EE1002: Introduction to Circuits and Systems

Chapter 2: Logic Circuits, Operational-Amplifiers and Sensors

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Learning Objectives

- Understand the advantage of digital technology over analog technology.
- Understanding of terminology of digital circuits.
- Understanding of binary arithmetic operations used in computers and other digital systems.
- Interconnections of logic gates of various types to implement a given logic function.
- Representation of logic expressions as sum of products (SOP) and products of sum (POS).
- Karnaugh maps
- Understand the properties of an ideal amplifiers and the concept of gain, input impedance and output impedance.

Learning Objectives cntd.

- Understand the difference between open-loop and closed-loop op-amp configuration and compute the gain of simple inverting and non-inverting amplifiers.
- LED drive circuit.
- LDR as sensor.

Introduction to Logic Circuits

- All the signals that we have considered so far are analog in nature i.e. an analog signal is an electric signal whose value varies in correspondence with a physical quantity e.g. (temperature, light intensity, force etc.).
- An analog signal *f(t)* as shown in Fig. 2.1 (a) has a single value for each value of time *t* that it can take from a series of values in a given range – for example the voltage proportional to measured variable pressure in an internal combustion engine (ICE).
- For a digital signal, can take *only a finite number of values* and each value in a given range has the same significance e.g. The binary signal can only take two values i.e. logic values "1" or "0" as shown in Fig. 2.1.

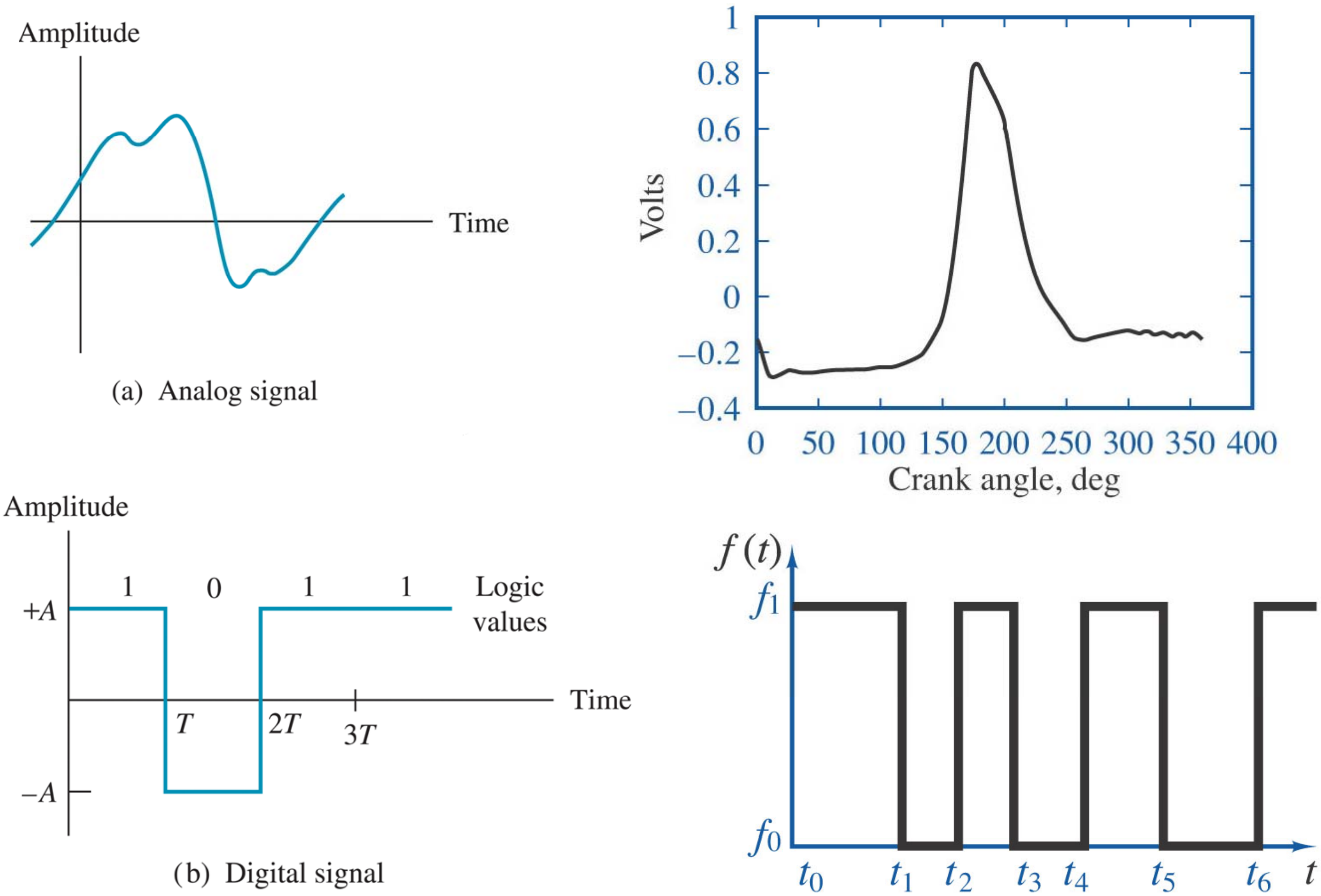


Fig. 2.1 : (a) Analog and (b) digital signals.

Advantages of Digital Approach

- When noise is added to analog signal then it becomes difficult to determine the actual amplitude of the original signal.
- On the other hand when noise is added to digital signal it is still possible to determine the logic values – provided the noise signal is not that high as shown in Fig. 2.2.
- Analog electronic circuits demand precision components that would be difficult to manufacture whereas it is much easier to produce digital circuits and even if the voltage fluctuates due to addition of noise still they would be around the logic values.
- Thus, the importance of digital systems in the past two decades.

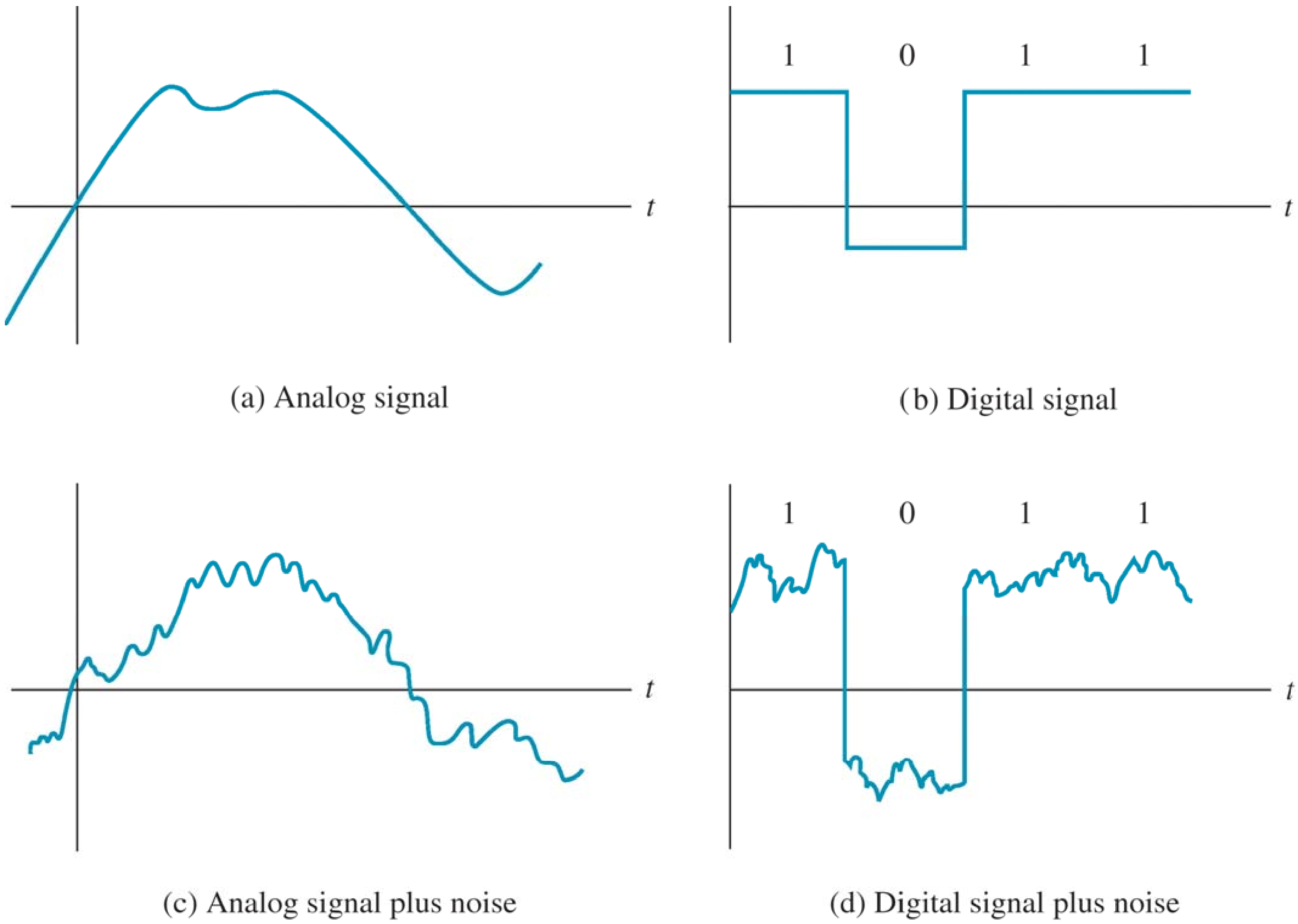


Fig. 2.2 : Analog and digital signals with noises.

Logic Ranges and Noise Margins

- Higher amplitude in a binary system represents "1" and the lower-amplitude range represents "0" and it is referred to as positive logic.
- Logic "1" is also referred to as **high**, **true** or **on** and logic "0" is also referred to **low**, **false** or **off**.
- Logic circuits are designed such that they accept a logic high or low for a range of input and output voltages.
- The largest input voltage that is considered as logic "0" is denoted as V_{IL} and the smallest input voltage accepted as logic "1" is denoted as V_{IH}.

- The output voltages fall into narrow ranges than the inputs – V_{OL} highest logic - 0 output voltage and V_{OH} highest logic -1 output voltage.
- Outputs have narrower ranges than the acceptable inputs as noise can be added at interconnections between inputs and outputs.
- The differences are called noise margins:

$$NM_L = V_{IL} - V_{OL} \qquad NM_H = V_{OH} - V_{IH} \qquad (2.1)$$

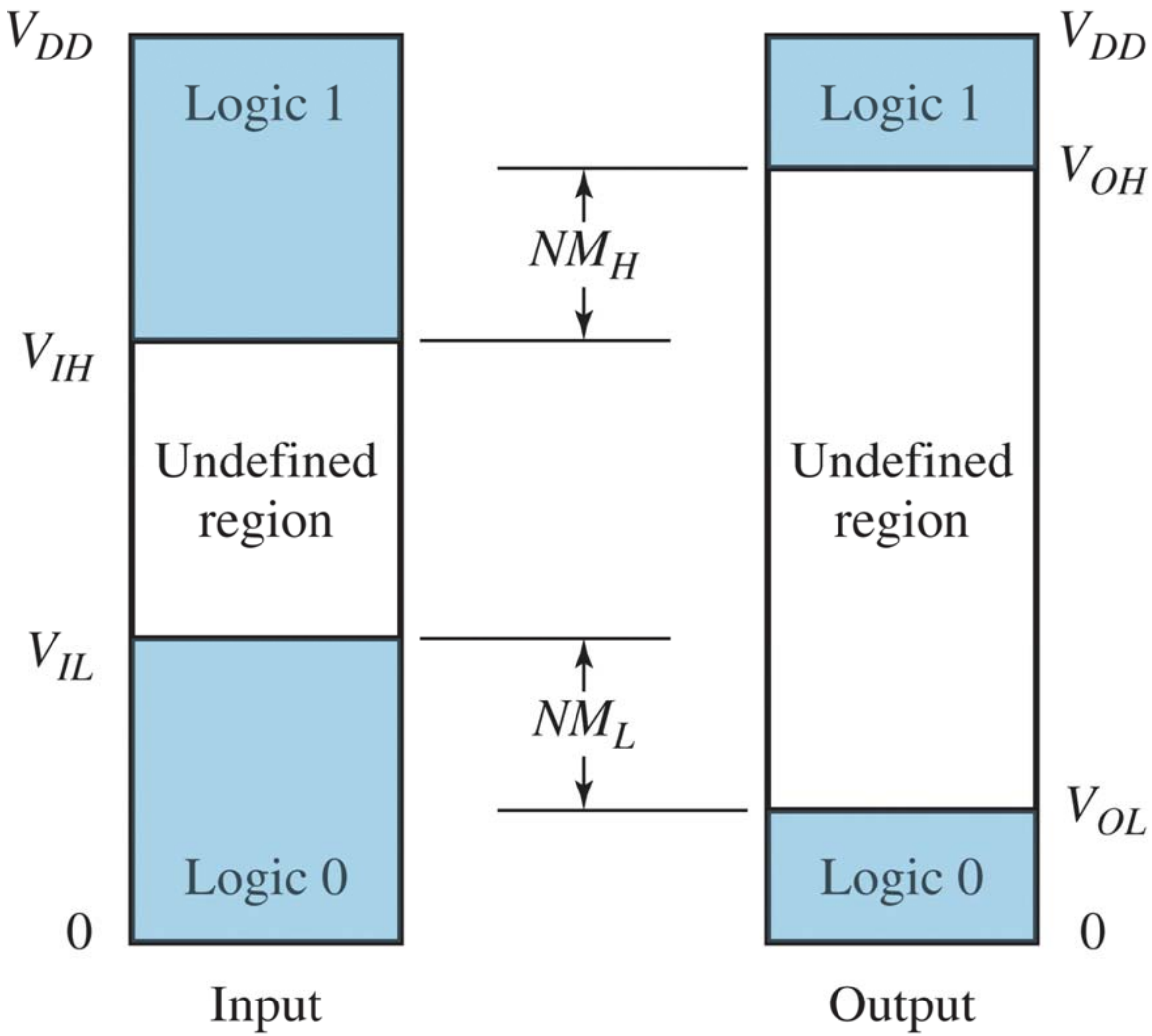


Fig. 2.3 : Voltage ranges for logic-circuit inputs and outputs.

Digital Words; Transmission of Digital Information

- A single binary digit is called a "**bit**", a "**byte**" is a word consisting of 8 bits and a "**nibble**" is a four-bit word.
- For parallel transmission of a *n*-bit digital word, *n+1* number of wires are needed (n for n bit data and one for GND signal).
- For serial transmission of a n-bit word the successive bits of the word are transmitted one after another on a single-pair of wire.
- Parallel transmission is faster but expensive and therefore used for short-distance transmission whereas serial-transmission is slower but cheap and typically used for long distances.

Representation of Numerical Data in Binary Form

- With three bits, we can have 2^3 distinct words.

000	–	0
001	–	1
010	–	2
011	–	3
100	–	4
101	–	5
110	–	6
111	–	7

- Similarly, a four-bit word can have $2^4 = 16$ combinations that represent integers 0 through 15.

Boolean Algebra

- The mathematics associated with binary numbers systems is called boolean – in honor of English Mathematician George Boole (1854).
- The basis of boolean algebra lies with the logical additions or the OR operation and logical multiplication or the AND operation.
- The OR gate represents the following logical statement:

$$\text{If either } A \text{ or } B \text{ is true (1) then } C \text{ is true (1)} \qquad \text{Logical OR} \quad (2.2)$$

- The AND gate represents the following logical statement:

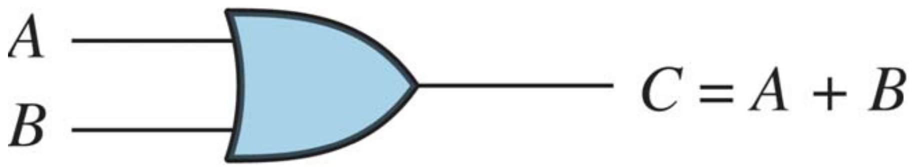
$$\text{If both } A \text{ and } B \text{ are true (1) then } C \text{ is true (1)} \quad \text{Logical AND} \quad (2.3)$$

A	B	$C = A + B$
0	0	0
0	1	1
1	0	1
1	1	1

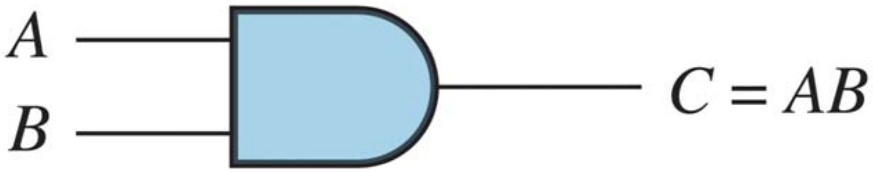
(a) Truth table

A	B	$C = AB$
0	0	0
0	1	0
1	0	0
1	1	1

(a) Truth table



(b) Symbol for two-input OR gate



(b) Symbol for two-input AND gate

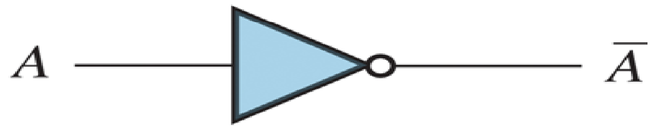
Fig. 2.4 : Symbol and truth-table for (a) OR gate and (b) AND gates..

- The NOT gate represents the following logical statement:

$$\text{If } A \text{ is true (1) then } \overline{\text{A}} \text{ is false (0)} \qquad \text{Logical NOT} \quad (2.4)$$

A	$\bar{A}$
0	1
1	0

(a) Truth table



(b) Symbol for an inverter

Fig. 2.5 : Symbol and truth-table for (a) NOT gate.

for AND operation

$AA = A$

$A1 = A$

$A0 = 0$

$AB = BA$

$A(BC) = (AB)C = ABC$

for OR operation

$A + A = A$

$A + 1 = 1$

$A + 0 = A$

$A(B + C) = AB + AC$

$(A + B) + C = A + (B + C) = A + B + C$

for NOT operation

$A\overline{A} = 0$

$\overline{\overline{A}} = A$

Implementation of Boolean Expressions

- Boolean algebra expression can be implemented using AND, OR and NOT gates.

$$F = A\overline{B}C + ABC + (C + D)(\overline{D} + E) \qquad (2.5)$$

$$= A\overline{B}C + ABC + C\overline{D} + CE + D\overline{D} + DE$$

$$= AC(\overline{B} + B) + C\overline{D} + CE + DE \qquad (\because D\overline{D} = 0)$$

$$= AC + C\overline{D} + CE + DE \qquad (\because B + \overline{B} = 1)$$

$$= C(A + \overline{D} + E) + DE \qquad (2.5a)$$

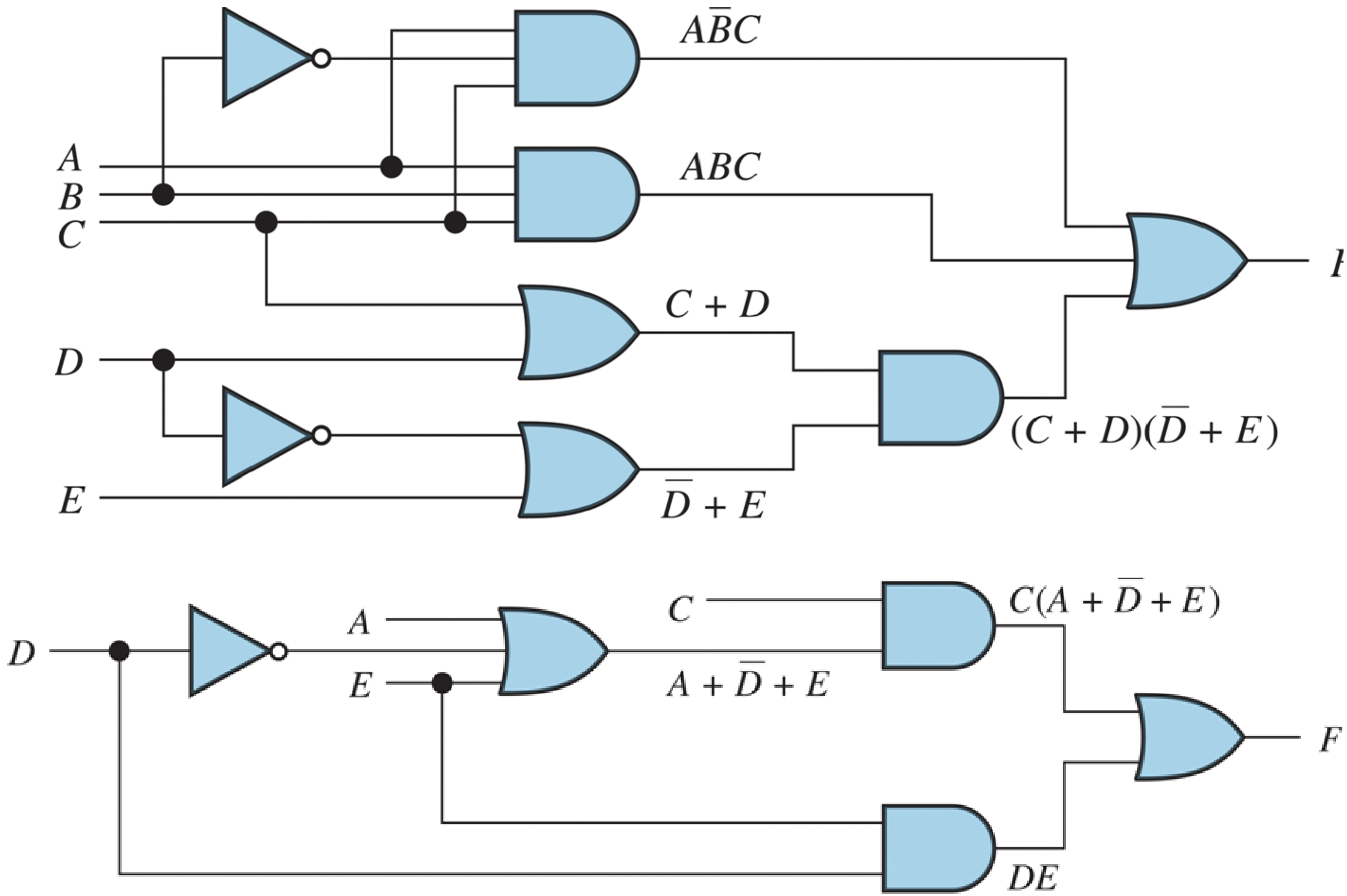


Fig. 2.6 : A circuit that implements the logic expressions F (a) complex circuit and (b) simpler circuit.

De Morgan's Laws

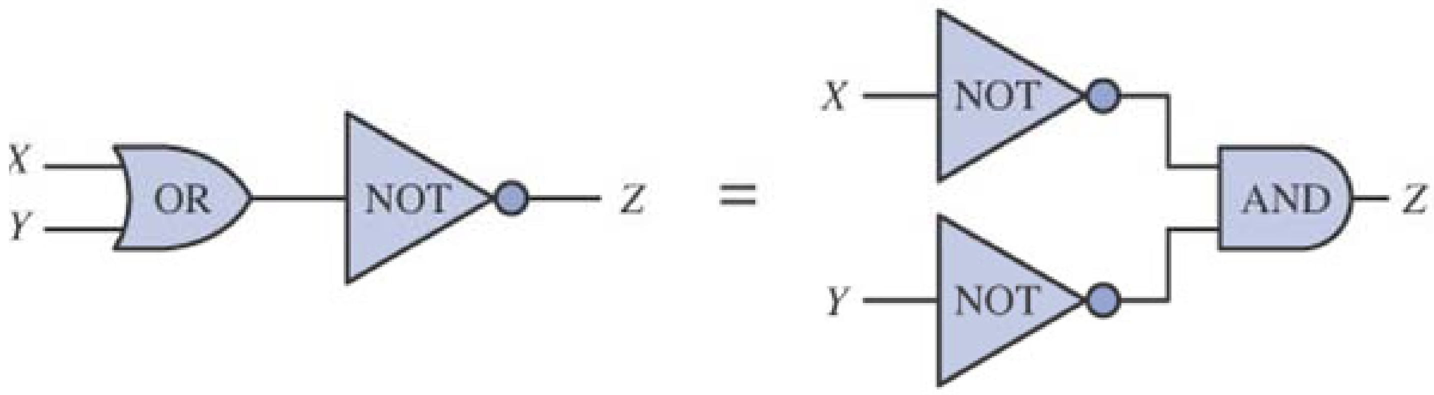
- Two important results of the Boolean algebra are the De Morgan's laws given by

$$ABC = \overline{\overline{\overline{A} + \overline{B} + \overline{C}}} \qquad (2.6)$$

$$(A + B + C) = \overline{\overline{ABC}} \qquad (2.7)$$

- If the variables in a logic expression are replaced by their inverses, the AND operation is replaced by OR, the OR operation is replaced by AND, and the entire expression is inverted.
- Any logic function can be implemented by using ONLY OR and NOT gates (2.6) or AND and NOT gates (2.7).

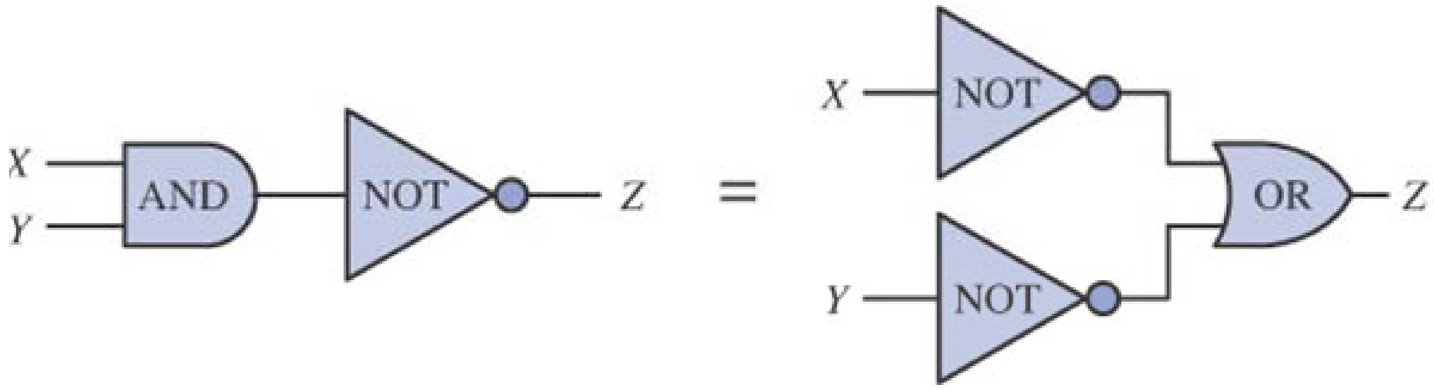
$(\overline{X+Y}) \quad = \quad \overline{X} \cdot \overline{Y}$



Truth table

X	Y	$Z = (\overline{X+Y}) = \overline{X} \cdot \overline{Y}$
0	0	1
0	1	0
1	0	0
1	1	0

$(\overline{X \cdot Y}) \quad = \quad \overline{X} + \overline{Y}$



Truth table

X	Y	$Z = (\overline{X+Y}) = \overline{X} +$
0	0	1
0	1	1
1	0	1
1	1	0

Fig. 2.7 : De Morgan's Laws..

- The importance of De Morgan's laws lies in the statement of the duality that exists between AND and OR operations; any function can be realized by just one of the two basic operations, plus the complement operation.
- This gives rise to families of logic functions, sum of products (SOP) and products of sums. Any logical expression can be reduced to one of the two basic forms.
- Although the two forms are equivalent but one of the two would be simpler from implementation point of view with fewer gates.

Example 2.1 Fail-safe Autopilot Logic: A fail-safe autopilot system in a commercial aircraft requires that, prior to initiating a take-off or landing manoeuvres, the following check must be passed i.e. two of three possible pilots' i.e. the *pilot*, the *co-pilot* and the *auto-pilot* must be available. Imagine there are switches installed on the pilot and co-pilot's seats so that if they are on their respective seats (due to their weight, the switch would have been closed) then the switches would provide a HIGH or 5V and if they are not on their seats then the switches would provide a LOW or 0 V signal. Similarly, the electronic circuit would provide a 5 V or 0 V if the auto-pilot circuit is working properly or not. Let the three logic variables X – represent the pilot, Y – represent the co-pilot and Z – represents the auto-pilot.

Solution: Since we wish two of the conditions out of the three must be active before the aircraft manoeuvre can be initiated, the logic function corresponding to the "system ready" is given by

The corresponding truth table is given by

Pilot (X)	Co-pilot (Y)	Auto-pilot (Z)	System ready
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Synthesis of Logic Circuits

- Method to implement logic circuits given the specifications for the output in terms of inputs.

Truth Table used to illustrate SOP Logical Expression

Rows	A	B	C	D	
0	0	0	0	1	$(\overline{A}\,\overline{B}\,\overline{C})$
1	0	0	1	0	
2	0	1	0	1	$(\overline{A}B\overline{C})$
3	0	1	1	0	
4	1	0	0	0	
5	1	0	1	0	
6	1	1	0	1	$(AB\overline{C})$
7	1	1	1	1	(ABC)

$D = \overline{A}\,\overline{B}\,\overline{C} + \overline{A}B\overline{C} + AB\overline{C} + ABC$ **(SOP)**

$$D = \bar{A}\bar{B}\bar{C} + \bar{A}B\bar{C} + AB\bar{C} + ABC \quad \textbf{(SOP)}$$

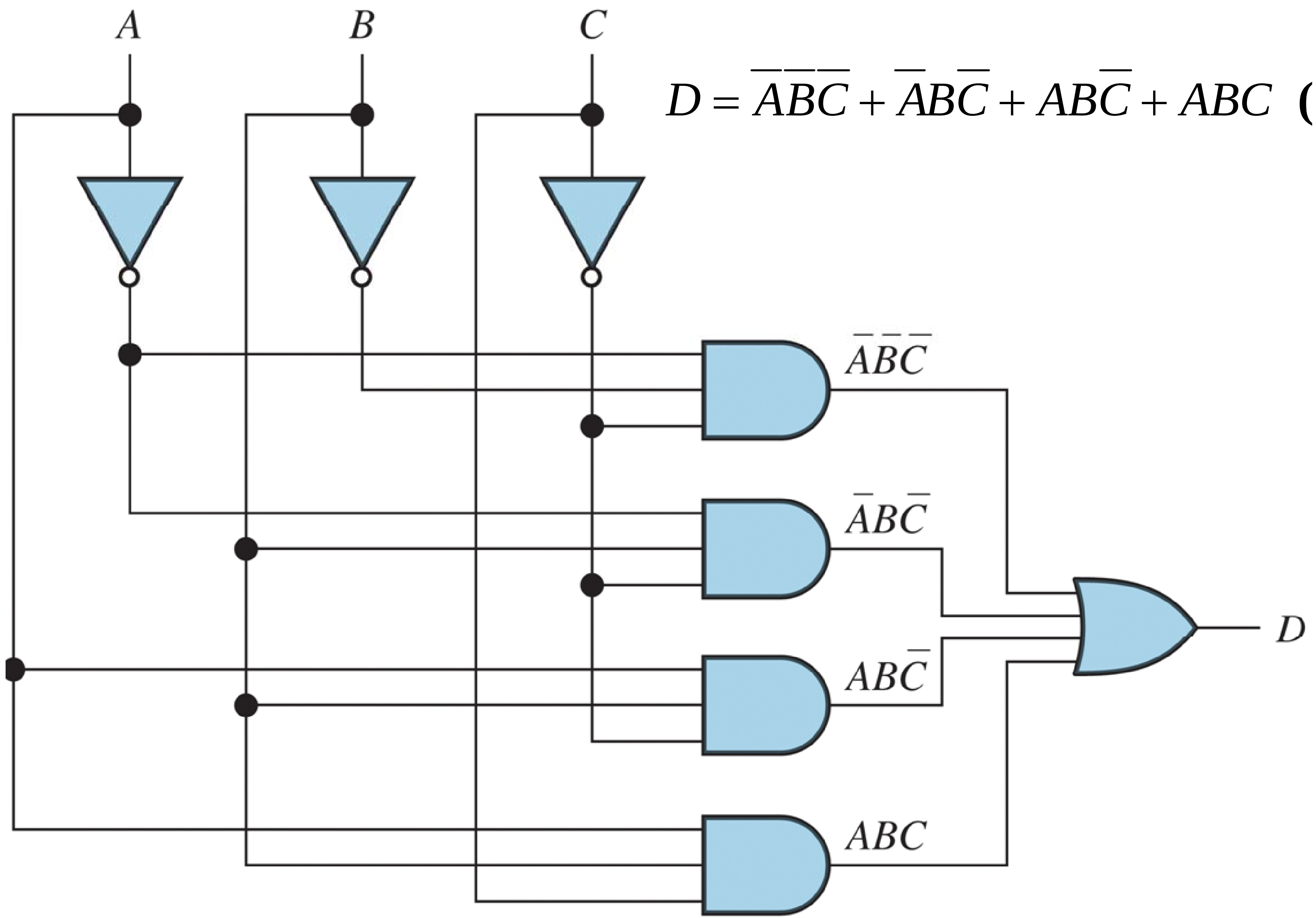


Fig. 2.8 : Boolean function implementation using SOP.

- Another way to write a logic expression for D is to consider the rows for which D is 0.

Truth Table used to illustrate POS Logical Expression

Rows	A	B	C	D	
0	0	0	0	1	
1	0	0	1	0	$(A+B+\overline{C})$
2	0	1	0	1	
3	0	1	1	0	$(A+\overline{B}+\overline{C})$
4	1	0	0	0	$(\overline{A}+B+C)$
5	1	0	1	0	$(\overline{A}+B+\overline{C})$
6	1	1	0	1	
7	1	1	1	1	

$$D=(A+B+\overline{C})(A+\overline{B}+\overline{C})(\overline{A}+B+C)(\overline{A}+B+\overline{C}) \quad \textbf{(POS)}$$

$$D = (A + B + \overline{C})(A + \overline{B} + \overline{C})(\overline{A} + B + C)(\overline{A} + B + \overline{C})$$ **(POS)**

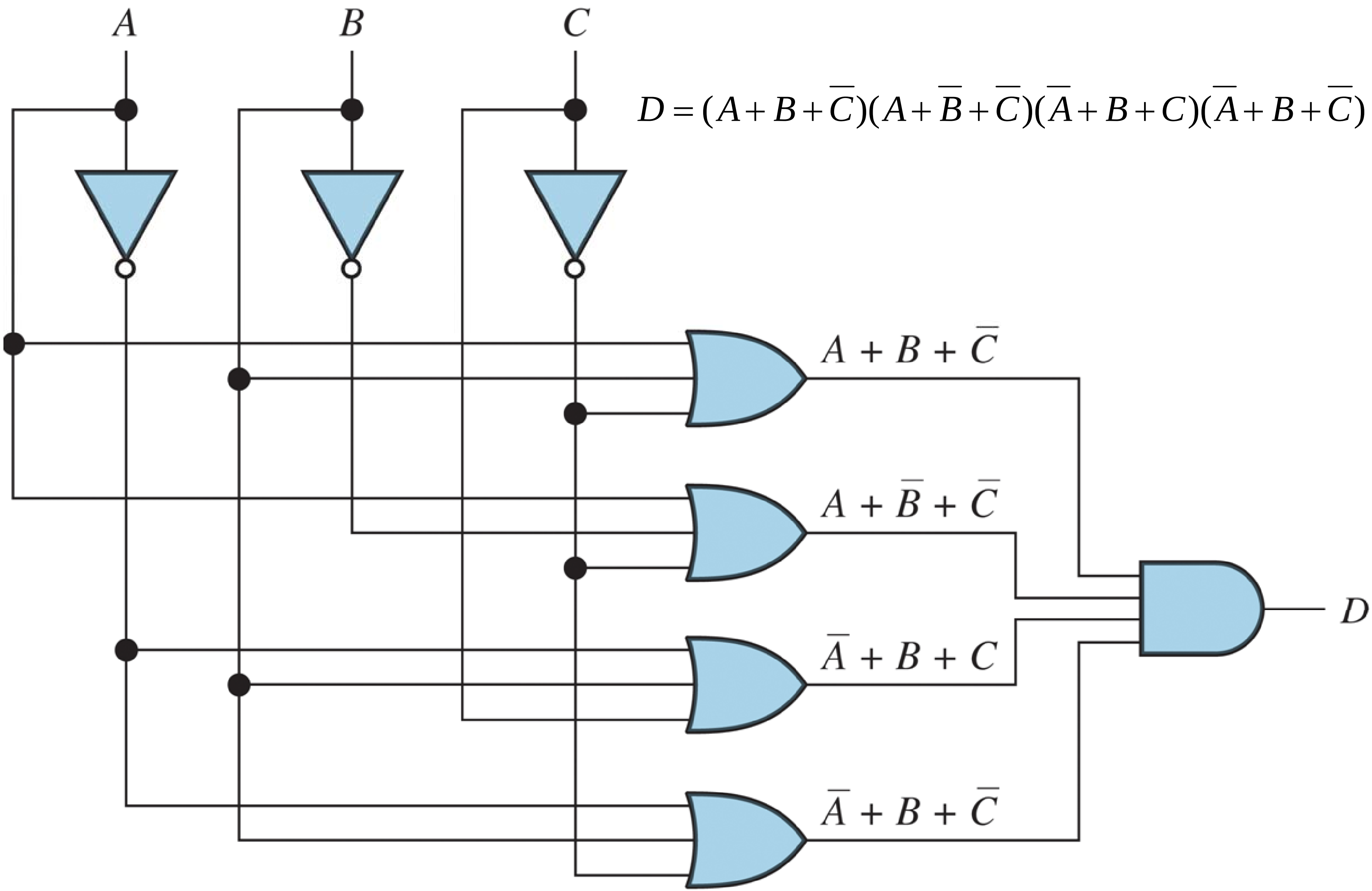


Fig. 2.9 : Boolean function implementation using POS.

Karnaugh Maps

- A graphical approach known as *Karnaugh map* can be used to minimize the number of terms in a logic expression.
- Consider the following truth table

A	*B*	*X*
0	0	1
0	1	0
1	0	0
1	1	1

	A	$\bar{A}$
B	1	0
B	0	1

$$X = \bar{A} \cdot \bar{B} + A \cdot B \qquad (4.12)$$

- Now consider the logical expression Y as given by eqn. (4.13)

$$Y = \bar{A} \cdot B + A \cdot B \qquad (4.13)$$

The corresponding Karnaugh map for this expression is shown.

	A	$\bar{A}$
B	1	1
$\bar{B}$	0	0

$$Y = \bar{A} \cdot B + A \cdot B = (\bar{A} + A) \cdot B = 1 \cdot B = B$$

- Now consider the logical expression Z as given by eqn. (4.14)

$$Z = \bar{A} \cdot B + A \cdot B + \bar{B} \cdot A \qquad (4.14)$$

The corresponding Karnaugh map for this expression is shown.

	A	$\bar{A}$
B	1	1
$\bar{B}$	1	0

$$Z = \bar{A} \cdot B + A \cdot B + \bar{B} \cdot A = \bar{A} \cdot B + A \cdot B + A \cdot B + \bar{B} \cdot A = (\bar{A} + A) \cdot B + A \cdot (\bar{B} + B)$$
$$= 1 \cdot B + A \cdot 1 = B + A$$

- Consider the truth table given as follows:

A	B	C	X
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	0

	AB	$A\bar{B}$	$\bar{A}\bar{B}$	$\bar{A}B$
C	0	0	1	0
$\bar{C}$	1	0	1	1

$$X = \bar{A} \cdot \bar{B} + B \cdot \bar{C} \quad (4.16)$$

$$X = \bar{A} \cdot \bar{B} \cdot \bar{C} + \bar{A} \cdot \bar{B} \cdot C + \bar{A} \cdot B \cdot \bar{C} + A \cdot B \cdot \bar{C} \quad (4.15)$$

Operational Amplifiers

- A major function of the electronic instrumentation circuit is the amplification of low level electric signal to a higher-level signal is of prime importance in many applications.
- For example, the low-level signal from a music player to be amplified to a level suitable for driving high-wattage speaker.
- Also amplifiers are needed to amplify the low-level signal from transducers such as temp. sensor, light sensor etc. to high-level so that it can be used for other function in an electronic circuit.

Ideal Amplifier Characteristics

- Simplest model of an amplifier is shown in Fig. 2.10(a), where $v_S(t)$ is the input signal, $v_L(t)$ is the output signal, R_S is the source resistance, R_L is the load resistance and A is the gain of the ideal amplifier.
- Ideally, the load voltage should be

$$v_L(t) = A \times v_S(t) \qquad (2.16)$$

- Source has been modeled as Thevenin's equivalent circuit and the load as an equivalent resistance.
- The amplifier can act as an equivalent load to the source and an equivalent source to the load as per the Thevenin's theorem.

- The equivalent circuit of the voltage amplifier circuit is shown in Fig. 2.10(b).

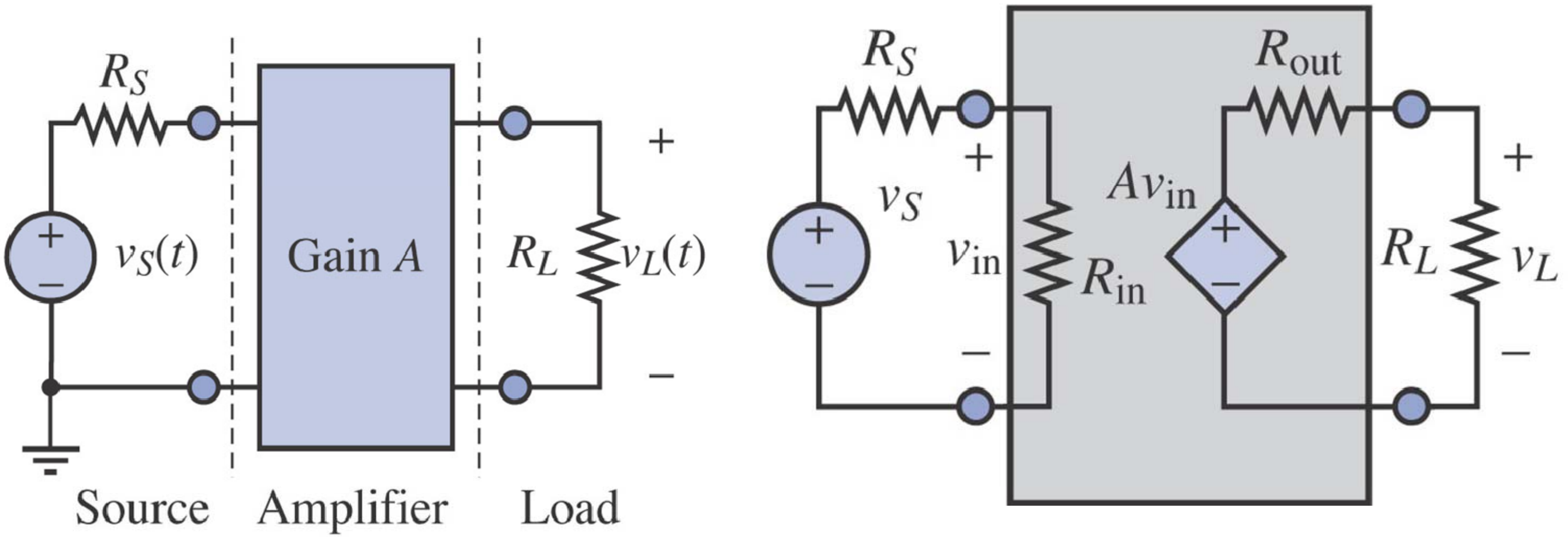


Fig. 2.10: (a) A voltage amplifier and (b) simple voltage amplifier model.

- $v_S(t)$ - input signal, $v_L(t)$ - output signal, R_S - source resistance, R_L - load resistance, A - gain of the ideal amplifier, $v_{in}(t)$ - input signal, R_{in} - input resistance, Av_{in} - controlled voltage source, and R_{out} -internal resistance.

$$v_{in} = \frac{R_{in}}{R_S + R_{in}} v_S \qquad v_L = Av_{in} \frac{R_L}{R_{out} + R_L} \qquad (2.17)$$

$$v_L = Av_{in} \frac{R_L}{R_{out} + R_L} = \left(A \left(\frac{R_{in}}{R_S + R_{in}} \right) \times \left(\frac{R_L}{R_{out} + R_L} \right) \right) v_S$$

v_L depends on R_S, R_L, R_{in} and R_{out} - not desirable

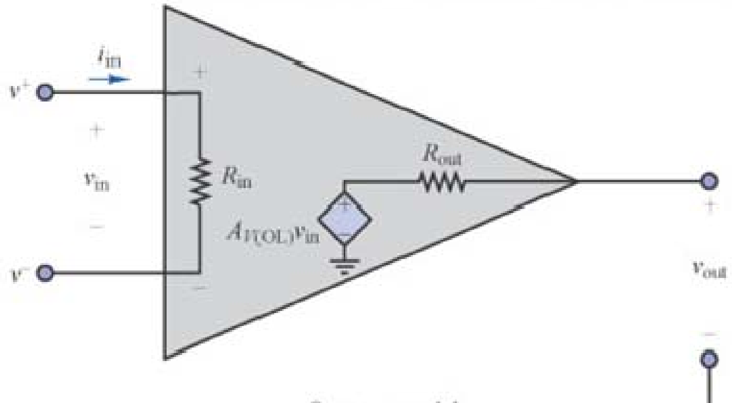
If $R_{in} >> R_S$ and $R_L >> R_{out}$ we have

$$v_L \approx Av_S \qquad (2.18)$$

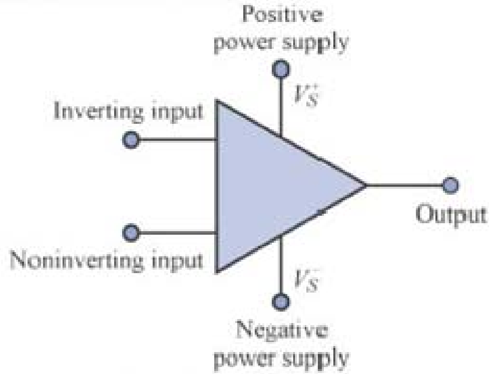
Thus, the two desirable characteristics for a general-purpose amplifier are: (1) large input impedance, R_{in} and a very small output impedance, R_{out}.

The Operational Amplifier

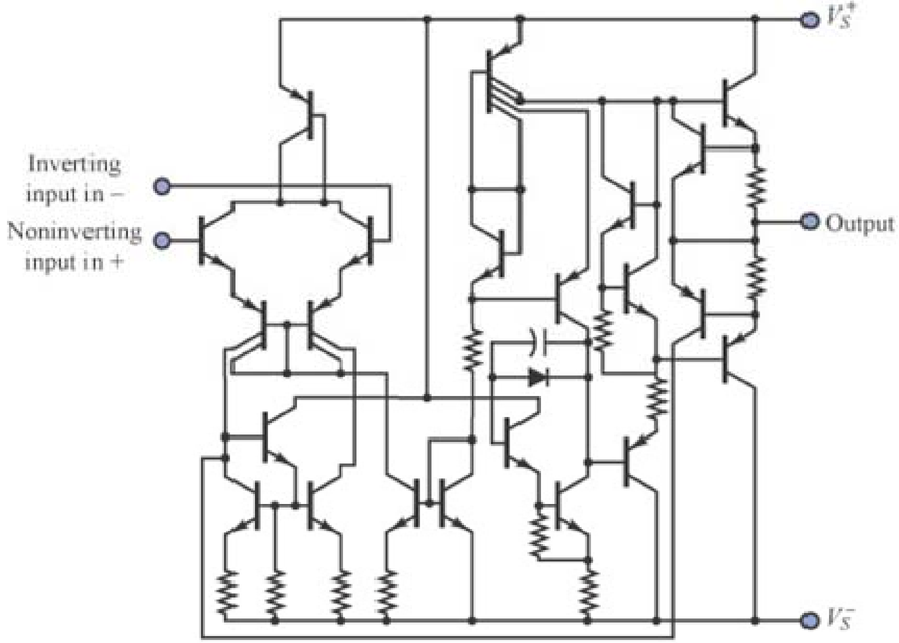
- The ideal operational-amplifier (op-amp) behaves like an ideal difference amplifier i.e. an amplifier that amplifies the difference between the two input voltages as shown in Fig. 2.11.
- The input voltage at the +ve terminal is the non-inverting input voltage, v^+ and the same at the –ve terminal is called the inverting input voltage, v^-, and $A_{V(OL)}$ is the open-loop voltage gain and is quite large of the order of 10^5 - 10^7.
- For analysis of op-amp we assume that input current, $i_{in} \sim 0$, which is realistic as R_{in} is almost infinite.



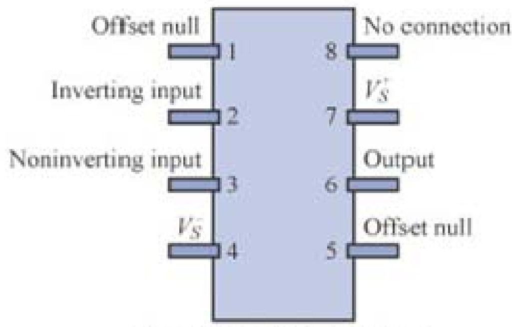
Op-amp model



Simplified circuit symbol



IC op-amp diagram



Integrated-circuit operational amplifier (IC op-amp)

Fig. 2.11: (a) OP-amp model, (b) symbol, (c) IC op-amp diagram and (d) IC op-amp.

Operational Amplifier in Closed-loop Mode - Inverting Amplifier

- The signal to be amplified is connected to the inverting terminal while the non-inverting terminal is grounded as shown in Fig. 2.12.
- It can be shown that the voltage gain of the amplifier can be set at any arbitrary value by choosing the ratio of two resistances R_S and R_F.
- The effect of the feedback connection from output to inverting input terminal is to force the voltage at the inverting input to be equal to that at the non-inverting input.

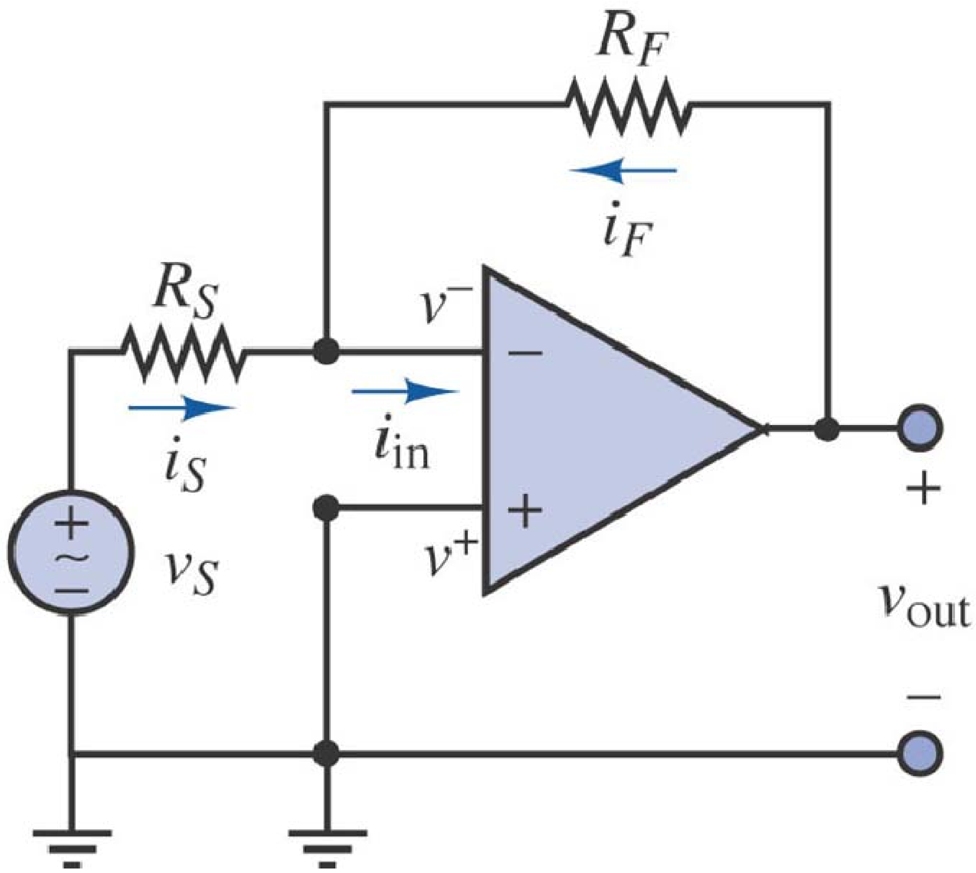


Fig. 2.12: Inverting amplifier.

$$i_S + i_F = i_{in} \quad (2.19), \qquad i_S = \frac{v_S - v^-}{R_S} \quad (2.20), \qquad i_F = \frac{v_{out} - v^-}{R_F} \quad (2.21), \qquad i_{in} = 0$$

$$v_{out} = A_{V(OL)}\left(v^+ - v^-\right) = A_{V(OL)}\left(0 - v^-\right) = -A_{V(OL)} v^- \Rightarrow v^- = -\frac{v_{out}}{A_{V(OL)}} \quad (2.22)$$

$$i_S = -i_F \Rightarrow i_S = \frac{v_S - v^-}{R_S} = \frac{v_S - \left(-\frac{v_{out}}{A_{V(OL)}}\right)}{R_S} = \frac{v_S}{R_S} + \frac{v_{out}}{A_{V(OL)} R_S}$$

$$-i_F = -\frac{v_{out} - v^-}{R_F} = -\frac{v_{out} - \left(-\frac{v_{out}}{A_{V(OL)}}\right)}{R_F} = -\frac{v_{out}}{R_F} - \frac{v_{out}}{A_{V(OL)} R_F}$$

$$\frac{v_S}{R_S} + \frac{v_{out}}{A_{V(OL)} R_S} = -\frac{v_{out}}{R_F} - \frac{v_{out}}{A_{V(OL)} R_F} \Rightarrow \frac{v_S}{R_S} = -\frac{v_{out}}{R_F} - \frac{v_{out}}{A_{V(OL)} R_F} - \frac{v_{out}}{A_{V(OL)} R_S}$$

$$v_S = -v_{out}\left(\frac{R_S}{R_F} + \frac{R_S}{A_{V(OL)} R_F} + \frac{R_S}{A_{V(OL)} R_S}\right)\left(\because A_{V(OL)} = 10^5 - 10^7\right)$$

$$v_S = -v_{out}\left(\frac{R_S}{R_F}\right) \Rightarrow v_{out} = -\left(\frac{R_F}{R_S}\right) v_S \qquad (2.23)$$

$$v^- = -\frac{v_{out}}{A_{V(OL)}} \approx 0 \Rightarrow v^- \approx v^+$$

Example 2.2 Determine the voltage gain and output voltage for the inverting amplifier circuit as shown in Fig. 4.23. Assume that R_s = 1 kΩ, R_F = 10 kΩ, $v_s(t)$ = 0.015 cos(50*t*) and the operational amplifier is ideal.

Solution:

The voltage gain of the inverting amplifier circuit is given by

$$A_v = \frac{R_F}{R_s} = \frac{10k\Omega}{1k\Omega} = 10, \qquad v_{out} = -\frac{R_F}{R_s} v_s = -10 \times 0.015\cos(50t) = -0.15\cos(50t)$$

The corresponding input and output voltage waveforms are as shown in Fig. 2. 13.

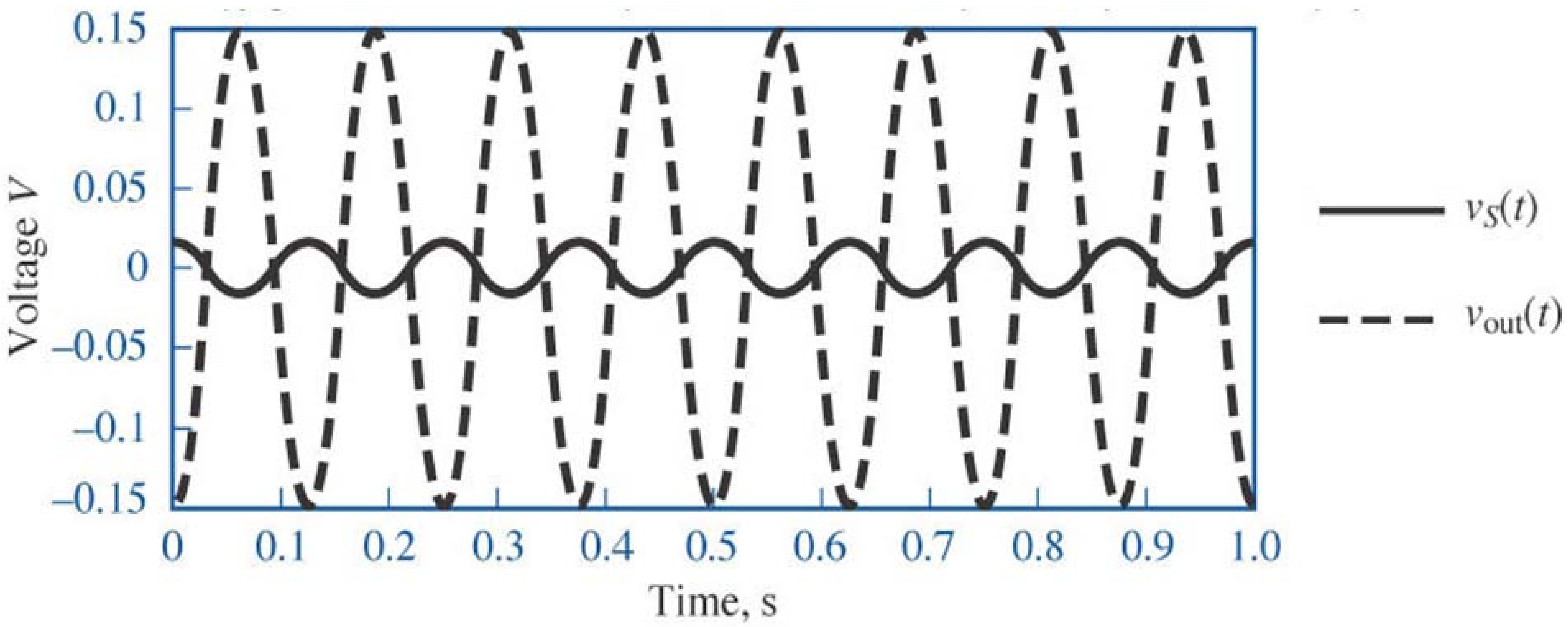


Figure 2.13: Plot of $v_s(t)$ and $v_o(t)$

- Note that v_S and v_{out} are out of phase due to the –ve sign.

- A useful op-amp circuit that is based on the inverting amplifier is the *summing amplifier* as shown in Fig. 2.14 that is used to add different signal sources.

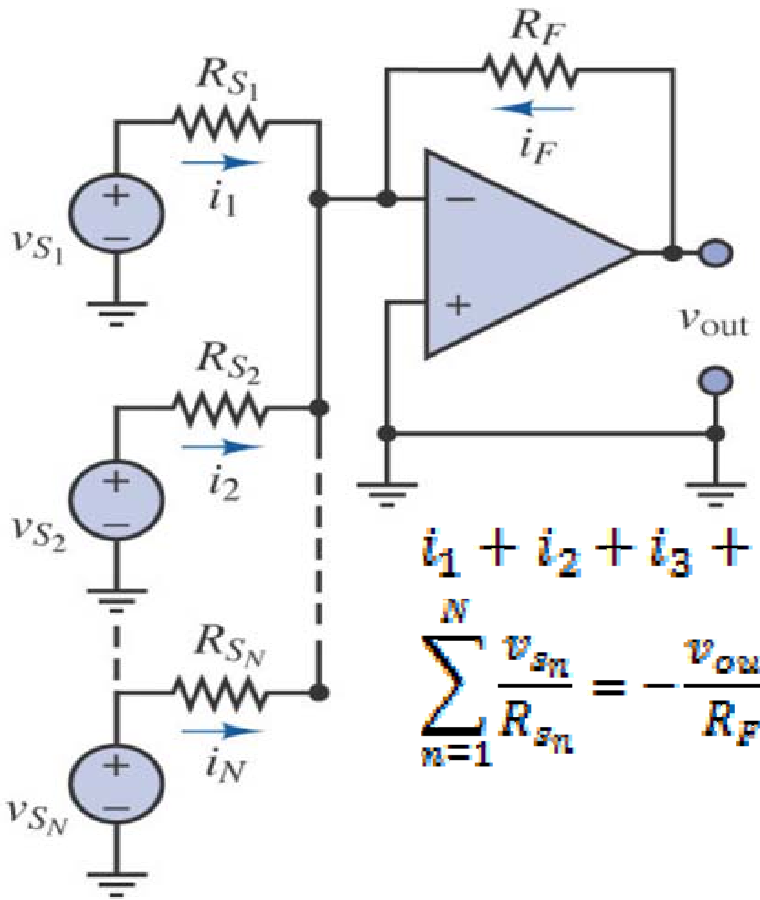


Figure 2.14: Summing amplifier

$$i_1 + i_2 + i_3 + i_4 + \cdots\cdots\cdots + i_N = -i_F$$

$$\sum_{n=1}^{N} \frac{v_{s_n}}{R_{s_n}} = -\frac{v_{out}}{R_F} \qquad v_{out} = -\sum_{n=1}^{N} \frac{R_F}{R_{s_n}} v_{s_n} \quad (4.25)$$

Example 2.3 Find an expression for the output voltage of the circuit as shown in Fig. 2.15.

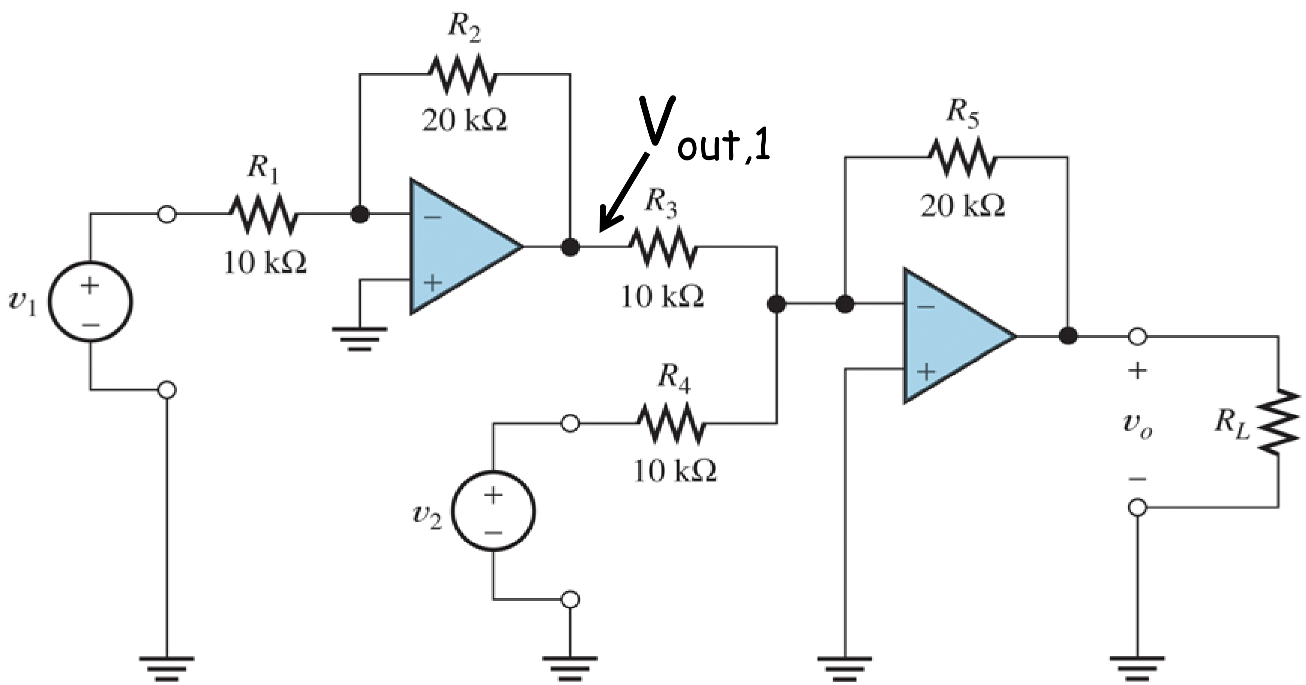


Figure 2.15: Circuit for Example 2.3

$$v_{out,1} = -\frac{R_2}{R_1}v_1 = -2v_1$$

$$v_o = -\left(\frac{R_5}{R_3}v_{out,1} + \frac{R_5}{R_4}v_2\right) = -\left(\frac{20}{10}(-2v_1) + \frac{20}{10}v_2\right) = 4v_1 - 2v_2$$

Non-inverting Amplifier

- To avoid the –ve sign i.e. phase inversion introduced by the inverting amplifier a *non-inverting* amplifier configuration as shown in Fig. 2.16 is shown.
- The signal, v_s to be amplified is connected to the non-inverting terminal while the inverting terminal is grounded through a resistance R_S as shown in Fig. 2.16.

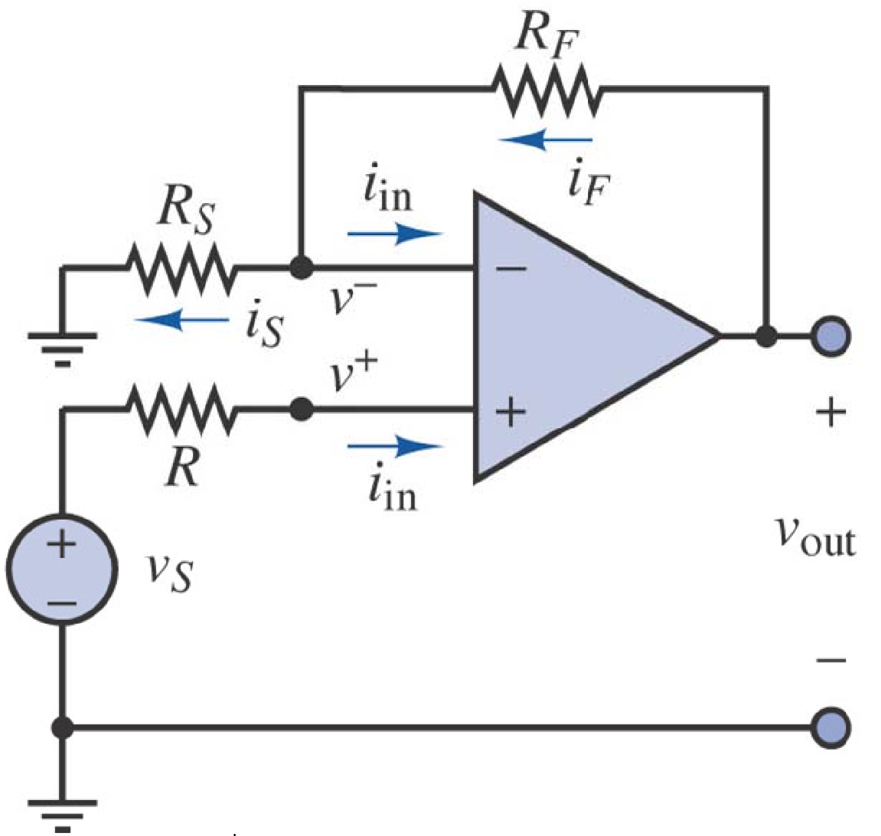


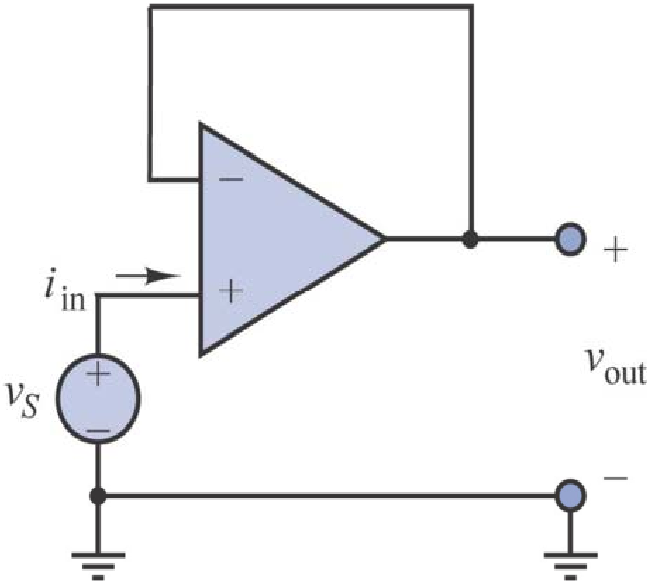
Fig. 2.16: Non-inverting amplifier.

$$i_F = i_S + i_{in} \approx i_S,\ i_S = \frac{v^-}{R_S},\ i_F = \frac{v_{out} - v^-}{R_F},\ i_{in} = 0 \Rightarrow v^+ = v_S = v^-$$

$$i_F = i_S \Rightarrow \left\{(i_F =)\frac{v_{out} - v^-}{R_F}\right\} = \left\{(i_S =)\frac{v^-}{R_S}\right\} \Rightarrow \frac{v_{out} - v_S}{R_F} = \frac{v_S}{R_S} \Rightarrow \frac{v_{out}}{v_S} = \left(1 + \frac{R_F}{R_S}\right) \quad (2.25)$$

- Thus, by constructing an non-ideal amplifier with a very large gain and near infinite input resistance, it is possible to design amplifiers that have near-ideal performance and can provide a variable range of gains, that can be easily controlled by the selection of external resistors such as R_F and R_S.
- The –ve feedback mechanism allows that to happen and unless and otherwise stated it is reasonable and sufficient to assume that:
  - $i_{in} = 0$ and
  - $v^- = v^+$

- Consider the non-inverting op-amp circuit as shown in Fig. 2.17 in which case $R_F = 0$ and R_s = very large, then according to eqn. (4.26) we have



$$\frac{v_{out}}{v_s} = \left(1 + \frac{R_F}{R_s}\right) = \left(1 + \frac{0}{\infty}\right) = 1$$

$$\Rightarrow v_{out} = v_s \qquad (4.27)$$

$$R_{in} = \frac{v_s}{i_{in}} = \frac{v_s}{0} = \infty$$

Figure 2.17: Voltage follower

- Thus the output voltage follows the input voltage and that is why the circuit is known as *voltage follower*.

The Differential Amplifier

- It is a combination of the inverting and non-inverting amplifiers and finds its application where the difference between the two signals needs to be amplified.

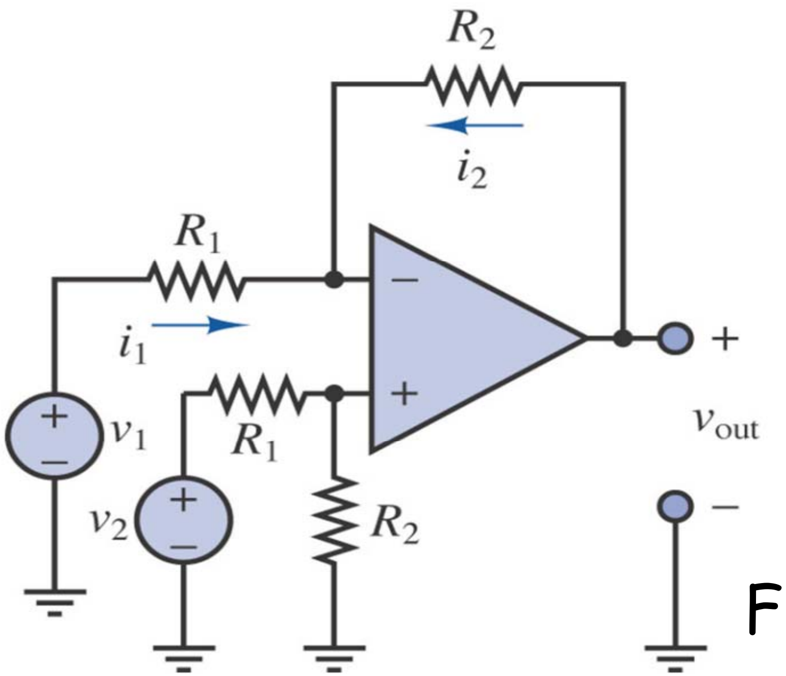


Figure 2.18: Differential amplifier

$$v^+ = \frac{R_2}{R_1 + R_2} v_2$$

$$i_1 = \frac{v_1 - v^+}{R_1}, \quad i_2 = \frac{v_{out} - v^+}{R_2}$$

$$i_2 = -i_1 \;\Rightarrow\; \frac{v_{out} - \frac{R_2}{R_1 + R_2} v_2}{R_2} = -\frac{v_1 - \frac{R_2}{R_1 + R_2} v_2}{R_1}$$

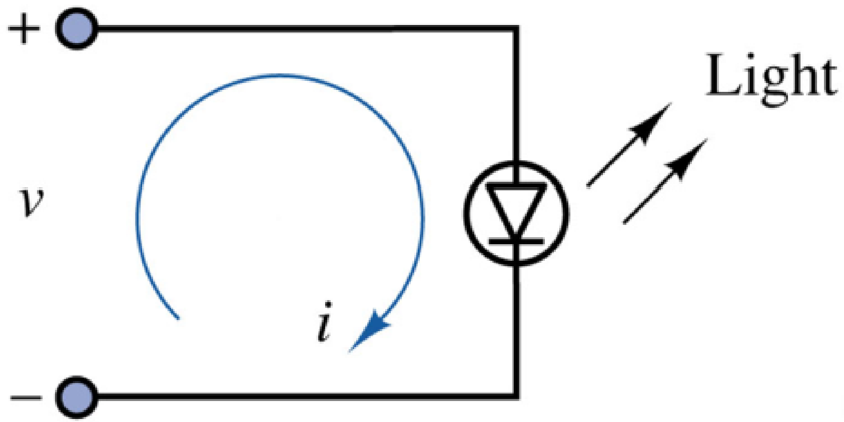
$$v_{out} = R_2 \left[\frac{-v_1}{R_1} + \frac{1}{R_1 + R_2} v_2 + \frac{R_2}{R_1 (R_1 + R_2)} v_2 \right]$$

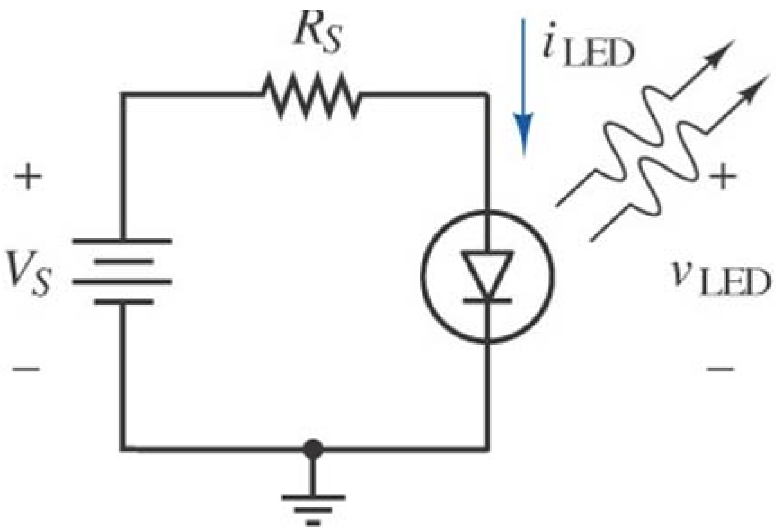
$$= \frac{R_2}{R_1}(v_2 - v_1) \quad (4.28)$$

- Thus, the differential amplifier amplifies the difference between the two input signals by the closed-loop gain of R_2/R_1

Light-emitting Diodes

- A light emitting diode (LED) is a special kind of diode which emits light when forward biased.





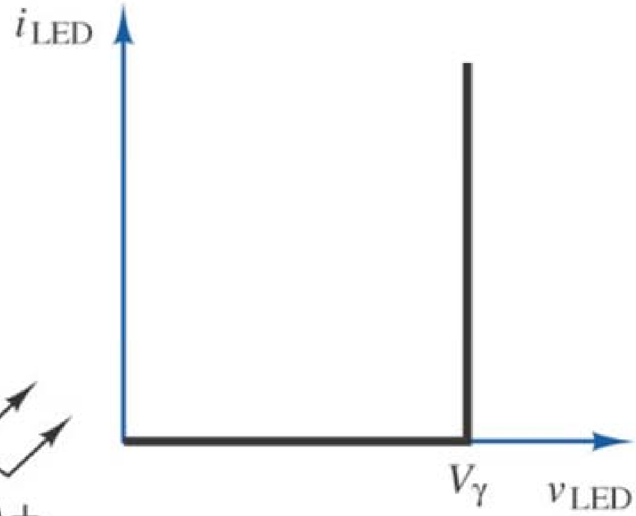


Figure 2.19: Light emitting diode (a) symbol, (b) drive circuit and (c) *i*-*v* characteristic

Example 2.4 For the LED circuit as shown in Fig. 2.19(b) determine (a) the LED power consumption, (b) the value of the resistance R_s and (c) the power delivered by the source. Assume that V_S = 5 V, V_{LED} = 1.7 V and i_{LED} = 40 mA.

Solution:

(a) $$P_{LED} = V_{LED} \times I_{LED} = 1.7\ V \times 40\ mA = 68\ mW$$

(b) $$R_s = \frac{V_s - V_{LED}}{I_{LED}} = \frac{5V - 1.7V}{40\ mA} = 82.5\ \Omega$$

(c) $$P_s = V_s \times I_{LED} = 5\ V \times 40\ mA = 200\ mW$$

Sensor - Light Dependent Resistor

- A **photo-resistor**, **light dependent resistor** (LDR) is a resistor whose resistance decreases with increasing incident light intensity.

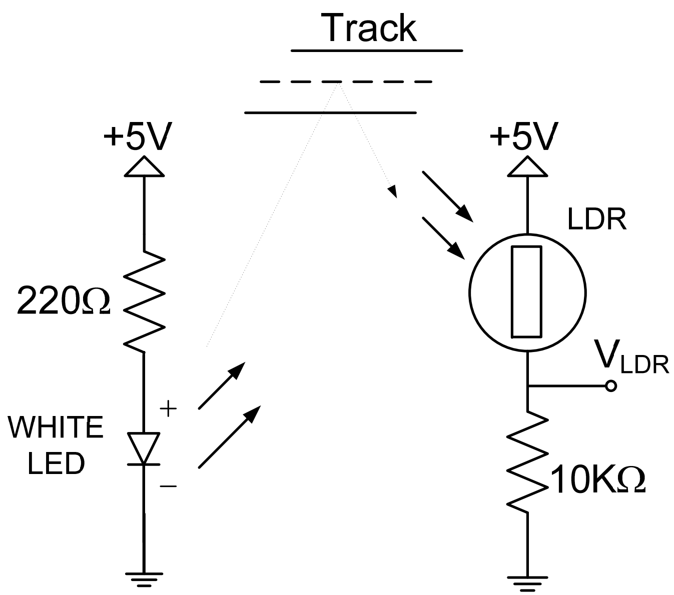
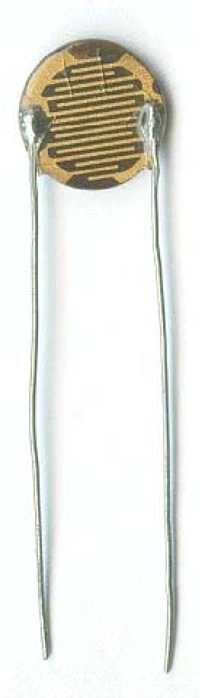
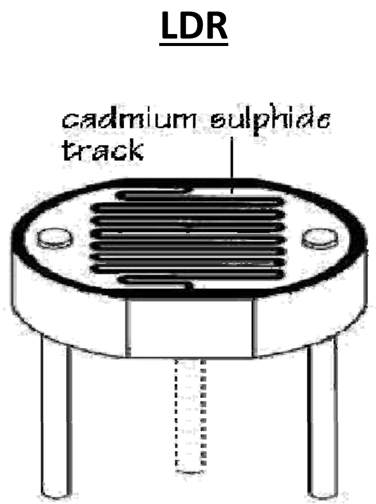


Fig. 2.20: LDR circuit.





Cut off the Middle Leg of the LDR

Summary

- Understanding the concepts of analog and digital signals and of quantization.
- Write truth tables, and realize logic functions from truth tables using logic gates.
- Understanding of the properties of ideal amplifiers and the concept of gain, input impedance and output impedance – ideal amplifiers form the basic fundamental building block of the electronic instrumentation system.
- Analysis of the op-amp circuit is carried out with the assumption that it has a very large input resistance, a very small output resistance and a large open-loop gain.
- The simple inverting and non-inverting amplifier configurations permit the design of useful circuits simply by appropriately selecting and placing few resistors.

References

1. "Principles and Applications of Electrical Engineering" – Giorgio Rizonni, Mc Graw Hill, 5th Edition 2007, Chapters 8 and 11.
2. "Electrical Engineering Principles and Applications", - Allan R. Hambley, Pearson – Prentice Hall, 5th Edition 2010, Chapters 7 and14.