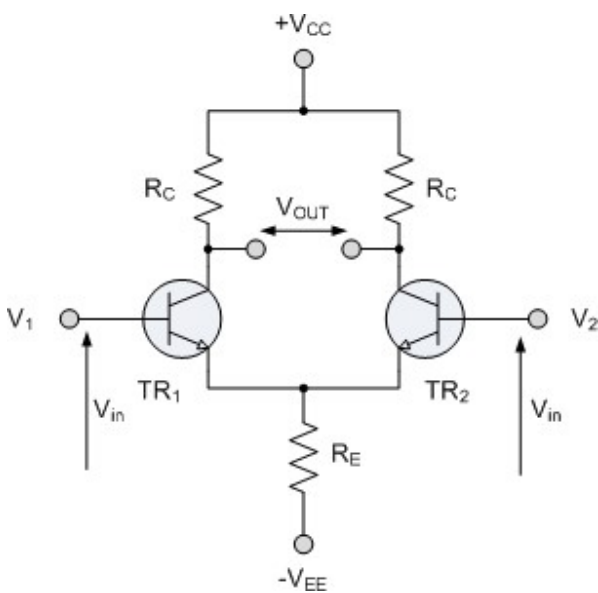# Operational Amplifiers
(Supplementary note)

Ideal Operational Amplifier

As well as resistors and capacitors, **Operational Amplifiers**, or **Op-amps** as they are more commonly called, are one of the basic building blocks of Analogue Electronic Circuits. It is a linear device that has all the properties required for nearly ideal DC amplification and is used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation. An ideal operational amplifier is basically a 3-terminal device that consists of two high impedance inputs, one an **Inverting input** marked with a negative sign, ("-") and the other a **Non-inverting input** marked with a positive plus sign ("+").

The amplified output signal of an Operational Amplifier is the difference between the two signals being applied to the two inputs. In other words the output signal is a *differential* signal between the two inputs and the input stage of an Operational Amplifier is in fact a differential amplifier as shown below.

Differential Amplifier

The circuit shows a generalized form of a differential amplifier with two inputs marked V_1 and V_2. The two identical transistors TR_1 and TR_2 are both biased at the same operating point with their emitters connected together and returned to the common rail, $-V_{EE}$ by way of resistor R_E. The circuit operates from a dual supply $+V_{CC}$ and $-V_{EE}$ which ensures a constant supply. As the two base inputs are out of phase with each other, the output voltage, V_{OUT}, is the difference between the two input signals. So, as the forward bias of transistor TR_1 is increased, the forward bias of transistor TR_2 is reduced and vice versa. Then if the two transistors are perfectly matched, the current flowing through the common emitter resistor, R_E will remain constant.

Ideal Operational Amplifiers have an output of low impedance that is referenced to a common ground terminal and it should ignore any common mode signals. That means, if identical signals are applied to both the inverting and non-inverting inputs there should be no change at the output. However, in real amplifiers there is always some variation and the ratio of the change to the output voltage with regards to the change in the common mode input voltage is called the **Common Mode Rejection Ratio** or **CMRR**.

Operational Amplifiers have a very high open loop DC gain, commonly known as the **Open Loop Differential Gain**, and is given the symbol (A_o). By applying some form of **Negative Feedback** we can produce an operational amplifier circuit with a very precise gain characteristic that is dependent only on the feedback used. An operational amplifier only responds to the difference between the voltages at its two input terminals, known commonly as the "*Differential Input Voltage*" and not to their common potential. Then if the same voltage potential is applied to both terminals the resultant output will be zero.
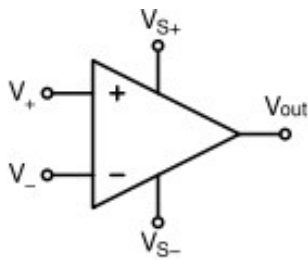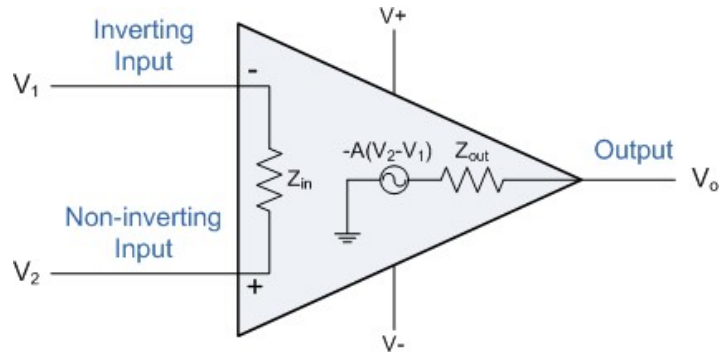
Symbol of OpAmp   **Equivalent Circuit for Ideal OpAmp**

Idealized Characteristics

| PARAMETER	IDEALIZED CHARACTERISTIC
Voltage Gain, (A)	**Infinite** - The main function of an operational amplifier is to amplify the input signal and the more open loop gain it has the better, so for an ideal amplifier the gain will be infinite.
Input impedance, (Z_{in})	**Infinite** - Input impedance is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry.
Output impedance, (Z_{out})	**Zero** - The output impedance of the ideal operational amplifier is assumed to be zero so that it can supply as much current as necessary to the load.
Bandwidth, (BW)	**Infinite** - An ideal operational amplifier has an infinite Frequency Response and can amplify any frequency signal so it is assumed to have an infinite bandwidth.
Offset Voltage, (V_{io})	**Zero** - The amplifiers output will be zero when the voltage difference between the inverting and non-inverting inputs is zero.

It is important to remember two properties known as the **golden rules**, as they help understand the working of the amplifier with regards to analysis and design of operational amplifier circuits.

1. **No current flows into either input terminal** (the current rule)
2. **The differential input offset voltage is zero** (the voltage rule).

However, real **Operational Amplifiers** (e.g. 741) do not have infinite gain or bandwidth but have a typical "Open Loop Gain" which is defined as the amplifiers output amplification without any external feedback signals connected to it and for a typical operational amplifier is about 100dB at DC (zero Hz). This output gain decreases linearly with frequency down to "Unity Gain" or 1, at about 1MHz and this is shown in the following open loop gain response curve. From this frequency response curve we can see that the product of the gain against frequency is constant at any point along the curve. Also that the unity gain (0dB) frequency also determines the gain of the amplifier at any point along the curve. This constant is generally known as the **Gain Bandwidth Product** or **GBP**.

Therefore, GBP = Gain × Bandwidth or A × BW.

Open-loop Frequency Response Curve
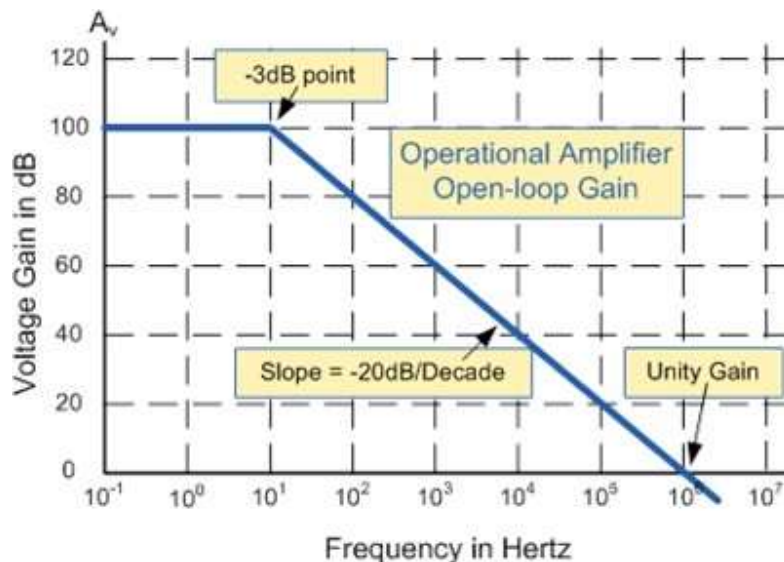
For example, from the graph above the gain of the amplifier at 100kHz = 20dB or 10, then the GBP = 100,000Hz x 10 = 1,000,000.
Similarly, a gain at 1kHz = 60dB or 1000, therefore the
GBP = 1,000 x 1,000 = 1,000,000. **The same!**.

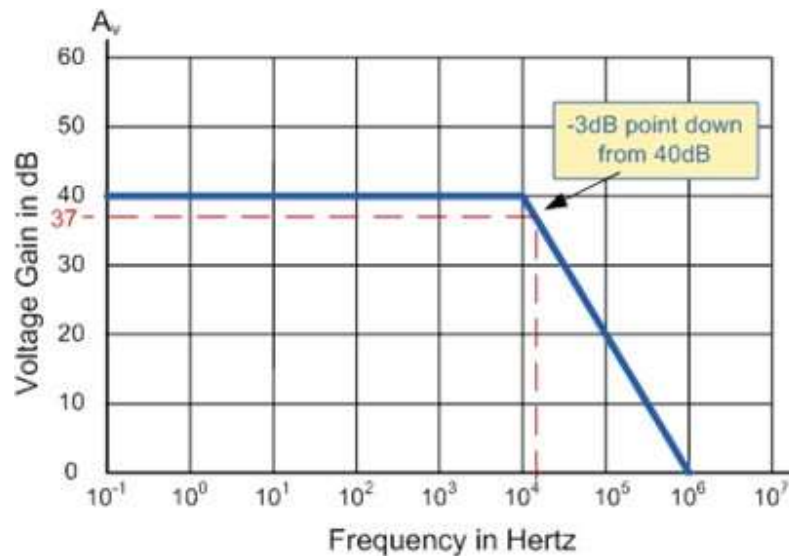The **Voltage Gain** (A) of the amplifier can be found using the following formula:

$$Gain, A = \frac{V_o}{V_i}$$

and in **Decibels** or (dB) is given as:

$$20 \log A = 20 \log \frac{V_o}{V_i}$$

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Bandwidth of Operational Amplifier

The operational amplifiers bandwidth is the frequency range over which the voltage gain of the amplifier is above **70.7%** or **-3dB** (where 0dB is the maximum) of its maximum output value as shown below.

Here we have used the 40dB line as an example. The -3dB or 70.7% of V_{max} down point from the frequency response curve is given as 37dB. Taking a line across until it intersects with the main GBP curve gives us a frequency point just above the 10kHz line at about 12 to 15kHz. We can now calculate this more accurately as we already know the GBP of the amplifier, in this particular case 1MHz.

Example No1.
Using the formula 20 log (A), we can calculate the bandwidth of the amplifier as:
37 = 20 log A therefore, A = anti-log (37 ÷ 20) = 70.8
GBP ÷ A = Bandwidth, therefore, 1,000,000 ÷ 70.8 = 14.124Hz, or 14kHz
Then the bandwidth of the amplifier at a gain of 40dB is given as **14kHz** as predicted from the graph.

Example No2.
If the gain of the operational amplifier was reduced by half to say **20dB** in the above frequency response curve, the -3dB point would now be at 17dB. This would then give us an overall gain of 7.08, therefore **A = 7.08**. If we use the same formula as above this new gain would give us a bandwidth of **141.2kHz**, ten times more than at 40dB.

It can therefore be seen that by reducing the overall open loop gain of an operational amplifier its bandwidth is increased and vice versa. The -3dB point is also known as the "half power point", as the output power of the amplifier is at half its maximum value at this point.

Op-amp types

Operational amplifiers can be connected using external resistors or capacitors in a number of different ways to form basic "Building Block" circuits such as, Inverting, Non-Inverting, Voltage Follower, Summing, Differential, Integrator and Differentiator type amplifiers. There are a very large number of operational amplifier IC's available to suit every possible application.

The most commonly available and used of all operational amplifiers is the industry standard **741** type IC.
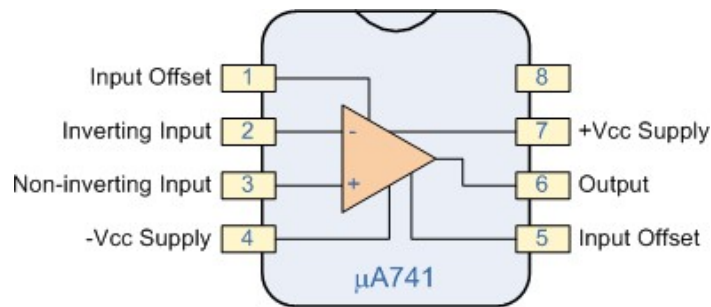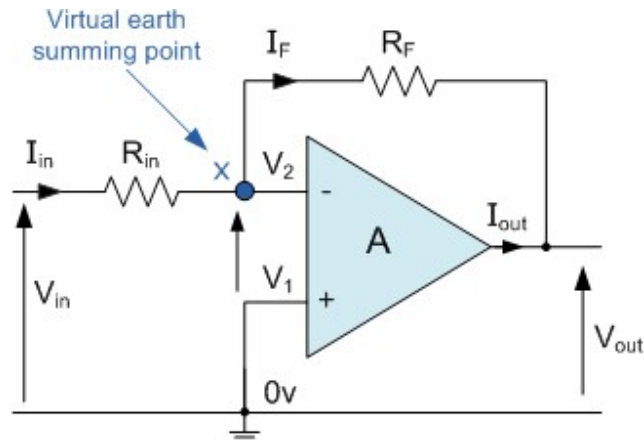

Inverting Amplifier

The open loop gain of an ideal Operational Amplifier can be very high, up to about 1,000,000 (120dB) or more. However, this very high gain is of no real use to us as it makes the amplifier both unstable and hard to control as the smallest of input signals, just a few micro-volts, would be enough to cause the output to saturate and swing towards one or the other of the voltage supply rails losing control. As the open loop DC gain of an operational amplifier is extremely high we can afford to lose some of this gain by connecting a suitable resistor across the amplifier from the output terminal back to the inverting input terminal to both reduce and control the overall gain of the amplifier. This then produces an effect known commonly as **Negative Feedback**, and thus produces a very stable Operational Amplifier system.

Negative Feedback is the process of "feeding back" some of the output signal back to the input, but to make the feedback negative we must feed it back to the "Negative input" terminal using an external **Feedback Resistor** called R_f. This feedback connection between the output and the inverting input terminal produces a closed loop circuit to the amplifier resulting in the gain of the amplifier now being called its **Closed-loop Gain**.

This results in the inverting input terminal having a different signal on it than the actual input voltage as it will be the sum of the input voltage plus the negative feedback voltage giving it the label or term of a *Summing Point*. We must therefore separate the real input signal from the inverting input by using an **Input Resistor**, R_{in}. As we are not using the positive non-inverting input this is connected to a common ground or zero voltage terminal as shown below. But the effect of this closed loop feedback circuit results in the voltage at the inverting input equal to that at the non-inverting input producing a *Virtual Earth* summing point because it will be at the same potential as the grounded reference input.
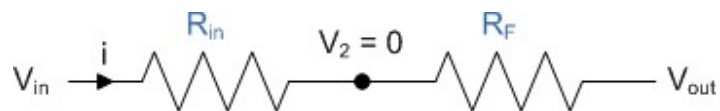
Inverting Amplifier Circuit

Virtual earth summing point

In inverting amplifier circuit the operational amplifier is connected with feedback to produce a closed loop operation. There are two very important rules to remember about inverting amplifiers: "no current flows into the input terminal" and that "V_1 equals V_2". This is because the junction of the input and feedback signal (X) is at the same potential as the positive (+) input which is at zero volts or ground then, the junction is a **"Virtual Earth"**. Because of this virtual earth node the input resistance of the amplifier is equal to the value of the input resistor, R_{in}. Then by using these two rules one can find the equation for calculating the gain of an inverting amplifier, using first principles.

Current (i) flows through the resistor network as shown.

$$i = \frac{V_{in}}{R_{in}} = -\frac{V_o}{R_f}$$

The negative sign in the equation indicates an inversion of the output signal with respect to the input as it is 180° out of phase. This is due to the feedback being negative in value.

Then, the **Closed-Loop Voltage Gain** of an Inverting Amplifier is given as.

$$Gain = \frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}}$$

Example No1
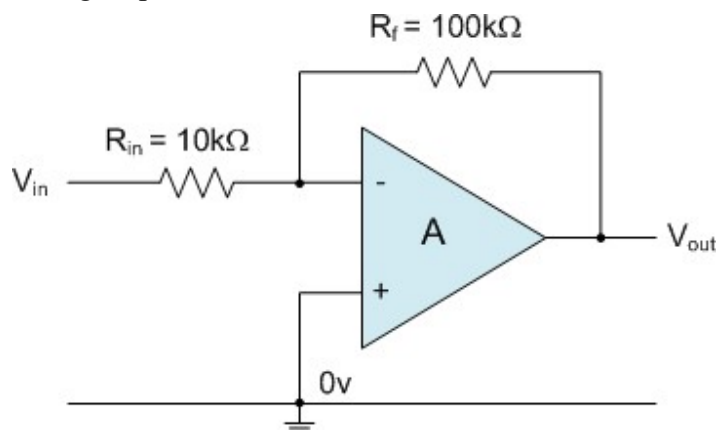Find the closed loop gain of the given inverting amplifier circuit.

Using the previously found formula for the gain of the circuit

$$Gain = \frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}}$$

R_{in} = 10kΩ and R_f = 100kΩ.
Gain = $-R_f/R_{in}$ = 100k/10k = 10.
Therefore, the closed loop gain of the given inverting amplifier circuit is given **10** or **20dB**.

Example No2.
The gain of the original circuit is to be increased to **40**, find the new values of the resistors required.
Assume that the input resistor is to remain at the same value of 10KΩ, then by re-arranging the closed loop voltage gain formula we can find the new value required for the feedback resistor R_f.
Gain = $-R_f/R_{in}$
So, R_f = Gain x R_{in}
Rf = 400,000 or 400KΩ
The new values of resistors required for the circuit to have a gain of **40** would be,
R_{in} = 10KΩ and R_f = 400KΩ.
The formula could also be rearranged to give a new value of R_{in}, keeping the same value of R_f.

Unity Gain Inverter
One final point to note about **Inverting Amplifiers**, if the two resistors are of equal value, R_{in} = R_f then the gain of the amplifier will be **-1** producing a complementary form of the input voltage at its output as V_{out} = $-V_{in}$. This type of inverting amplifier configuration is generally called a **Unity Gain Inverter** of simply an *Inverting Buffer*.

Non-inverting Amplifier

The second basic configuration of an operational amplifier circuit is that of a **Non-inverting Amplifier**. In this configuration, the input voltage signal, (V_{in}) is applied directly to the Non-inverting (+) input terminal which means that the output gain of the amplifier becomes "Positive" in value in contrast to the "Inverting Amplifier" circuit whose output gain is negative in value. Feedback control of the non-inverting amplifier is achieved by applying a small part of the output voltage signal back to the inverting (-) input terminal via a R_f - R_2 voltage divider network, again producing negative feedback. This produces a Non-inverting Amplifier circuit with very good stability, a very high input impedance, R_{in} approaching infinity (as no current flows into the positive input terminal) and a low output impedance, r_{out} as shown below.

Non-inverting Amplifier Circuit
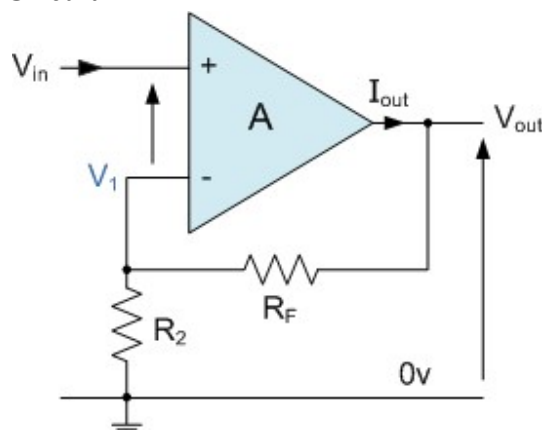
Since no current flows into the input of the amplifier, V_1 = V_{in}. In other words the junction is a **"Virtual Earth"** summing point. Because of this virtual earth node, the resistors R_f

and R_2 form a simple voltage divider network across the amplifier and the voltage gain of the circuit is determined by the ratios of R_2 and R_f as shown below.

Equivalent Voltage Divider Network

Then using the formula to calculate the output voltage of a potential divider network, we can calculate the output Voltage Gain of the **Non-inverting Amplifier** as:

$$V_0 = V_{in}(1 + \frac{R_f}{R_2})$$

$$Gain = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_2}$$
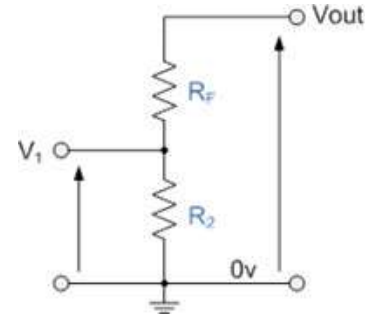
We can see that the overall gain of a Non-Inverting Amplifier is greater but never less than 1, is positive and is determined by the ratio of the values of R_f and R_2. If the feedback resistor R_f is zero the gain will be equal to 1, and if resistor R_2 is zero the gain will approach infinity, but in practice it will be limited to the operational amplifiers open-loop differential gain, (A_o).

Voltage Follower (Unity Gain Buffer)

If we made the feedback resistor, $R_f = 0$ then the circuit will have a fixed gain of "1" and would be classed as a **Voltage Follower**. As the input signal is connected directly to the non-inverting input of the amplifier the output signal is not inverted resulting in the output voltage being equal to the input voltage, $V_{out} = V_{in}$. This then makes the Voltage Follower circuit ideal as a *Unity Gain Buffer* circuit because of its isolation properties as impedance or circuit isolation is more important than amplification. The input impedance of the voltage follower circuit is very high, typically above 1MΩ.
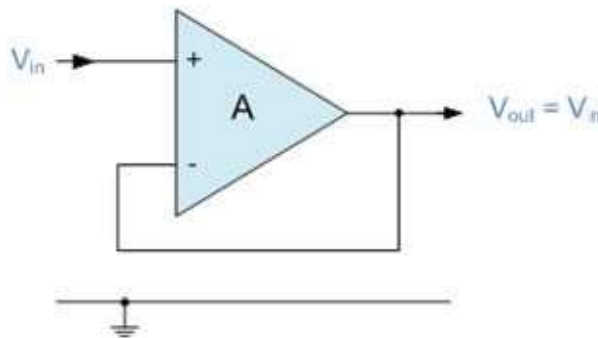
In this circuit, R_{in} has increased to infinity and R_f reduced to zero, the feedback is 100% and V_{out} is exactly equal to V_{in} giving it a fixed gain of 1 or unity. As the input voltage V_{in} is applied to the non-inverting input the gain of the amplifier is given as:

$$V_o = A(V_{in} - V_o)$$

$$V_{in} = V_+ \qquad V_o = V_-$$

$$Gain = \frac{V_o}{V_{in}} = 1$$

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The voltage follower or unity gain buffer is a special and very useful type of **Non-inverting amplifier** circuit that is commonly used in electronics to isolate circuits from each other especially in High-order state variable or Sallen-Key type active filters to separate one filter stage from the other. Typical digital buffer IC's available are the 74LS125 Quad 3-state buffer or the more common 74LS244 Octal buffer.

One final thought, the output voltage gain of the voltage follower circuit with closed loop gain is **Unity**, the voltage gain of an ideal operational amplifier with open loop gain (no feedback) is infinite. Then by carefully selecting the feedback components we can control the amount of gain produced by an Operational Amplifier anywhere from 1 to infinity.

Summing Amplifier

The **Summing Amplifier** is a very flexible circuit based upon the standard *Inverting Operational Amplifier* configuration. We saw previously that the inverting amplifier has a single input signal applied to the inverting input terminal. If we add another input resistor equal in value to the original input resistor, R_{in} we end up with another operational amplifier circuit called a **Summing Amplifier**, "*Summing Inverter*" or even a "*Voltage Adder*" circuit as shown below

Summing Amplifier Circuit
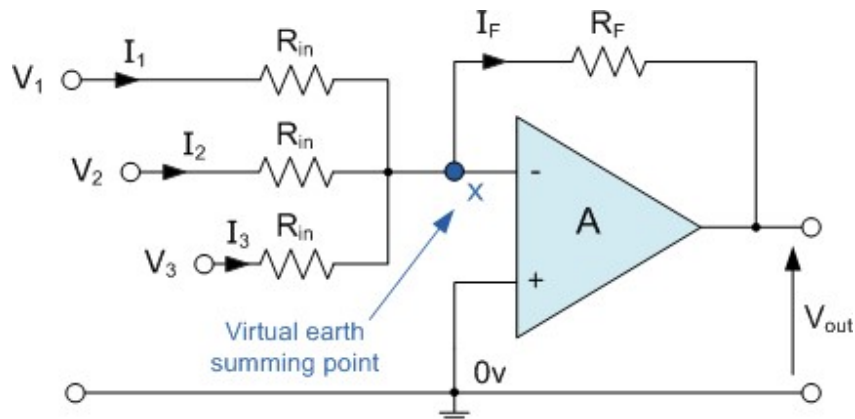
The output voltage, (V_{out}) now becomes proportional to the sum of the input voltages, V_1, V_2, V_3 etc. Then we can modify the original equation for the inverting amplifier to take account of these new inputs thus:

$$I_F = I_1 + I_2 + I_3 = -\left(\frac{V_1}{R_{in}} + \frac{V_2}{R_{in}} + \frac{V_3}{R_{in}} \right)$$

$$\text{then,} \quad V_{out} = -\frac{R_F}{R_{in}}(V_1 + V_2 + V_3)$$

The **Summing Amplifier** is a very flexible circuit indeed, enabling us to effectively "Add" or "Sum" together several individual input signals. If the input resistors are all equal a unity gain inverting adder can be made. However, if the input resistors are of different values a "scaling summing amplifier" is produced which gives a weighted sum of the input signals.

Example No1
Find the output voltage of the following *Summing Amplifier* circuit.
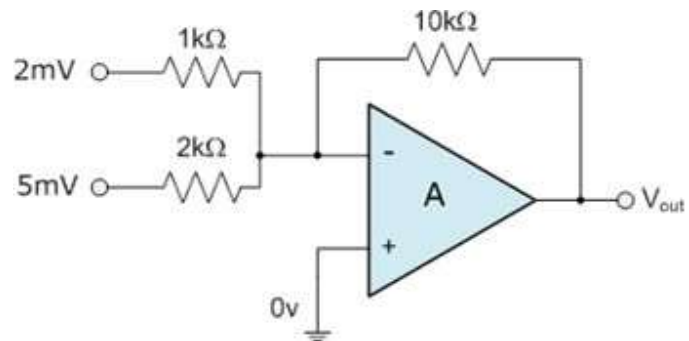The gain of the circuit

$$Gain = \frac{V_o}{V_{in}} = -\frac{R_f}{R_{in}}$$

substituting the values of the resistors,

$$A_1 = \frac{10k\Omega}{1k\Omega} = -10, \qquad A2 = \frac{10k\Omega}{2k\Omega} = -5$$

The output voltage is the sum of the
two amplified input signals:

$$V_o = (-10(2mV)) + (-5(5mV))$$
$$= -45 \, mV$$

If the input resistances of a summing amplifier are connected to potentiometers the individual input signals can be mixed together by varying amounts. For example, for measuring temperature, you could add a negative offset voltage to make the display read "0" at the freezing point or produce an audio mixer for adding or mixing together individual waveforms (sounds) from different source channels (vocals, instruments, etc) before sending them combined to an audio amplifier.

Differential Amplifier

Up to now we have used only one input to connect to the amplifier, using either the "Inverting" or the "Non-inverting" input terminal to amplify a single input signal with the other input being connected to ground. But we can also connect signals to both of the inputs at the same time producing another common type of operational amplifier circuit called a differential amplifier.
The resultant output voltage will be proportional to the "Difference" between the two input signals, V_1 and V_2. This type of circuit can also be used as a subtractor.

Differential Amplifier Circuit
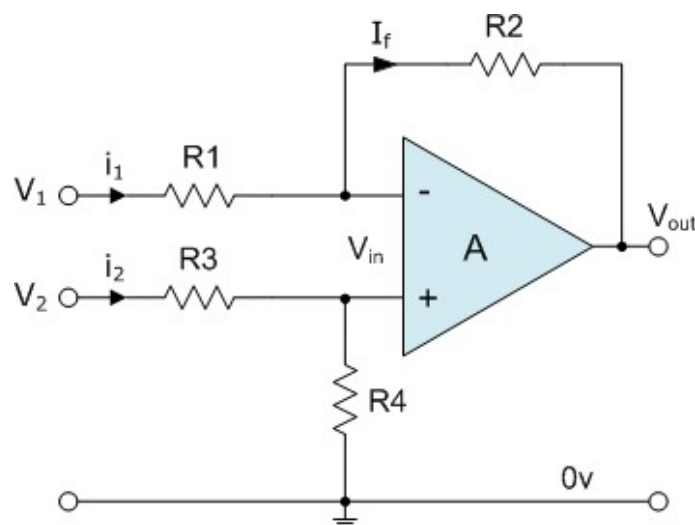
The transfer function for a differential amplifier circuit is given as:

$$V_o = -\frac{R_2}{R_1} V_1 + (1 + \frac{R_2}{R_1})(\frac{R_4}{R_3 + R_4})V_2$$

When R1 = R3 and R2 = R4 the transfer function formula can be modified to the following:

$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

If all the resistors are all of the same ohmic value the circuit will become a **Unity Gain Differential Amplifier** and the gain of the amplifier will be 1 or Unity.

One major limitation of this type of amplifier design is that its input impedances are lower compared to that of other operational amplifier configurations, for example, a non-inverting (single-ended input) amplifier. Each input voltage source has to drive current through an input resistance, which has less overall impedance than that of the op-amps input alone. One way to overcome this problem is to add a *Unity Gain Buffer Amplifier* such as the voltage follower seen in the previous tutorial to each input resistor. This then gives us a differential amplifier circuit with very high input impedance and is the basis for most "Instrumentation Amplifiers", mainly used to amplify very small differential signals from strain gauges, thermocouples or current sensing resistors in motor control systems.

The Integrator Amplifier

Till now we saw how an operational amplifier can be used as part of a positive or negative feedback amplifier or as an adder or subtractor type circuit using pure resistors in both the input and the feedback loop. But what if we were to change the purely Resistive (R_f) feedback element of an inverting amplifier to that of a reactive element, such as a *Capacitor, C.* We now have a resistor and capacitor combination forming an *RC Network* across the operational amplifier as shown below.

Integrator Amplifier Circuit
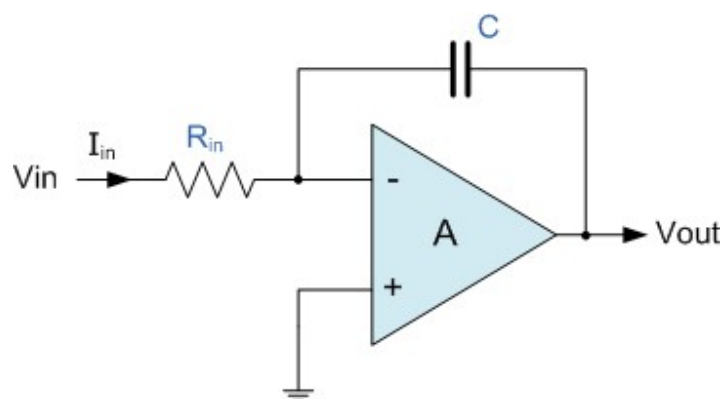

The integrator amplifier performs the mathematical operation of **integration**, that is, we can cause the output to respond to changes in the input voltage over time and the integrator amplifier produces a voltage output which is proportional to that of its input voltage with respect to time. In other words the magnitude of the output signal is determined by the length of time a

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voltage is present at its input as the current through the feedback loop charges or discharges the capacitor.

When a voltage, V_{in} is firstly applied to the input of an integrating amplifier, the uncharged capacitor C has very little resistance and acts a bit like a short circuit (voltage follower circuit) giving an overall gain of less than 1, thus resulting in zero output. As the feedback capacitor C begins to charge up, the ratio of Z_f/R_{in} increases producing an output voltage that continues to increase until the capacitor is fully charged. At this point the ratio of feedback capacitor to input resistor (Z_f/R_{in}) is infinite resulting in infinite gain and the output of the amplifier goes into saturation as shown in the diagram. (Saturation is when the output voltage of the amplifier swings heavily to one voltage supply rail or the other with no control in between).
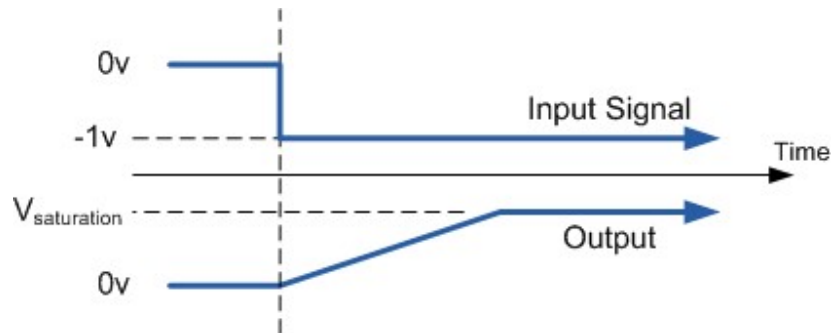
The rate at which the output voltage increases (the rate of change) is determined by the value of the resistor and the capacitor, "RC time constant". By changing this RC time constant value, either by changing the value of the Capacitor, C or the Resistor, R, the time in which it takes the output voltage to reach saturation can also be changed.
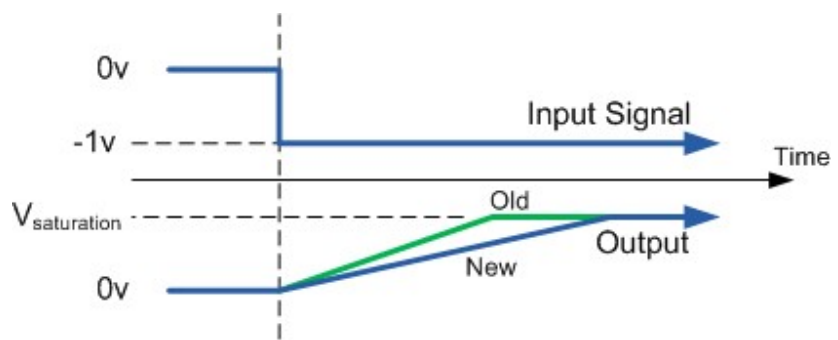
If we apply a constantly changing input signal such as a square wave to the input of an **Integrator Amplifier** then the capacitor will charge and discharge in response to changes in the input signal. This results in an output signal with a sawtooth waveform and its frequency is dependent upon the time constant (RC) of the circuit. This type of circuit is also known as a **Ramp Generator** and the transfer function is given below.
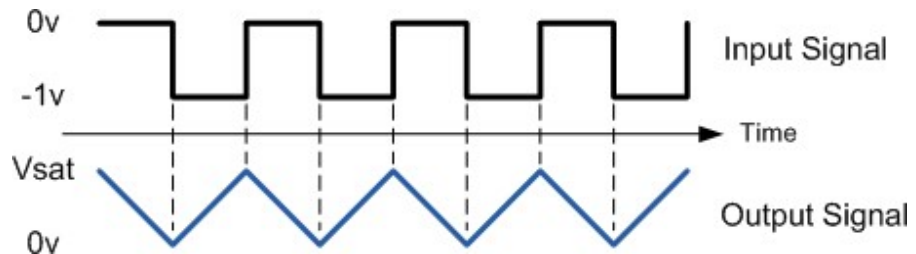
Since the node voltage of the integrating op-amp at its inverting input terminal is zero, the current I_{in} flowing through the input resistor is given as:

$$I_{in} = \frac{V_{in}}{R}$$

The current flowing through the feedback capacitor C is given as:

$$I_{in} = C\frac{dV_{out}}{dt}$$

Assuming that the input impedance of the op-amp is infinite (ideal op-amp), no current flows into the op-amp terminal. Therefore, the nodal equation at the inverting input terminal is given as:

$$\frac{V_{in}}{R} = C\frac{dV_{out}}{dt} = 0$$

From which we have an ideal voltage output for the Integrator Amplifier as:

$$V_{out} = -\frac{1}{RC}\int V_{in}\,dt = -\frac{1}{j\omega RC}V_{in}$$

Where $j\omega = 2\pi f$ and the output voltage V_{out} is a constant 1/RC times the integral of the input voltage V_{in} with respect to time. The minus sign (-) indicates a 180^0 phase shift because the input signal is connected directly to the inverting input terminal of the op-amp.

Active Low Pass Filter

If we changed the above square wave input signal to that of a sine wave of varying frequency the **Integrator Amplifier** begins to behave like an active "Low Pass Filter", passing low frequency signals while attenuating the high frequencies. However, at DC (0Hz) the capacitor acts like an open circuit blocking any feedback voltage resulting in zero negative feedback from the output back to the input of the amplifier. Then the amplifier effectively is connected as a normal open-loop amplifier with very high open-loop gain resulting in the output voltage saturating.

The addition of a large value resistor, R_2 across the capacitor, C gives the circuit the characteristics of an inverting amplifier with finite closed-loop gain of R_2/R_{in} at very low frequencies while acting as an integrator at higher frequencies. This then forms the basis of an *Active Low Pass Filter*.
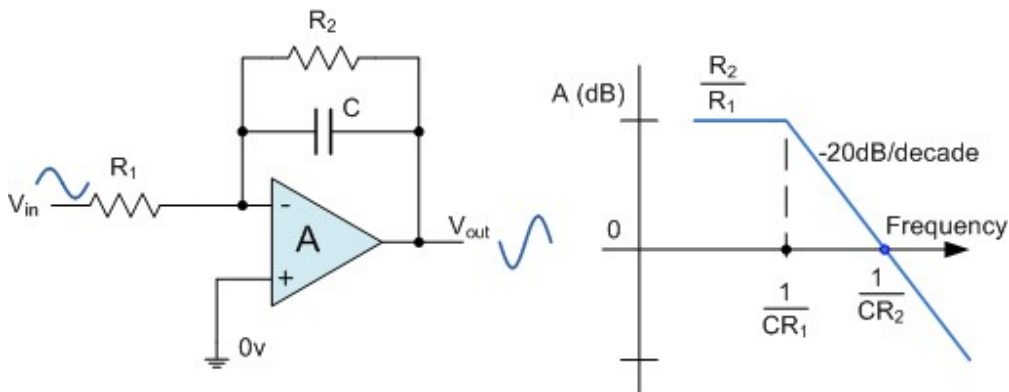

The AC Integrator with DC Gain Control

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The Differentiator Amplifier

The basic differentiator amplifier circuit is the exact opposite to that of the *Integrator* operational amplifier circuit. Here, the position of the capacitor and resistor have been reversed and now the Capacitor, C is connected to the input terminal of the inverting amplifier while the Resistor, R$_f$ forms the negative feedback element across the operational amplifier. This circuit performs the mathematical operation of **Differentiation**, i.e. it produces a voltage output which is proportional to **rate-of-change** of the input voltage and the current flowing through the capacitor. In other words the faster or larger the change to the input voltage signal, the greater the input current, the greater will be the output voltage change in response becoming more of a "spike" in shape.

As with the integrator circuit, we have a resistor and capacitor forming an RC Network across the operational amplifier and the reactance (Xc) of the capacitor plays a major role in the performance of a differentiator amplifier.

Differentiator Amplifier Circuit
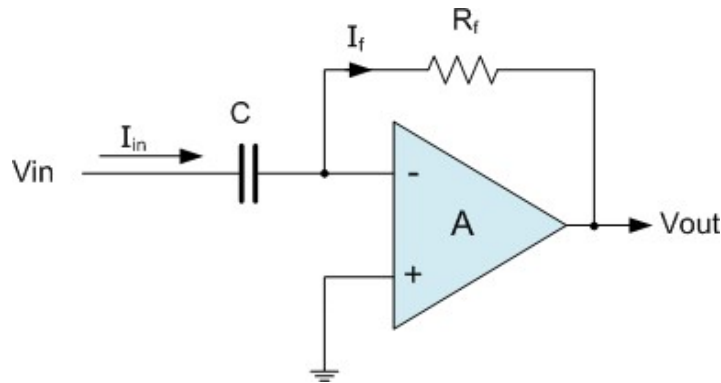
Since the node voltage of the operational amplifier at its inverting input terminal is zero, the current, i flowing through the capacitor will be given as:

$$i_{IN} = I_F \quad \text{and} \quad I_F = -\frac{V_o}{R_F}$$

The Charge on the Capacitor = Capacitance x Voltage across the Capacitor

$$Q = C \times V_{IN}$$

The rate of change of this charge is

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

but dQ/dt is the capacitor current i

$$i_{IN} = C\frac{dV_{IN}}{dt} = I_F$$

From which we have an ideal voltage output for the Differentiator Amplifier is given as:

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$$V_O = -R_F C \frac{dV_{IN}}{dt}$$

Therefore, the output voltage V_{out} is a constant $-R_f.C$ times the derivative of the input voltage V_{in} with respect to time. The minus sign indicates a 180^0 phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.

Active High Pass Filter

The capacitor blocks any DC content only allowing AC type signals whose frequency is dependent on the rate of change of the input signal, to pass through. At low frequencies the reactance of the capacitor is "High" resulting in a low gain (Rf/Xc) and low output voltage from the op-amp. At higher frequencies the reactance of the capacitor is much lower resulting in a higher gain and higher output voltage from the differentiator amplifier. Thus with sinusoidal wave at the input this circuit will act as an active high pass filter circuit.

The basic single resistor and single capacitor differentiator circuit is not widely used to reform the mathematical function of differentiation because of the two inherent faults mentioned above: Instability and Noise.

At high frequencies a differentiator circuit becomes unstable and will start to oscillate. To avoid this, the high frequency gain of the circuit needs to be reduced by adding an additional small value capacitor, C_f, across the feedback resistor R_f. Also, the capacitive input makes it very susceptible to random noise signals and any noise or harmonics present in the circuit will be amplified more than the input signal itself. This is because the output is proportional to the slope of the input voltage. So some means of limiting the bandwidth in order to achieve closed-loop stability is required. In order to reduce the overall closed-loop gain of the circuit at high frequencies, an extra Resistor, R_{in} is added to the input as shown below. Thus, the new circuit acts like a Differentiator amplifier at low frequencies and an amplifier with resistive feedback at high frequencies giving much better noise rejection.
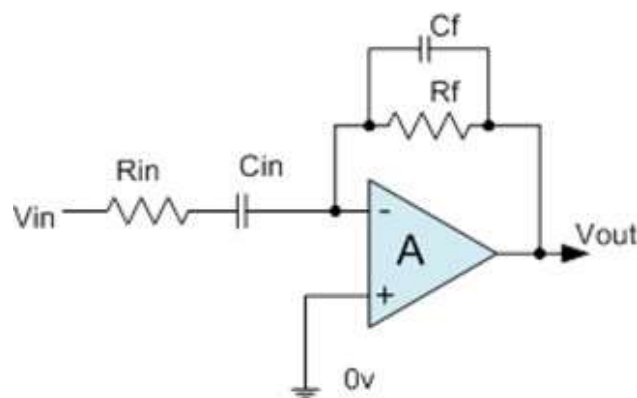
Differentiator Waveforms

If we apply a constantly changing signal such as a Square-wave, Triangular or Sine-wave type signal to the input of a differentiator amplifier circuit the resultant output signal will be changed and whose final shape is dependent upon the RC time constant of the Resistor/Capacitor combination.

16
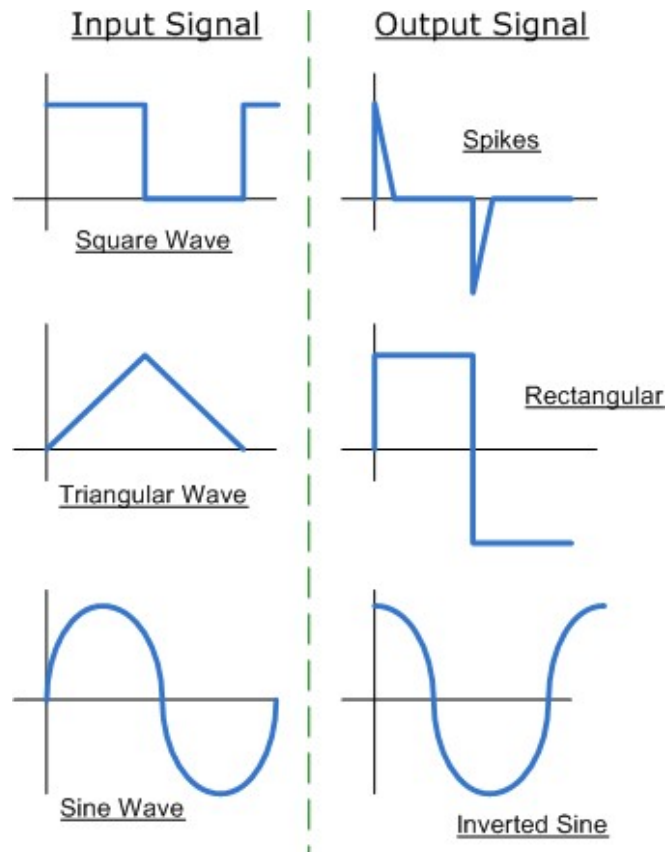
Lab# 1(A): Study of Basic OPAMP Configurations and Simple Mathematical Operations

Objectives:

(I)   Study of the inverting amplifier configuration and to find its gain
(II) Study of the non-inverting amplifier configuration and to find its gain
(III) Study simple mathematical operation and design an averaging amplifier

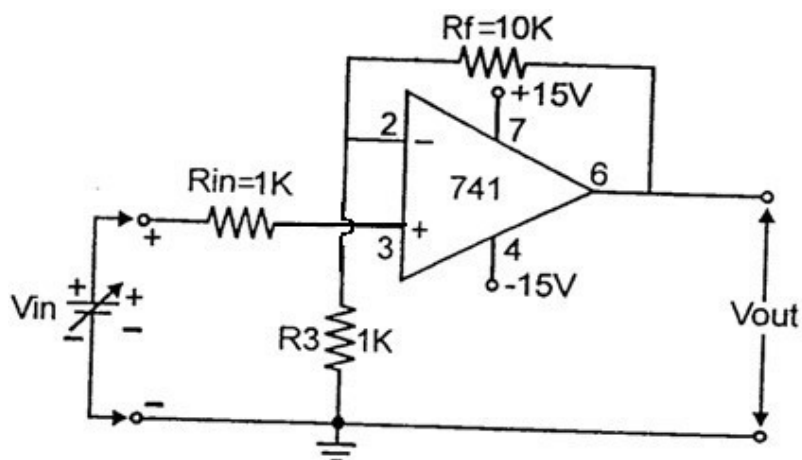**Components:** OPAMP 741 chip, Resistors, Oscilloscope, DC voltage source, Bread board

Theory: Please refer the supplementary note.

Circuit Diagram:
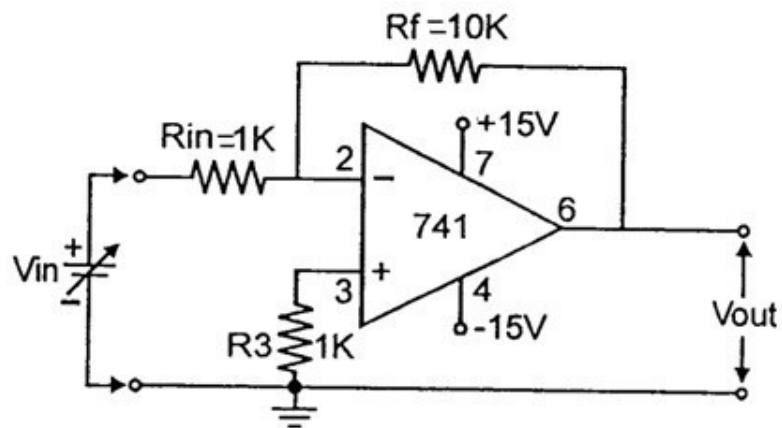
Inverting amplifier

Non-inverting amplifier

Procedure:

(I) Inverting amplifier

1. Configure the circuit as shown in the circuit diagram. Connect the pins 7 and 4 of the IC to the ±15V output terminals of the D.C. power supply. Connect the 0V terminal to ground. Choose R_{in} = 1KΩ and R_f = 10KΩ. Measure the resistance values with multimeter and calculate gain, $-(R_f/R_{in})$. Connect a resistor R_3 (= $R_{in} \| R_f \approx R_{in}$) as shown in the circuit diagram so as to minimize offset due to input bias current.
2. **Connect one of the output terminals of the D.C. power supply (0-30V) at the inverting input (pin no. 2).**
3. Switch on the power supply and apply different voltages in the range 0- 1.5V (why?) in steps of 0.2 V at the inverting terminal. Measure this input using a digital multimeter.
4. Measure the corresponding output voltages with the multimeter and calculate gain V_o/V_{in}. Note the sign of the output voltage.
5. Now, replace R_f by 50KΩ. Measure the resistance value with multimeter and calculate gain, $-(R_f/R_{in})$.
6. Apply different voltages in the range 0- 0.5V in steps of 0.1 V at the inverting terminal. Measure this input using a digital multimeter.
7. Measure the corresponding output voltages with the multimeter and calculate gain V_o/V_{in}.
8. Plot graphs for $V_{in} \sim V_o$ for both the values of R_F.
9. You may also use a function generator to give a sinusoidal input and notice the output waveform using an oscilloscope.

(II) Non-inverting amplifier

1. Configure the circuit as shown in the circuit diagram with R_{in} = 1KΩ and R_f = 10KΩ. using the measured value of resistance calculate gain, $1+ (R_f/R_{in})$.
2. **Connect one of the output terminals of the D.C. power supply (0-30V) at the non-inverting input (pin no. 3).**
3. Repeat steps 3 onwards of procedure (I) with inputs applied at non-inverting terminal.

Observations

Table (I):

Obs. No.	Input (V)	$-\dfrac{R_f}{R_{in}}=$ ------			$-\dfrac{R_f}{R_{in}}=$ ------		
		Output (V)	Gain V_o/V_{in}	Average	Output (V)	Gain V_o/V_{in}	Average
	0.2						
	0.4						
	…						

Table (For II):

Obs. No.	Input (V)	$1+\dfrac{R_f}{R_{in}}=$ ------			$1+\dfrac{R_f}{R_{in}}=$ ------		
		Output (V)	Gain V_o/V_{in}	Average	Output (V)	Gain V_o/V_{in}	Average
1	0.1						
2	0.2						
..	…						

(III) Simple mathematical operations using OPAMP

a. To study OPAMP as summing amplifier
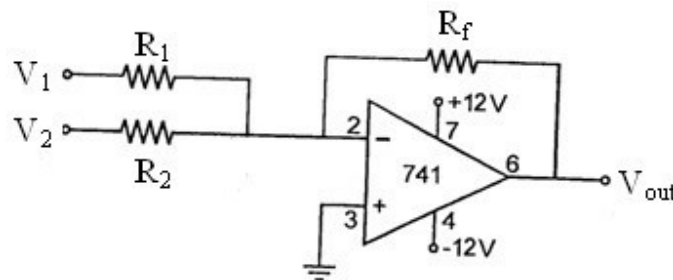
Circuit Diagram:

Procedure:
1. Assemble the circuit as shown in circuit diagram choosing R_1, R_2, R_f = 10KΩ each. Use 0- ±15V terminal output to provide supply to the IC.
2. Using 0 – 30V and 5V terminals of the power supply, apply two inputs at the inverting terminal. Measure each input with multimeter.
3. Measure the output with multimeter for at least five input combinations.
4. Compare the output with the sum of the two inputs.

Observations:

Obs.No	V_1 (V)	V_2 (V)	V_{out} (V)	$V_1 + V_2$ (V)
1				
..				
5				

b. To study OPAMP as difference amplifier

Circuit Diagram:

Procedure:

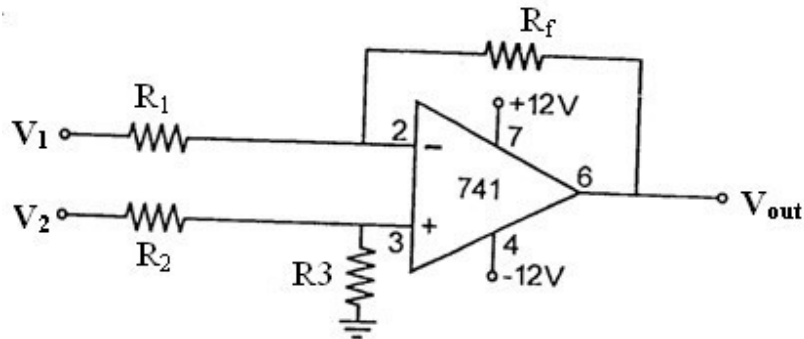1. Assemble the circuit as shown in circuit diagram choosing R_1, R_2, R_3, $R_f = 10K\Omega$ each. Use 0- ±15V terminal output to provide supply to the IC.
2. Using 0 – 30V and 5V terminals of the power supply, apply two inputs, one at the inverting and the other at the non-inverting terminal. Measure each input with multimeter.
3. Measure output with multimeter for at least five input combinations.
4. Compare the output with the difference of the two inputs.

Observations:

Obs.No	V_1 (V)	V_2 (V)	V_{out} (V)	$V_2 - V_1$ (V)
1				
..				
5				

c. **Inverting amplifier configuration of OPAMP is nothing but multiplication or division of input voltage with a number equal to R_f/R_1. With the knowledge of division and addition design an averaging amplifier of inputs V_1 and V_2 and tabulate.**

Conclusions:

Lab#1(B): Applications of OPAMP as Comparator and Schmitt Trigger

Objectives:

    (i)   Study of OPAMP as comparator

    (ii)   Study of OPAMP as Schmitt trigger

(i) Comparator

Theory

       When the feedback signal (voltage) is applied to the inverting (-) input of the op-amp then the feedback is negative. Negative feedback tends to reduce the difference between the voltages at the inverting and non-inverting terminals and make linear circuits. Without negative feedback the op-amp output is highly sensitive to the input, which can be used to design *switching* or *nonlinear* circuits. The voltage *comparator* is a device which uses no feedback; then saturation is the desired result. In this circuit we want a simple yes-no answer to be signified by either positive saturation or negative saturation of the output.

       In the circuit diagrams shown below, for Fig.(i), if $V_{in} > 0$, $V_o \approx V_{++}$ and if $V_{in} < 0$, $V_o \approx V_{--}$. The output is no longer linearly related to the input– it's more like a digital signal, high or low depending on how V_{in} compares to ground (0 V). Needless to mention that, if V_{in} is applied at the inverting terminal with respect to a grounded non-inverting terminal, the output will switch to low when $V_{in} > 0$. Figure (ii) shows a small modification, allowing the circuit to switch its output when V_{in} crosses a certain preset voltage level, often called the **threshold voltage**, V_{th}.

       Typical applications of this circuit are crossover detectors, analog to digital converters or counting applications where one wants to count pulses that exceed a certain voltage level.
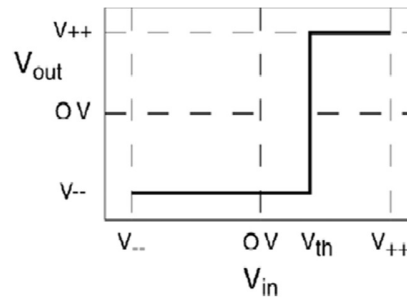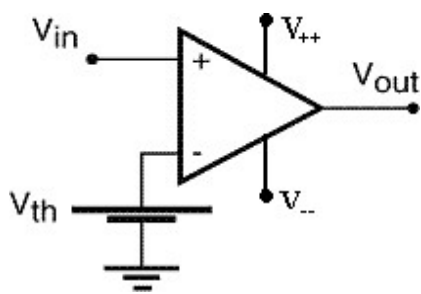
Components/Equipments:

(i) OPAMP (IC-741) chip, (ii) A D.C. power supply, (iii) A digital multimeter (DMM), (iv) A digital storage oscilloscope (DSO), (v) Connecting wires, (vi) Breadboard

Circuit Diagram:
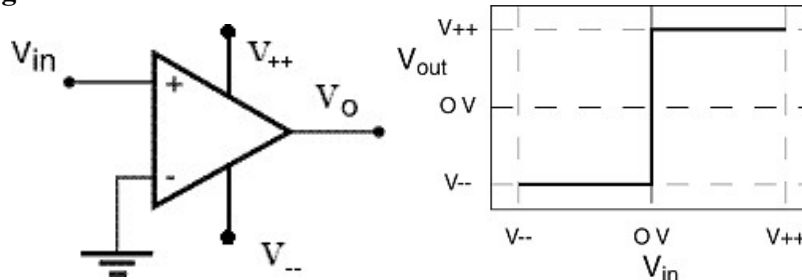
(i)

(ii)

Procedure:

1. Construct the comparator circuit on the breadboard as shown in the circuit diagram. Take care to give proper connections at the desired pins of the IC.
2. Use terminal **C** of the d.c. power supply (denoted by V_+ and V_- knobs) to provide power supply to IC. Connect the 0Vterminal to ground.
3. Connect terminal A of the d.c. power supply (0-30V) at the input. Use terminal B (5V) to provide threshold voltage V_{th} for circuit shown in Fig. (ii).
4. Vary the input from a negative value to a positive value through 0.
5. Using the DMM, measure and tabulate V_{in} and V_{out}. You can also look at the output using a DSO by coupling the output to it in DC mode.
6. Make a plot of V_{out} vs V_{in} for each circuit. Estimate V_{th} from graph for Fig. (ii) and compare with the V_{th} value actually applied. You can repeat the same procedure for different values of threshold.
7. Repeat the entire procedure described above with input at the inverting terminal and the non-inverting terminal being grounded w/o and with the threshold voltage connected to it.

Observations:

For Fig. (i)

Obs.No	V_i (V)	V_o (V)
1		
..		
..		

For Fig. (ii)

V_{th} =------ V

Obs.No	V_i (V)	V_o (V)
1		
..		
..		

2

Disscusions:

Discuss the graphs you obtained.

Precautions:

(ii) Schmitt trigger

      The Schmitt trigger is a variation of the simple comparator which has hysteresis, that is, it has a toggle action. It uses a positive feedback. When the output is high, positive feedback makes the switching level higher than it is when the output is low. A little positive feedback makes a comparator with better noise immunity.

      Now, to understand what causes the hysteresis let's analyze the circuit diagram given below, using the same rules as in the previous section for the comparator. The key in understanding this circuit will again be in calculating the voltages that cause its output to switch. If V_+ and V_- are the actual voltages at the non-inverting and inverting terminals of the OPAMP, then the output will be the following, considering that $V_-=0$:

$$\text{if } \quad V_+ > 0, \qquad V_{out} \approx V_{++}$$
$$\&\quad \text{if } \quad V_+ < 0, \qquad V_{out} \approx V_{---}$$

Since V_{out} changes its state whenever V_+ crosses 0V, we need to find what value of V_{in} results in $V_+ = 0$. The two values of V_{in} for which the output switches are called the trip points. V_+ acts as a voltage divider formed by R_1 and R_2 between V_{in} and V_{out}. Thus the trip points of a noninverting Schmitt trigger are:
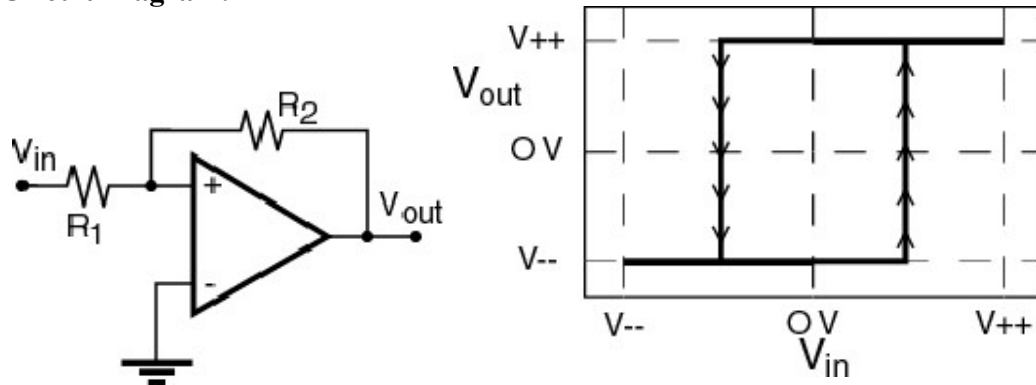
$$\textbf{V}_{\textbf{in}} = \textbf{-V}_{\textbf{out}} \textbf{ (R}_\textbf{1}\textbf{/R}_\textbf{2}\textbf{) (Lower trip point, LTP)}$$
$$\textbf{= + V}_{\textbf{out}} \textbf{ (R}_\textbf{1}\textbf{/R}_\textbf{2}\textbf{) (Upper trip point, UTP)}$$

Choosing suitable ratios of R_1 to R_2, enough hysteresis can be created in order to prevent unwanted noise triggers.

Components/Equipments:

    (i)   OPAMP (IC-741) chip
    (ii)   A D.C. power supply
    (iii)   A digital multimeter
    (iv)   Connecting wires
    (v)   Breadboard
    (vi)   Digital storage oscilloscope (DSO)

Circuit Diagram:

Procedure:

1. Construct the schmitt trigger circuit on the breadboard as shown in the circuit diagram.
2. Connect the d.c. power supply at the input. Vary the input from a negative value to a positive value through 0.
3. Using the DMM, measure and tabulate V_{in} and V_{out}.
4. **Make a plot of V_{out} vs V_{in}. Estimate the trip points from the graph and compare with the computed value, i.e. $V_{in} = \pm V_{out} R_1/R_2$**
5. You can also look at the output using a DSO by coupling the output to it in DC mode.

Observations:

Obs. No	V_i (V)	V_o (V)
1		
..		
..		

Discussions:

Analyze the graph you obtained. Discuss the switching action.

Precautions:

Lab#2a: Differentiation and Integration using OPAMP

Objectives:

   (I)   To study OPAMP as a differentiator
   (II)   To study OPAMP as an integrator
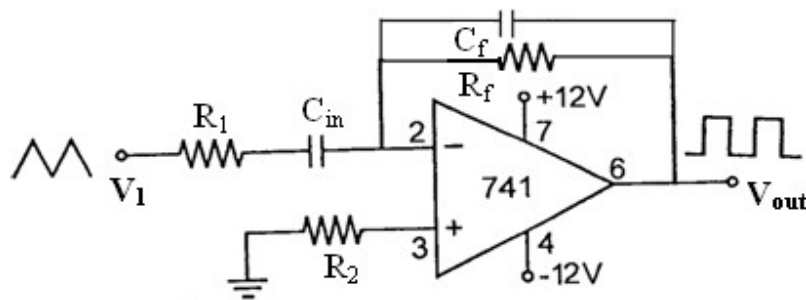
Apparatus:

1. OPAMP IC 741
2. D.C. power supply
3. Resistors
4. Digital multimeter
5. Connecting wires
6. Breadboard
7. Function generator
8. Digital storage oscilloscope

Theory:

Please refer to the supplementary note.

(I) To study OPAMP as a differentiator

Circuit Diagram of practical differentiator:

Differentiator action can be performed by the circuit given in supplementary material, which consists of only R_f in the feedback and input capacitor C_{in} with a gain equal to R_f/C_{in}. With increase in frequency gain, R_f/C_{in} increases which makes differentiator unstable. Further input impedance decreases at high frequency, which makes noise to amplify and override the signal. For the practical differentiator, C_f is added in parallel to R_f to control the gain and a small resistance R_1 at the input in series with C_{in} drops the noise at the input. R_2 is known as offset minimizing resistor (R_{OM}) which reduces output offset voltage due to input bias current.

1

Procedure:

1. Assemble the circuit as shown in circuit diagram choosing R_1, $R_2 = 1K\Omega$ each, $R_f = 10K\Omega$, $C_{in} = 0.1\ \mu F$ and $C_f = 0.01\mu F$. Use 0- ±15V terminal output to provide supply to the IC.
2. Feed a triangular input signal of required amplitude from the function generator, which is set at 1K frequency.
3. Feed both the input and output signals to an oscilloscope and save. The output should be approximately a square wave.
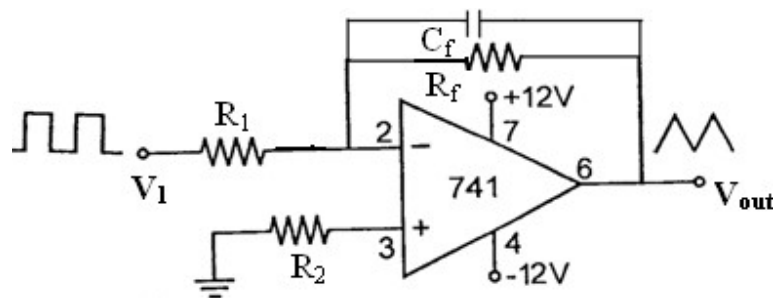4. Check the output waveform with sine and square waves as inputs and save.

Observations: (Paste the various input and corresponding output waveforms here)

Observation	Waveform		
Input	triangular	sine	square
Output			

Discussions

(VII) To study OPAMP as an integrator

Circuit Diagram of practical integrator

In this practical integrator circuit R_f is connected parallel with C_f which is absent in the integrator circuit given in supplementary material. R_f discharges left over charges present in the capacitor before next pulse being applied and limits the gain of the circuit at low frequencies, which is infinite at D.C. R_2 is known as offset minimizing resistor (ROM) which reduces output offset voltage due to input bias current.

Procedure:

2. Assemble the circuit as shown in circuit diagram choosing R_1, $R_2 = 10K\Omega$ each, $R_f = 100K\Omega$, and $C_f = 0.1\mu F$. Use 0- ±15V terminal output to provide supply to the IC. Feed a

square wave input of required amplitude from the function generator, which is set at 1KΩ frequency.

3. Feed both the input and output signals to an oscilloscope. The output should be a triangular wave.

Observations: (Paste the various input and corresponding output waveforms here)

Observation	Waveform
Input	
Output	

Lab#2b: Active filter using OPAMP

Objective:

      (I)   To construct a low pass active filter using OPAMP

Filters: The main disadvantage of passive filters (as you have already seen in one of your previous labs) is the fact that the maximum gain that can be achieved with these filters is 1. In other words, the maximum output voltage is equal to the input voltage. If we make filter circuits using Opamps, then the gain can be greater than 1.

The circuits employed are all based on the inverting Opamps with the addition of a capacitor placed in the correct position for the particular type of filter. These circuits are called active filter circuits because they use Opamps which require a power supply.

Low-Pass filters - the integrator reconsidered

      A low pass filter passes only low frequency signals and attenuates signals of high frequencies. We have already considered the time response of the integrator circuit, but its frequency response can also be studied. Figure 1 shows a low pass active filter in inverting configuration.
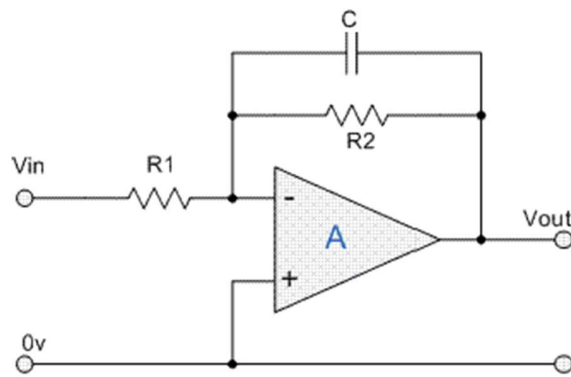
Fig. 1: First Order Low Pass Filter with Op Amp

Gain of the above circuit, $A = -$ (R$_2$|| X$_c$)/R$_1$, where $X_c = 1/(2\pi fC)$, is the impedance of the capacitor and f is the frequency of the input signal.

At high frequencies the capacitor acts as a short, so the gain of the amplifier approaches zero. At very low frequencies the capacitor is open and the gain of the circuit is $-(R_2/R_1)$. We can consider the frequency to be high when the large majority of current goes through the capacitor; i.e., when the magnitude of the capacitor impedance is much less than that of R$_2$. In other words, we have high frequency when $X_C << R_2$. Since R$_2$ now has little effect on the circuit, it should act as an integrator. Likewise low frequency occurs when $R_2 << X_C$, and the circuit will act as an amplifier with gain $-R_2/R_1$. Thus, the cut-off frequency is given as $f_c = \dfrac{1}{2\pi R_2 C}$ and the frequency response is as shown below (Fig.2). The frequency response curve of the filter decreases by 20dB/Decade or 6dB/Octave from the determined cut-off frequency point which is always at -3dB below the maximum gain value.
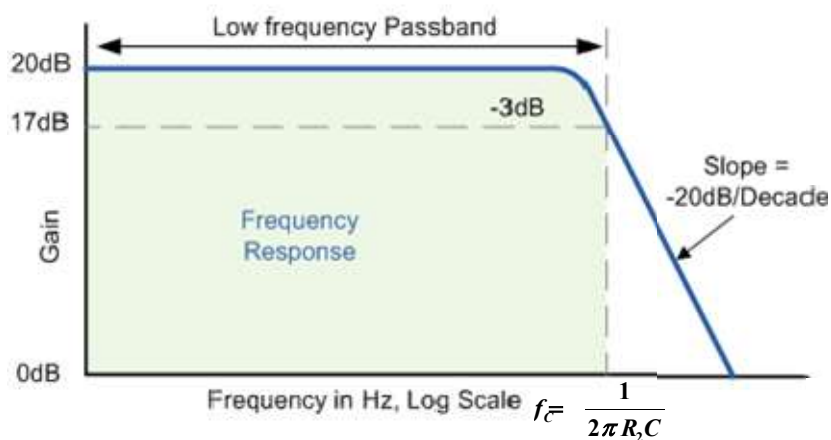

4

Fig. 2: Frequency response curve of an active low pass filter

Similarly high pass filter can be constructed with differentiator circuit and using a low pass filter and high pass filter, a band pass filter can be constructed.

Procedure:

1. Read/measure the values of all circuit components to be used. Calculate the cut-off frequencies in each case.
2. Using the scope set the function generator to produce an input voltage of approximately 100 mV(pp) sine wave.
3. Set up the low/high/band pass active filter on the breadboard as shown in the circuit diagrams. Connect the function generator to apply input. Use the dual trace oscilloscope to look at both V_{in} and V_{out}. Be sure that the two oscilloscope probes have their grounds connected to the function generator ground. Match the magnification control both at the probe and the oscilloscope.
4. Set the RANGE of the function generator between 20 Hz to 20 kHz. Measure the V_{in}(pp) and V_{out}(pp). Use **digital filter** or **average** options from oscilloscope to measure voltages whenever needed.
5. From your measurements determine the gain, $\dfrac{V_o(pp)}{V_{in}(pp)}$ and compare with the calculated value.
6. Plot log f ~ gain (dB).

Observations:

(I)   For Low Pass Filter:

$$R_1 = \underline{\hspace{2cm}}, \quad R_2 = \underline{\hspace{1.5cm}}, \quad C = \underline{\hspace{2cm}},$$

$$\text{Max Gain(calculated)} = -\frac{R_2}{R_1} = \underline{\hspace{2cm}}, \qquad f_c = \frac{1}{2\pi R_2 C} = \underline{\hspace{1.5cm}}$$

Table:

Sl. No.	Frequency, f (kHz)	V_{in}(pp) (Volt)	V_o(pp) (Volt)	Gain, $A_V = \dfrac{V_o(pp)}{V_i(pp)}$	Gain (dB)
1					
2					
..					
..					

Lab#3: Phase Shift Oscillator using Opamps

Objectives:

To construct and determine the resonant frequency of
(i)   A phase shift oscillator

Overview:

The main principle of oscillator is positive feedback. Block diagram of oscillator is shown in Figure 1.
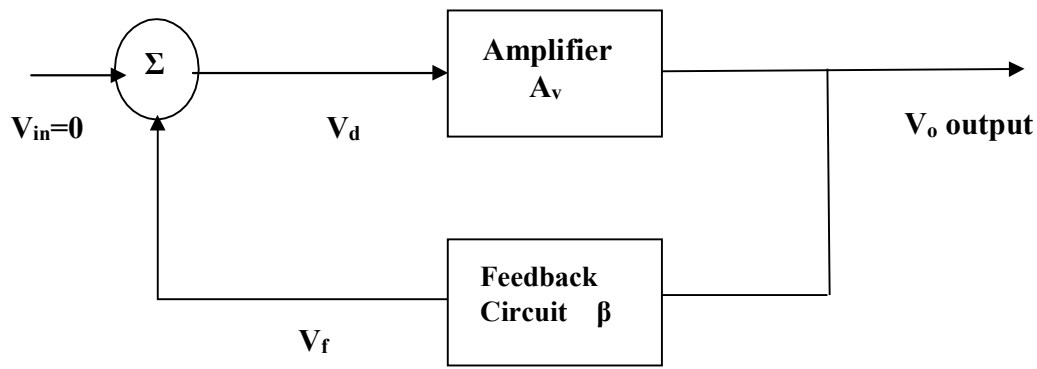

Figure.1

In the block diagram (Fig.1), $V_d = V_f + V_{in}$

$$V_o = A_v V_d \text{ and } V_f = \beta V_o$$

Using these relationships, following equation can be obtained:

$$\frac{V_o}{V_{in}} = \frac{Æ7}{1 - Æ7\text{þ}}$$

.

When $A_V\beta = 1$, $A_{fb} = \infty = \frac{V_o}{V_{in}}$, This will happen only when $V_{in} = 0$. That is we get a signal at output without any input. The condition $A_V\beta = 1$ is known as Barkhausen condition. This condition expressed in polar form as follows. $A_V\beta = 1 \angle 0°$ or $360°$

Barkhausen condition gives two requirements for oscillation.
1) The magnitude of the loop gain must be equal to 1.
2) The total phase shift of the loop gain must be equal to 0° or 360°.

Phase shift Oscillator: Figure.2 gives the circuit diagram for a phase shift oscillator, which consists of an op-amp as the amplifying stage and three RC cascaded networks as the feedback circuit. The opamp used in this oscillator is in the inverting mode, output is 180° is phase shifted. To feedback the output to input, additional 180° degree phase shift is achieved by RC network.
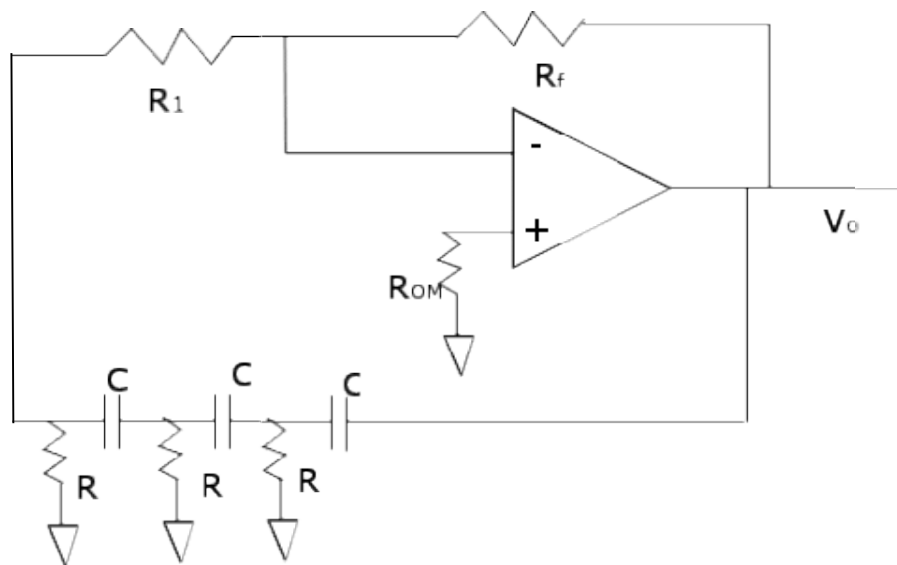

Figure.2

The frequency of oscillation is given by, $f = \frac{1}{2G\sqrt{6}RC}$ and at this frequency gain must be *at least* 29. That is $|\frac{RF}{R_1}| = 29$.

Feedback circuit with RC network gives 180 degree phase shift but decreases the output voltage by a factor of 29. That is β=1/29. For the oscillations $A_V\beta = 1$. Therefore, gain should be at least 29.

Procedure: Choose R_f = 100 KΩ, R = 2 KΩ, C = 0.1 uF, R=1 KΩ and construct a phase shift oscillator. Determine the oscillating frequency using oscilloscope and compare with calculated oscillation frequency.

Experimentally determine the minimum gain required to sustain oscillations by varying the gain in the circuit. Obtain Lissajous figure (circle) with X-Y mode of the oscilloscope and estimate oscillating frequency. Try to make the circuit for some other oscillating frequency by choosing components appropriately.

2

References: 1) OPAMPS and linear integrated circuits –Ramakant Gaykwad

2) http://textofvideo.nptel.iitm.ac.in/122106025/lec35.pdf