

Chapter – 5

Operational Amplifier

5-1: Introduction:

Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as : addition , subtraction , integration , differentiation - thus the term (**operational**).

Operational Amplifier Definition:

operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

An **Operational Amplifier**, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or “operation” of the **amplifier** and by virtue of the different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations, giving rise to its name of “Operational Amplifier”.

Symbol and Terminals:

An **Operational Amplifier** is basically a three-terminal device which consists of two high impedance inputs:

- one called the **Inverting Input**, marked with a negative or “minus” sign, (–) and
- the other one called the **Non-inverting Input**, marked with a positive or “plus” sign (+)
- The third terminal represents the operational amplifiers output port which can both sink and source either a voltage or a current, as shown in Fig. (5-1).

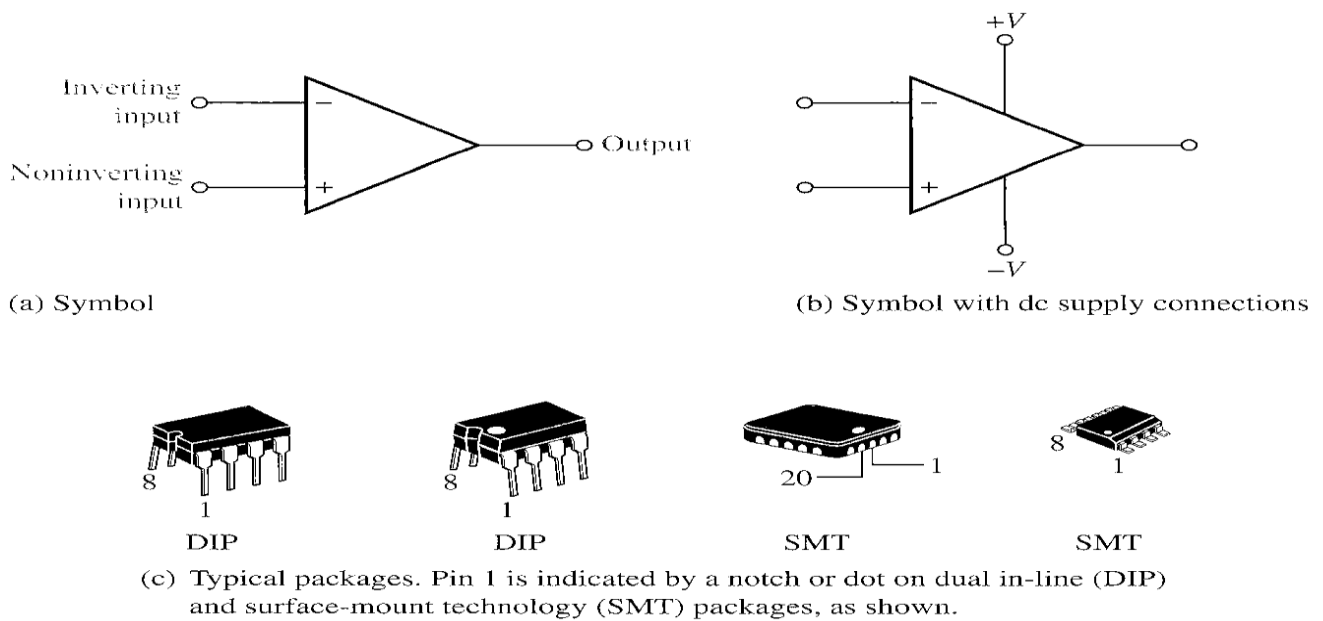


Fig.(5-1). Op-amp symbols and packages

Ideal op-Amp :

To illustrate what an op-amp is, let's consider its ideal characteristics. A practical op-amp, of course, falls short of these ideal standards, but it is much easier to understand and analyze the device from an ideal point of view.

First, the ideal op-amp has *infinite voltage gain* and *infinite bandwidth*. Also, it has an *infinite input impedance* (open) so that it does not load the driving source. Finally, it has a *zero output impedance*. These characteristics are illustrated in Figure (a). The input voltage, V_{in} appears between the two input terminals, and the output voltage is $A_v V_{in}$, as indicated by the internal voltage source symbol. The concept of infinite input impedance is a particularly valuable analysis tool for the various op-amp configurations.

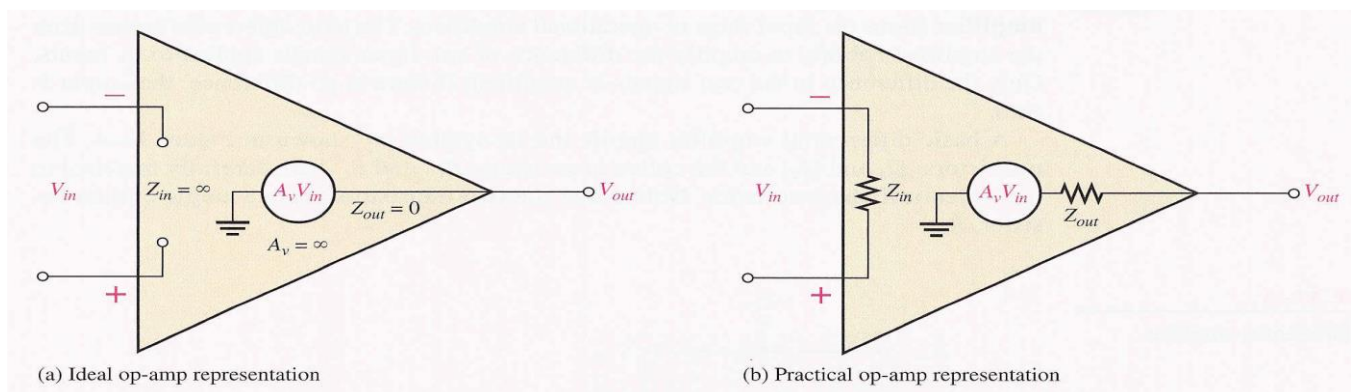


Fig.(5-2).Basic op-amp representations

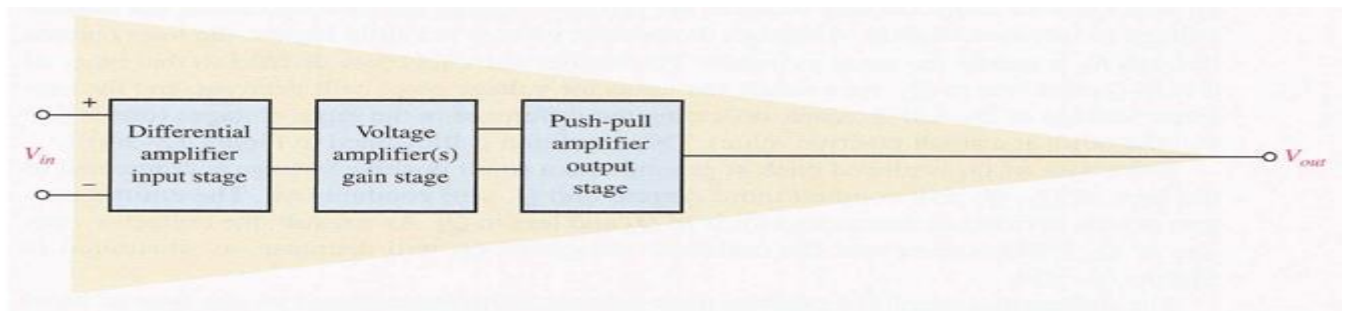
The Practical op-Amp:

Although **integrated circuit (IC)** op-amps approach parameter values that can be treated as ideal in many cases, the ideal device can never be made. Any device has limitations, and the IC op-amp is no exception. Op-amps have both voltage and current limitations. Peak-to-peak output voltage, for example, is usually limited to slightly less than the two supply voltages. Output current is also limited by internal restrictions such as power dissipation and component ratings.

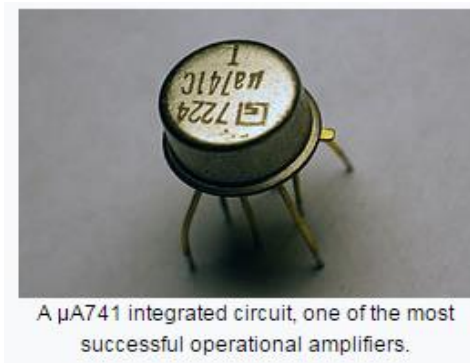
Characteristics of a practical op-amp are *very high voltage gain*, *very high input impedance*, *very low output impedance*, and *wide bandwidth*. Three of these are labelled in Figure (b).

Internal Block Diagram and circuit diagrams of an op-amp :

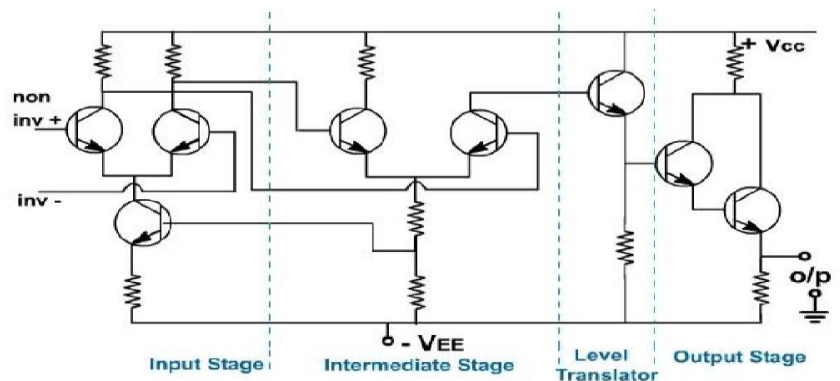
A typical op-amp is made up of three types of amplifier circuit: a differential amplifier, a voltage amplifier, and a push-pull amplifier, as shown in Figure



a). Basic internal arrangement of an op-amp.



b). metal can op-amp $\mu A741$.



c). component –level diagram of op-amp

Fig.(5- 3).Basic internal arrangement of an op-amp and one of the famous op-amp IC.

A differential amplifier is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs. The second stage is usually a class A amplifier that provides additional gain. Some op-amps may have more than one voltage amplifier stage. A push-pull class B amplifier is typically used for the output stage.

Operational Amplifiers Applications:

Op amps are very widely used in electronic devices and can be found in several consumers, industrial and scientific applications. Operational amplifiers started being used in analog computers for mathematical operations in several circuits. Op amps are also widely used as building blocks for circuit design. This is due to the fact that the characteristics of circuits using op amps are set by external components with little dependence on manufacturing variations or temperature changes in the op amp. Other applications include:

- 1). audio- and video-frequency pre-amplifiers and buffers
- 2). differentiators and integrators
- 3). filters
- 4). voltage and current regulators
- 5). analog calculators
- 6). precision rectifiers
- 7). precision peak detectors
- 8). analog-to-digital and digital-to-analog converters
- 9). voltage clamps
- 10). oscillators and waveform generators

The Op-Amp has two inputs and usually one output as shown earlier . The input terminals are labeled **(+)** and **(-)**. A positive (+ve) input voltage at the **(+)** terminal, drives the output towards **+V_{cc}** and a **+ve** input voltage at the negative **(-ve)** terminal drives the output towards **-V_{cc}**.

The approximate values for the Op-Amp parameters are:

Table (5- 1). Approximate values for the Op-Amp parameters

Input Resistance, R _i	2MΩ High
Output Resistance, R _o	100Ω Low
Voltage Gain	1.5x10⁵ High

From the table, it is seen the Op-Amp has close to **ideal characteristics** for an amplifier:

- (a) Very high input resistance: makes the Op-Amp useful as it will not load any preceding circuit stage, i.e. the voltage applied at the input will not be affected.
- (b) Very low output resistance: ensures that the Op-Amp's output will not be loaded by any following stage, i.e. the Op-Amp can be used to drive any following circuit stage.
- (c) Very high voltage gain. The Op-Amp amplifies the voltage difference between its input terminal,

$$V_o = A(V^+ - V^-).$$

The output voltage range depends on the dc power supply **(±V_{cc})**.

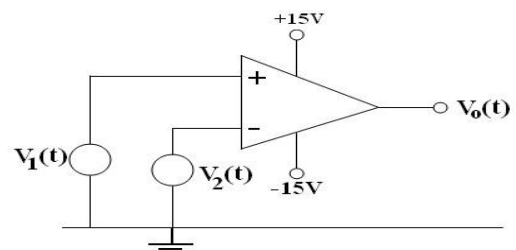
Ex -1 :An Example of Op-Amp Behavior

For the Op-Amp circuit:(Fig.5-4)

$$V_1 = 1 * \sin(100pt)$$

and: $V_2 = 5 * \sin(100pt)$

Fig.(5-4).Differential op-amp



Solution:

The Op-Amp output equation is given by:

$$V_o(t) = A(V^+ - V^-)$$

In this case $V^+ = V_1(t)$, $V^- = V_2(t)$, and since $A = 1.5 \times 10^5$, then

The output voltage $V_o(t) = 1.5 \times 10^5(1 \cdot \sin(100\pi t) - 5 \cdot \sin(100\pi t))$

$$V_o(t) = -6 \times 10^5 \sin(100\pi t)$$

But, the maximum possible output voltage of the Op-Amp is limited by the DC power supply ($\pm V_{cc}$). In this case, the output saturates to the power supply voltage. The output is shown in the figure below.

To find the input voltage, when the Op-Amp's output just saturates:

$$-15V = 1.5 \times 10^5 (V_x)$$

$$V_x = 10^{-4} V$$

$$V_x = 0.1 mV$$

In other words, the Op-Amp has such a high gain that, even if there is a small difference between the input voltages, the output saturates.

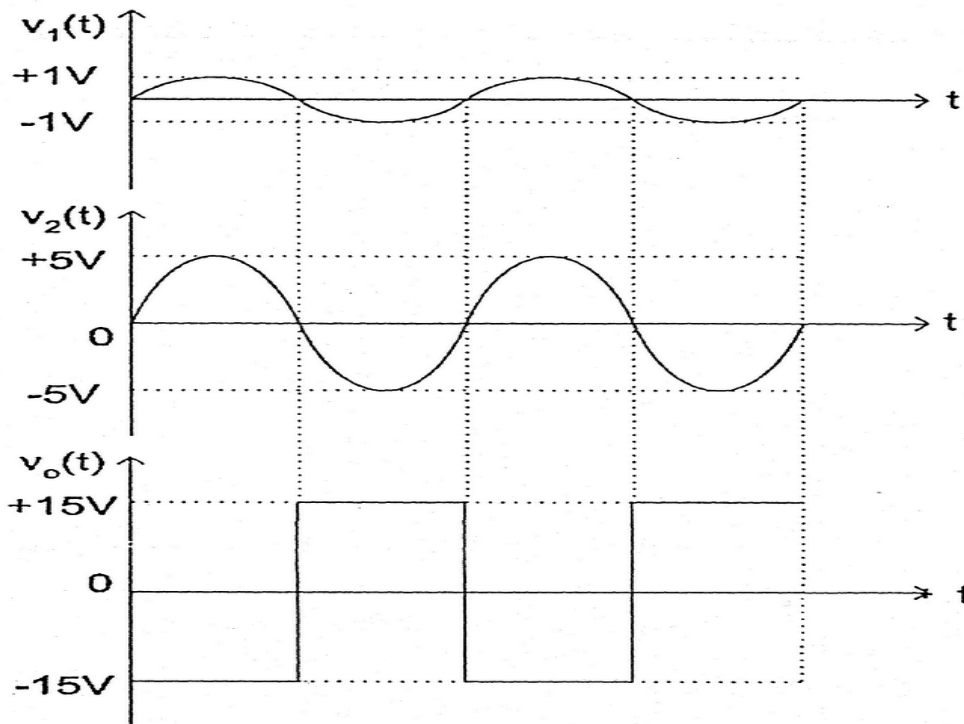


Fig.(5- 5).The inputs and output waveforms of the Ex-1.

5-2: Invertors and Non-Invertors:

Non-Inverting Op-Amp:

Fig. (5-6) shows Op-Amp non-inverting amplifier. The input is applied to the +ve terminal and the output is fed-back to the -ve terminal through R_F and R_1 .

The feedback circuit of R_F and R_1 should ensure that:

$$V_x = 0 \quad \text{or} \quad V^+ - V^- = 0$$

And since $V^+ = V_{in}$, then $V^- = V^+ = V_{in}$

REMEMBER that because of the very high input resistance of Op-Amp, almost no current

flows into the +ve or -ve terminals of the Op-Amp.

To find the value of V^- , consider the feedback circuit. As no current flows into the Op-Amp terminal, the feedback circuit forms a voltage divider supplied by V_o .

$$V^- = \frac{R_1}{R_1 + R_F} V_o$$

Substituting $V^- = V_i$

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

$$V_o = \frac{R_1 + R_F}{R_1} V_i = \left(1 + \frac{R_F}{R_1} \right) V_i$$

Hence, the closed-loop gain, A_{CL} is given by:

The gain, A_{CL} is set only by the feedback resistor.

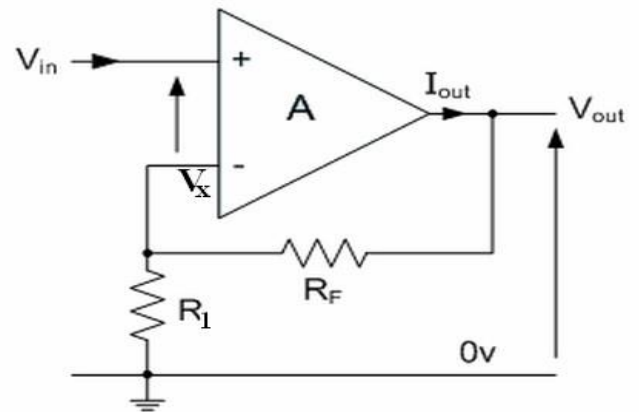


Fig.(5- 6). Non-Inverting Op-Amp.

$$A_{CL} = \left(1 + \frac{R_F}{R_1} \right)$$

Op-Amp Inverting Amplifier

In this circuit, the +ve terminal of the Op-Amp is grounded, $V^+ = 0$. For proper operation, the feedback system tries to keep the difference voltage, V_x at approximately "0V".

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

$$\text{Hence } V^- = 0$$

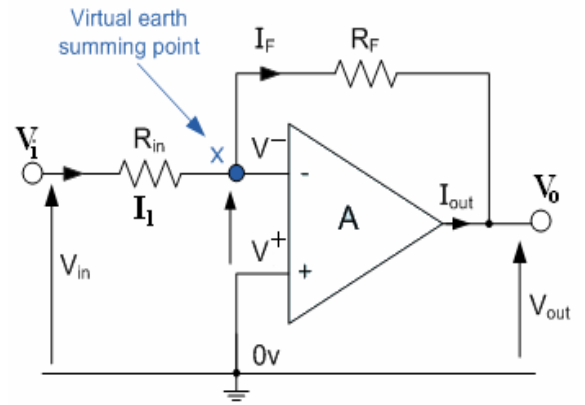


Fig.(5- 7). Inverting Amplifier

Although the (-ve) terminal of the Op-Amp is not connected to physical ground, it is still held at a potential of "0V" because of the circuit conditions. Such a point in the circuit is known as **Virtual Earth**, in this case it behaves as a virtual ground.

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

and
$$I_2 = \frac{V^- - V_o}{R_F} = -\frac{V_o}{R_F}$$

Since no current enters the Op-Amp, because of the high input resistance,

$$I_1 = I_2$$

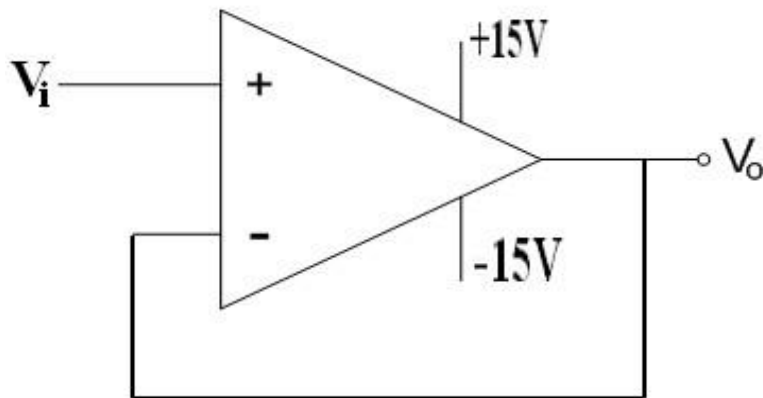
$$\frac{V_1}{R_1} = -\frac{V_o}{R_F}$$

$$A_{CL} = \frac{V_o}{V_1} = -\left(\frac{R_F}{R_1}\right)$$

The **(-ve) sign in the A_{CL} expression** indicates that the amplifier **inverts the input at the output**. The gain is set only by the feedback circuit parameters.

Unity Gain Buffer Amplifier

The unity gain buffer amplifier is essentially a non-inverting Op-Amp amplifier with feedback factor =



$$V^+ = V_i$$

$$V^- = V_o$$

Assuming $V^+ = V^-$

$$V_o \downarrow V_i$$

Fig.(5- 8).Buffer amplifier $A=1$

The Op-Amp unity gain buffer amplifier is a very useful circuit as it has near infinite input impedance and near $0\ \Omega$ output impedance.

5-3: Summer (Adder) and Subtractor:

Summing Amplifier (Inverting Summer Configuration)

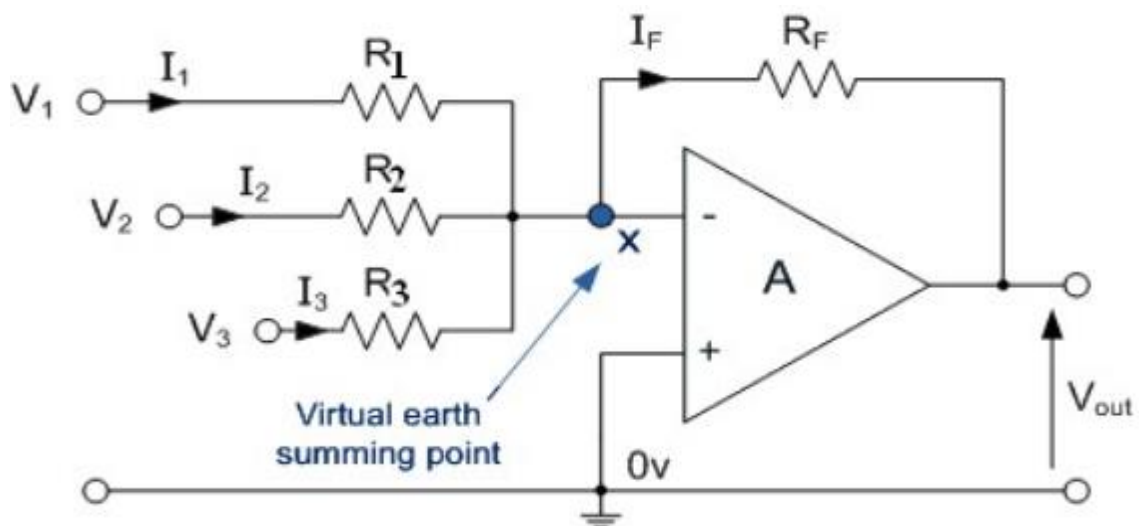


Fig.(5-9).Summing Amplifier

Assuming that the feedback circuit tries to maintain V_x at $0V$, i.e. $V^+ = V^-$.

As V^+ is connected to ground, $V^+ = 0V$, therefore, $V^- = 0V$ (Virtual Ground). Now assuming no current enters the Op-Amp because of very high input impedance, and writing Kirchhoff's

law at the (-ve) terminal of the Op-Amp.
$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_o}{R_F};$$

Rewritten as
$$V_o = -\left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2 + \frac{R_F}{R_3} V_3\right)$$

If $R_1 = R_2 = R_3 = \dots$ the output voltage, V_o becomes

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

The magnitude of the output is the same as the sum of the inputs, but the output is inverted.

Example 5-2 :

Find the expression for the output for the circuit below and sketch the output waveform over 2 cycles.

$$V_o = -\left(\frac{10K}{10K} 1V + \frac{10K}{5K} 0.2 \sin(100\pi t) + \frac{10K}{2K} 0.5 \sin(100\pi t)\right)$$

$$V_o = -(1V + 0.4 \sin(100\pi t) + 2.5 \sin(100\pi t))$$

$$V_o = -(1V + 2.9 \sin(100\pi t))$$

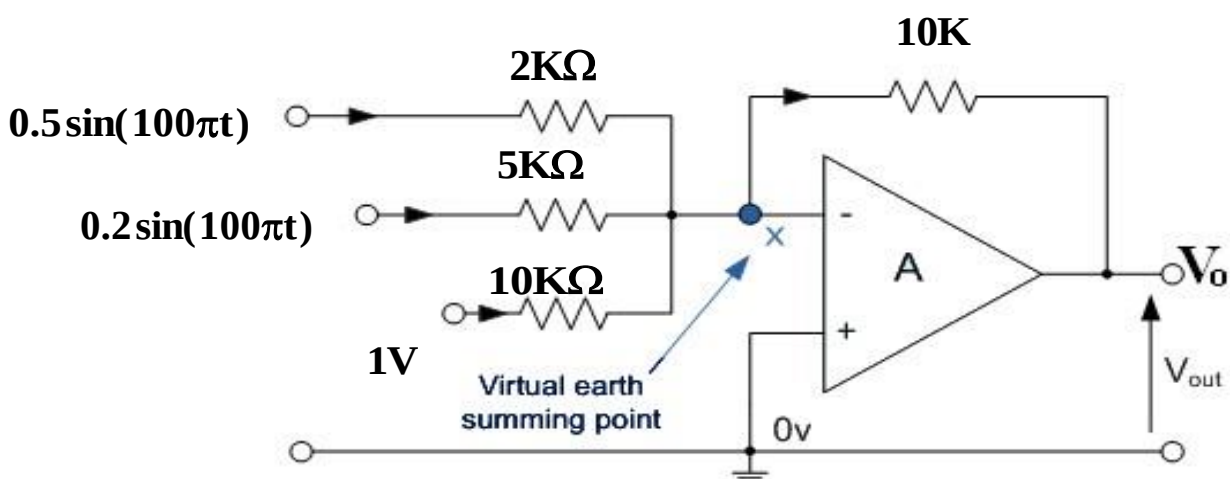


Fig.(5-10).

The plot of the output waveform is shown below:

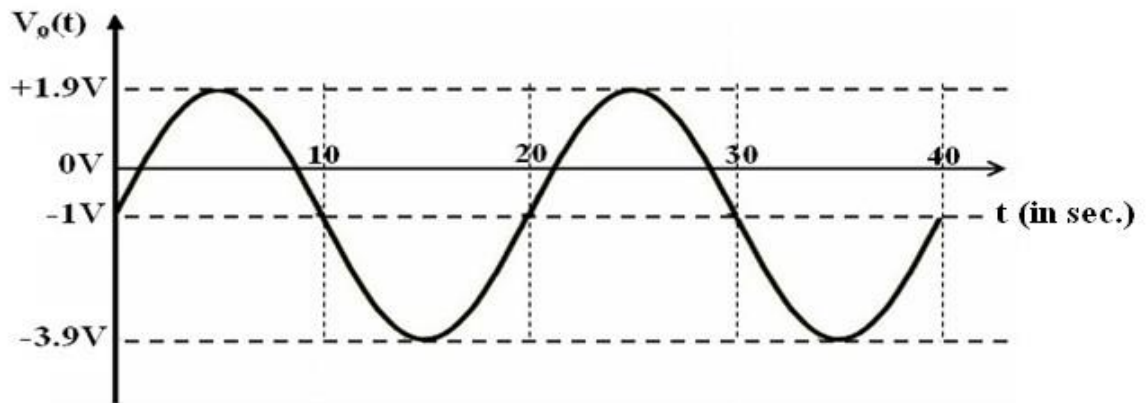


Fig.(5- 11).

5-4: Differentiators and Integrators:

The Op-Amp Differentiator:

The Op-Amp differentiator circuit performs the mathematical operation of differentiation, i.e. the output waveform of the circuit is the derivative of the input waveform.

In simple terms, differentiation of a given curve gives the slope of the curve. If the given curve is only a straight line, then the slope (derivative) is a constant value. For a curve, which is not necessarily a straight line, the slope (derivative) varies along all the different points of the curve, as shown in Fig.(5-12).

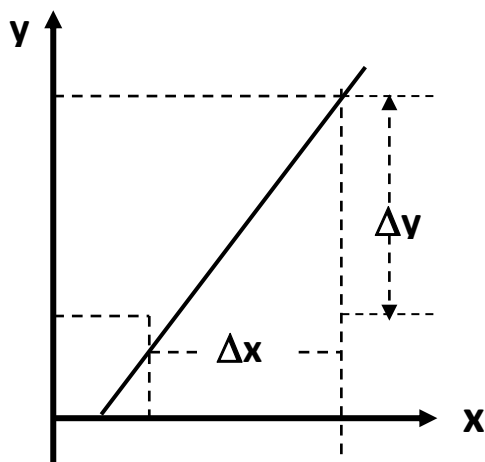
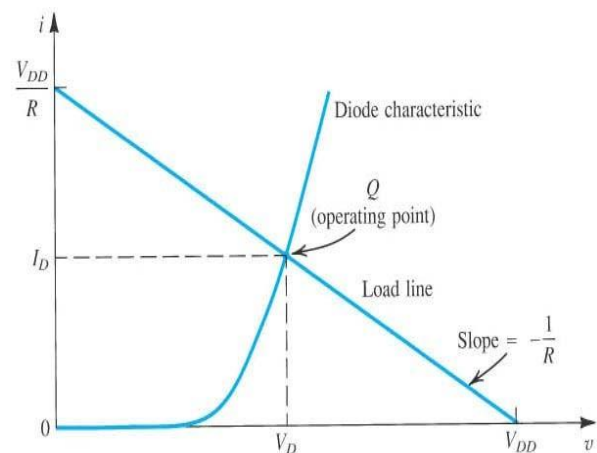


Fig.(5- 12).



$$\frac{dy}{dx} = \frac{\Delta y}{\Delta x} = \text{slope}$$

$\frac{dy}{dx}$ varies all along the curve

The Differentiation Amplifier circuit is shown below, Fig. (5-13):

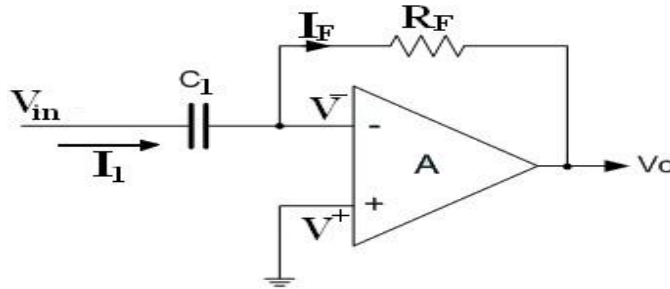


Fig.(5- 13). Differentiation Amplifier circuit

Assuming, that the feedback circuit tries to maintain V_x at 0V, i.e. $V^+ = V^-$. As V^+ is connected to ground, then $V^+ = 0V$, and, $\therefore V^- = 0V$.

Assuming, no current enters the Op-Amp because of very high input impedance, and applying Kirchhoff's circuit laws at the terminal of OP-Amp, then

$$I_1 = I_F \quad C_1 \frac{dV_1}{dt} = \frac{V_o}{R_F} \implies V_o = -R_F C_1 \frac{dV_1}{dt}$$

The Op-Amp Integrator:

The Op-Amp is a circuit in which the output voltage waveform is the integral of the input voltage waveform, as shown below:

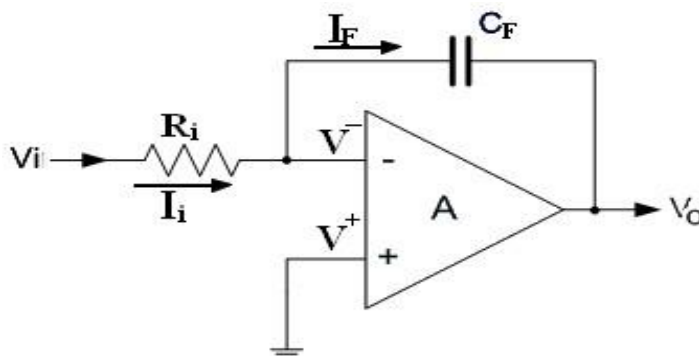


Fig.(5-14).The integrator circuit.

The Op-Amp is built using the inverting amplifier circuit configuration.

Assuming, that the feedback circuit tries to maintain V_x at 0V, i.e. $V^+ = V^-$. As V^+ is connected to ground, then $V^+ = 0V$, and, $\therefore V^- = 0V$.

Assuming, no current enters the Op-Amp because of very high input impedance, and applying Kirchhoff's circuit laws at the terminal of OP-Amp, then

$$I_1 = I_F \quad \frac{V_1}{R_1} = -C_F \frac{dV_o}{dt} \quad \Longrightarrow \quad V_o = -\frac{1}{R_1 C_F} \int_0^t V_1 dt + K$$

Where K is the integration constant and is proportional to the value of the output voltage V_o at time $t = 0$.

Slew Rate, (SR):

Another parameter reflecting the op-amp's ability to handling varying signals is slew rate, defined as slew rate = maximum rate at which amplifier output can change in volts per microsecond (V/ μ s)

$$SR = \frac{\Delta V_o}{\Delta t} \text{ (V / } \mu\text{s)} \quad [t \text{ in } \mu\text{s}]$$

The slew rate provides a parameter specifying the maximum rate of change of the output voltage when driven by a large step-input signal.* If one tried to drive the output at a rate of voltage change greater than the slew rate, the output would not be able to change fast enough and would not vary over the full range expected, resulting in signal clipping or distortion. In any case, the output would not be an amplified duplicate of the input signal if the op-amp slew rate is exceeded.

EXAMPLES

Ex 5-3: Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $R_F = 1 \text{ M}\Omega$ in all cases.

- (a) $V_1=+1V, V_2=+2V, V_3=+3V, R_1=500K\Omega, R_2=1 \text{ M}\Omega, R_3=1 \text{ M}\Omega$
 (b) $V_1=-2V, V_2=+3V, V_3=+1V, R_1=200K\Omega, R_2=500 \text{ K}\Omega, R_3=1 \text{ M}\Omega$

Using the equat
$$V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)$$

$$\begin{aligned}
 \text{(a) } V_o &= -\left[\frac{1000 \text{ k}\Omega}{500 \text{ k}\Omega}(+1 \text{ V}) + \frac{1000 \text{ k}\Omega}{1000 \text{ k}\Omega}(+2 \text{ V}) + \frac{1000 \text{ k}\Omega}{1000 \text{ k}\Omega}(+3 \text{ V}) \right] \\
 &= -[2(1 \text{ V}) + 1(2 \text{ V}) + 1(3 \text{ V})] = -7 \text{ V} \\
 \text{(b) } V_o &= -\left[\frac{1000 \text{ k}\Omega}{200 \text{ k}\Omega}(-2 \text{ V}) + \frac{1000 \text{ k}\Omega}{500 \text{ k}\Omega}(+3 \text{ V}) + \frac{1000 \text{ k}\Omega}{1000 \text{ k}\Omega}(+1 \text{ V}) \right] \\
 &= -[5(-2 \text{ V}) + 2(3 \text{ V}) + 1(1 \text{ V})] = +3 \text{ V}
 \end{aligned}$$

Ex 5-4: Calculate the output voltage of a non-inverting amplifier (as in figure below) for values of:

$$V_1=2\text{V}, R_f=500\text{K}\Omega, \text{ and } R_1=100\text{K}\Omega$$

Solution

From the equation
$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

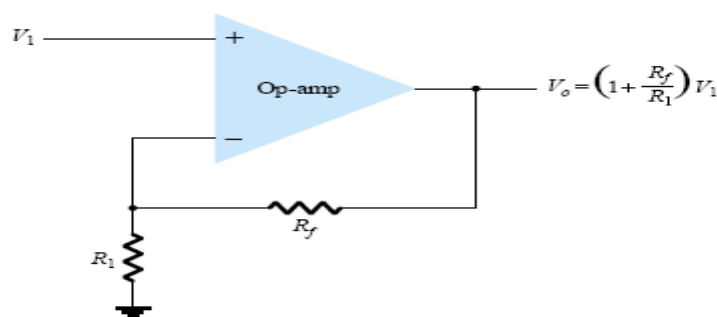


Fig.(5-15).

$$V_o = \left(1 + \frac{R_f}{R_1} \right) V_1 = \left(1 + \frac{500 \text{ k}\Omega}{100 \text{ k}\Omega} \right) (2 \text{ V}) = 6(2 \text{ V}) = +12 \text{ V}$$

Ex 5-5: If the circuit below has $R_1=100\text{K}\Omega$, $R_f=500\text{K}\Omega$, and input voltage of $V_1=2\text{V}$, what is the output voltage?

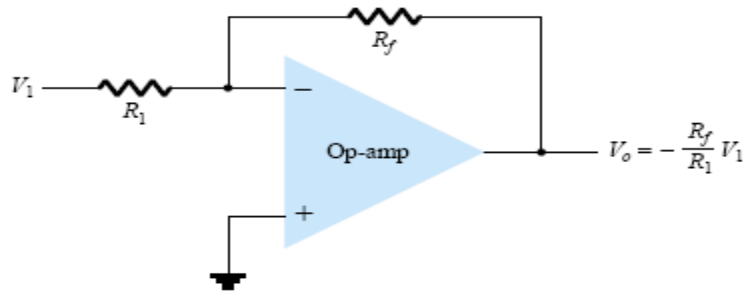


Fig.(5- 16).

From equation
$$V_o = -\frac{R_f}{R_1} V_1 = -\frac{500\text{K}\Omega}{100\text{K}\Omega} (2\text{V}) = -10\text{V}$$

Ex 5-6: For an op-amp having a slew rate of $\text{SR} = 2\text{ V}/\mu\text{s}$, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in $10\mu\text{s}$?

Solution

Since $V_o = A_{\text{CL}} V_i$, we can use the relation $\frac{\Delta V_o}{\Delta t} = A_{\text{CL}} \frac{\Delta V_i}{\Delta t}$ to give

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

Any closed-loop voltage gain of magnitude greater than 40 would drive the output at a rate greater than the slew rate allows, so the maximum closed-loop gain is 40.

Chapter – 6

Oscillators and Integrated Circuits (IC)

6-1: Oscillators**:

Definition: An oscillator is a circuit that is capable of sustaining an ac output signal by converting dc power to ac power (power converter in the sense that its only input is the dc supply potential and its output is a time varying wave form).

Essentially, an **oscillator** converts electrical energy from the dc power supply to periodic waveforms. A basic oscillator is shown in Figure 6-1.

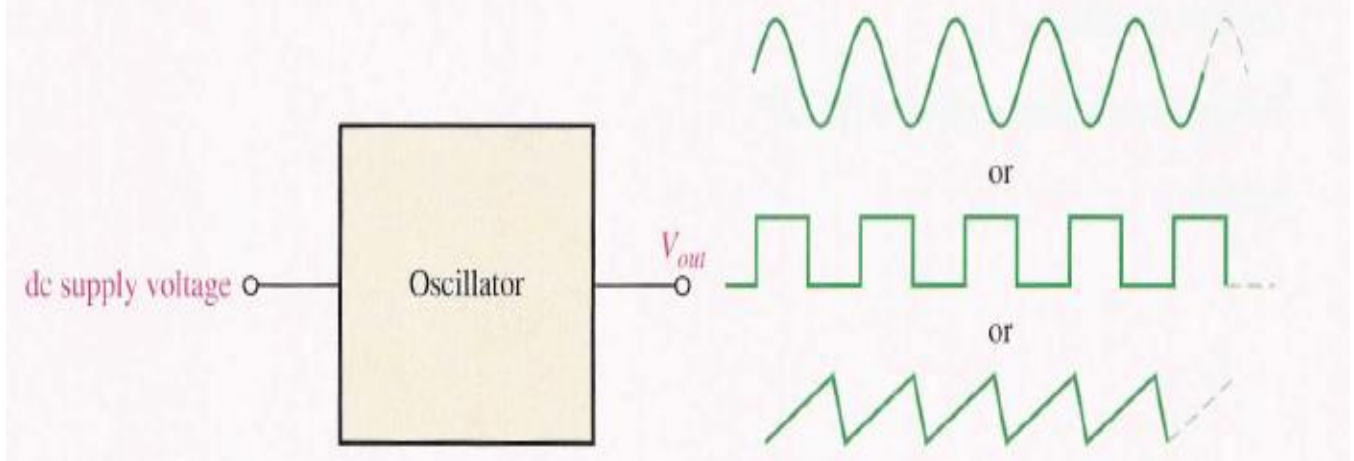


Fig.(6-1).The oscillator with 3 common output waveforms: sine, square and sawtooth.

** From Dr.Muataz Al-Azawi Lectures , Al-Mamoon University College ,2013

Oscillator Types:

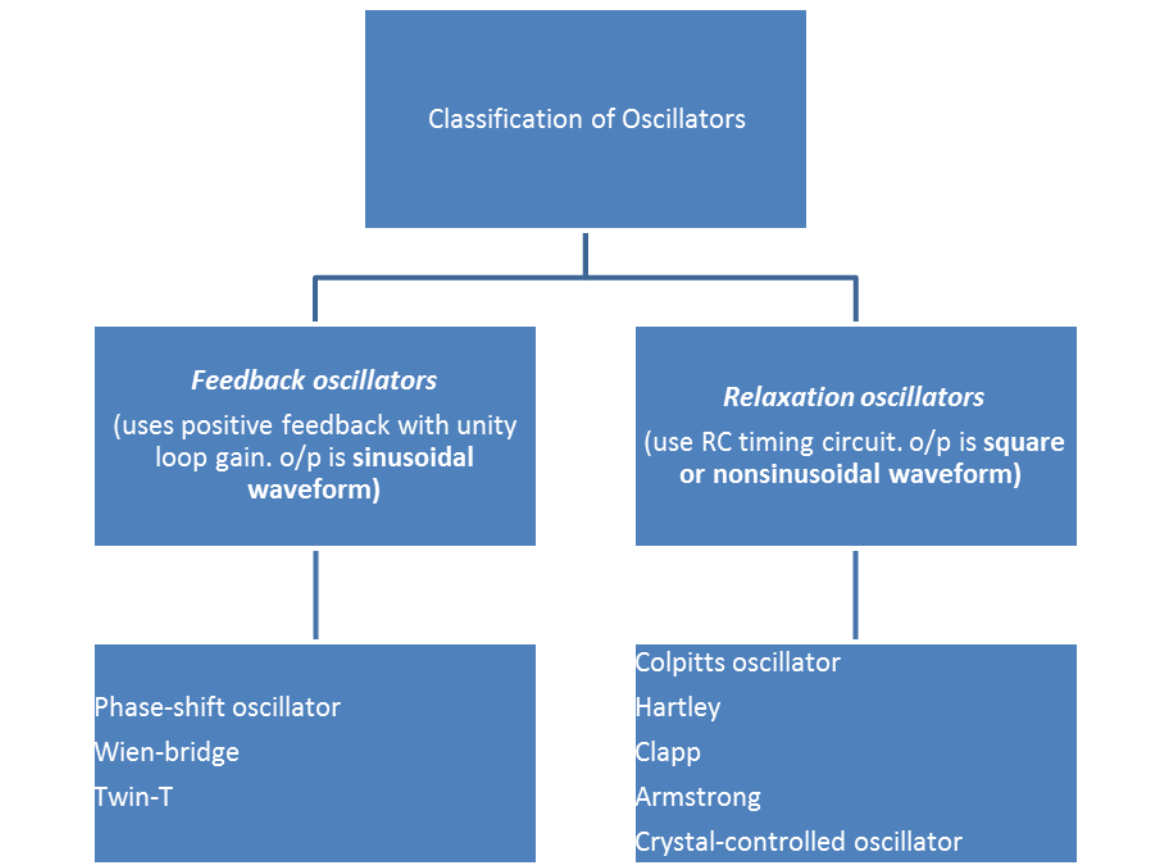


Fig.(6-2). Types of oscillators

1. Feedback (sinusoidal) Oscillators:

Conditions for oscillation:

Two conditions (as shown if Fig. 6-3) are required for sustained state of oscillation:

- The phase shift around the feedback loop must be effectively 0° .
- The voltage gain A_{cl} around the feedback loop must equal 1.

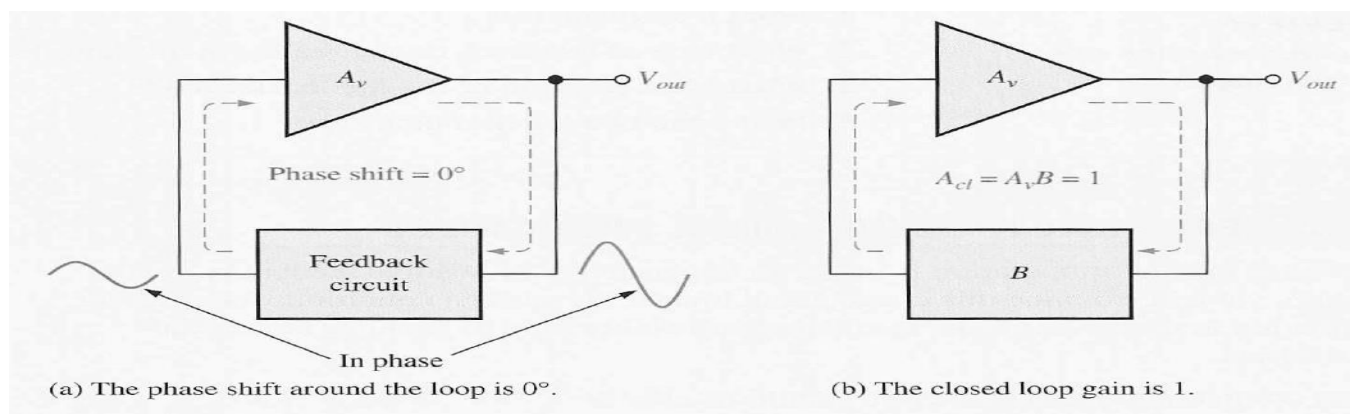


Fig.(6-3).General conditions to sustain oscillation

Phase shift Op-Amp Oscillator:

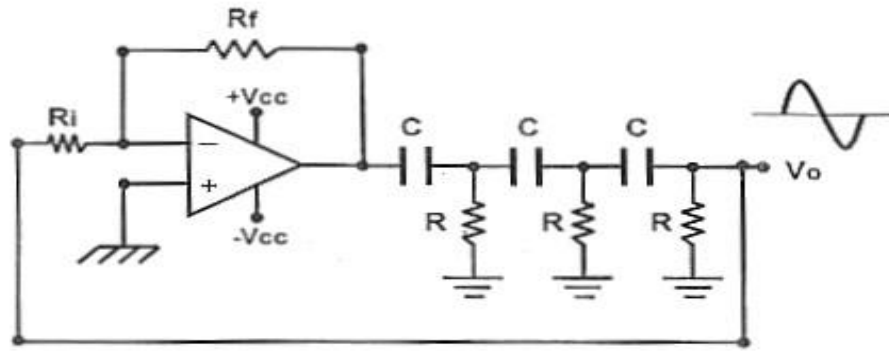


Fig.(6-4). Phase shift Op-Amp Oscillator

Each of the three RC networks in the feedback loop (Fig. 6-4) can provide a maximum phase shift of 60° , oscillation occurs at the frequency where the total phase shift through the three RC networks is 180° . The inversion of the op-amp, itself, provides the additional 180° to meet the requirement for oscillation.

The frequency of oscillation is given by $f_o = \frac{1}{2\pi\sqrt{6} RC}$

The gain for the feedback network, $\frac{-1}{29}$,

and the closed-loop gain must be (≥ -29)

Example 6-1 :

R1

For the circuit shown below, Fig.(6-5):

- Determine the value of R_f necessary for this circuit to operate as an oscillator;
- Determine the frequency of oscillation.

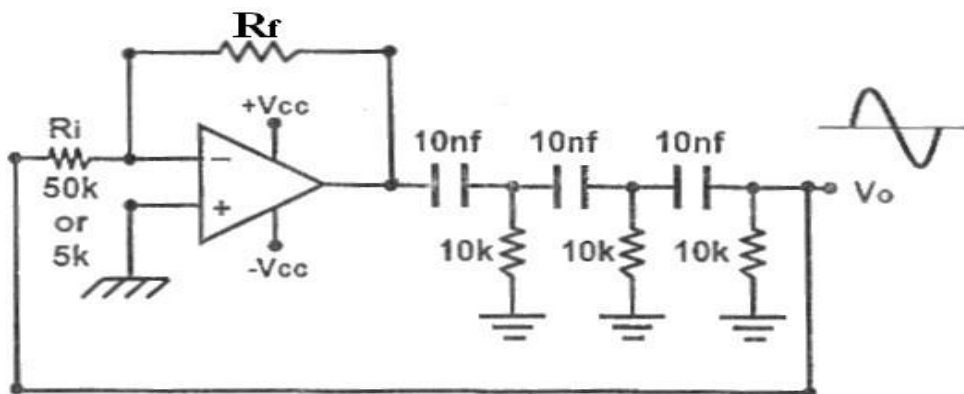


Fig.(6-5).

Solution

$$\beta = \frac{-1}{29} \quad \text{and} \quad (1 - A\beta) = 0 \Rightarrow A = -29$$

(a)

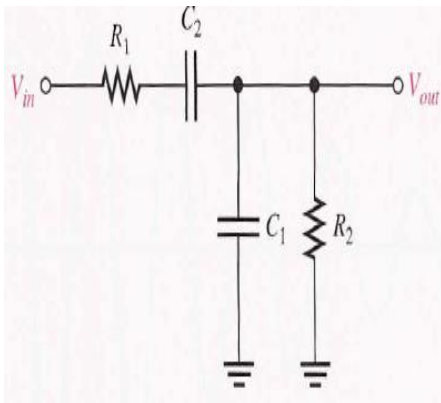
$$A = -\frac{R_f}{R_i} = -29 \Rightarrow R_f = 145\text{k}\Omega$$

(b)

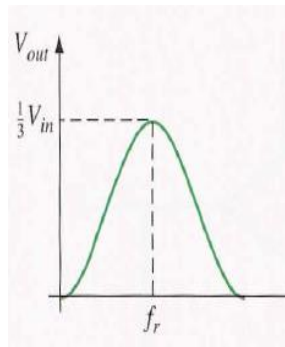
$$f_o = \frac{1}{2\pi\sqrt{6}} \frac{1}{RC} \approx 6.5\text{kHz}$$

Wien-Bridge Oscillator:

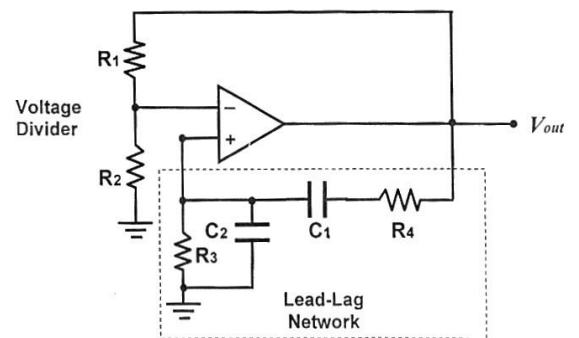
It can be viewed as a noninverting amplifier configuration with the input signal fed back from the output through the lead-lag circuit. Recall that the closed-loop gain of the amplifier is determined by the voltage divider, Fig.(6-6).



a) Lead-Lag circuit



b). Response curve



c). Wien-Bridge Oscillator

Fig. (6-6). Wien-Bridge Oscillator

and C_1 together form the lag portion of the circuit; R_2 and C_2 form the lead portion. The operation of this lead-lag circuit is as follows. At lower frequencies, the lead circuit dominates due to the high reactance of C_2 . As the frequency increases, X_{C2} decreases, thus allowing the output voltage to increase. At some specified frequency, the response of the lag circuit takes over, and the decreasing value of X_{C1} causes the output voltage to decrease.

The response curve for the lead-lag circuit shown in Figure 16-6(b) indicates that the output voltage peaks at a frequency called the resonant frequency, f_r . At this point, the attenuation (V_{out}/V_{in}) of the circuit is $1/3$ if $R_1 = R_2$ and $X_{C1} = X_{C2}$ as stated by the following equation

$$\frac{V_{out}}{V_{in}} = \frac{1}{3}, \text{ and resonant frequency equation:}$$

$$f_r = \frac{1}{2\pi RC}$$

And the closed-loop gain is determined
by the voltage divider:

$$A_{cl} = \frac{1}{B} = \frac{1}{R_2/(R_1 + R_2)} = \frac{R_1 + R_2}{R_2}$$

2. Relaxation (non-sinusoidal) Oscillators:

Colpitts Oscillator

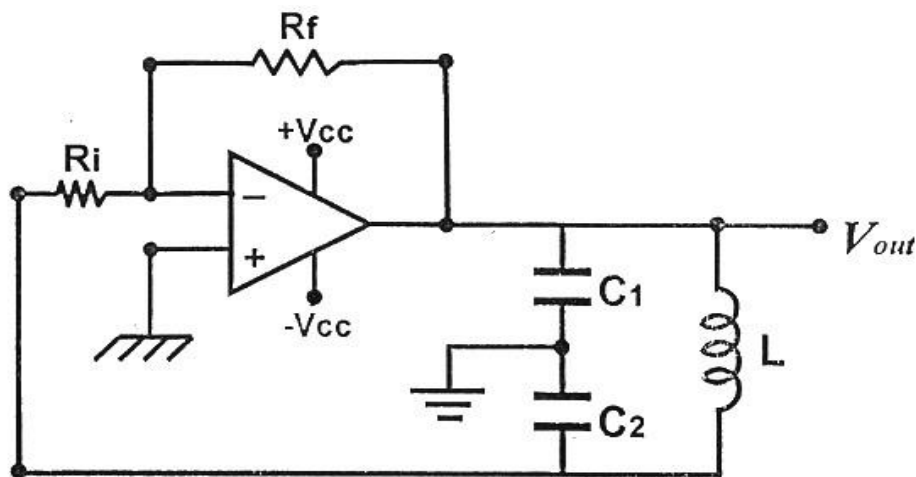


Fig.(6-7). Colpitts Oscillator circuit

The combination of C_1 , C_2 , and L acts as a parallel resonant circuit in the feedback loop and frequency of oscillation, f_o is given by:

$$f_o = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

Where $C_{eq} = \frac{C_1 \times C_2}{C_1 + C_2}$ since C_1 is in series with C_2

The Hartley Oscillator

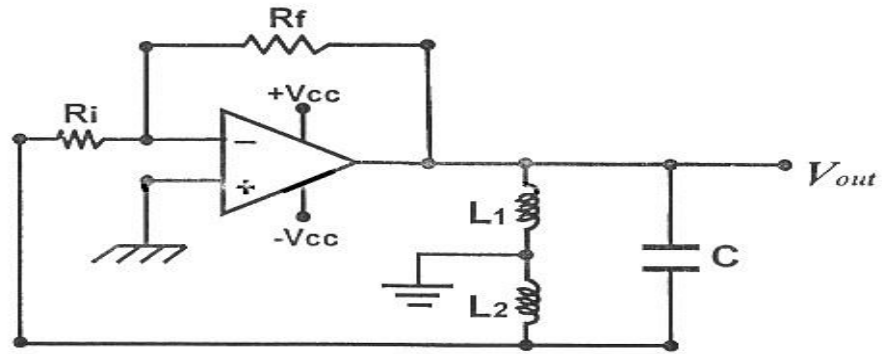


Fig.(6-8). Hartley Oscillator circuit

L_1 and L_2 and C act as a resonant circuit in the feedback loop. The frequency of oscillation is given as:

$$f_o = \frac{1}{2\pi\sqrt{L_{eq}C}}$$

Where $L_{eq} = L_1 + L_2$ since L_1 and L_2 are in series.

6-2: Integrated Circuits:

Integrated Circuits: An integrated circuit (also referred to as an **IC**, a **chip**, or a **microchip**) is a miniature, low cost electronic circuit consisting of active and passive components fabricated together on a single crystal of silicon. The active components are transistors and diodes and passive components are resistors and capacitors.

Advantages of integrated circuits:

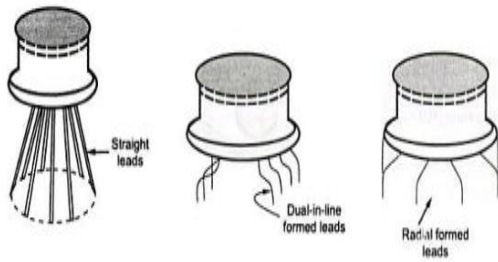
1. Miniaturization and hence increased equipment density.
2. Cost reduction due to batch processing.
3. Increased system reliability due to the elimination of soldered joints.
4. Improved functional performance.
5. Matched devices.
6. Increased operating speeds.
7. Reduction in power consumption

IC Package Types:

The op-amp ICs are available in various packages. The IC packages are classified as,

1. Metal Can
2. Dual In Line (DIP)
3. Flat Pack

Metal Can package:

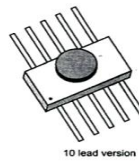


a).metal can

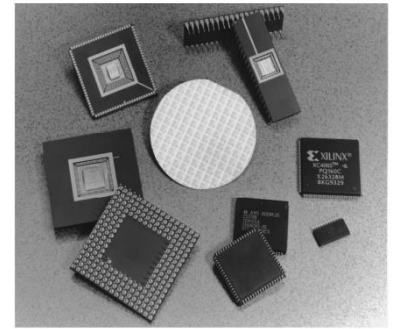
1.5 Dual-in-Line Package:



1.6 Flat Pack:



b). DIP and Flat



c). wafer & different packages

Fig.(6-9).Different IC packages

IC classification :

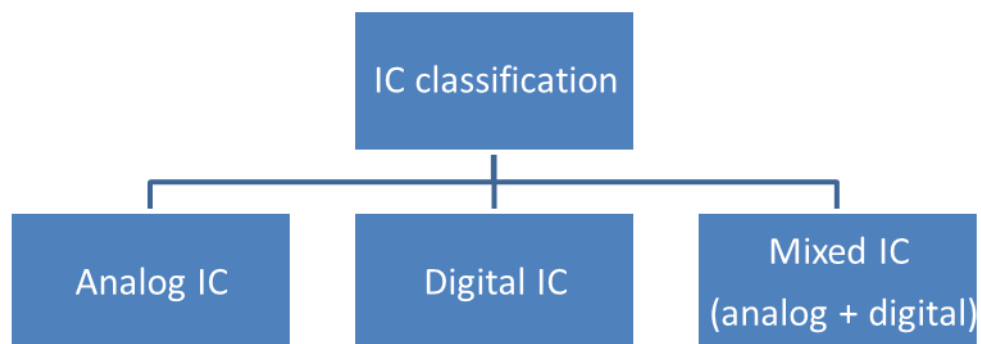


Fig.(6-10).classification of the integrated circuits

IC classification		
Analog IC	Digital IC	Mixed IC (analog + digital)
Analog ICs, such as sensors, power management circuits, and operational amplifiers, work by processing continuous signals. They perform functions like amplification, active filtering, demodulation, mixing, etc.	Digital integrated circuits can contain anything from one to millions of logic gates, flip-flops, multiplexers, and other circuits in a few square millimeters. The small size of these circuits allows high speed, low power dissipation, and reduced manufacturing cost compared with board-level integration. These digital ICs, typically microprocessors, DSPs, and micro controllers work using binary mathematics to process "one" and "zero" signals.	ICs can also combine analog and digital circuits on a single chip to create functions such as A/D converters and D/A converters. Such circuits offer smaller size and lower cost, but must carefully account for signal interference

Technology of IC's:

As shown in Fig.5-11.

IC Generations:

Depending upon the number of active devices per chip, there are different levels of integration

Table (6-1). Levels of IC integration

	Level of integration	Number of active devices per chip
1.	Small scale integration (SSI)	Less than 100
2.	Medium scale integration (MSI)	100 - 10000
3.	Large scale integration (LSI)	1000 - 100,000
4.	Very large scale integration (VLSI)	Over 100,000
5.	Ultra large scale integration (ULSI)	Over 1 million

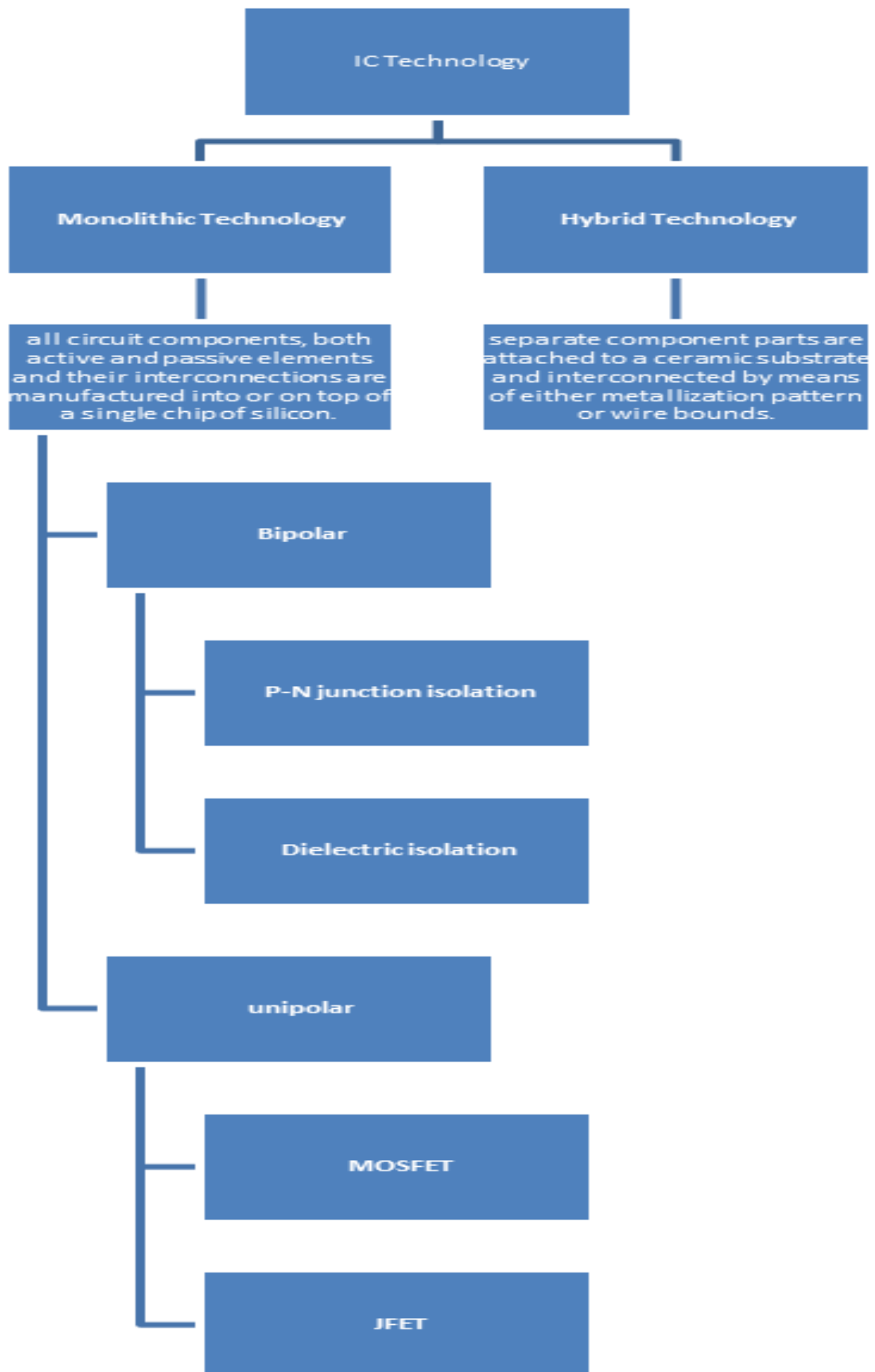


Fig.(6-11).Two types of IC technologies

SSI, MSI and LSI

The first integrated circuits contained only a few transistors. Called "Small-Scale Integration"(SSI), digital circuits containing transistors numbering in the tens provided a few logic gates for example, while early linear ICs such as the Plessey SL201 or the Philips TAA320 had as few as two transistors. The term Large Scale Integration was first used by IBM scientist Rolf Landauer when describing the theoretical concept, from there came the terms for SSI, MSI, VLSI, and ULSI.

The next step in the development of integrated circuits, taken in the late 1960s, introduced devices which contained hundreds of transistors on each chip, called "Medium-Scale Integration" (MSI).

They were attractive economically because while they cost little more to produce than SSI devices, they allowed more complex systems to be produced using smaller circuit boards, less assembly work (because of fewer separate components), and a number of other advantages.

VLSI

The final step in the development process, starting in the 1980s and continuing through the present,

was "very large-scale integration" (VLSI). The development started with hundreds of thousands of transistors in the early 1980s, and continues beyond several billion transistors as of 2007.

In 1986, the first one megabit RAM chips were introduced, which contained more than one million transistors. Microprocessor chips passed the million-transistor mark in 1989 and the billion transistor mark in 2005

ULSI, WSI, SOC and 3D-IC

To reflect further growth of the complexity, the term ULSI that stands for "Ultra-Large Scale Integration" was proposed for chips of complexity of more than 1 million transistors.

Wafer-scale integration (WSI) is a system of building very-large integrated circuits that uses an entire silicon wafer to produce a single "super-chip". Through a combination of large size and reduced packaging, WSI could lead to dramatically reduced costs for some systems, notably massively parallel supercomputers. The name is taken from the term Very-Large-Scale Integration, the current state of the art when WSI was being developed.

System-on-a-Chip (SoC or SOC) is an integrated circuit in which all the components needed for a

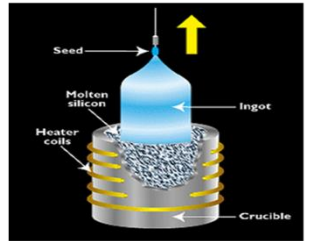
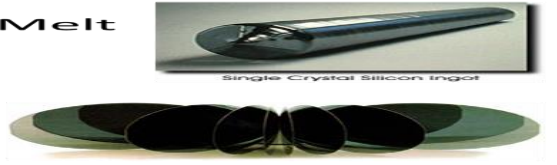
computer or other system are included on a single chip. The design of such a device can be complex and costly, and building disparate components on a single piece of silicon may compromise the efficiency of some elements.

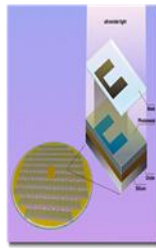
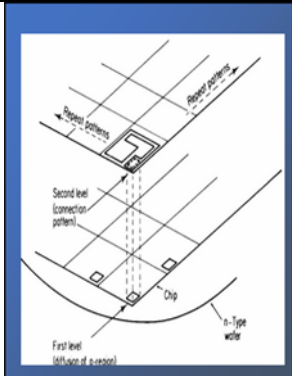
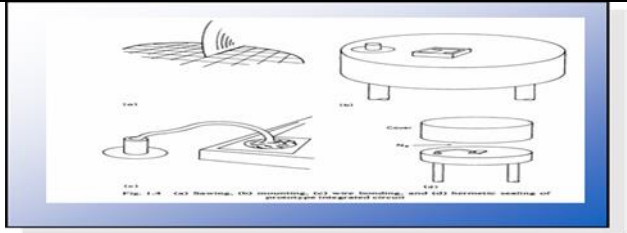
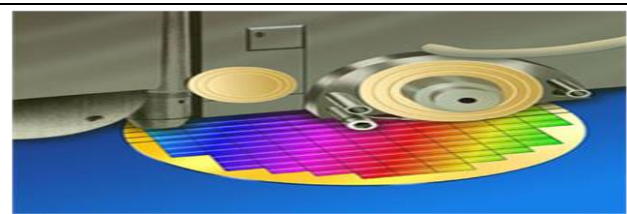
However, these drawbacks are offset by lower manufacturing and assembly costs and by a greatly reduced power budget: because signals among the components are kept on-die, much less power is required. Three-Dimensional Integrated Circuit (3D-IC) has two or more layers of active electronic components that are integrated both vertically and horizontally into a single circuit.

Communication between layers uses on-die signaling, so power consumption is much lower than in equivalent separate circuits. Judicious use of short vertical wires can substantially reduce overall wire length for faster operation.

Designing Steps of Transistor or an IC :Table (6-2) below shows the details

Table (6-2). The design steps of Transistor or IC

Step no.	Design step	details	notes
1.	Material selection	Si , GaAs, or others. Normally using Si : cheap and available	
2.	Purification	External and internal purification of sand from impurities to get pure Si	External : by using sieves , internal by chemical methods
3.	Crystal growth	Using Czochralski (زوكراالسكي) pulling method to get Si single crystal ingot	◆Crucible of Molten Silicon ◆Seed Crystal ◆Dip into melt surface. ◆Withdraw Slowly ◆Cools + Solidifies 
4.	Ingot slicing to wafers	Using diamond saw to slice the ingot to wafers	

5.	Wafer etching & polishing	Using chemical solutions for coarse etching, then mechanical polishing by using diamond paste for one face of wafer												
6.	Batch processing to required circuit	The required electronic circuit map is processed in many steps on the Si wafer such as:	Photolithography ◆Photoresist ◆Quartz Mask ◆UV Light ◆Exposure ◆Development ◆Process ◆Alignment ◆Repeat 											
		<table><tr><td>1. Epitaxial growth</td><td>6. Emitter diffusion</td></tr><tr><td>2. Oxidation</td><td>7. Contact mask</td></tr><tr><td>3. Photolithography</td><td>8. Aluminium metallization</td></tr><tr><td>4. Isolation diffusion</td><td>9. Passivation</td></tr><tr><td>5. Base diffusion</td><td></td></tr></table>			1. Epitaxial growth	6. Emitter diffusion	2. Oxidation	7. Contact mask	3. Photolithography	8. Aluminium metallization	4. Isolation diffusion	9. Passivation	5. Base diffusion	
		1. Epitaxial growth			6. Emitter diffusion									
2. Oxidation	7. Contact mask													
3. Photolithography	8. Aluminium metallization													
4. Isolation diffusion	9. Passivation													
5. Base diffusion														
This map is copied thousand times on wafer														
7.	Wafer slicing to chips (dies)	Wafer is sliced to thousands of dies												
8.	Die mounting & wire bonding	The die is mounted on a base and then soldered with wires to the pins of the base												
9.	Hermetic sealing, marking and testing	A cover is placed on the base for sealing. Then the IC is marked by its number.												

ICs and IC families:

- The [555 timer IC](#)
- The [741 operational amplifier](#)
- [7400 series TTL](#) logic building blocks
- [4000 series](#), the CMOS counterpart to the 7400 series (see also: [74HC00](#))
- [Intel 4004](#), the world's first [microprocessor](#), which led to the famous [8080](#) CPU and then the [IBM PC's 8088, 80286, 486](#) etc.
- The [MOS Technology 6502](#) and [Zilog Z80](#) microprocessors, used in many [home computers](#) of the early 1980s
- The [Motorola 6800](#) series of computer-related chips, leading to the [68000](#) and [88000](#) series (used in some [Apple computers](#) and in the 1980s Commodore [Amiga](#) series).
- The [LM-series](#) of analog integrated circuits.