- The output is always a square wave where:
  - The maximum high output voltage is $+V_{SAT}$.
  - The minimum low output voltage is $–V_{SAT}$.

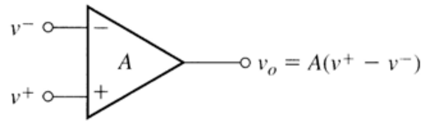




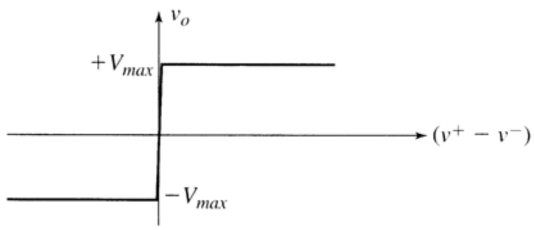




- Since $A_O = \infty$, V_O will become maximum i.e either at $+V_{Osat}$ or $-V_{Osat}$.
- If input $V^+ > V^-$, then $V_O = +V_{Osat}$.
- If input $V^- > V^+$, then $V_O = -V_{Osat}$.

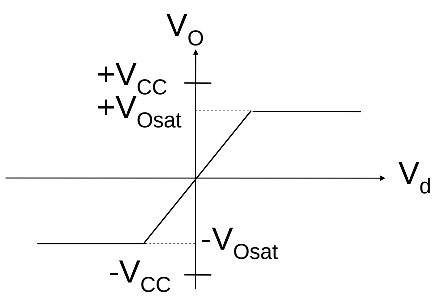


(a) Open-loop operation as a voltage comparator



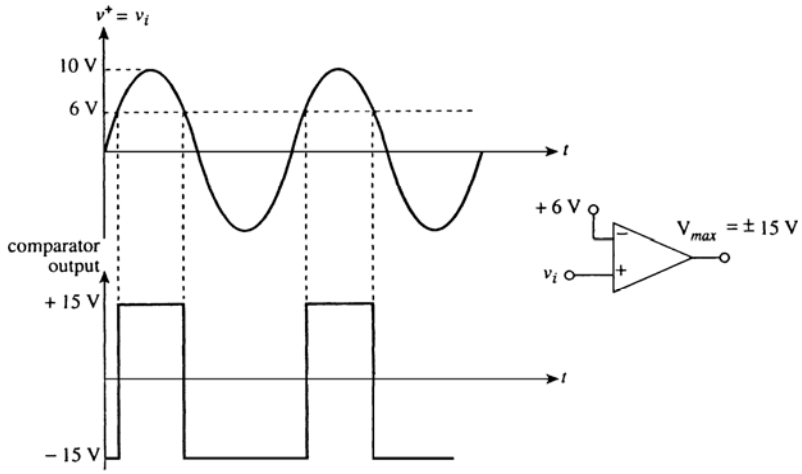
(b) Transfer characteristic of the voltage comparator. When $v^+ > v^-$, the output is at its maximum positive limit, and when $v^+ < v^-$, the output switches to its maximum negative limit.

- Since $A_O = \infty$, V_O will become maximum i.e either at $+V_{Osat}$ or $-V_{Osat}$.
- If input $V^+ > V^-$, then $V_O = +V_{Osat}$.
- If input $V^- > V^+$, then $V_O = -V_{Osat}$.



Practical Transfer Characteristics

- For ideal Op-Amp, $\pm V_{Osat} = \pm V_{CC}$.
- But in practice $\pm V_{Osat}$ usually 1 or 2 volt less than $\pm V_{CC}$.
- Only one input reference will be connected to either inputs of op-amp while the other will be the required voltage that need to compare.

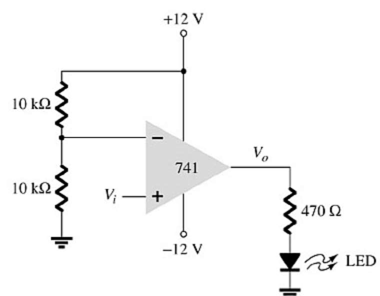


The comparator output switches to $+V_{osat} = +V_{max}$ when $v^+ - v^- > 0$ V, which corresponds to the time points where v^+ rises through +6 V. The output remains high as long as $v^+ - v^- > 0$, or $v^+ > 6$ V.

Non-Inverting Op-Amp Comparator

For a non-inverting op-amp comparator:

- The output goes to $+V_{SAT}$ when input V_i is greater than the reference voltage.
- The output goes to $–V_{SAT}$ when input V_i is less than the reference voltage.



Example:

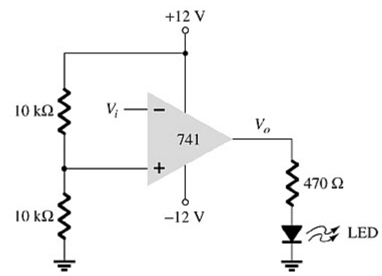
- V_{ref} in this circuit is +6V (taken from the voltage divider)
- $+V_{SAT}$ = +V, or +12V
- $-V_{SAT}$ = -V or –12V

When V_i is greater than +6V the output swings to +12V and the LED goes on. When V_i is less than +6V the output is at –12V and the LED goes off.

Inverting Op-Amp Comparator

For an inverting op-amp comparator:

- The output goes to $-V_{SAT}$ when input V_i is greater than the reference voltage.
- The output goes to $+V_{SAT}$ when input V_i is less than the reference voltage.



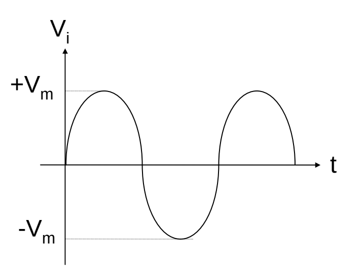
Example:

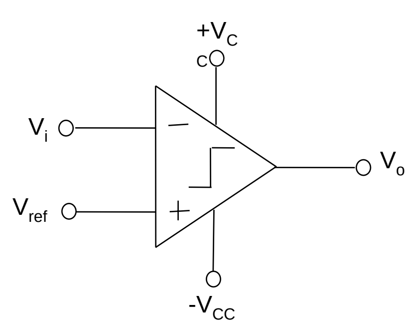
- V_{ref} in this circuit is +6V (taken from the voltage divider)
- $+V_{SAT}$ = +V, or +12V
- $-V_{SAT}$ = -V or –12V

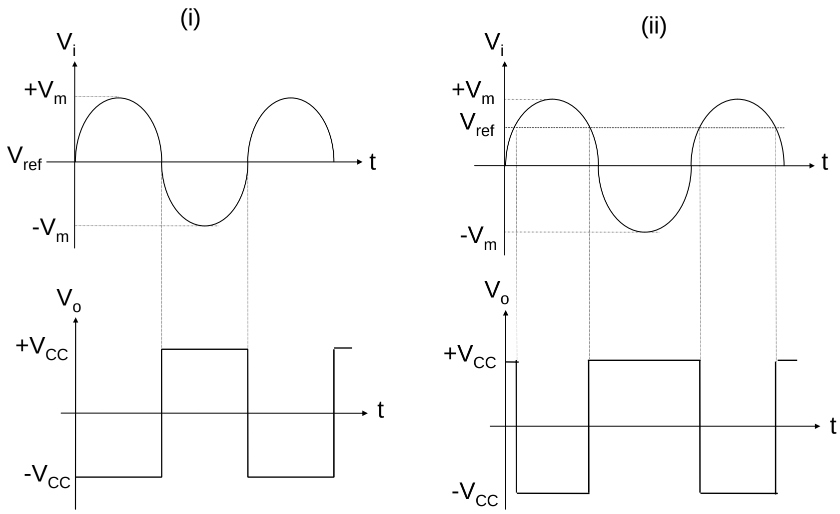
When V_i is greater than +6V the output swings to -12V and the LED goes off. When V_i is less than +6V the output is at +12V and the LED goes on.

Example:

- ☐ Draw the output waveform, v_o for the given sinusoidal input as shown if (i) V_{ref} = 0 and (ii) $V_{ref} = V_m/2$
- ☐ Assume $\pm V_{Osat} = \pm V_{CC}$.







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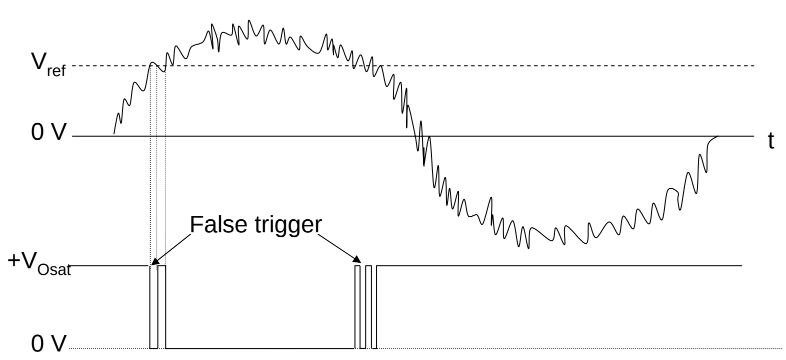
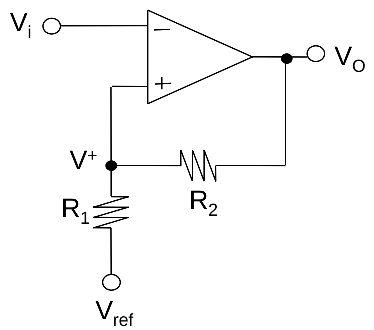
- Comparator has problem with noise.
- If input voltage, V_i is superimposed with noise, this will cause a false triggering.
- One way to overcome this is by using Schmitt Trigger.



Schmitt Trigger

- Comparator with positive feedback will form a Schmitt Trigger.



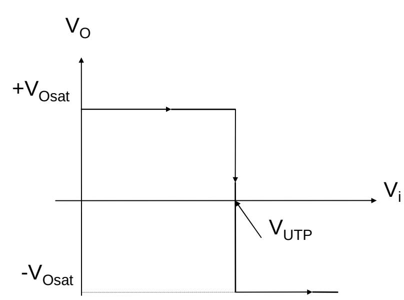
$$V^+ = \frac{V_{ref} R_2}{R_1 + R_2} + \frac{V_O R_1}{R_1 + R_2}$$

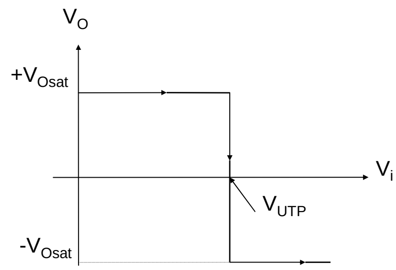
When $V_i < V^+$, then $V_O = + V_{Osat}$

$$V^+ = \frac{V_{ref} R_2}{R_1 + R_2} + \frac{V_{Osat} R_1}{R_1 + R_2} = V_{UTP}$$

$\mathbf{V_{UTP}}$ is known as Upper Trigger voltage

- If v_i increases, output voltage $v_O = +V_{Osat}$ and stays at this value until $v_i = V^+ = V_{UTP}$.
- Beyond this point, if v_i keep increasing, then v_i is larger than V_{UTP}.
- v_O will change to $-V_{Osat}$.
- This is shown in the diagram below:

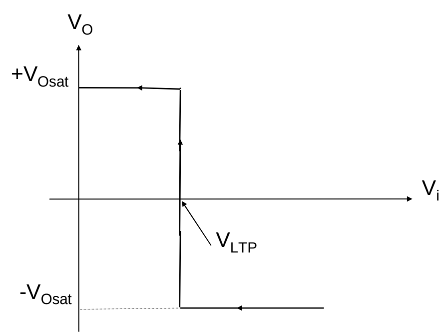




- When $v_i > V_{UTP}$, output $v_O = -V_{Osat}$, then output at V^+ terminal:

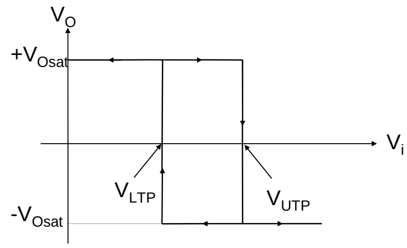
$$V^+ = \frac{V_{ref} R_2}{R_1 + R_2} - \frac{V_{Osat} R_1}{R_1 + R_2} = V_{LTP}$$

- **V_{LTP}** is known as Lower Trigger voltage



- $v_O = -V_{Osat}$ and stays as long as $v_i > V_{LTP}$.
- But if v_i is reduce to $v_i = V_{LTP}$ and keep reducing until $v_i < V_{LTP}$, then v_O will change to $+V_{Osat}$, and stay at that value as long as $v_i < V_{LTP}$.

- Diagram below shows the transfer characteristic for Schmitt Trigger.



- This shows that when $v_i < V_{UTP}$ then $v_O = +V_{Osat}$.
- If $v_i > V_{UTP}$, output will change to $v_O = -V_{Osat}$.
- At this point, compare v_i with V_{LTP}.
- If $v_i > V_{LTP}$ then $v_O = -V_{Osat}$ and if $v_i < V_{LTP}$ then $v_O = +V_{Osat}$
- In this situation, there are two references i.e V_{UTP} and V_{LTP} .

Hysteresis

- Is a property that means a device behaves differently when its input is increasing from the way it behaves when its input is decreasing.
- In other words, the output will switch when the input increases to one level but will not switch back until the input falls below a different level.
- It is a desirable characteristic because it prevents the comparator from switching back and forth in response to random noise fluctuations in the input.
- Quantitatively, the hysteresis voltage (V_H) of a Schmitt trigger is defined as the difference between the input trigger levels.

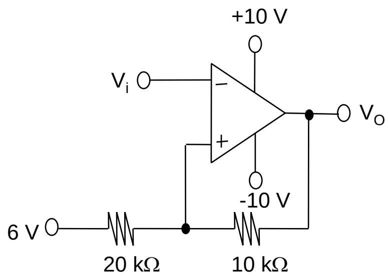
$$V_H = V_{UTP} - V_{LTP}$$

$$= \left(\frac{R_1}{R_1 + R_2}\right)(+V_{CC}) - \left(\frac{R_1}{R_1 + R_2}\right)(-V_{CC})$$

$$\boxed{V_H = \left(\frac{R_1}{R_1 + R_2}\right)\left(+V_{CC} - (-V_{CC})\right)}$$

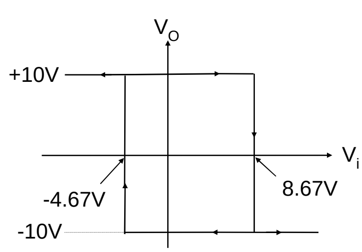
Example:

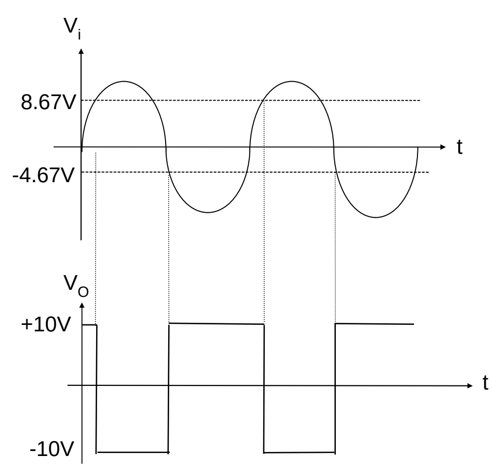
- If v_i = 10 sin ωt Volt, determine V_{UTP} and V_{LTP}. Sketch the output waveform and the transfer characteristic.



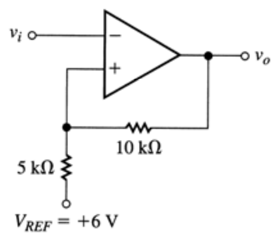
$$V_{UTP} = \frac{6(10k)}{10k+20k} + \frac{10(20k)}{10k+20k} = 8.67\,V$$

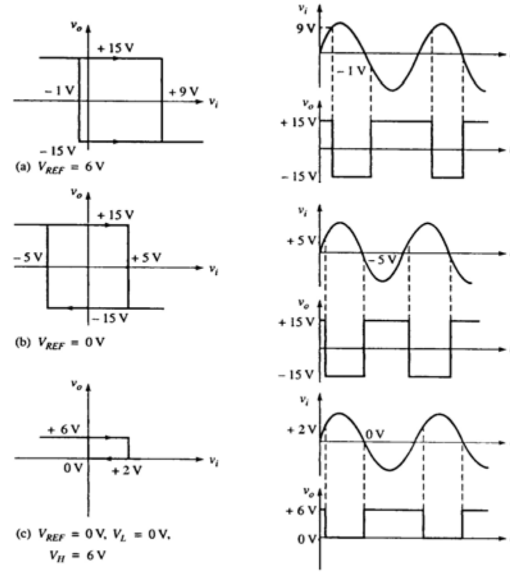
$$V_{LTP} = \frac{6(10k)}{10k+20k} - \frac{10(20k)}{10k+20k} = -4.67\,V$$





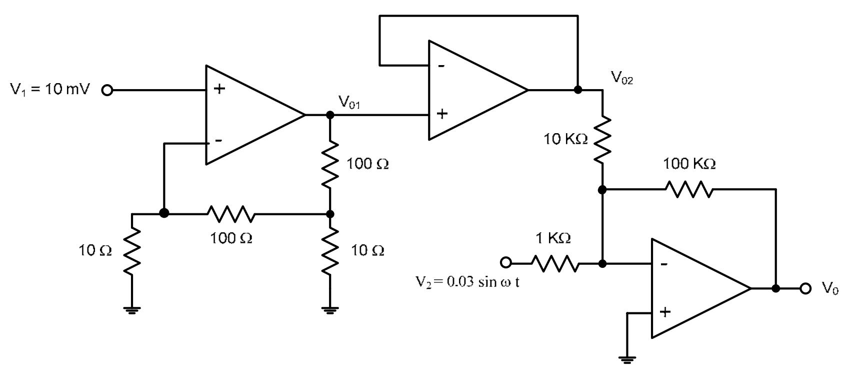
Example:





Exercise:

- ☐ Determine v_{o1} and v_{o2}.



Exercise:

- Draw the output waveform of v_{o1} and v_{o2}.