CHAPTER 5
OPERATIONAL AMPLIFIER FUNDAMENTALS

1

INTRODUCTION

- The term operational amplifier, or op-amp, was originally applied to high-performance **DC differential amplifiers** that used vacuum tubes.
- These amplifiers formed the basis of the analog computer, which was capable of solving differential equations.
- Early operational amplifiers (op-amps) were used primarily to perform **mathematical operations** such as addition, subtraction, integration, and differentiation, hence the term operational.

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INTRODUCTION

- In the present day the term operational amplifier is used to refer to **very high gain** DC **coupled differential amplifiers** with single-ended outputs.
- Most of these amplifiers appear in **integrated circuit** form. Today's op-amps are linear integrated circuits that use relatively low supply voltages.
- Except for the reduction in size and cost, the function of today's op-amp has changed very little from the original version.
- The first series of commercially available op-amps was uA702, introduced by Fairchild Semiconductor (later bought over by National Semiconductor) in 1963.
- In 1965, National Semiconductor had introduced the LM101, while Fairchild unveiled the ever-popular **uA741** in 1967.
- The 741 series op-amp remains until today.

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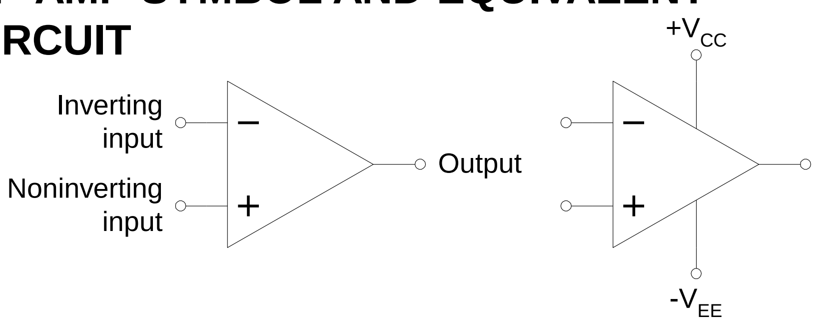
OP-AMP SYMBOL AND EQUIVALENT CIRCUIT



(a) Basic symbol (b) Symbol with dc supply

Figure: Symbol for op-amp

- The circuit symbol for the op-amp is a triangle with two inputs and one output.
- The minus (-) and plus (+) at the input specifies the inverting and non-inverting inputs respectively.
- The former will produce an inverted output, while the latter producing an output of the same polarity as that of the applied input.

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OP-AMP SYMBOL AND EQUIVALENT CIRCUIT

- The op-amp, being an active element, must also be powered by a voltage supply.

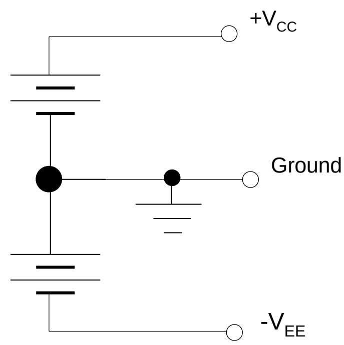

Figure: Dual, or split voltage power supply used with op-amps

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OP-AMP SYMBOL AND EQUIVALENT CIRCUIT

The equivalent circuit of an op-amp:

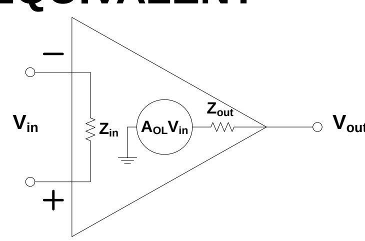

Figure: Approximate equivalent circuit of a non-ideal op-amp

- The op-amp amplifies the voltage difference between non-inverting and inverting input. It senses the difference between the two inputs, and produces an output which forms the product of both the difference v_D, and the gain A_{OL}.

$$\mathbf{v_O = A_{OL}(V_+ - V_-) = A_{OL}v_D} \qquad \textbf{[1]}$$

where
A_{OL} = open-loop voltage gain
Z_{out} = output impedance
Z_{in} = input impedance

- A_{OL} is called the open-loop voltage gain because it is the gain of the op-amp without any external feedback from the output to the input.

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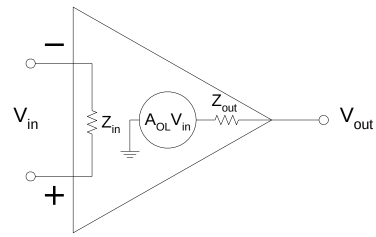
IDEAL OPERATIONAL AMPLIFIER

The ideal op-amp would be expected to have the following **important characteristics:**



- Infinite open-loop voltage gain, $A_{OL} \to \infty$.
- Infinite input impedance, $Z_{in} \to \infty$.
- Zero output impedance, $Z_o \to 0$.
- Infinite bandwidth, A_{OL} remains unchanged from DC to very high frequency.
- Zero offset voltage, zero input ($V_+ = V_-$) produces zero output.
- Infinite common-mode rejection only amplifies voltage difference between non-inverting and inverting input.

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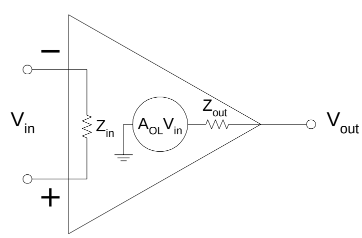
5.1 IDEAL OPERATIONAL AMPLIFIER



The ideal characteristics in turn form the basis for two fundamental rules of an ideal op-amp:

1. no current flows into either of the input terminal
2. there is no voltage difference between the two input terminals

While in practice, no commercial op-amp can meet these 6 ideal characteristics, it is still possible to achieve high-performance circuits despite this fact.

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5.2 IDEAL INVERTING AMPLIFIER

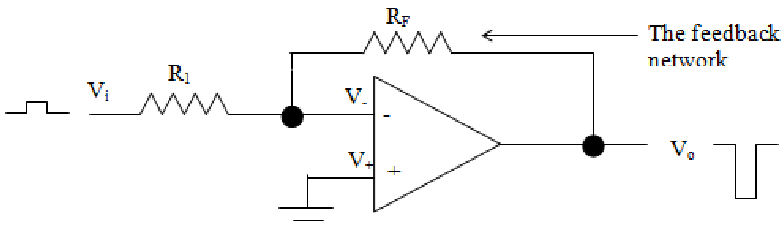

Figure: Ideal inverting amplifier.

- The schematic of an inverting amplifier using op-amp with negative feedback is shown in Fig above.
- The feedback network consists of a single resistor R_F while R_1 is usually known as the input resistor.
- A small signal at the input will be amplified, and its polarity inverted, hence the name inverting amplifier.

IDEAL INVERTING AMPLIFIER (ANALYSIS)

- Assuming ideal op-amp, the input impedance for inverting input will be infinite.
- There will be no current flowing into the inverting input (V_-). Applying Kirchhoff Current Law (KCL) at the inverting input:

$$I_1 = I_F \Rightarrow \frac{V_o - V_-}{R_F} = \frac{V_- - V_i}{R_1}$$

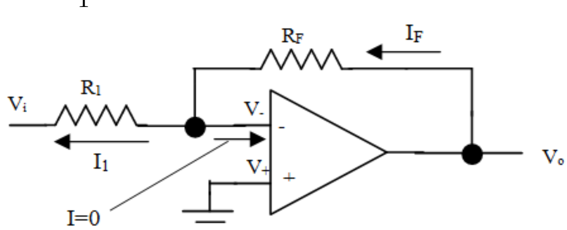

Figure: Current flow convention

IDEAL INVERTING AMPLIFIER (ANALYSIS)

$$I_1 = I_F \Rightarrow \frac{V_o - V_-}{R_F} = \frac{V_- - V_i}{R_1}$$

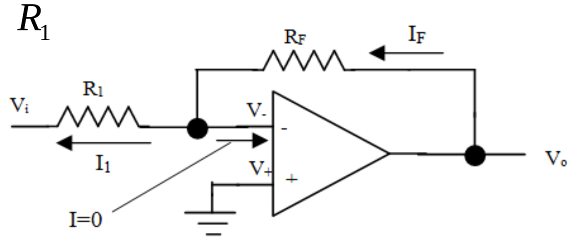

Figure: Current flow convention

- Since V_+ is at ground potential, voltage V_- must also be approximately zero volts. This is what we term as ‘virtual ground’, which essentially means that the negative terminal is at zero volts, but it does not provide a current path to ground i.e. it is not directly connected to ground potential.

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IDEAL INVERTING AMPLIFIER (ANALYSIS)

$$I_1 = I_F \Rightarrow \frac{V_o - V_-}{R_F} = \frac{V_- - V_i}{R_1}$$

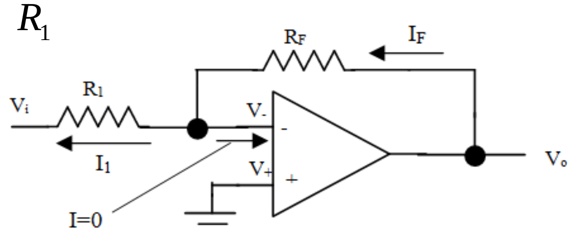

Figure: Current flow convention

Since $V_- = 0$ (virtual ground),

$$\frac{V_o}{R_F} = -\frac{V_i}{R_1}$$

And we have the closed-loop gain

$$A_{CL} = \frac{V_o}{V_i} = -\frac{R_F}{R_1} \qquad [2]$$

Note the negative in Eqn. (2) which account for the reversal of polarity of the output signal.

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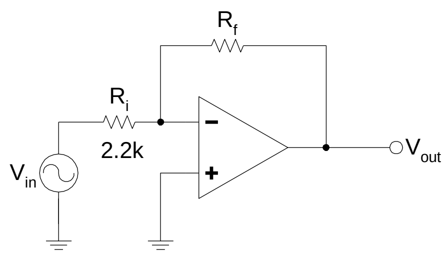
IDEAL INVERTING AMPLIFIER (ANALYSIS)

Example

Given the op-amp configuration in Fig. below, determine the value of R_f required to produce a closed loop voltage gain of –100.



Solution

Knowing that R_i = 2.2kΩ and A_{CL} = -100

$$A_{CL} = -\frac{R_f}{R_i} \qquad R_f = -A_{CL} R_i = -(-100)(2.2k) = 220k\Omega$$

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5.3 IDEAL NON-INVERTING AMPLIFIER

- As opposed to the inverting amplifier, the non-inverting amplifier will amplify a small input signal with no polarity reversal at the output.

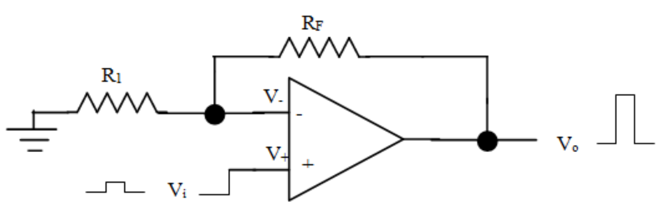

Figure: Ideal non-inverting amplifier

- Again, assuming ideal op-amp, the input impedance for inverting input will be infinite.
- There will be no current flowing into the inverting input. Using the current convention and applying KCL at the inverting input:

$$I_1 = I_F \Rightarrow \frac{V_o - V_-}{R_F} = \frac{V_-}{R_1}$$

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IDEAL NON-INVERTING AMPLIFIER

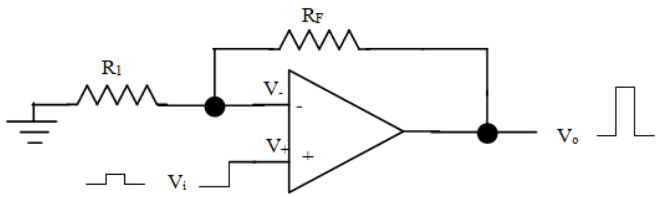

Figure: Ideal non-inverting amplifier

Since $V_- = V_+ = V_i$,

$$\frac{V_o - V_i}{R_F} = \frac{V_i}{R_1}$$

And we have

$$A_{CL} = \frac{V_o}{V_i} = \left(\frac{R_F}{R_1} + 1\right) \qquad [3]$$

Note: with ideal op-amp there is no restriction on the values of R_F and R_1 because closed loop gain A_{CL} is only dependent on the ratio of R_F and R_1. However there are several practical considerations that should be kept in mind when we actually build the circuit using real op-amps. More will be discussed on this later.

5.4 IDEAL VOLTAGE FOLLOWER

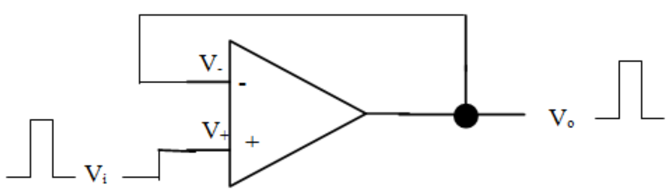

Figure: Ideal voltage follower

- From Eqn. (3), when R_F goes to zero and R_1 approaches infinity, the closed loop gain A_{CL} becomes one or unity.
- In this case the output voltage actually follows the input voltage, hence the name voltage follower.

The reader might ask what is the purpose of having an amplifier with a voltage gain of one?

IDEAL VOLTAGE FOLLOWER

- In many instances, the voltage follower is useful as a buffer.
- The input impedance of the voltage follower is essentially infinite while the output impedance is zero. As an example, consider the case below.

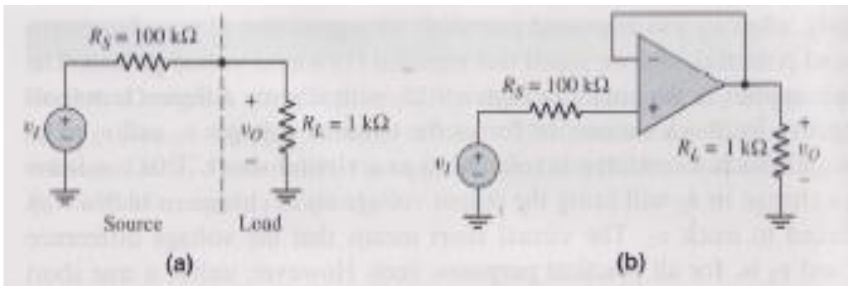

Figure: (a) source with a 100kΩ output resistance driving a 1kΩ load, and (b) source with a 100kΩ output resistance, voltage follower, and 1kΩ load

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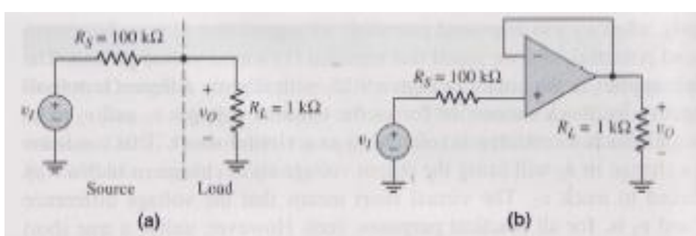
IDEAL VOLTAGE FOLLOWER



- In (a), the ratio of output voltage to input voltage is:

$$\frac{v_o}{v_i} = \frac{R_L}{R_L + R_S} = \frac{1}{1+100} \cong 0.01$$

There is severe loading effect, whereby the output signal undergoes high attenuation.

- In (b) however, $\frac{v_o}{v_i} \cong 1$

due to the presence of the buffer, hence the loading effect is eliminated.

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IDEAL SUMMING AMPLIFIER

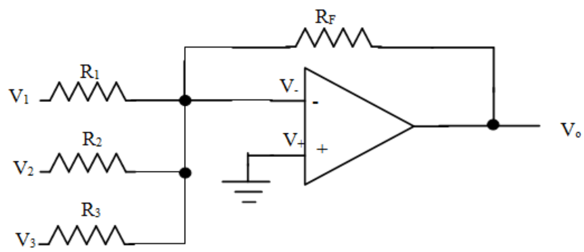

Figure : Ideal inverting summing amplifier

- The output of the summing amplifier is proportional to the algebraic sum of its separate inputs.
- It is frequently called a signal mixer as it is used to combine audio signal from several microphones, guitars, tape recorders, etc., to provide a single output.
- There are two types of summing amplifiers, the inverting and non-inverting.
- We will consider the inverting summing amplifier first.

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5.5 IDEAL SUMMING AMPLIFIER

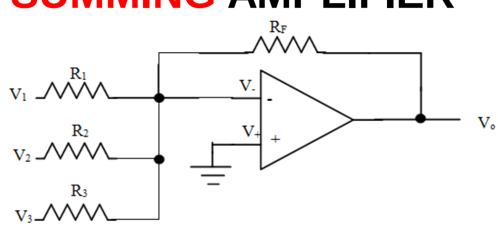

Figure : Ideal inverting summing amplifier

Similar to the analysis of the inverting amplifier, by applying KCL at the inverting input of the op-amp, we obtain:

$$\frac{V_o - V_-}{R_F} = \frac{V_- - V_1}{R_1} + \frac{V_- - V_2}{R_2} + \frac{V_- - V_3}{R_3} \qquad [4]$$

Taking V_- as virtual ground,

$$V_o = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right) \qquad [5]$$

In the special case when $R_1 = R_2 = R_3 = R_F$,

$$V_o = -(V_1 + V_2 + V_3) \qquad [6]$$

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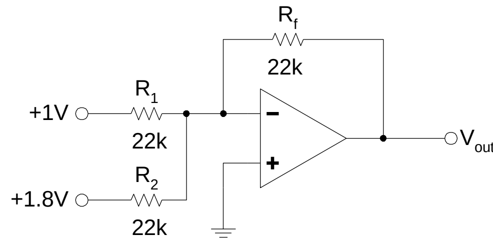
Example

Refer to Fig. below. Determine the following:

(a)V_{R1} and V_{R2}

(b)Current through R_f

(c)V_{out}



Solution

(a) V_{R1} = 1V V_{R2} = 1.8V

(b) $I_{R1} = \dfrac{1}{22k} = 45.5\mu A \quad I_{R2} = \dfrac{1.8}{22k} = 81.8\mu A$

$$I_f = I_{R1} + I_{R2} = 45.5\mu + 81.8\mu = 127\,\mu A$$

(c) $V_{out} = -I_f R_f = -(127\,\mu)(22k) = -2.80V$

or $V_{out} = -(V_1 + V_2) = -(1 + 1.8) = -2.80V$

- In addition to the inverting summing amplifier, it is possible to have a non-inverting summing amplifier, as shown by the schematic in Fig. below.

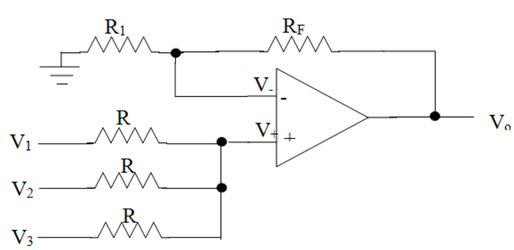


Figure: Ideal non-inverting summing amplifier

- Derivation of the expression for the output voltage will be left to the reader as an exercise. Superposition theorem is needed to find the total voltage for V_+.
- The expression for V_o is given as:

$$V_o = \frac{1}{N}(V_1 + V_2 + \Lambda + V_N)\left(\frac{R_F}{R_1} + 1\right) \qquad [7]$$

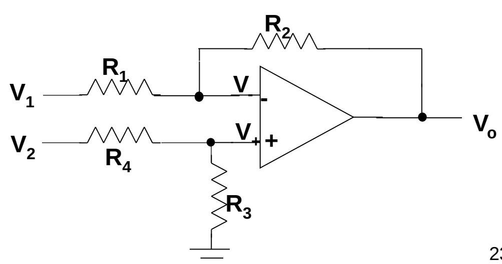
5.6 IDEAL DIFFERENCE AMPLIFIER

- a difference or differential amplifier has input voltages that [8] are applied simultaneously to both the inverting and non-inverting inputs. Its output voltage V_o is proportional to the voltage difference ($V_2 – V_1$). An ideal difference amplifier only amplifies the difference between two signals.

Applying KCL at the inverting input:

$$\frac{V_o - V_-}{R_2} = \frac{V_- - V_1}{R_1}$$

$$\Rightarrow V_o = \left(\frac{R_2}{R_1} + 1\right) V_- - \frac{R_2}{R_1} V_1$$



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R_3 and R_4 form a voltage divider at the non-inverting input, therefore:

$$V_+ = \frac{R_3}{R_3 + R_4} V_2$$

$V_+ = V_-$ for an ideal op-amp, and substituting Eqn. we get:

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

$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$ **Now if we make *$R_1 = R_4$ and $R_2 = R_3$*,**

Here the ratio R_2/R_1 is referred to as the differential gain. When all resistors are equal

$$V_o = V_2 - V_1$$

Such a circuit is called a unity-gain analog subtractor.

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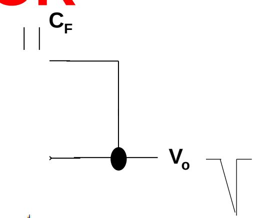
5.7 IDEAL INTEGRATOR



The current across capacitor C_F from V_o to V_- is:

$$i = C_F \frac{d(V_o - V_-)}{dt}$$

Applying KCL at the inverting input and using the virtual ground concept:

$$C_F \frac{d(V_o - V_-)}{dt} = \frac{V_- - V_i}{R_1}$$

$$V_- = 0, \Rightarrow \frac{d(V_o)}{dt} = \frac{-V_i}{R_1 C_F}$$

or $$V_o(t) - V_o(0_+) = \frac{-1}{R_1 C_F} \int_0^t V_i(\tau) d\tau$$

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5.8 IDEAL DIFFERENTIATOR

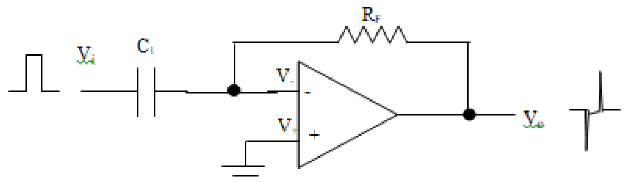


Figure : Ideal differentiator

The current across capacitor C_1 from V_- to V_i is:

$$i = C_1 \frac{d(V_- - V_i)}{dt}$$

Applying KCL at the inverting input,

$$C_1 \frac{d(V_- - V_i)}{dt} = \frac{V_o - V_-}{R_F}$$

Since $V_- = 0$, $V_o = -R_F C_1 \frac{dV_i}{dt}$

Example

A triangular waveform is applied to the input of the circuit in Fig. 18 as shown. Determine what the output should be and sketch its waveform in relation to the input.

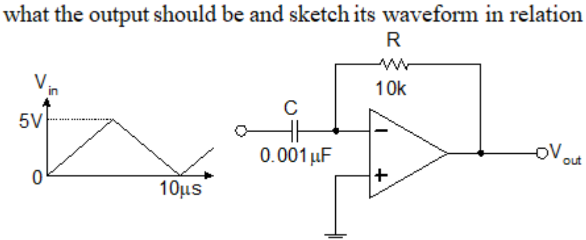


Figure 18

Solution

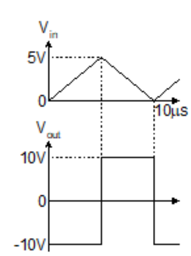
$$V_{out} = -RC\frac{dV_{in}}{dt} = -(10k)(0.001\mu)\frac{dV_{in}}{dt} = -1\times10^{-5}\frac{dV_{in}}{dt}$$

From time 0s to 5µs,

$$V_{out} = -1\times10^{-5}\frac{5}{5\mu} = -10V$$

From time 5µs to 10µs,

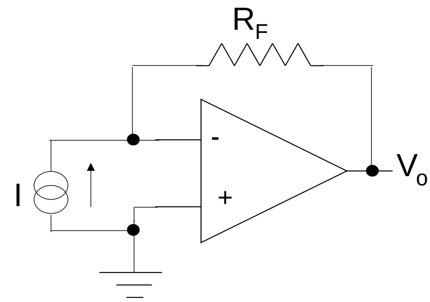
$$V_{out} = -1\times10^{-5}\frac{-5}{5\mu} = 10V$$

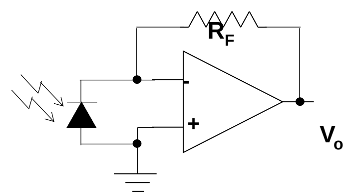


5.9 IDEAL CURRENT TO VOLTAGE CONVERTER

From the usual approach of applying virtual ground and KCL, it it evident that the output voltage V_o is given as:

$$V_o = -R_F I$$





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5.10 IDEAL VOLTAGE TO CURRENT CONVERTER

- From the usual approach of applying virtual ground and KCL, it it evident that the load current i_L is given as:
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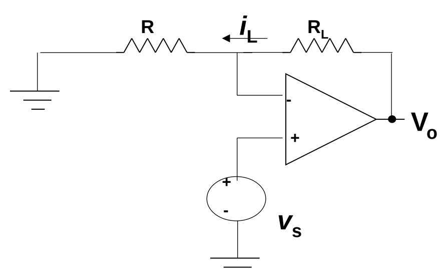
$$i_L = \frac{V_s}{R}$$



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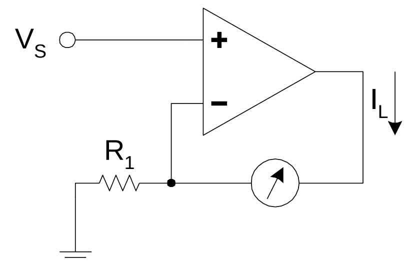
- **Example**
- A voltage to current converter can be used as a dc voltmeter. Fig. 24 shows a dc voltmeter, where a moving coil meter is conntected as the load. The full scale current of the moving coil is I_M = 200μA. Determine the value of R_1 to give a full-scale reading of $V_{S(max)}$ = 300V.



Solution

$$I_L = \frac{V_s}{R_1}$$

$$R_1 = \frac{V_{S(\max)}}{I_M} = \frac{300}{200\mu} = 1.5M\Omega$$

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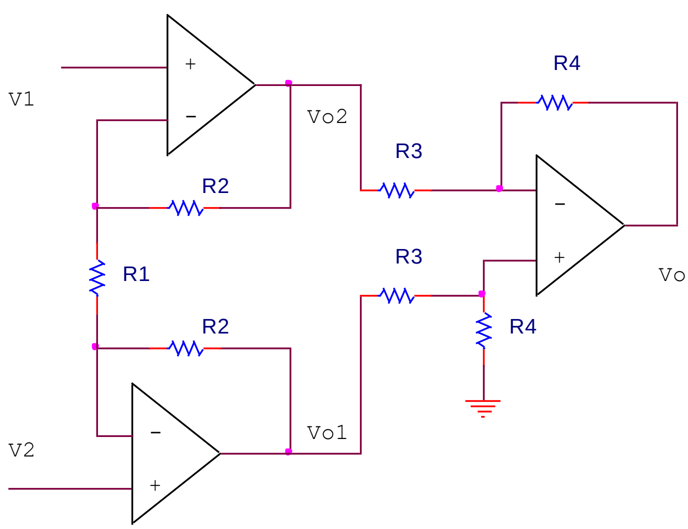
5.11 Ideal Instrumentation Amplifier



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The current in resistor R_1 is given by: $i_1 = \frac{v_1 - v_2}{R_1}$ [25]

The output voltages of the first stage op-amps are:

$$v_{o2} = v_1 + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right)v_1 - \frac{R_2}{R_1}v_2 \quad [26a]$$

$$v_{o1} = v_2 - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1 \quad [26b]$$

We have seen previously that the output of a difference amplifier is given as

$$v_o = \frac{R_4}{R_3}(v_{o1} - v_{o2}) \quad [27]$$

Combining Eqns. (26a), (26b), and (27), the output voltage for the instrumentation amplifier is found to be:

$$v_o = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_2 - v_1) \quad [28]$$

- From Eqn. (28), it can be seen that the differential gain is a function of resistor R_1, which can easily be varied by using a potentiometer, thus providing a variable amplifier gain with the adjustment of only one resistance.

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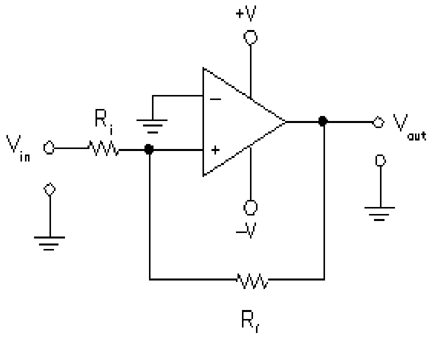
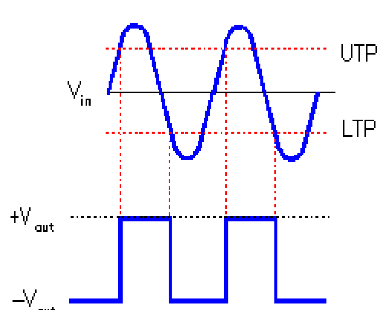
Schmitt Trigger Circuit

Schmitt Trigger Circuit

- A Schmitt Trigger can be considered as a comparator with variable threshold or reference voltage.
- It is often known as a squaring circuit. It is used to convert a regular or irregular waveform into a square or pulse waveform.
- Its input signal is a varying AC voltage.
- Its output has two opposite stable states i.e. High and Low.





input

output

Schmitt Trigger Circuit

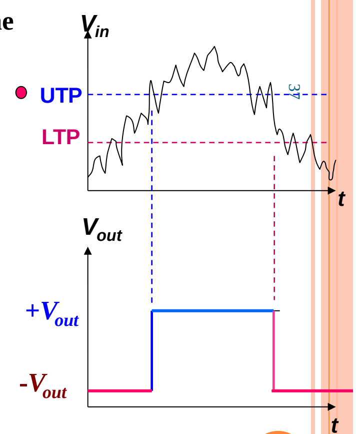
<u>The input/output waveforms are described as follows:</u>

1) When the input makes a positive-going transition past a *specified voltage*, the output of the Schmitt trigger goes from ($-V_{out}$ to $+V_{out}$).

The input voltage at which this change occurs is called the *Upper Trigger Point (UTP).*

2) When the input makes a negative-going transition past a *specified voltage,* the output of the Schmitt trigger goes from ($+V_{out}$ to $-V_{out}$).

The input voltage at which this change occurs is called the *Lower Trigger Point* (*LTP*).



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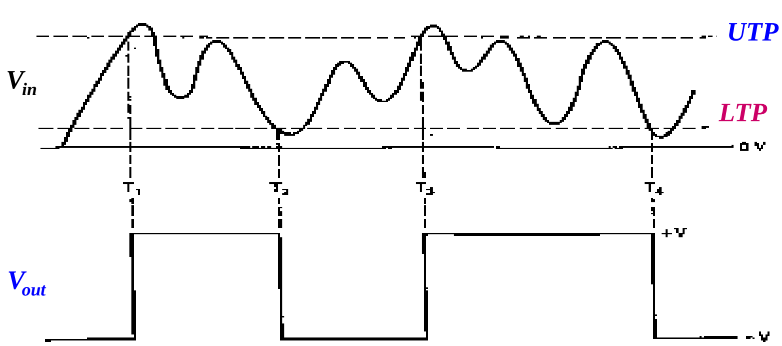
Dr. Wael Salah

- Input voltage levels that fall between these two trigger points *do not affect the output of the Schmitt trigger*.
- Once the UTP is exceeded, the output will not change its state until the input makes a negative-going transition that passes the LTP. The opposite is also true for the LTP .
- The voltage difference between the UTP and LTP = hysteresis.



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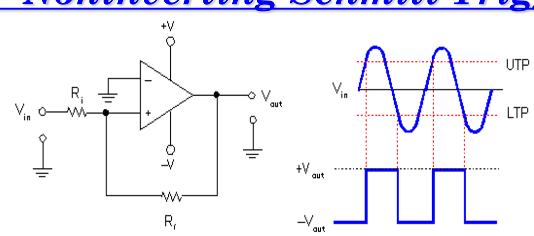
Some of the Schmitt Trigger Characteristics:

- ***UTP*** and ***LTP*** levels are determined **by** the component values in the circuit such as the $\boldsymbol{R_i}$, $\boldsymbol{R_f}$, $\boldsymbol{+V}$.
- ***UTP*** and ***LTP*** values may or **may not be equal**
- ***LTP*** value can never be greater (more positive) than ***UTP*** .
- The output from a Schmitt trigger changes when:
  - The ***UTP*** is reached by a ***positive****-going transition.*
  - The ***LTP*** is reached by a ***negative****-going transition.*

Schmitt Trigger Circuits

- ***(I) Noninverting Schmitt Triggers***



- ***(II) Inverting Schmitt Triggers***