

COURSE CONTENT

Course Information

Course Title: Analogue and Digital Electronics

Course module: Electronics

Course Code: EMEg 3211

Pre-requisites: Applied Electronics

ECTS Credits 6

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CHAPTER ONE: OPERARIONAL AMPLIFIERS FUNDAMENTALS

1.1 Op-amps:

1.2 Op-amp fundamentals

1.3 Parameters Offset errors and compensation techniques,

1.4 Comparison of inverting Vs. non-inverting configurations.

1.5 Signal conditioning concepts.

1.6 Amplifiers:

1.7 Difference amplifiers,

1.8 Effect of resistance mismatches on CMRR, ground loop interference

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Part I: Analog Electronics

Operational Amplifiers

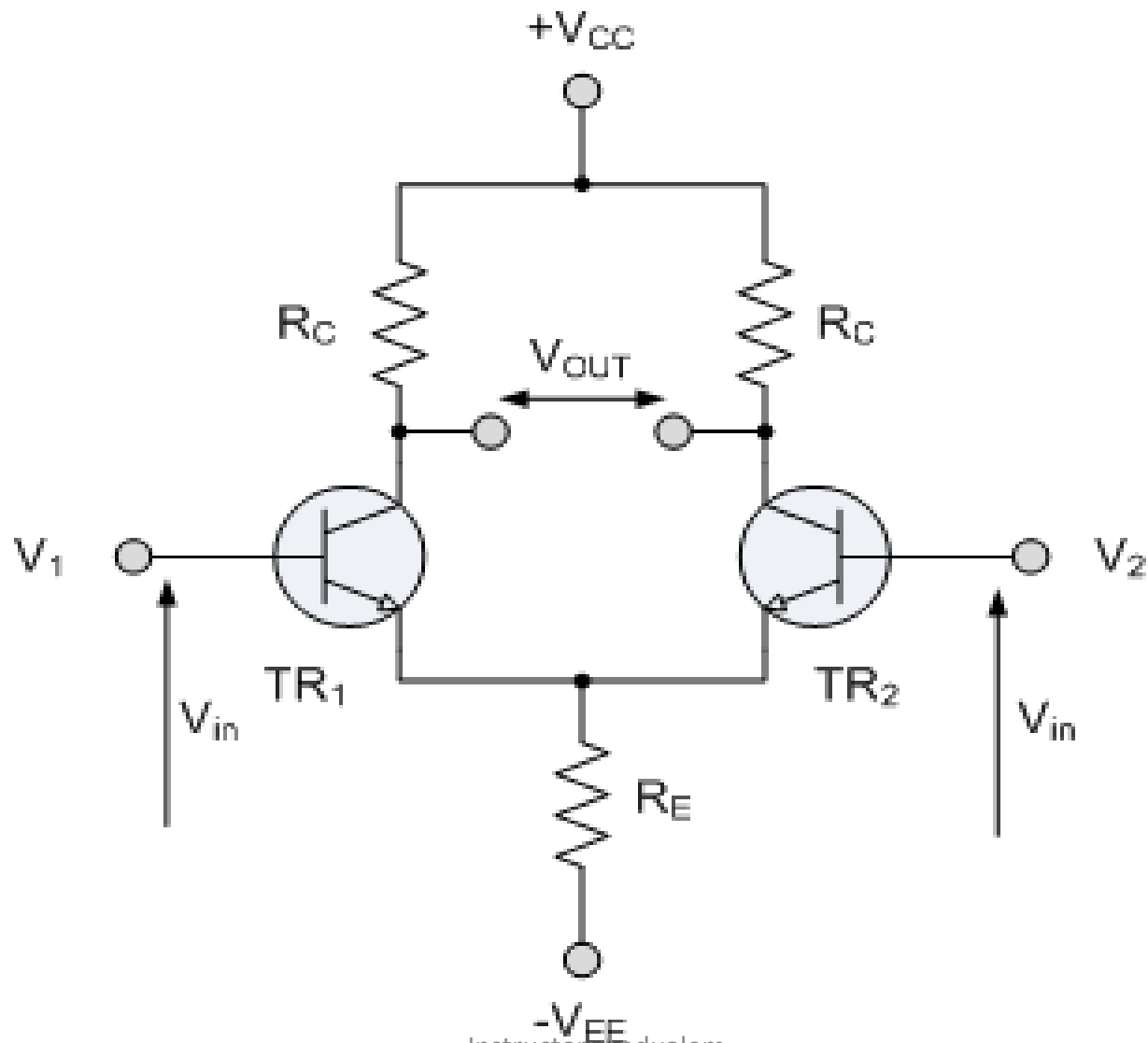
Ideal Operational Amplifier

- As well as resistors and capacitors, **Operational Amplifiers**, or **Op-amps** as they are commonly called, are in the list of 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.

Cont...

- 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.

Differential Amplifier



Cont...

- 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.

Cont...

- The voltage that appears at the output, V_{out} of the amplifier is the difference between the two input signals as the two base inputs are in *anti-phase* with each other.
- So as the forward bias of transistor, TR1 is increased, the forward bias of transistor TR2 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.

Cont...

- Like the input signal, the output signal is also balanced and since the collector voltages either swing in opposite directions (anti-phase) or in the same direction (in-phase) the output voltage signal, taken from between the two collectors is, assuming a perfectly balanced circuit the zero difference between the two collector voltages.
- This is known as the *Common Mode of Operation* with the **common mode gain** of the amplifier being the output gain when the input is zero.

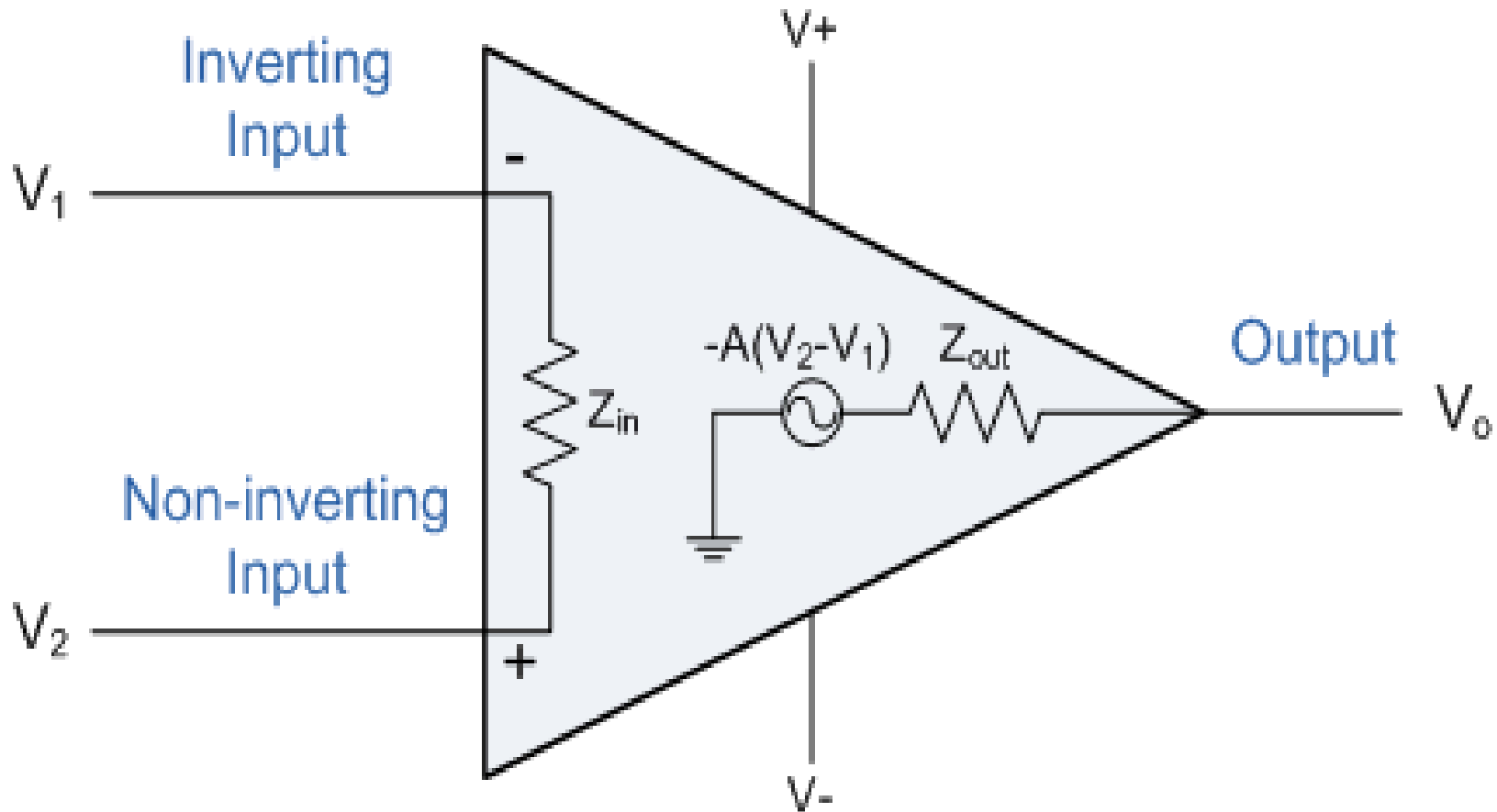
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- Ideal Operational Amplifiers also have one output (although there are ones with an additional differential output) of low impedance that is referenced to a common ground terminal and it should ignore any common mode signals that is, if an identical signal is applied to both the inverting and non-inverting inputs there should be no change to 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**.

Cont...

- Operational Amplifiers on their own have a very high open loop DC gain and by applying some form of **Negative Feedback** we can produce an operational amplifier circuit that has a very precise gain characteristic that is dependant only on the feedback used.
- An operational amplifier only responds to the difference between the voltages on 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. An Operational Amplifiers gain is commonly known as the **Open Loop Differential Gain**, and is given the symbol (A_o).

Equivalent Circuit for Ideal Operational Amplifiers



Characteristics of ideal Operational Amplifier

Parameters	ideal 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.

Characteristics of ideal Operational Amplifier

Parameters	ideal characteristic
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.

Characteristics of ideal Operational Amplifier

Parameters	ideal characteristic
Offset Voltage, (V_{io})	Zero - The amplifiers output will be zero when the voltage difference between the inverting and non-inverting inputs is zero.

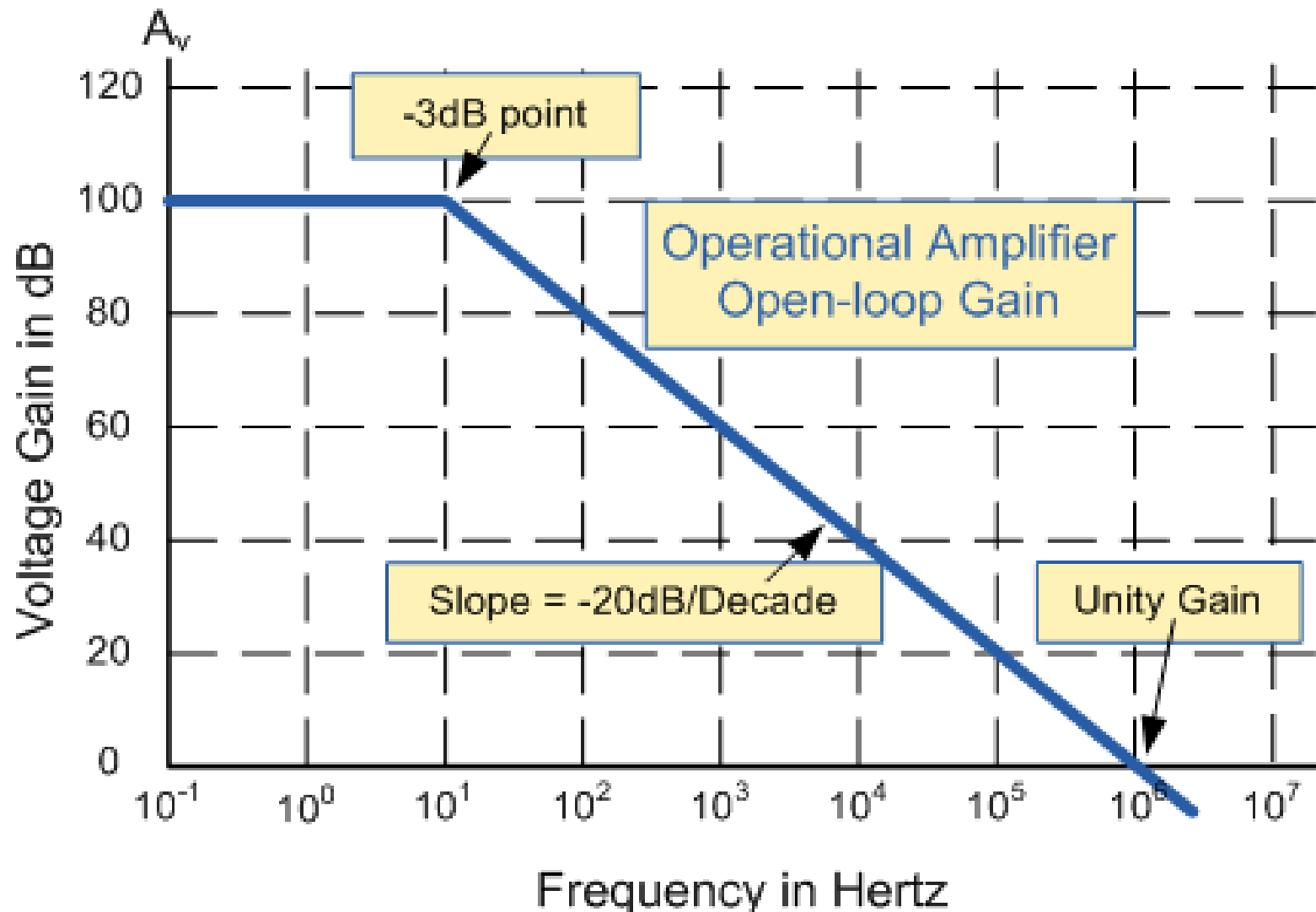
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- From these "idealized" characteristics above, we can see that the input resistance is infinite, so **no current flows into either input terminal** (the current rule) and that the **differential input offset voltage is zero** (the voltage rule).
- It is important to remember these two properties as they help understand the workings of the amplifier with regards to analysis and design of operational amplifier circuits.
- Real **Operational Amplifiers** such as the commonly available **uA741**, for example do not have infinite gain or bandwidth but have a typical "Open Loop Gain"

Cont...

- Open Loop Gain is defined as the amplifiers output amplification without any external feedback signals connected to it.
- For a typical operational amplifier Open Loop Gain 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.

Open-loop Frequency Response Curve



Cont...

- 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**.

Cont...

Therefore,

- $GBP = \text{Gain} \times \text{Bandwidth}$ or $A \times BW$.
- For example, from the graph above the gain of the amplifier at 100kHz = 20dB or 10, then the

$$GBP = 100,000\text{Hz} \times 10 = 1,000,000.$$

- Similarly, a gain at 1kHz = 60dB or 1000, therefore the

$$GBP = 1,000 \times 1,000 = 1,000,000. \text{ The same!}$$

Cont...

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

$$\text{Voltage Gain, (A)} = \frac{V_{\text{out}}}{V_{\text{in}}}$$

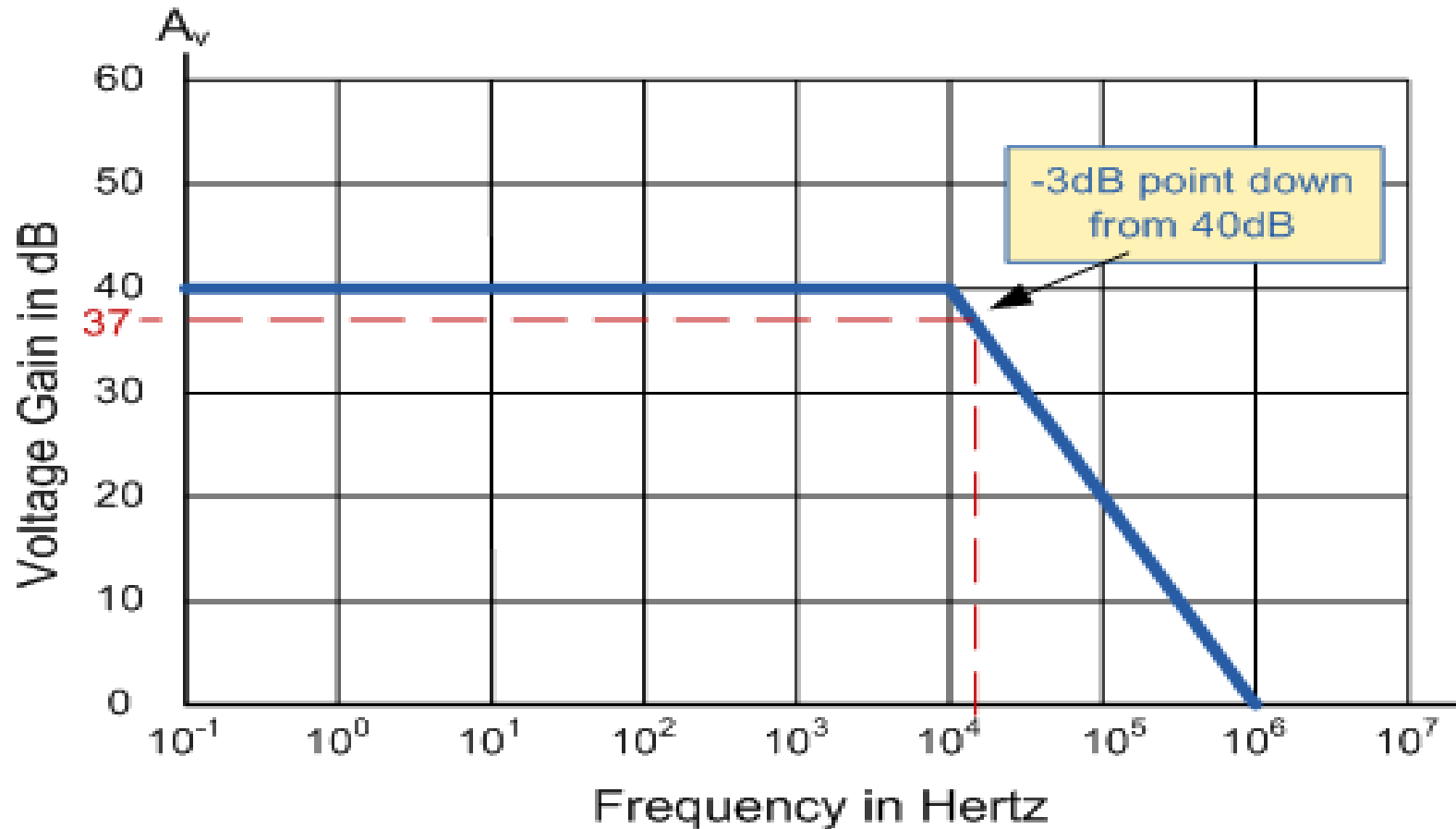
and in **Decibels** or (dB) is given as

$$20\log(A) \text{ or } 20\log \frac{V_{\text{out}}}{V_{\text{in}}} \text{ in dB}$$

An Operational Amplifiers Bandwidth

- 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.

Cont...



Cont...

Let us use 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.

Cont...

Using the formula **$20 \log (A)$** , we can calculate the bandwidth of the amplifier as:

$$37 = 20 \log A$$

$$A = \text{Inverse-log} (37 \div 20) = 70.8$$

$$\text{Bandwidth} = \text{GBP} \div A$$

$$= 1,000,000 / 70.8$$

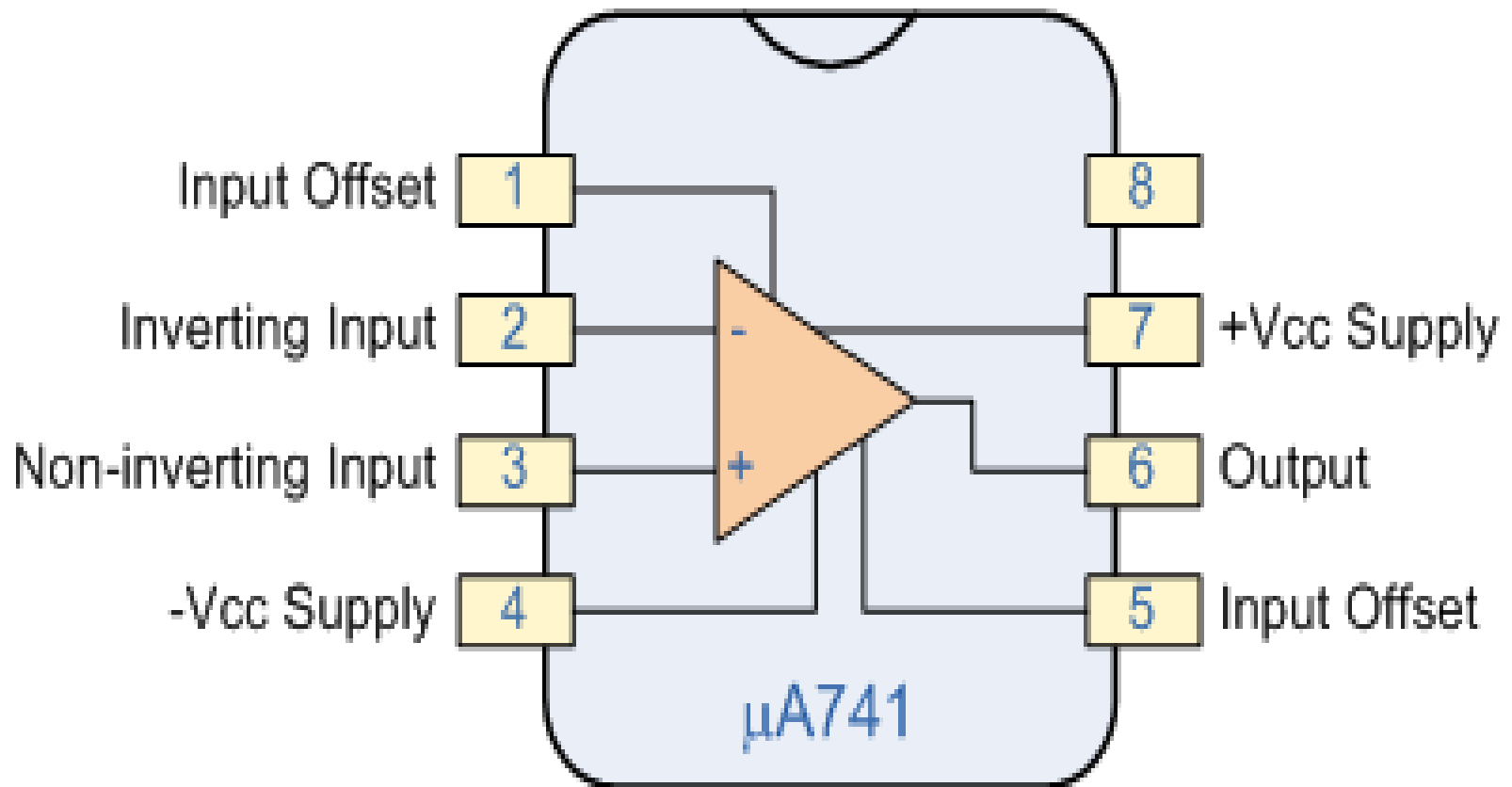
$$= \underline{14,124\text{Hz, or } 14\text{kHz}}$$

Then the bandwidth of the amplifier at a gain of 40dB is given as **14kHz** as previously predicted from the graph.

Circuits with Operational Amplifiers

- 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 such as bipolar standard, precision, high-speed, low-noise, high-voltage, etc and again with internal JFET transistors.
- The most commonly available and used of all operational amplifiers is the industry standard **μA-741**.

Cont...



Inverting Amplifier

- We saw in the last tutorial that 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.

Cont...

- 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.

Cont...

- **Negative Feedback** is the process of "feeding back" some of the output signal back to the input.
- 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**.

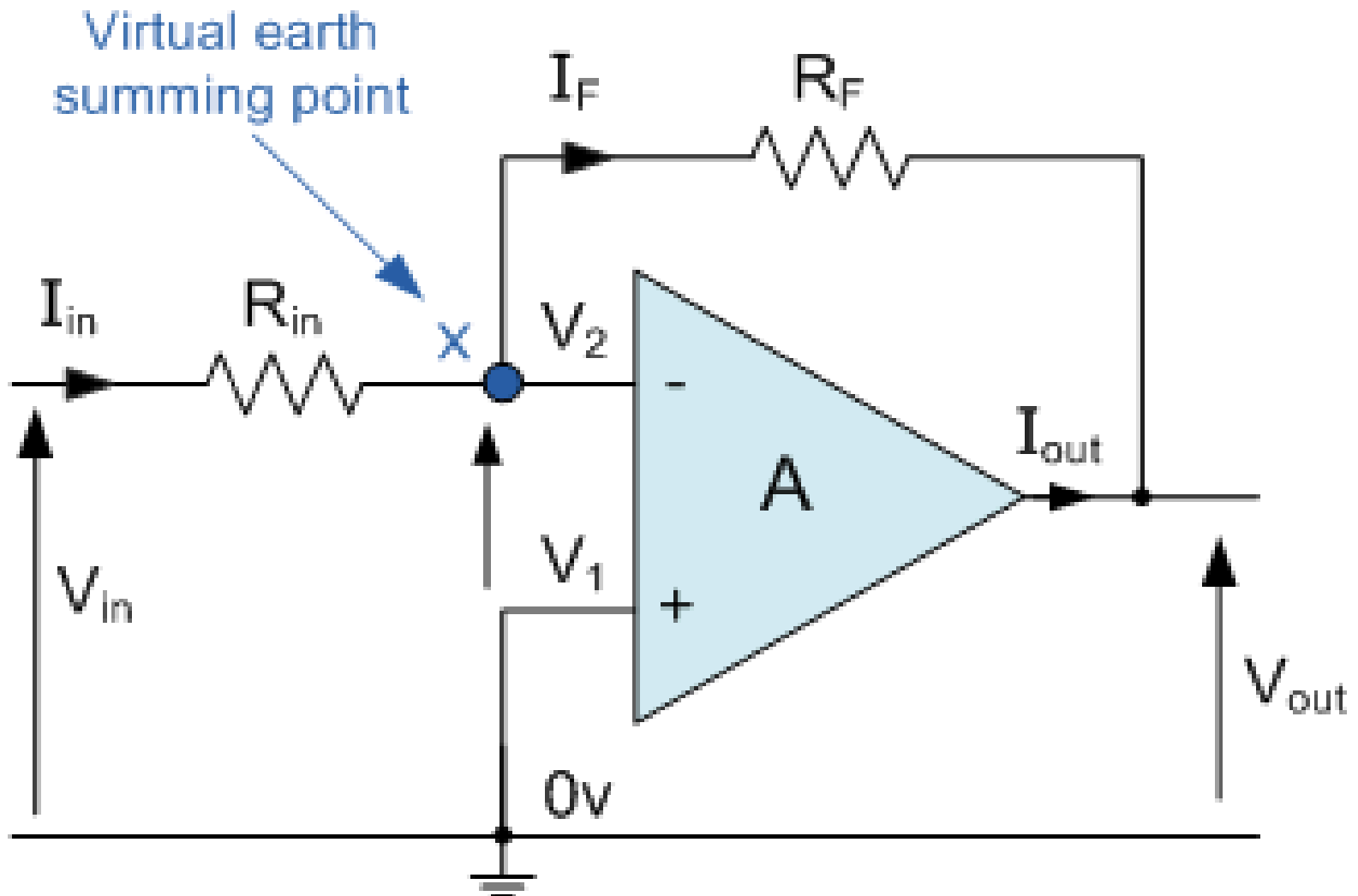
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- This results in the inverting input terminal having a different signal on it than the actual input voltage as it will be the sum of the input voltage plus the negative feedback voltage giving it the label or term of a *Summing Point*.
- We must therefore separate the real input signal from the inverting input by using an **Input Resistor, R_{in}** .

Cont...

- As we are not using the positive non-inverting input this is connected to a common ground or zero voltage terminal.
- The effect of this closed loop feedback circuit results in the voltage potential at the inverting input being 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



Cont...

- In this **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 is that, "no current flows into the input terminal" and that " V_1 equals V_2 ".

Cont...

- 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} and the closed loop gain of the inverting amplifier can be set by the ratio of the two external resistors.

Cont...

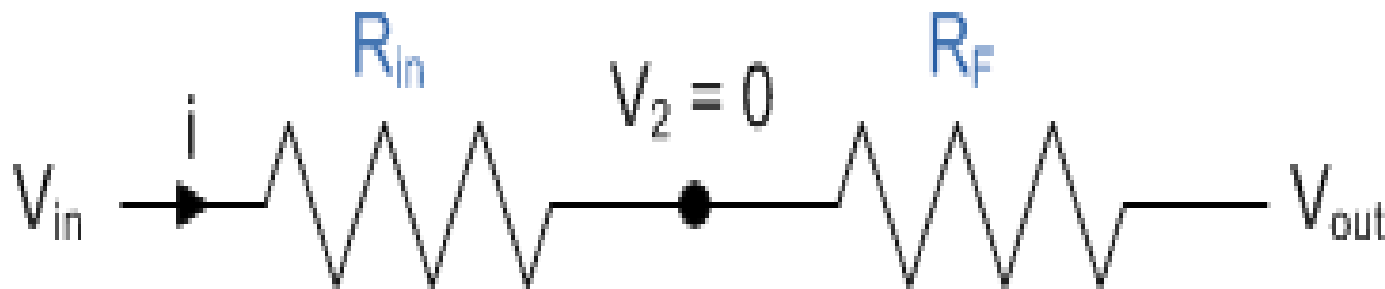
- We said above that there are two very important rules to remember about **Inverting Amplifiers** or any operational amplifier for that matter and they are.

1. No Current Flows into the Input Terminals
2. The Differential Input Voltage is Zero as $V_1 = V_2 = 0$ (Virtual Earth)

Cont...

- Then by using these two rules we can find the equation for calculating the gain of an inverting amplifier, using first principles.

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



Cont...

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

$$\text{therefore, } i = \frac{V_{in} - V_2}{R_{in}} = \frac{V_2 - V_{out}}{R_f}$$

$$i = \frac{V_{in}}{R_{in}} - \frac{V_2}{R_{in}} = \frac{V_2}{R_f} - \frac{V_{out}}{R_f}$$

$$\text{so, } \frac{V_{in}}{R_{in}} = V_2 \left[\frac{1}{R_{in}} + \frac{1}{R_f} \right] - \frac{V_{out}}{R_f}$$

$$\text{and as, } i = \frac{V_{in} - 0}{R_{in}} = \frac{0 - V_{out}}{R_f} \quad \frac{R_f}{R_{in}} = \frac{0 - V_{out}}{V_{in} - 0}$$

$$\text{the Closed Loop Gain is given as, } \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

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Cont...

- The **Closed-Loop Voltage Gain** of an Inverting Amplifier is given as

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

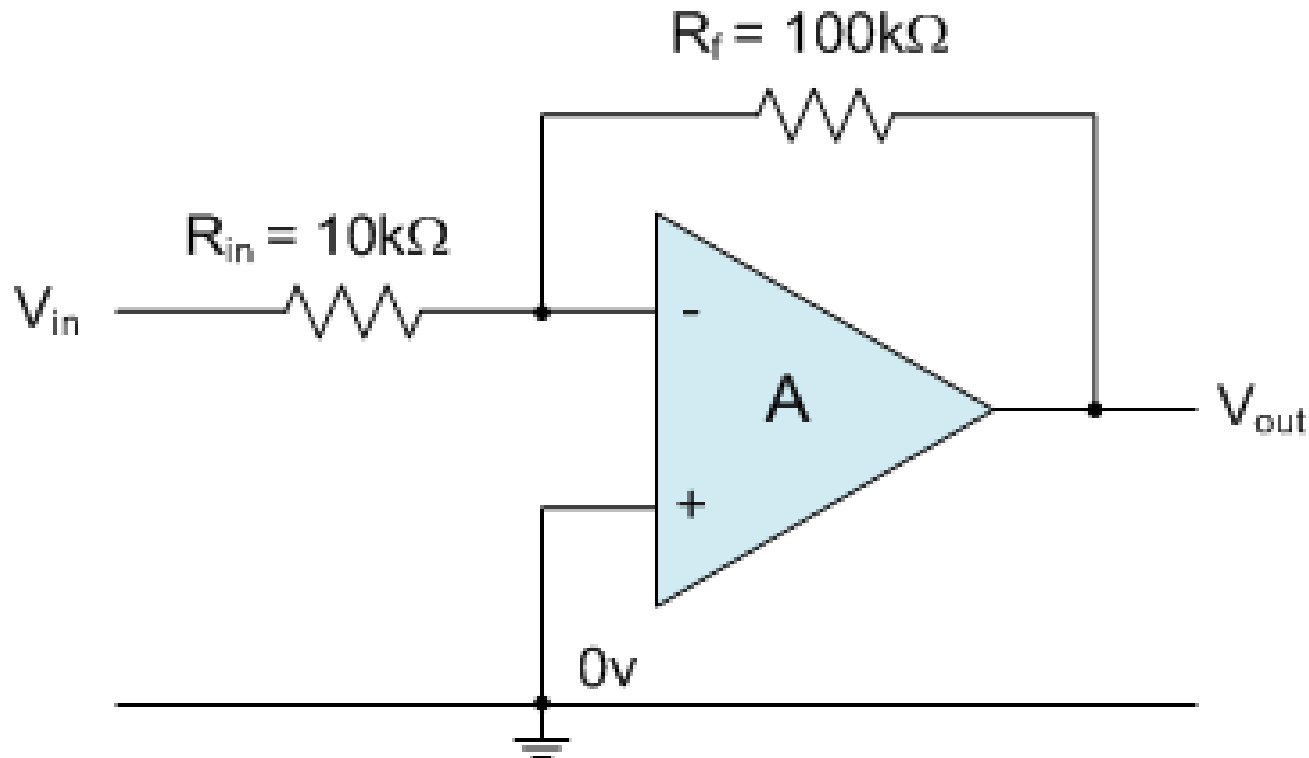
and this can be transposed to give:

$$V_{\text{out}} = -\frac{R_f}{R_{\text{in}}} \times V_{\text{in}}$$

- 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.

Example No1

Find the closed loop gain of the following inverting amplifier circuit.



Solution

Using the formula for the gain of the circuit:

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

We can now substitute the values of the resistors in the circuit as follows,

$$R_{\text{in}} = 10\text{k}\Omega$$

$$R_f = 100\text{k}\Omega.$$

and the gain of the circuit is calculated as -

$$R_f/R_{\text{in}} = 100\text{k}/10\text{k} = 10.$$

Therefore, the closed loop gain of the inverting amplifier circuit above is given **10 or 20dB**.

Cont...

- 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 or simply an *Inverting Buffer*.

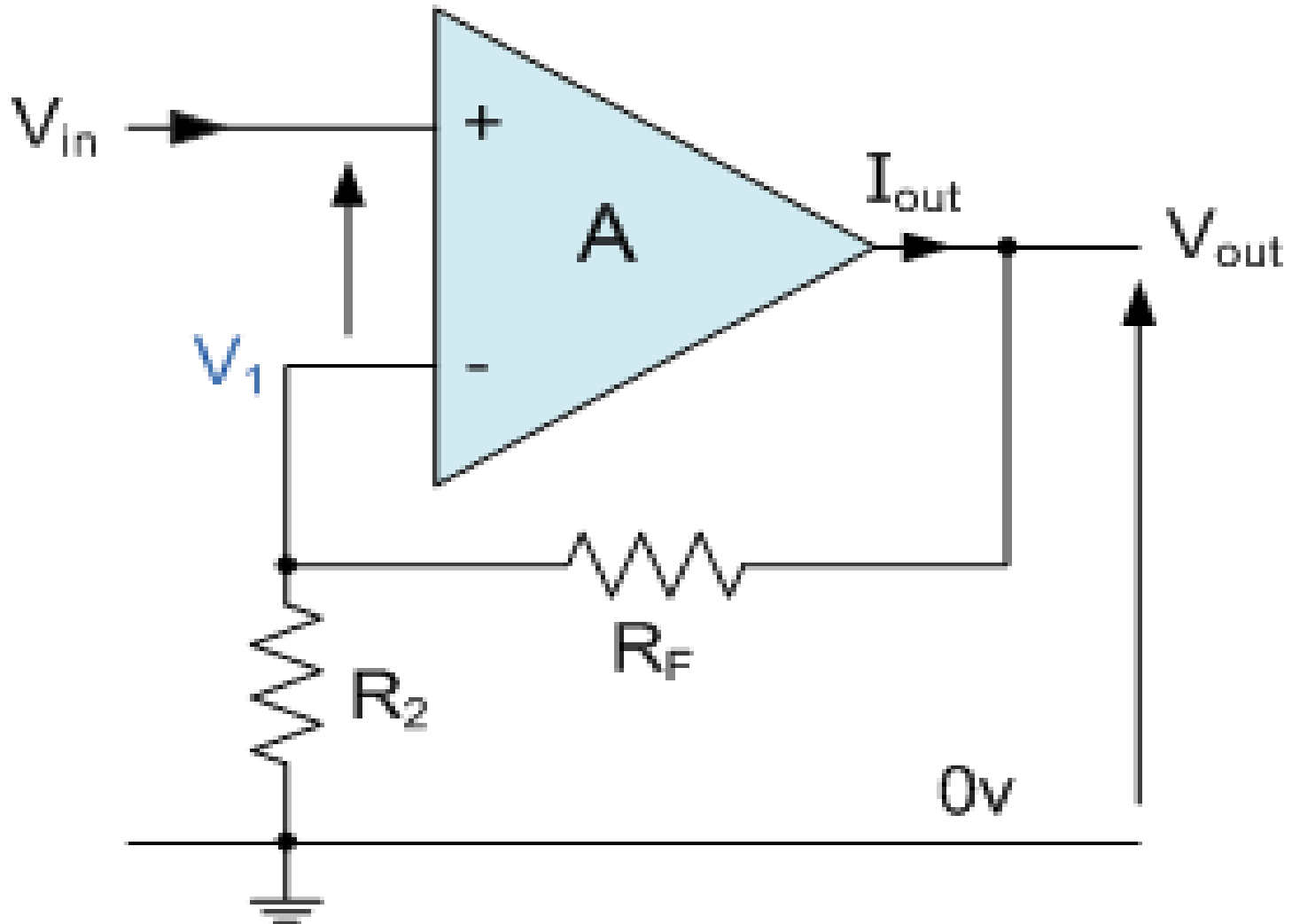
Non-inverting Amplifier

- 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 we saw in the last tutorial and whose output gain is negative in value.

Cont...

- 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.

Schematic diagram of Non-inverting Amplifier

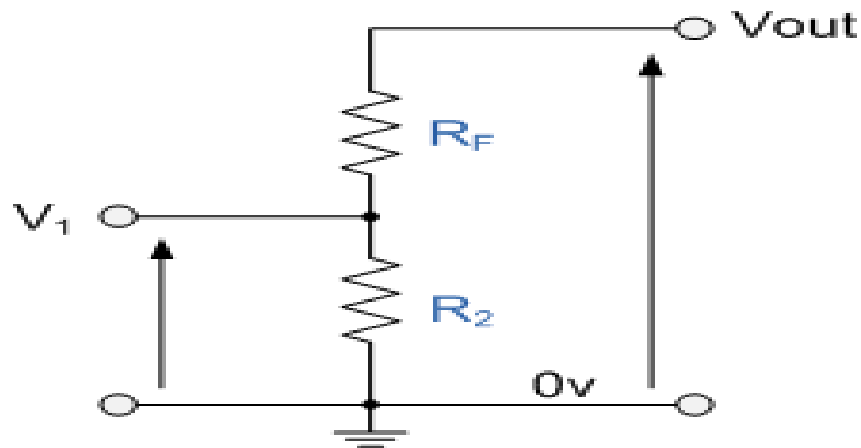


Cont...

- In the previous *Inverting Amplifier* tutorial, we said that "no current flows into the input" of the amplifier and that " V_1 equals V_2 ".
- This was because the junction of the input and feedback signal (V_1) are at the same potential in other words the junction is a "**Virtual Earth**" summing point.

Equivalent Voltage Divider Network

- 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.



Cont...

- 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:

$$V_1 = \frac{R_2}{R_2 + R_F} \times V_{OUT}$$

Voltage Gain, $A_{(V)}$ is equal to: $\frac{V_{OUT}}{V_{IN}}$

$$\text{Then, } A_{(V)} = \frac{V_{OUT}}{V_{IN}} = \frac{R_2 + R_F}{R_2}$$

$$\text{Transpose to give: } A_{(V)} = 1 + \frac{R_F}{R_2}$$

Cont...

- Then the closed loop voltage gain of a **Non-inverting Amplifier** is given as:

$$A_{(V)} = 1 + \frac{R_F}{R_2}$$

- We can see that the overall gain of a Non-Inverting Amplifier is greater but never less than 1 (unity), 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 (unity), 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).

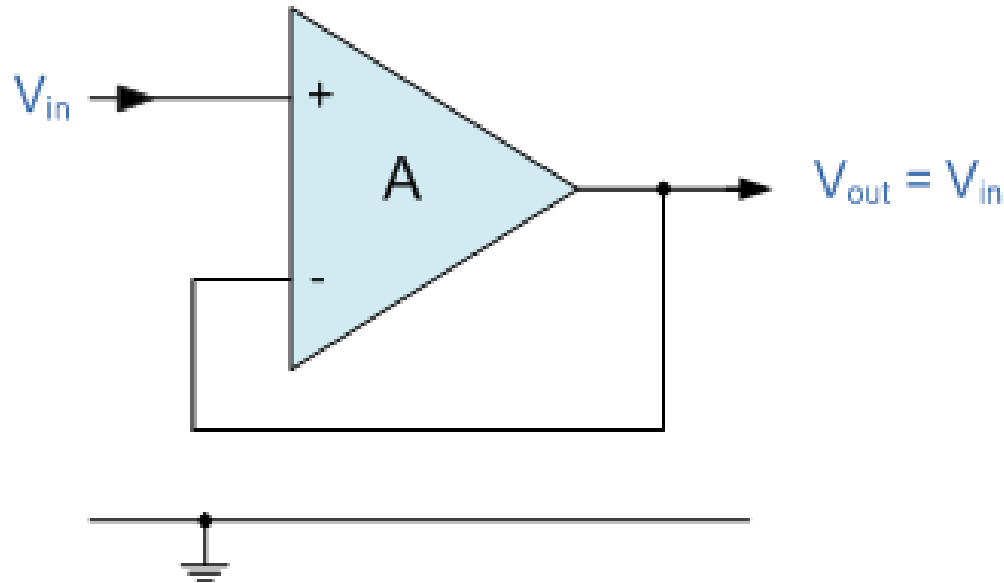
Voltage Follower (Unity Gain Buffer)

- 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** and this type of Non-inverting amplifier circuit is sometimes called a Voltage follower with gain.
- 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, $V_{out} = V_{in}$.

Cont...

- 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 $1\text{M}\Omega$ as it is equal to that of the operational amplifiers input, since an ideal op-amp condition is assumed.

Cont...



- 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.

Cont...

- As the input voltage V_{in} is applied to the non-inverting input the gain of the amplifier is given as:

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

$$\text{as } V_{in} = V_{+} \text{ and } V_{out} = V_{-}$$

$$\text{therefore, Gain} = \frac{V_{out}}{V_{in}} = 1$$

Cont...

- Since no current flows into the non-inverting input terminal the input impedance is infinite and also no current flows through the feedback loop so any value of resistance may be placed in the feedback loop without affecting the characteristics of the circuit as no voltage is dissipated across it, zero current, zero voltage, zero power drop.
- However in most real unity gain buffer circuits a low value (typically $1\text{k}\Omega$) resistor is required to reduce any offset input leakage currents, and also if the operational amplifier is of a current feedback type.

Cont...

- 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.

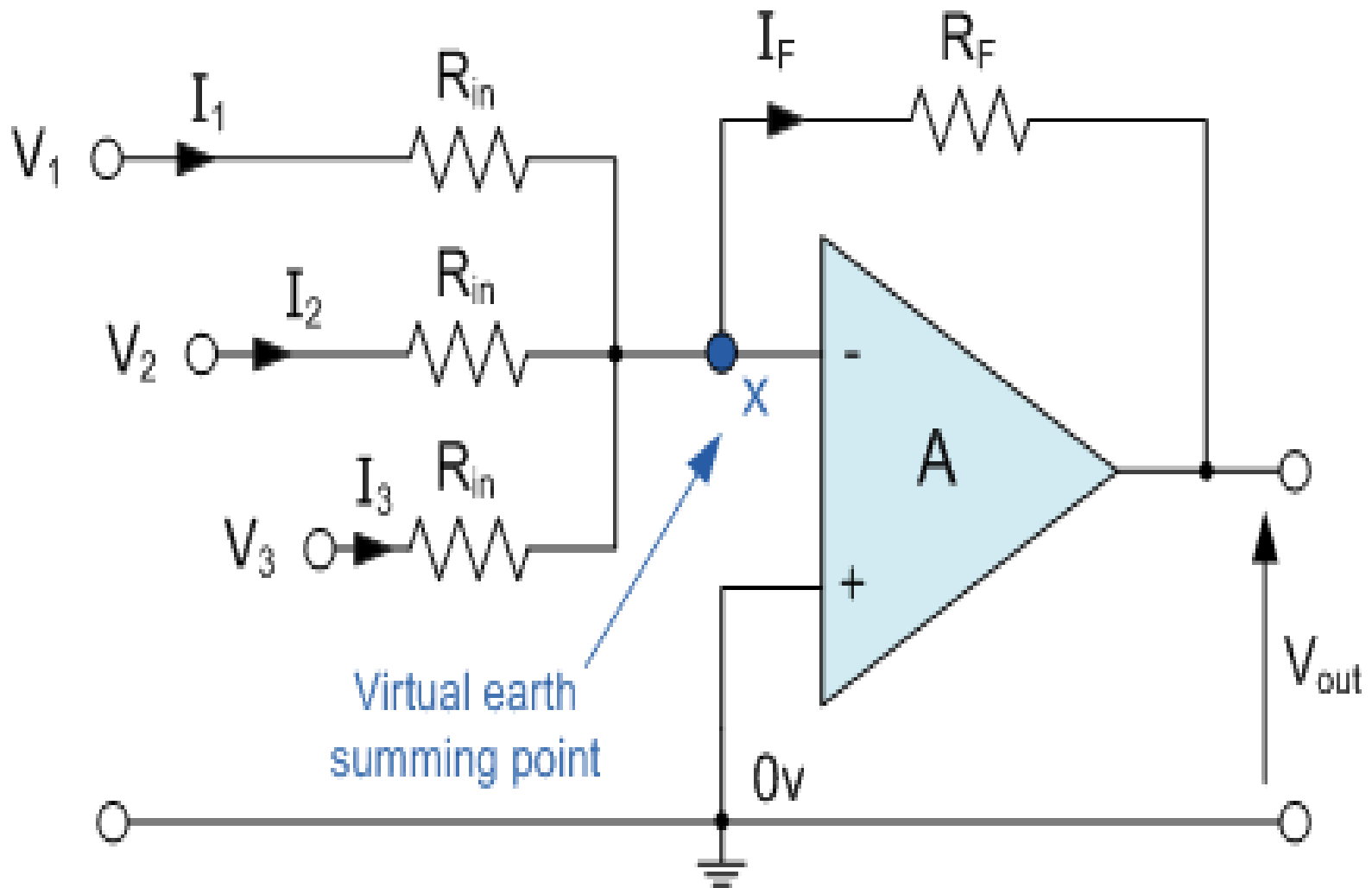
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- One final thought, the output voltage gain of the voltage follower circuit with closed loop gain is **Unity**, the voltage gain of an ideal operational amplifier with open loop gain (no feedback) is **Infinite**.
- Then by carefully selecting the 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 in the Inverting Amplifier tutorial 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.

Cont...



Cont...

- 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:

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

$$\text{then, } -V_{out} = \left[\frac{R_F}{R_{in}} V_1 + \frac{R_F}{R_{in}} V_2 + \frac{R_F}{R_{in}} V_3 \right]$$

Cont...

However, if all the input impedances, (R_{in}) are equal in value the final equation for the output voltage is given as:

$$-V_{out} = \frac{R_F}{R_{IN}} (V_1 + V_2 + V_3 \dots \text{etc})$$

Cont...

- We now have an operational amplifier circuit that will amplify each individual input voltage and produce an output voltage signal that is proportional to the algebraic "SUM" of the three individual input voltages V_1 , V_2 and V_3 .
- We can also add more inputs if required as each individual input "see's" their respective resistance, R_{in} as the only input impedance.

Cont...

- This is because the input signals are effectively isolated from each other by the "virtual earth" node at the inverting input of the op-amp.
- A direct voltage addition can also be obtained when all the resistances are of equal value and R_f is equal to R_{in} .

Cont...

A **Scaling Summing Amplifier** can be made if the individual input resistors are "NOT" equal. Then the equation would have to be modified to:

$$-V_{out} = V_1 \left(\frac{R_f}{R_1} \right) + V_2 \left(\frac{R_f}{R_2} \right) + V_3 \left(\frac{R_f}{R_3} \right) \dots \text{etc}$$

Cont...

We can also rearrange the formula to make the feedback resistor R_F the subject and the output voltage is found from

$$-V_{out} = R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right) \dots \text{etc}$$

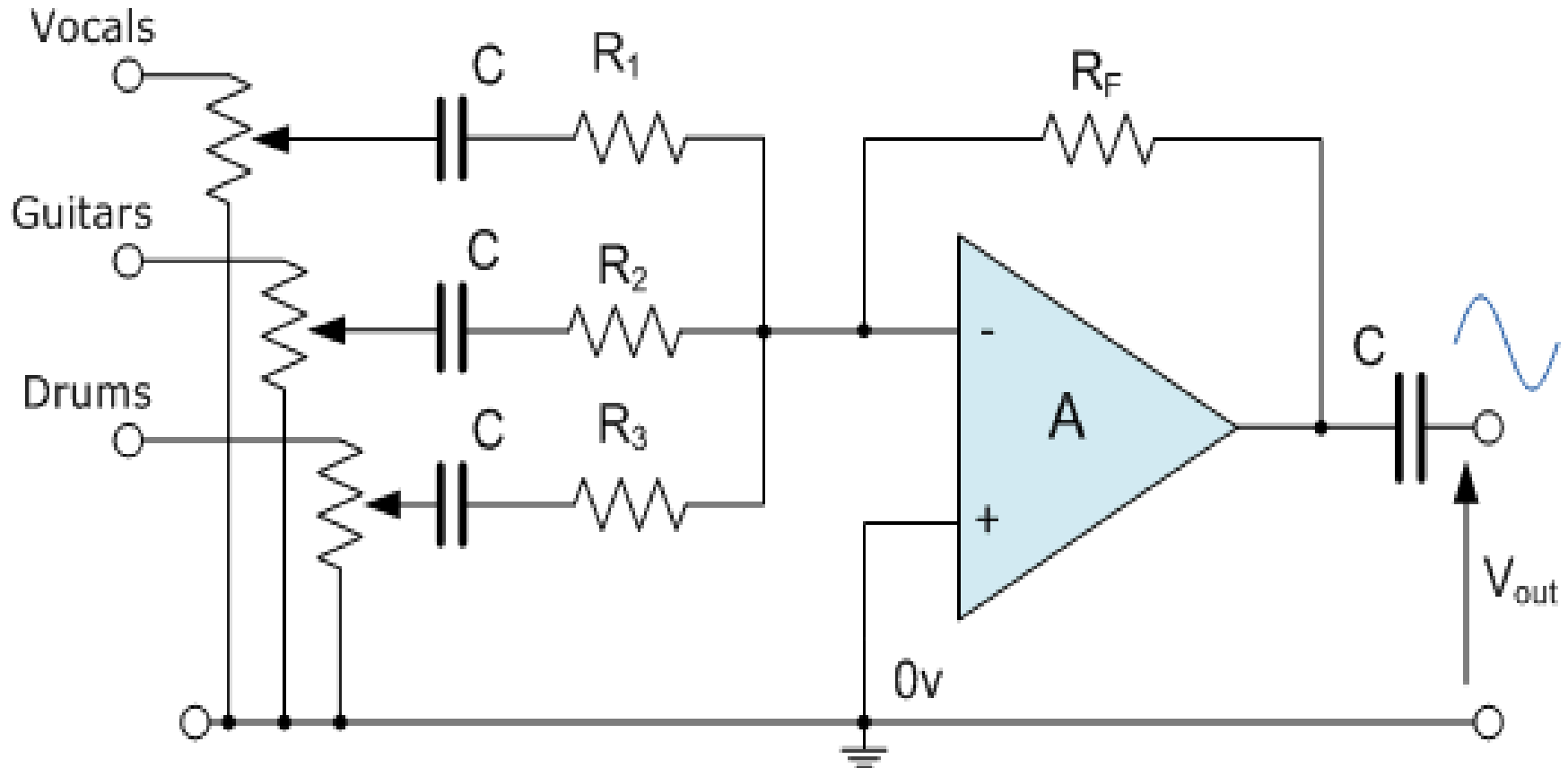
Cont...

- Allowing the output voltage to be easily calculated if more input resistors are connected to the amplifiers input.
- The input impedance of each individual channel is the value of their respective input resistors, ie, R_1 , R_2 , R_3 ... etc.
- The **Summing Amplifier** is a very flexible circuit indeed, enabling us to effectively "Add" or "Sum" together several individual input signals.
- If the inputs resistors, R_1 , R_2 , R_3 etc, 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.

Cont...

- 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, 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.

Summing Amplifier Audio Mixer



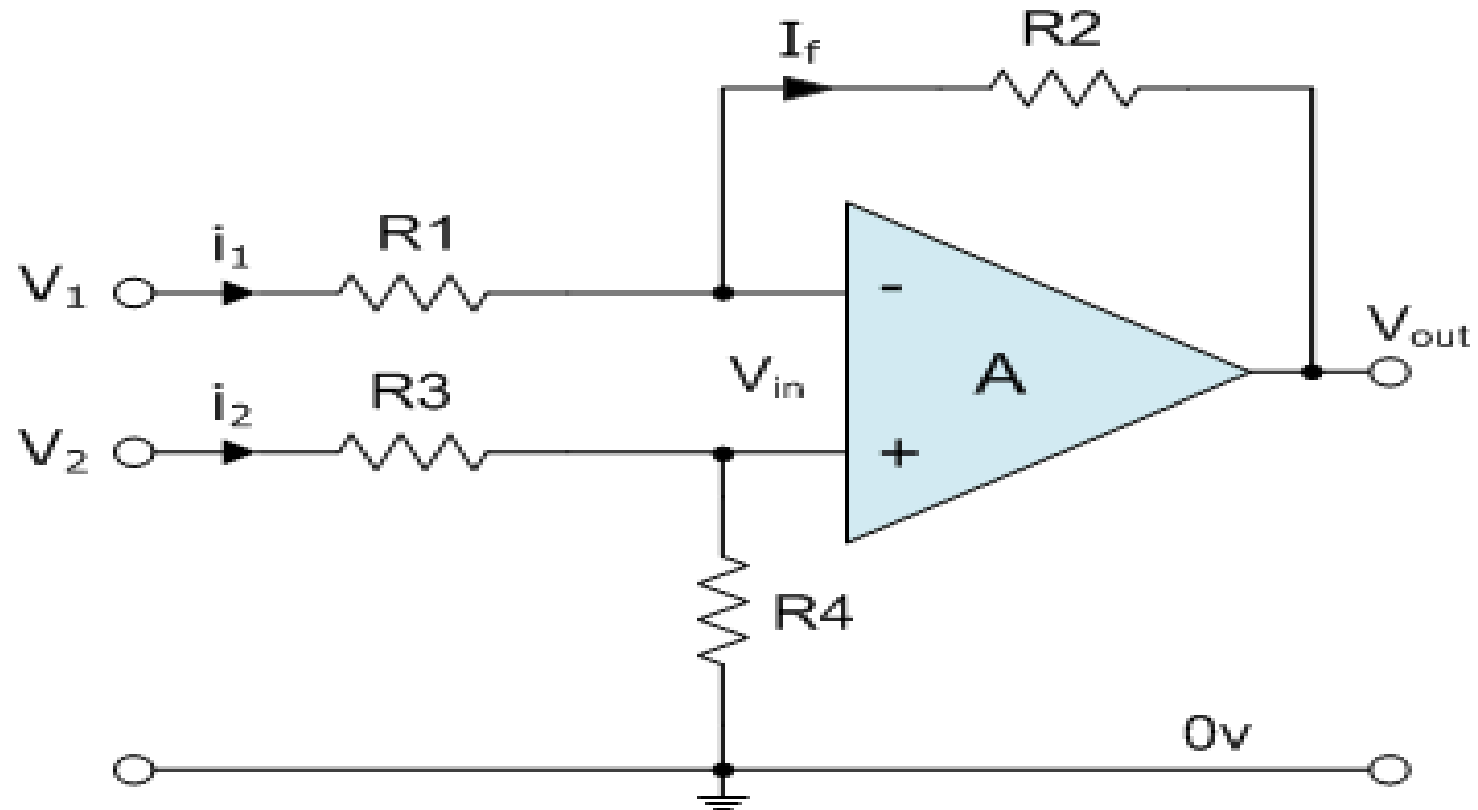
Differential Amplifier

- 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**.

Cont...

- By connecting one voltage signal onto one input terminal and another voltage signal onto the other input terminal the resultant output voltage will be proportional to the "Difference" between the two input signals of V_1 and V_2 and this type of circuit can also be used as a **Subtractor**.
- Then, this type of Operational Amplifier circuit is commonly known as a **Differential Amplifier** configuration and is shown below:

Schematic diagram of Differential Amplifier



Cont...

- The transfer function for a **Differential Amplifier** circuit is given as:

$$V_{OUT} = -\frac{R_2}{R_1} V_1 + \left(1 + \frac{R_2}{R_1}\right) \left(\frac{R_4}{R_3 + R_4}\right) V_2$$

- When $R_1 = R_3$ and $R_2 = R_4$ the transfer function formula can be modified to the following

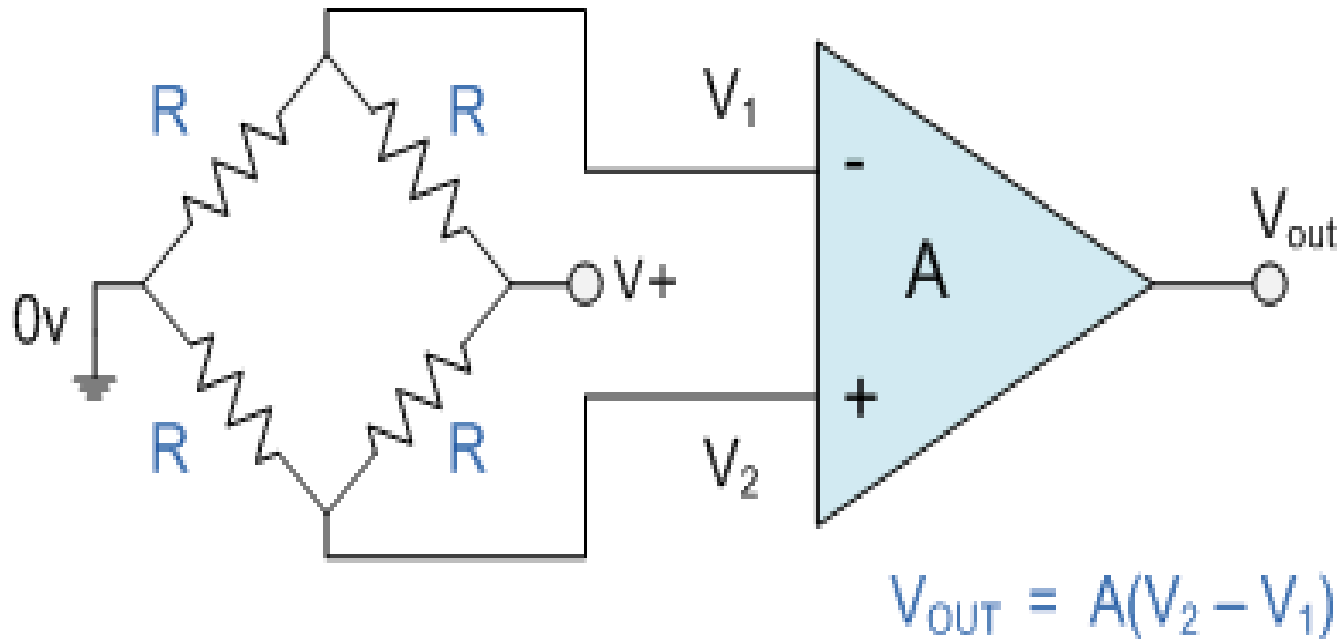
$$V_{OUT} = \frac{R_2}{R_1} (V_2 - V_1)$$

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Cont...

- If all 4 resistors are of the same value the circuit will become a **Unity Gain Differential Amplifier** and the gain of the amplifier will be 1 or Unity.
- The **Differential Amplifier** circuit is a very useful op-amp circuit and by adding more resistors in parallel with the input resistors R1 and R3, the resultant circuit can be made to either "Add" or "Subtract" the voltages applied to their respective inputs.
- One of the most common ways of doing this is to connect a "Resistive Bridge" commonly called a *Wheatstone Bridge* to the input of the amplifier as shown below.

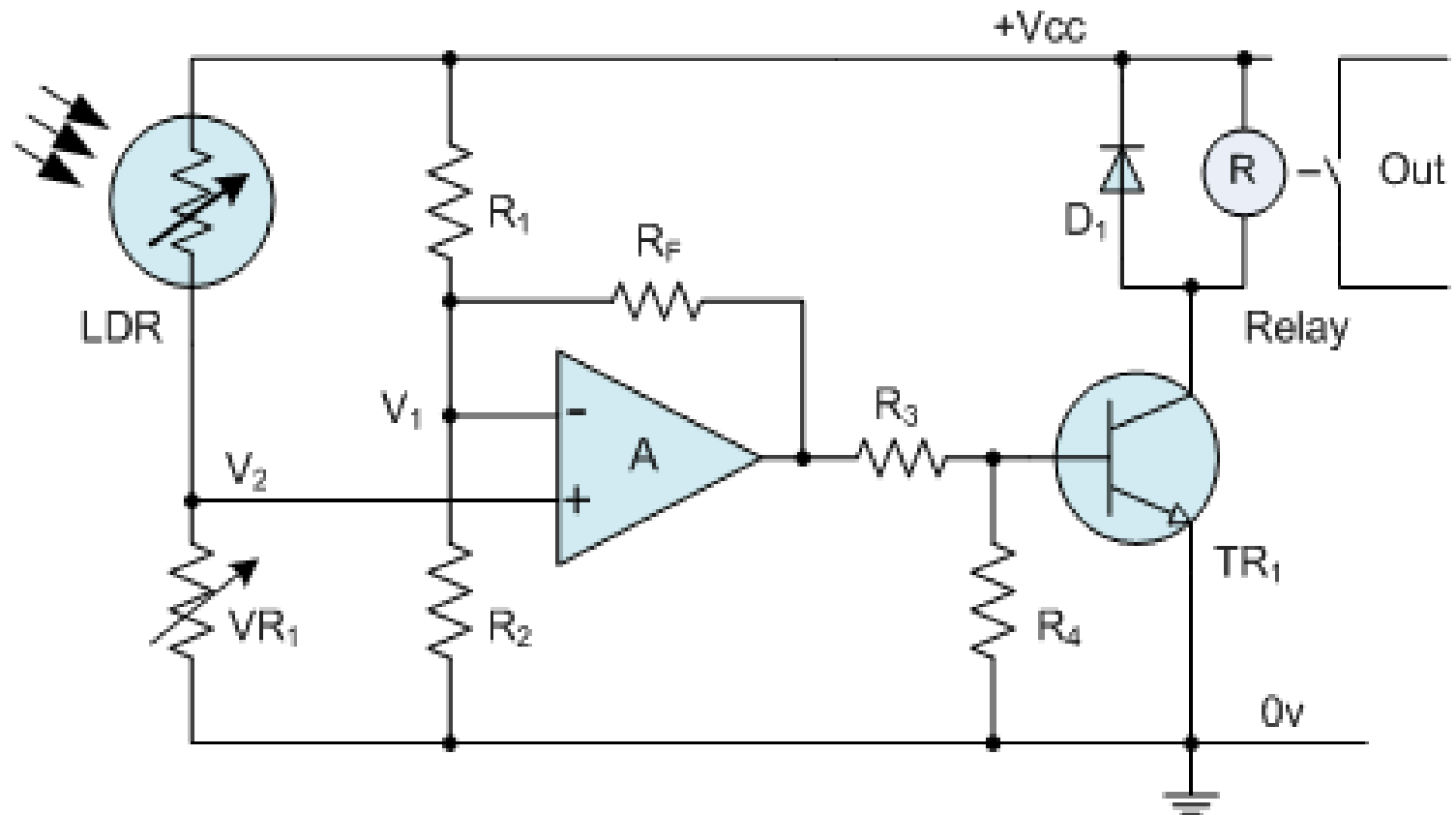
Bridge Amplifier



Cont...

- The standard Differential Amplifier circuit now becomes a differential voltage comparator by "Comparing" one input voltage to the other.
- For example, by connecting one input to a fixed voltage reference set up on one leg of the resistive bridge network and the other to either a "Thermistor" or a "Light Dependant Resistor" the amplifier circuit can be used to detect either low or high levels of temperature or light as the output voltage becomes a linear function of the changes in the active leg of the resistive bridge and this is shown below.

Light Activated Switch



Cont...

- Here the circuit above acts as a light-activated switch which turns the output relay either "ON" or "OFF" as the light level detected by the LDR resistor exceeds or falls below the pre-set value of VR1.
- The fixed voltage reference is applied to the inverting input terminal V1 via the R1 - R2 voltage divider network and the variable voltage (proportional to the light level) applied to the non-inverting input terminal V2.
- It is also possible to detect temperature using this type of circuit by simply replacing the Light Dependant Resistor (LDR) with a thermistor

Cont...

- 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.

Cont...

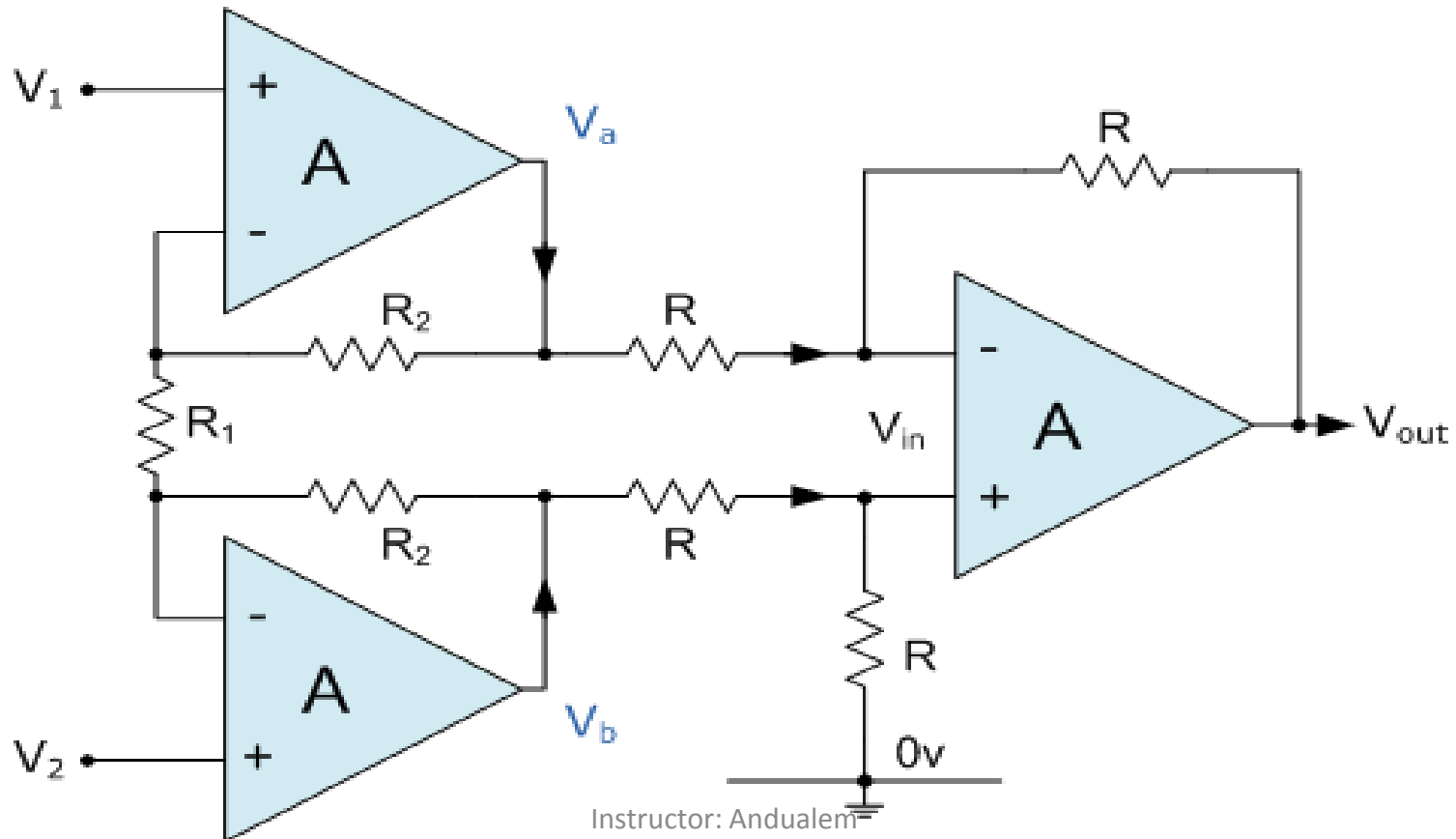
- One way to overcome this problem is to add a *Unity Gain Buffer Amplifier* such as the voltage follower seen in the previous tutorial to each input resistor.
- This then gives us a differential amplifier circuit with very high input impedance and is the basis for most "Instrumentation Amplifiers".

Instrumentation Amplifier

- *Instrumentation Amplifiers* are high gain differential amplifiers with high input impedance and a single ended output.
- They are mainly used to amplify very small differential signals from strain gauges, thermocouples or current sensing resistors in motor control systems.
- They also have very good common mode rejection (zero output when $V_1 = V_2$) in excess of 100dB at DC.

Cont...

A typical example of an instrumentation amplifier with a high input impedance (Z_{in}) is given below:



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and Digital Electronics :EMEg2251

Cont...

- The negative feedback of the top op-amp causes the voltage at V_a to be equal to the input voltage V_1 .
- Likewise, the voltage at V_b is equal to the value of V_2 .
- This produces a voltage drop across R_1 which is equal to the voltage difference between V_1 and V_2 .

Cont...

- This voltage drop causes a current to flow through R1, and as the two inputs of the buffer op-amps draw no current (virtual earth), the same amount of current flowing through R1 must also be flowing through the two resistors R2.
- This then produces a voltage drop between points Va and Vb equal to:

$$\frac{(V_a - V_b)}{(V_1 - V_2)} = \left[1 + \frac{2R_2}{R_1} \right]$$

Cont...

- This voltage drop between points Va and Vb is connected to the inputs of the differential amplifier which amplifies it by a gain of 1 (assuming that all the "R" resistors are of equal value).
- Then we have a general expression for overall voltage gain of the instrumentation amplifier circuit as:

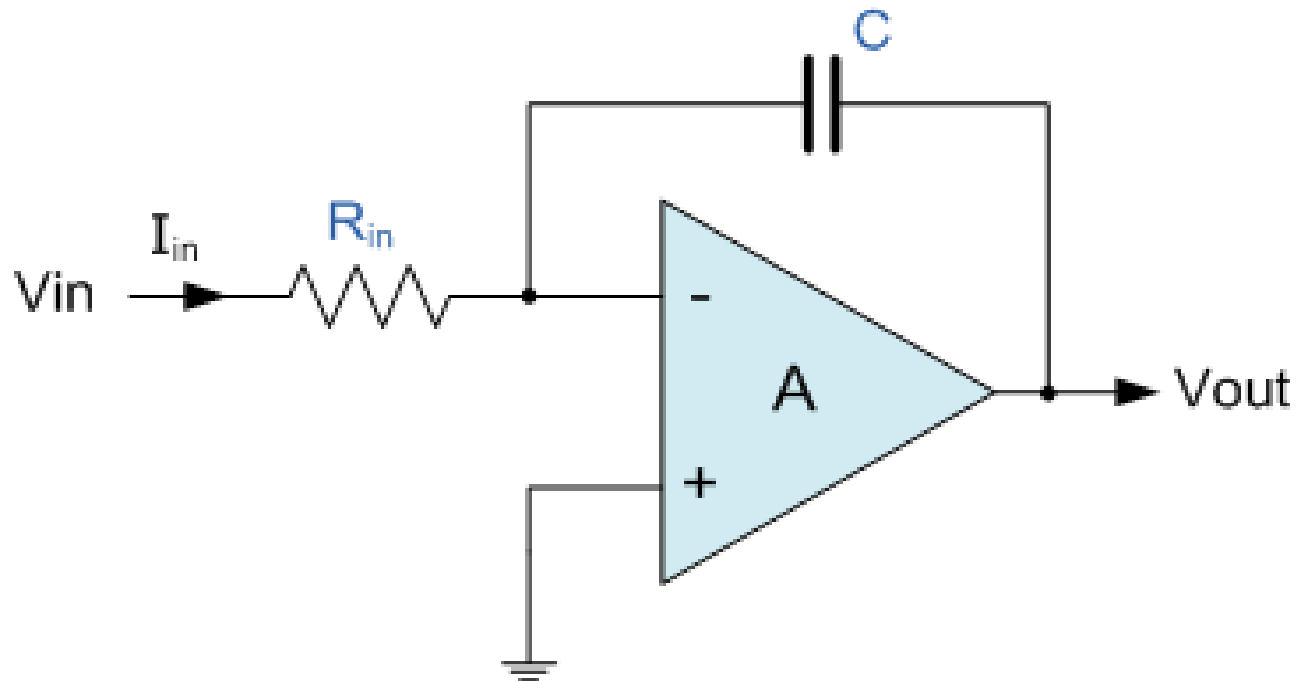
$$V_{\text{out}} = (V_1 - V_2) \left[1 + \frac{2R_2}{R_1} \right]$$

- The differential gain of the circuit can be changed by changing the value of R1.

The Integrator Amplifier

- In the previous tutorials we have seen circuits which show 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 just 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 Frequency Dependant Impedance, (Z) type 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



Cont...

- The **Integrator Amplifier** is an operational amplifier circuit that performs the mathematical operation of **Integration**.
- It's output responds to the changes in the input voltage over time and the integrator amplifier produces a voltage output.
- The produced out put voltage is proportional to that of its input voltage with respect to time.

Cont...

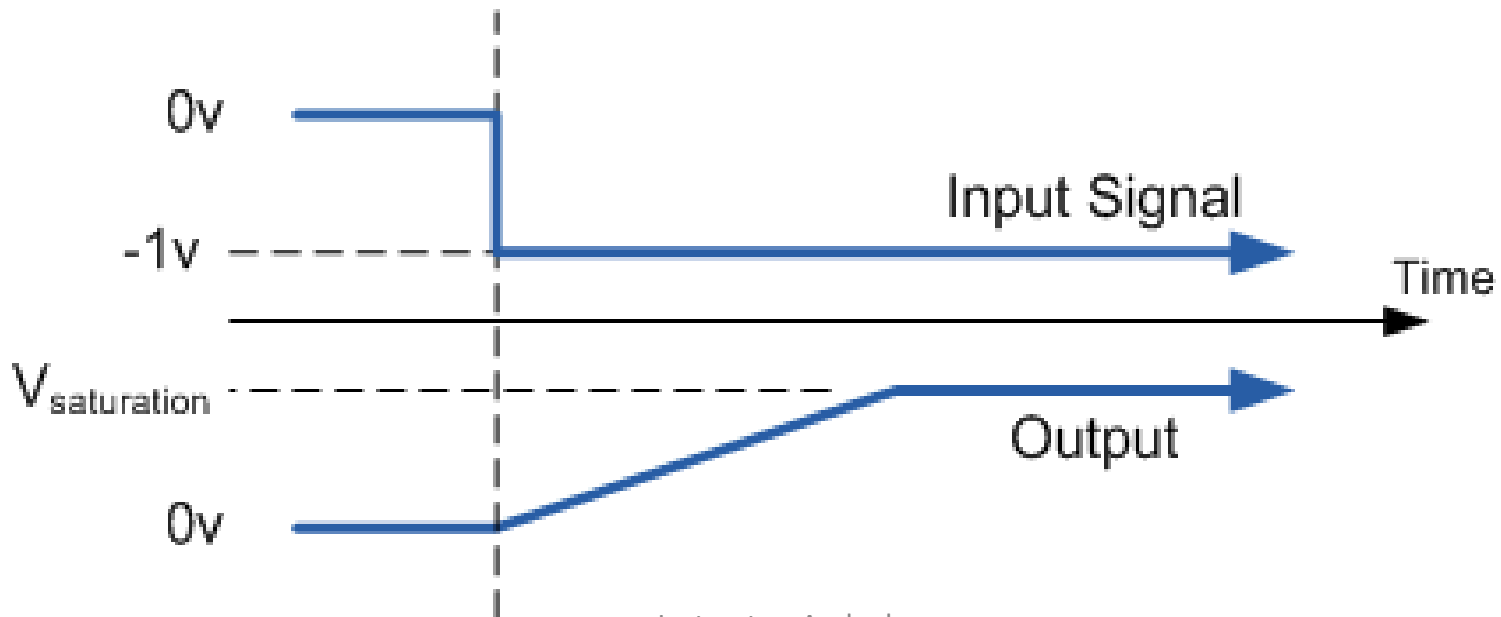
- When a voltage, V_{in} is firstly applied to the input of an integrating amplifier, the uncharged capacitor C has very little resistance and acts a bit like a short circuit (voltage follower circuit) giving an overall gain of less than 1, thus resulting in zero output.
- As the feedback capacitor C begins to charge up, its reactance X_c decreases and the ratio of Z_f/R_{in} increases producing an output voltage that continues to increase until the capacitor is fully charged.

Cont...

- 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 below.
- (Saturation is when the output voltage of the amplifier swings heavily to one voltage supply rail or the other with no control in between).

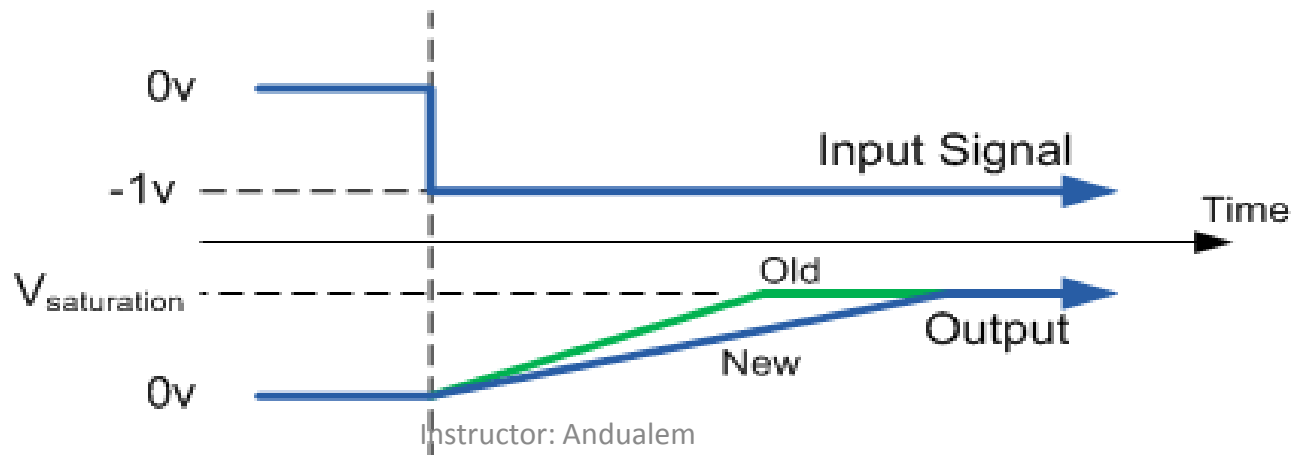
Cont...

In other words the magnitude of the output signal is determined by the length of time a voltage is present at its input as the current through the feedback loop charges or discharges the capacitor.



Cont...

- 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 for example.

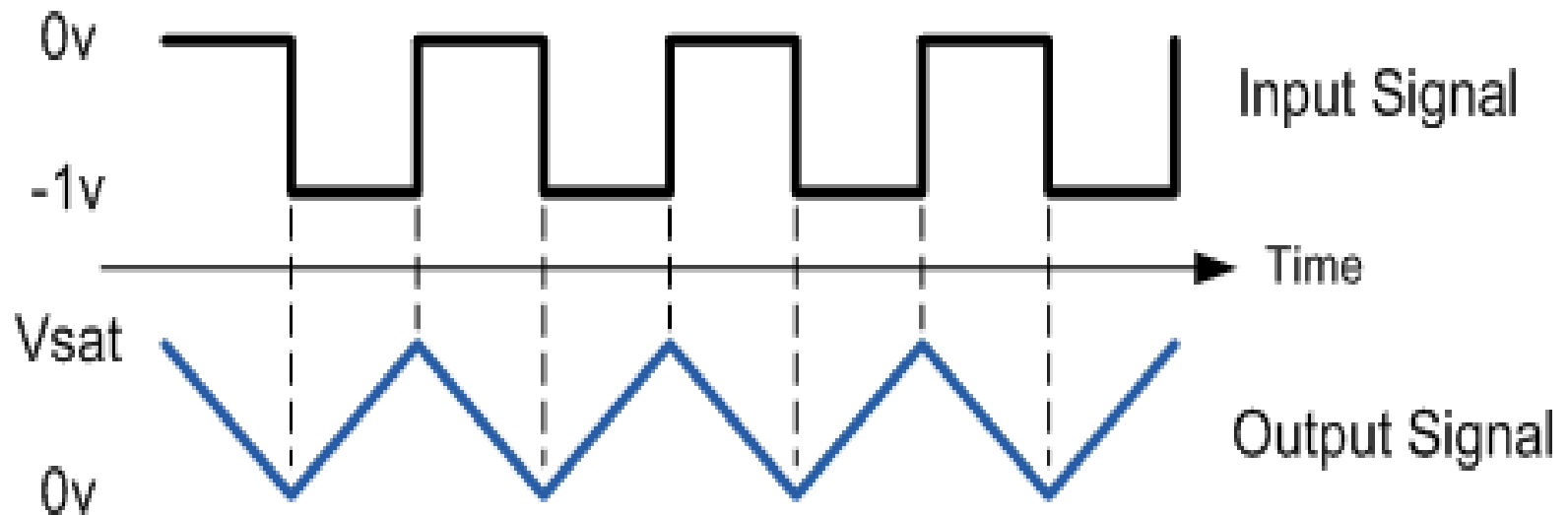


Cont...

- 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 the output signal being that of a saw-tooth waveform whose frequency is dependent upon the RC time constant of the resistor/capacitor combination.

Ramp Generator

This type of circuit is also known as a **Ramp Generator** and the transfer function is given below.



Cont..

- Since the node voltage of the integrating op-amp at its inverting input terminal is zero, the current i flowing through the input resistor is given as:

$$i = \frac{V_{in} - 0}{R} = \frac{V_{in}}{R}$$

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

$$i = C \frac{d}{dt} (0 - V_{out}) = C \frac{dV_{out}}{dt}$$

Cont...

- 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

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

Cont...

- This can also be re-written as:

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

Where , $j\omega = 2\pi f$ and

- 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° phase shift because the input signal is connected directly to the inverting input terminal of the op-amp.

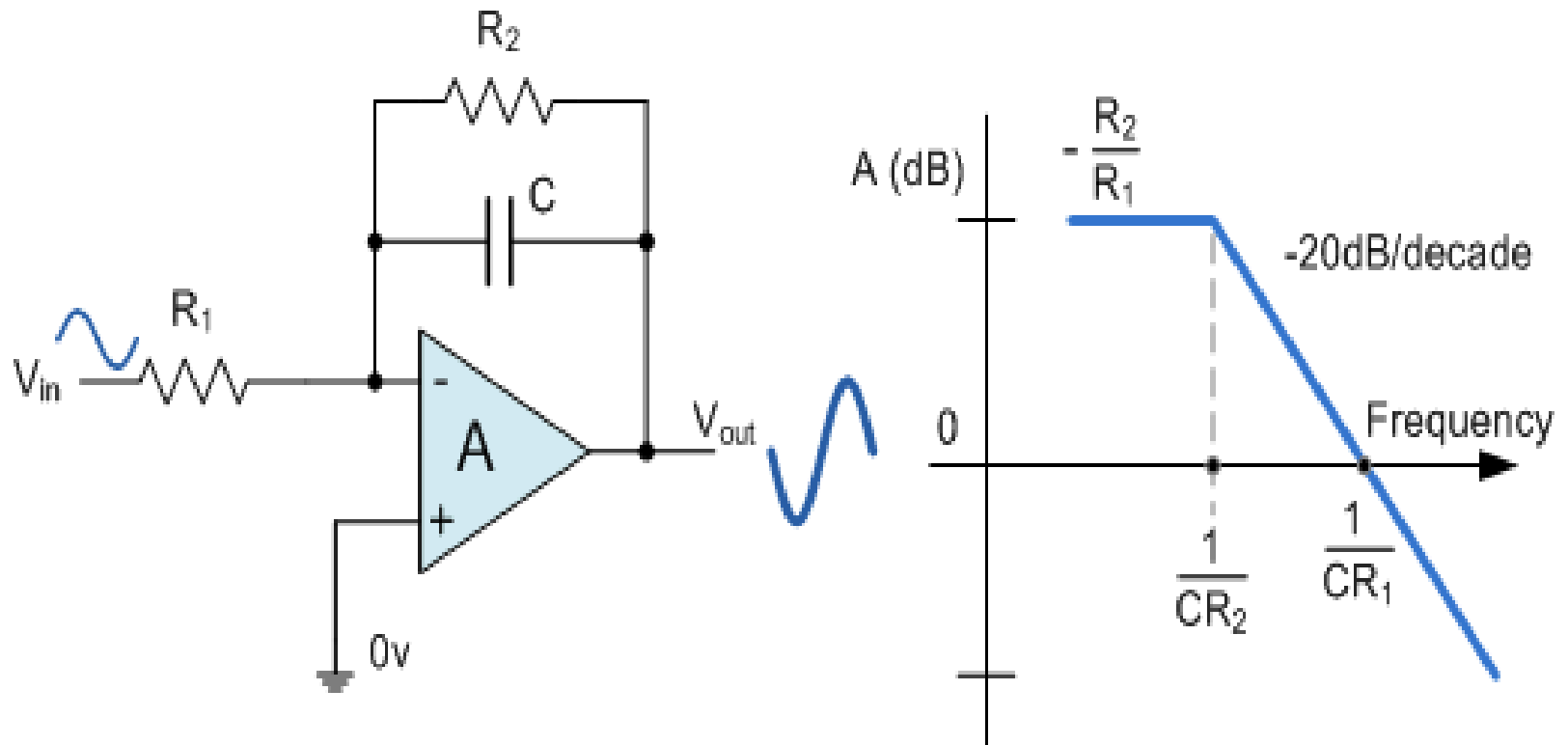
The AC or Continuous Integrator

- 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.
- At 0Hz or DC, the capacitor acts like an open circuit blocking any feedback voltage resulting in very little negative feedback from the output back to the input of the amplifier.
- Then with just the feedback capacitor, C , the amplifier effectively is connected as a normal open-loop amplifier which has very high open-loop gain resulting in the output voltage saturating.

Cont...

- This circuit connects a high value resistance in parallel with a continuously charging and discharging capacitor.
- The addition of this 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_1 at very low frequencies while acting as an integrator at higher frequencies has the capacitor shorts out the feedback resistor, R_2 .

The AC Integrator with DC Gain Control



Cont...

- This then forms the basis of a *Active Low Pass Filter* as seen before in the filters section tutorials with a corner frequency given as

$$\text{D.C. Voltage Gain, } (A_{v_o}) = -\frac{R_2}{R_1}$$

$$\text{A.C. Voltage Gain, } (A_v) = -\frac{R_2}{R_1} \times \frac{1}{(1 + 2\pi f C R_2)}$$

$$\text{Corner Frequency, } (f_o) = \frac{1}{2\pi C R_2}$$

The Differentiator Amplifier

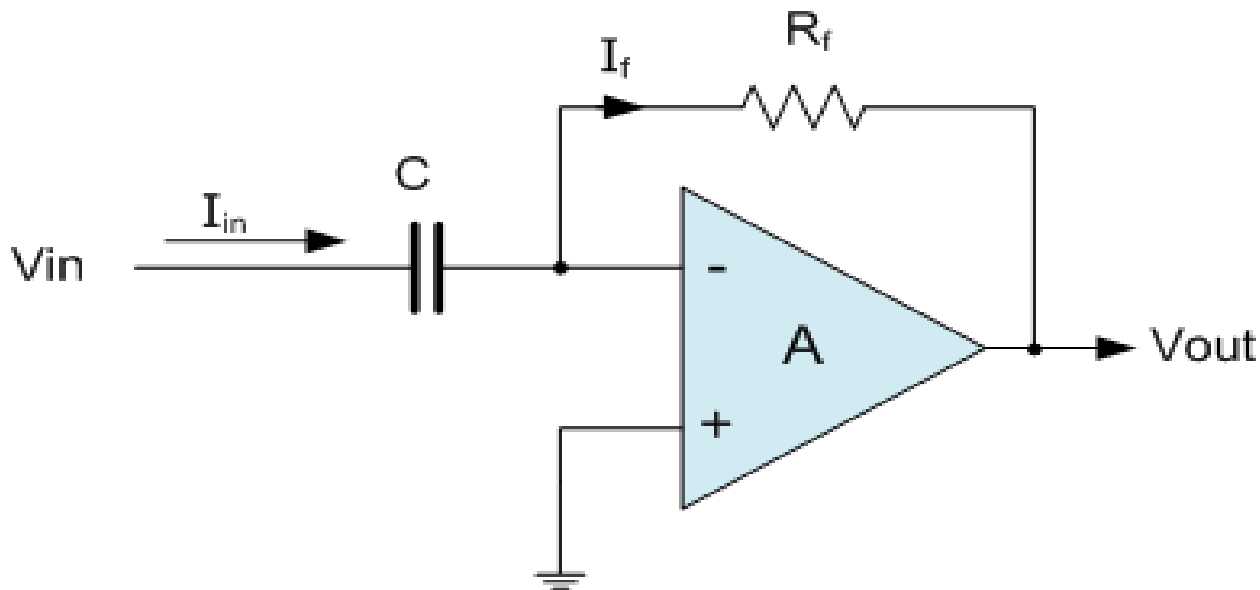
- The basic **Differentiator Amplifier** circuit is an exact opposite to that of the *Integrator* operational amplifier circuit that we saw in the previous tutorial.
- Here, the position of the capacitor and resistor have been reversed and now the Capacitor, C is connected to the input terminal of the inverting amplifier while the Resistor, R_f forms the negative feedback element across the operational amplifier.

Cont...

- This circuit performs the mathematical operation of **Differentiation** that is it produces a voltage output which is proportional to the input voltage's **rate-of-change** 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.

Differentiator Amplifier Circuit

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



Cont...

- The capacitor blocks any DC content only allowing AC type signals to pass through and whose frequency is dependent on the rate of change of the input signal.
- At low frequencies the reactance of the capacitor is "High" resulting in a low gain (R_f/X_c) 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.

Cont...

- However, at high frequencies a differentiator circuit becomes unstable and will start to oscillate.
- This is due mainly to the First-order effect, which determines the frequency response of the op-amp circuit causing a Second-order response which, at high frequencies gives an output voltage far higher than what was expected.
- To avoid this the high frequency gain of the circuit needs to be reduced by adding an additional small value capacitor across the feedback resistor R_f .

Cont...

- Ok, some math's to explain what's going on. 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:

$$i_{IN} = I_F \text{ and } I_F = - \frac{V_{OUT}}{R_F}$$

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

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

Cont...

- The rate of change of this charge is;

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

- But, dQ/dt is the capacitor current I

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

∴

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

Cont...

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

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

Cont...

- 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° phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.
- One final point to mention, the **Differentiator Amplifier** circuit in its basic form has two main disadvantages compared to the previous Integrator circuit.

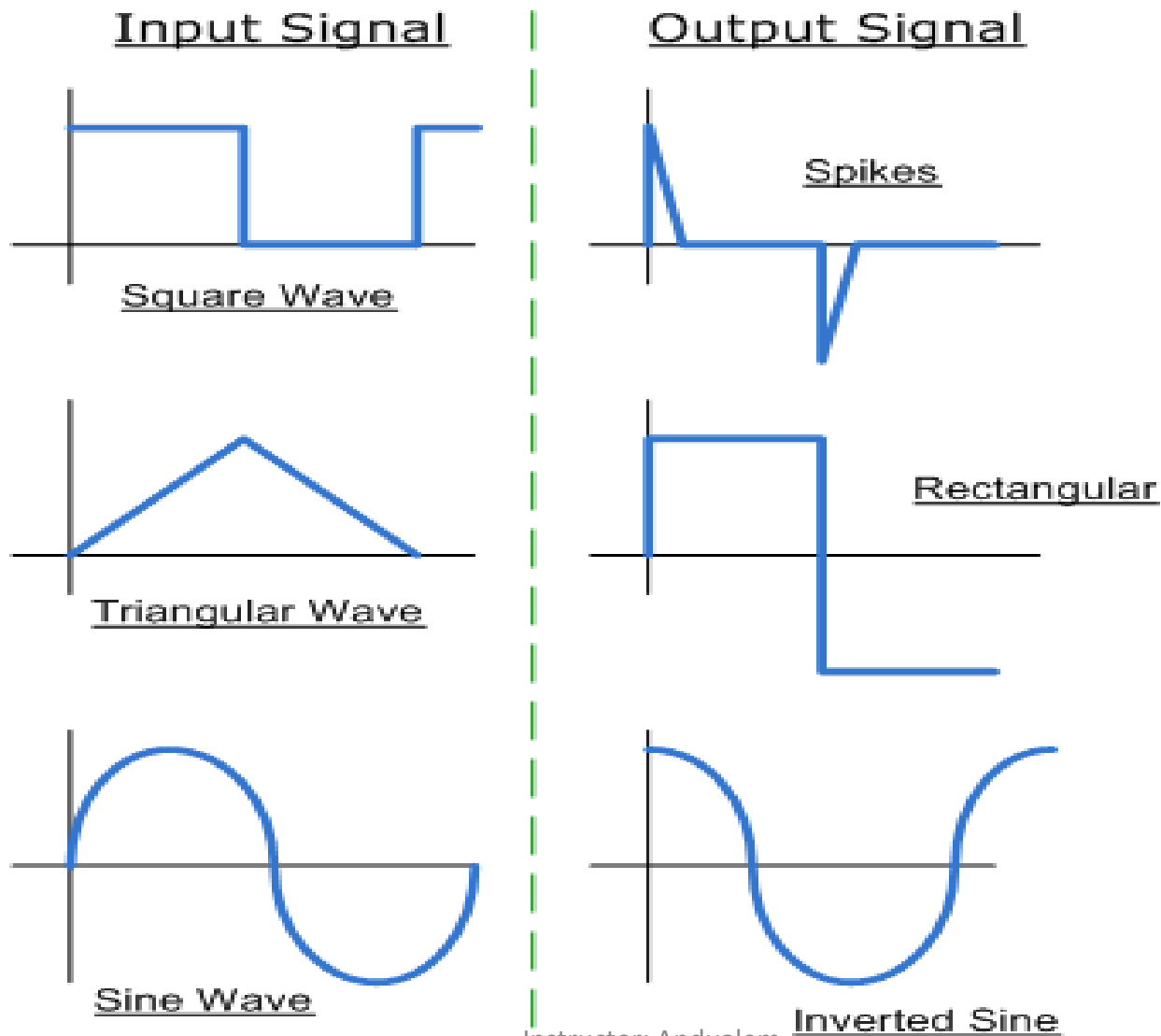
Cont...

- One is that it suffers from instability at high frequencies as mentioned above, and the other is that 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

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.

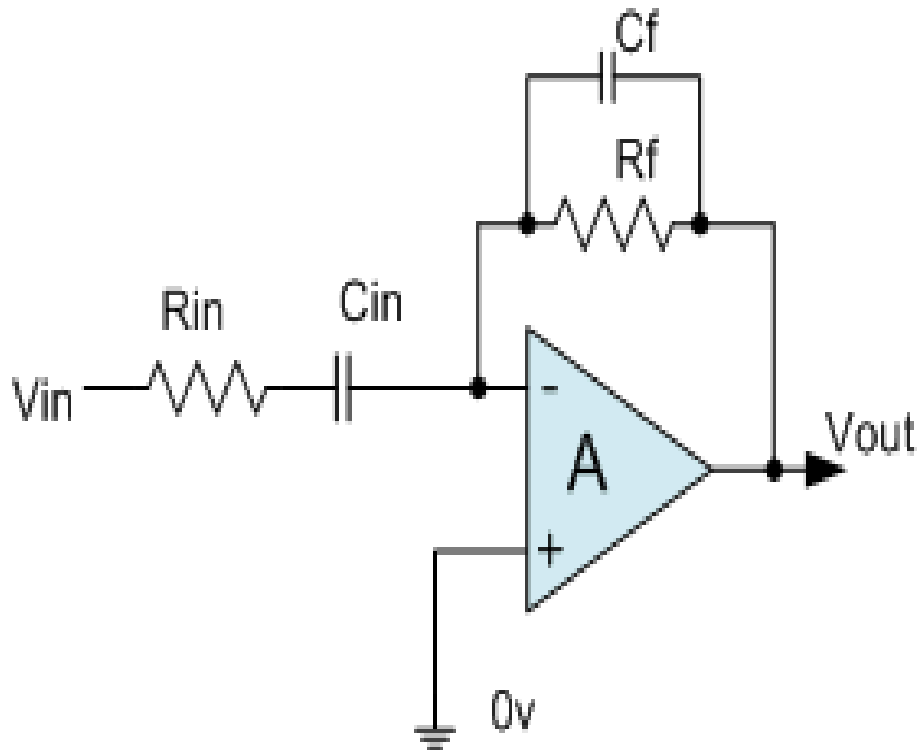
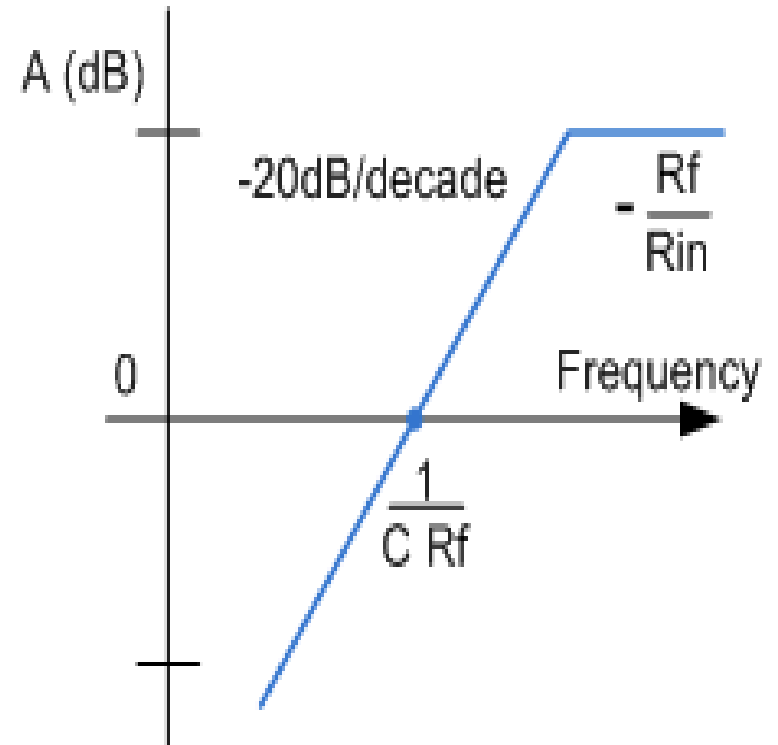
The input & changed output signals



Improved Differentiator Amplifier

- 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.
- So in order to reduce the overall closed-loop gain of the circuit at high frequencies, an extra Resistor, R_2 is added to the input as shown below

Improved Differentiator Amplifier Circuit



Cont...

- The circuit which we have now acts like a Differentiator amplifier at low frequencies and an amplifier with resistive feedback at high frequencies giving much better noise rejection.
- This then forms the basis of a *Active High Pass Filter* as seen before in the filters section.