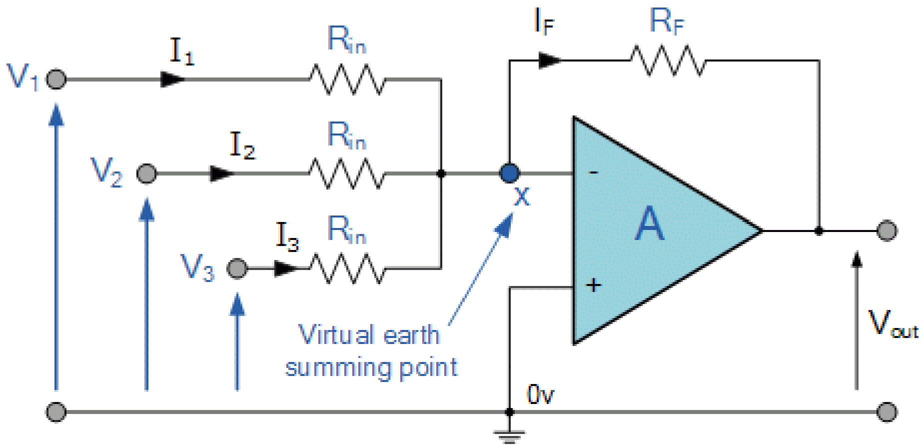
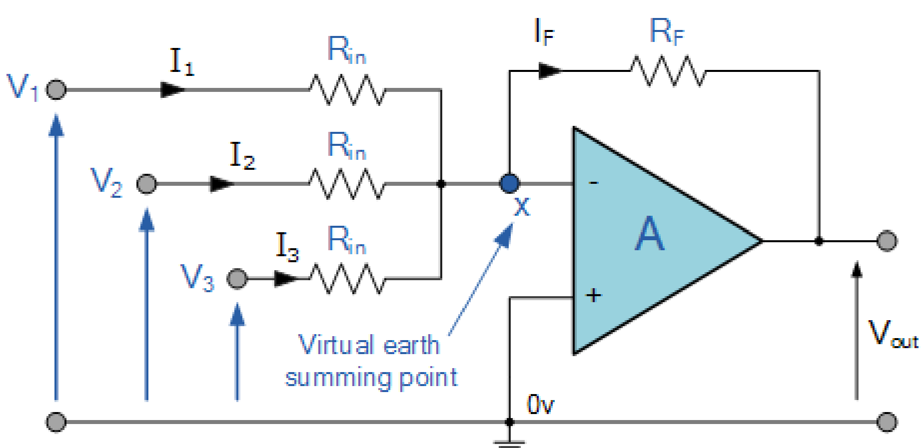


The Summing Amplifier

The **Summing Amplifier** is another type of operational amplifier circuit configuration that is used to combine the voltages present on two or more inputs into a single output voltage.

We saw previously in the inverting operational amplifier that the inverting amplifier has a single input voltage, (Vin) applied to the inverting input terminal. If we add more input resistors to the input, each equal in value to the original input resistor, (Rin) 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



In this simple summing amplifier circuit, the output voltage, (Vout) 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:

$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin} \right]$$

$$\text{Inverting Equation: } Vout = -\frac{Rf}{Rin} \times Vin$$

$$\text{then, } -Vout = \left[\frac{R_F}{Rin} V1 + \frac{R_F}{Rin} V2 + \frac{R_F}{Rin} V3 \right]$$

However, if all the input impedances, (R_{IN}) are equal in value, we can simplify the above equation to give an output voltage of:

Summing Amplifier Equation

$$-Vout = \frac{R_F}{R_{IN}} \left(V1 + V2 + V3 \ldots etc \right)$$

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, Rin as the only input impedance.

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 Rf is equal to Rin.

Note that when the summing point is connected to the inverting input of the op-amp the circuit will produce the negative sum of any number of input voltages. Likewise, when the summing point is connected to the non-inverting input of the op-amp, it will produce the positive sum of the input voltages.

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

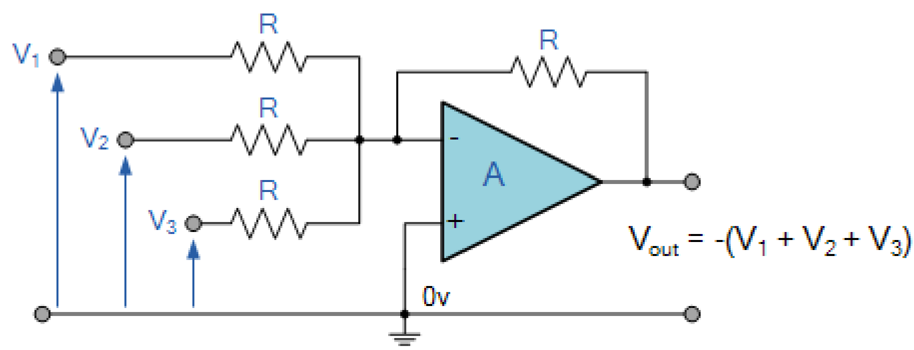
$$-V_{OUT} = V_1\left(\frac{R_f}{R_1}\right) + V_2\left(\frac{R_f}{R_2}\right) + V_3\left(\frac{R_f}{R_3}\right) \ldots\text{etc}$$

To make the math's a little easier, we can rearrange the above formula to make the feedback resistor R*ƒ* the subject of the equation giving the output voltage as:

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

This allows the output voltage to be easily calculated if more input resistors are connected to the amplifiers inverting input terminal. The input impedance of each individual channel is the value of their respective input resistors, ie, R_1, R_2, R_3 ... etc.

Sometimes we need a summing circuit to just add together two or more voltage signals without any amplification. By putting all of the resistances of the circuit above to the same value R, the op-amp will have a voltage gain of unity and an output voltage equal to the direct sum of all the input voltages as shown:

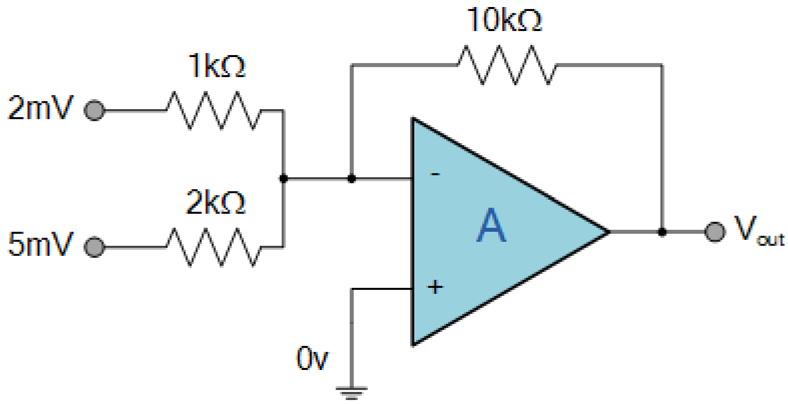


The **Summing Amplifier** is a very flexible circuit indeed, enabling us to effectively "Add" or "Sum" (hence its name) together several individual input signals. If the inputs resistors, R_1, R_2, R_3 etc, are all equal a "unity gain inverting adder" will be made. However, if the input resistors are of different values a "scaling summing amplifier" is produced which will output a weighted sum of the input signals.

Summing Amplifier Example No1

Find the output voltage of the following *Summing Amplifier* circuit.

Summing Amplifier



Using the previously found formula for the gain of the circuit:

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

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

$$A_1 = \frac{10k\Omega}{1k\Omega} = -10$$

$$A_2 = \frac{10k\Omega}{2k\Omega} = -5$$

We know that the output voltage is the sum of the two amplified input signals and is calculated as:

$$V_{out} = (A_1 \times V_1) + (A_2 \times V_2)$$

$$V_{out} = (-10(2mV)) + (-5(5mV)) = -45mV$$

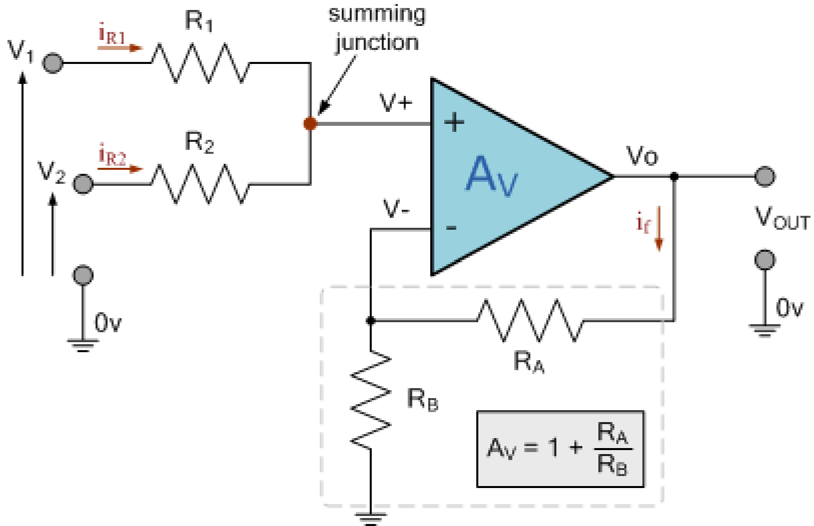
Then the output voltage of the **Summing Amplifier** circuit above is given as **-45 mV** and is negative as its an inverting amplifier.

Non-inverting Summing Amplifier

But as well as constructing inverting summing amplifiers, we can also use the non-inverting input of the operational amplifier to produce a *non-inverting summing amplifier*. We have seen above that an inverting summing amplifier produces the negative sum of its input voltages then it follows that the non-inverting summing amplifier configuration will produce the positive sum of its input voltages.

As its name implies, the non-inverting summing amplifier is based around the configuration of a non-inverting operational amplifier circuit in that the input (either ac or dc) is applied to the non-inverting (+) terminal, while the required negative feedback and gain is achieved by feeding back some portion of the output signal (V_{OUT}) to the inverting (-) terminal as shown.

Non-inverting Summing Amplifier



So what's the advantage of the non-inverting configuration compared to the inverting summing amplifier configuration. Besides the most obvious fact that the op-amps output voltage V_{OUT} is in phase with its input, and the output voltage is the weighted sum of all its inputs which themselves are determined by their resistance ratios, the biggest advantage of the non-inverting summing amplifier is that because there is no virtual earth condition across the input terminals, its input impedance is much higher than that of the standard inverting amplifier configuration.

Also, the input summing part of the circuit is unaffected if the op-amps closed-loop voltage gain is changed. However, there is more maths involed in selecting the weighted gains for each individual input at the summing junction especially if there are more than two inputs each with a different weighting factor. Nevertheless, if all the inputs have the same resistive values, then the maths involved will be a lot less.

If the closed-loop gain of the non-inverting operational amplifier is made equal the number of summing inputs, then the op-amps output voltage will be exactly equal to the sum of all the input voltages. That is for a two input non-inverting summing amplifier, the op-amps gain is equal to 2, for a three input summing amplifier the op-amps gain is 3, and so on. This is because the currents which flow in each input resistor is a function of the voltage at all its inputs. If the input resistances made all equal, ($R_1 = R_2$) then the circulating currents cancel out as they can not flow into the high impedance non-inverting input of the op-amp and the voutput voltage becomes the sum of its inputs.

So for a 2-input non-inverting summing amplifier the currents flowing into the input terminals can be defined as:

$$I_{R1} + I_{R2} = 0 \quad (\text{KCL})$$

$$\frac{V_1 - V+}{R_1} = \frac{V_2 - V+}{R_2} = 0$$

$$\therefore \left(\frac{V_1}{R_1} - \frac{V+}{R_1} \right) + \left(\frac{V_2}{R_2} - \frac{V+}{R_2} \right) = 0$$

If we make the two input resistances equal in value, then $R_1 = R_2 = R$.

$$V+ = \frac{\frac{V_1}{R} + \frac{V_2}{R}}{\frac{1}{R} + \frac{1}{R}} = \frac{\frac{V_1 + V_2}{R}}{\frac{2}{R}}$$

$$\text{Thus} \quad V+ = \frac{V_1 + V_2}{2}$$

The standard equation for the voltage gain of a non-inverting summing amplifier circuit is given as:

$$A_V = \frac{V_{OUT}}{V_{IN}} = \frac{V_{OUT}}{V+} = 1 + \frac{R_A}{R_B}$$

$$\therefore \quad V_{OUT} = \left[1 + \frac{R_A}{R_B} \right] V+$$

$$\text{Thus:} \quad V_{OUT} = \left[1 + \frac{R_A}{R_B} \right] \frac{V_1 + V_2}{2}$$

The non-inverting amplifiers closed-loop voltage gain A_V is given as: $1 + R_A/R_B$. If we make this closed-loop voltage gain equal to 2 by making $R_A = R_B$, then the output voltage V_O becomes equal to the sum of all the input voltages as shown.

Non-inverting Summing Amplifier Output Voltage

$$V_{OUT} = \left[1 + \frac{R_A}{R_B}\right]\frac{V_1 + V_2}{2}$$

$$\text{If } R_A = R_B$$

$$V_{OUT} = [1 + 1]\frac{V_1 + V_2}{2} = \cancel{2}\frac{V_1 + V_2}{\cancel{2}}$$

$$\therefore V_{OUT} = V_1 + V_2$$

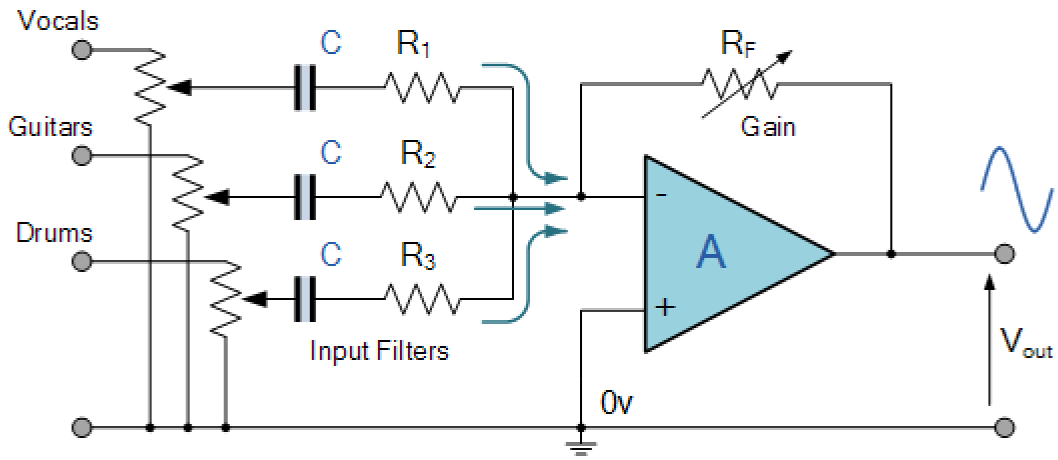
Thus for a 3-input non-inverting summing amplifier configuration, setting the closed-loop voltage gain to 3 will make V_{OUT} equal to the sum of the three input voltages, V_1, V_2 and V_3. Likewise, for a four input summer, the closed-loop voltage gain would be 4, and 5 for a 5-input summer, and so on. Note also that if the amplifier of the summing circuit is connected as a unity follower with R_A equal to zero and R_B equal to infinity, then with no voltage gain the output voltage V_{OUT} will be exactly equal the average value of all the input voltages. That is $V_{OUT} = (V_1 + V_2)/2$.

Summing Amplifier Applications

So what can we use summing amplifiers for, either inverting or non-inverting. If the input resistances of a summing amplifier are connected to potentiometers the individual input signals can be mixed together by varying amounts.

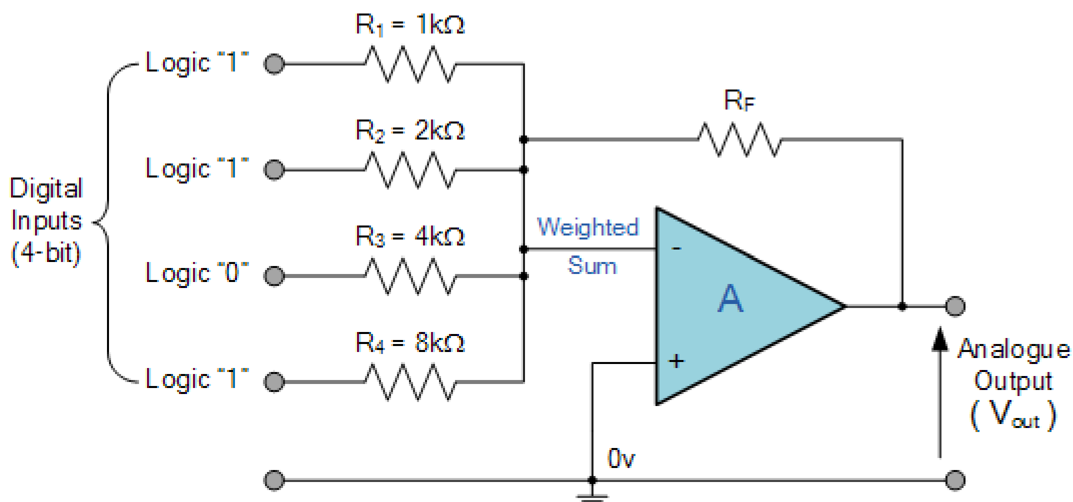
For example, measuring temperature, you could add a negative offset voltage to make the output voltage or display read “0” at the freezing point or produce an audio mixer for adding or mixing together individual waveforms (sounds) from different source channels (vocals, instruments, etc) before sending them combined to an audio amplifier.

Summing Amplifier Audio Mixer



Another useful application of a **Summing Amplifier** is as a weighted sum digital-to-analogue converter, (DAC). If the input resistors, R_{IN} of the summing amplifier double in value for each input, for example, 1kΩ, 2kΩ, 4kΩ, 8kΩ, 16kΩ, etc, then a digital logical voltage, either a logic level "0" or a logic level "1" on these inputs will produce an output which is the weighted sum of the digital inputs. Consider the circuit below.

Digital to Analogue Converter

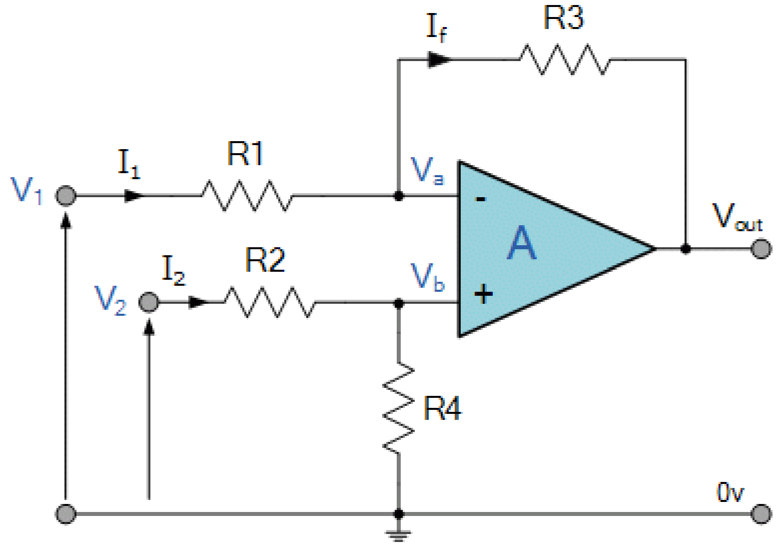


Of course this is a simple example. In this DAC summing amplifier circuit, the number of individual bits that make up the input data word, and in this example 4-bits, will ultimately determine the output step voltage as a percentage of the full-scale analogue output voltage.

Also, the accuracy of this full-scale analogue output depends on voltage levels of the input bits being consistently 0V for "0" and consistently 5V for "1" as well as the accuracy of the resistance values used for the input resistors, R_{IN}.

Fortunately to overcome these errors, at least on our part, commercially available Digital-to Analogue and Analogue-to Digital devices are readily available with highly accurate resistor ladder networks already built-in.

In the next tutorial about operational amplifiers, we will examine the effect of the output voltage, Vout when a signal voltage is connected to the inverting input and the non-inverting input at the same time to produce another common type of operational amplifier circuit called a Differential Amplifier which can be used to “subtract” the voltages present on its inputs.



The Differential Amplifier

The differential amplifier amplifies the voltage difference present on its inverting and non-inverting inputs

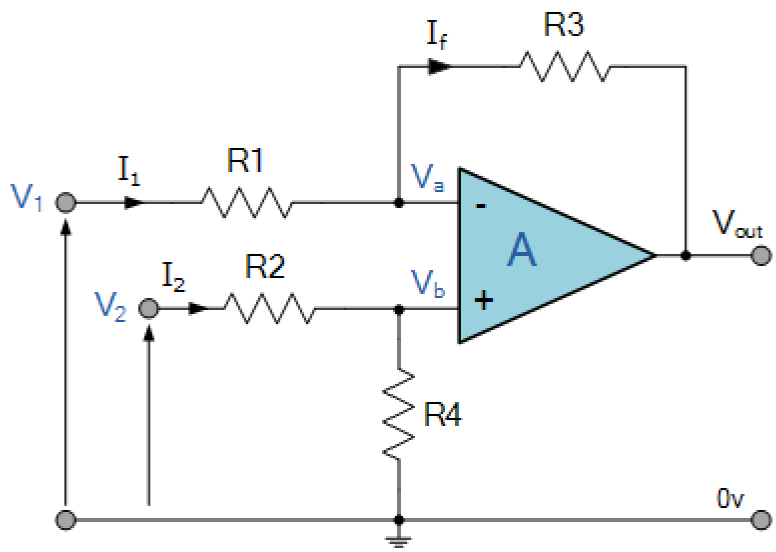
Thus far we have used only one of the operational amplifiers inputs to connect to the amplifier, using either the "inverting" or the "non-inverting" input terminal to amplify a single input signal with the other input being connected to ground.

But as a standard operational amplifier has two inputs, inverting and no-inverting, we can also connect signals to both of these inputs at the same time producing another common type of operational amplifier circuit called a **Differential Amplifier**.

Basically, as we saw in the first tutorial about operational amplifiers, all op-amps are "Differential Amplifiers" due to their input configuration. But 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 voltage signals of V_1 and V_2.

Then *differential amplifiers* amplify the difference between two voltages making this type of operational amplifier circuit a **Subtractor** unlike a summing amplifier which adds or sums together the input voltages. This type of operational amplifier circuit is commonly known as a **Differential Amplifier** configuration and is shown below:

Differential Amplifier



By connecting each input in turn to 0v ground we can use superposition to solve for the output voltage Vout. Then the transfer function for a **Differential Amplifier** circuit is given as:

$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (V_{out})}{R_3}$$

$$\text{Summing point } V_a = V_b$$

$$\text{and } V_b = V_2\left(\frac{R_4}{R_2 + R_4}\right)$$

$$\text{If } V_2 = 0, \text{ then: } V_{out(a)} = -V_1\left(\frac{R_3}{R_1}\right)$$

$$\text{If } V_1 = 0, \text{ then: } V_{out(b)} = V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

$$V_{out} = -V_{out(a)} + V_{out(b)}$$

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

When resistors, R1 = R2 and R3 = R4 the above transfer function for the differential amplifier can be simplified to the following expression:

Differential Amplifier Equation

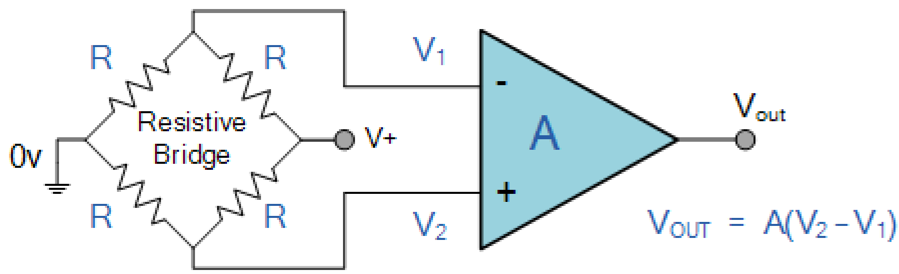
$$V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)$$

If all the resistors are all of the same ohmic value, that is: R1 = R2 = R3 = R4 then the circuit will become a **Unity Gain Differential Amplifier** and the voltage gain of the amplifier will be exactly one or unity. Then the output expression would simply be Vout = $V_2 - V_1$.

Also note that if input V1 is higher than input V2 the output voltage sum will be negative, and if V2 is higher than V1, the output voltage sum will be positive.

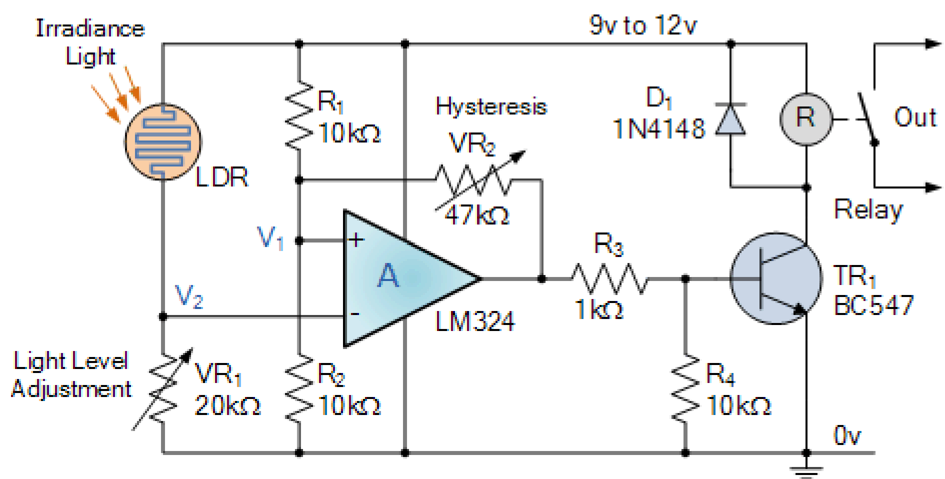
The **Differential Amplifier** circuit is a very useful op-amp circuit and by adding more resistors in parallel with the input resistors R1 and R3, the resultant circuit can be made to either "Add" or "Subtract" the voltages applied to their respective inputs. One of the most common ways of doing this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

Wheatstone Bridge Differential Amplifier



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 demonstrated below.

Light Activated Differential Amplifier



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 some pre-set value. A fixed voltage reference is applied to the non-inverting input terminal of the op-amp via the R1 – R2voltage divider network.

The voltage value at V_1 sets the op-amps trip point with a feed back potentiometer, VR2 used to set the switching hysteresis. That is the difference between the light level for "ON" and the light level for "OFF".

The second leg of the differential amplifier consists of a standard light dependant resistor, also known as a LDR, photoresistive sensor that changes its resistive value (hence its name) with the amount of light on its cell as their resistive value is a function of illumination.

The LDR can be any standard type of cadmium-sulphide (cdS) photoconductive cell such as the common NORP12 that has a resistive range of between about 500Ω in sunlight to about 20kΩ or more in the dark.

The NORP12 photoconductive cell has a spectral response similar to that of the human eye making it ideal for use in lighting control type applications. The photocell resistance is proportional to the light level and falls with increasing light intensity so therefore the voltage level at V2 will also change above or below the switching point which can be determined by the position of VR1.

Then by adjusting the light level trip or set position using potentiometer VR1 and the switching hysteresis using potentiometer, VR2 an precision light-sensitive switch can be made. Depending upon the application, the output from the op-amp can switch the load directly, or use a transistor switch to control a relay or the lamps themselves.

It is also possible to detect temperature using this type of simple circuit configuration by replacing the light dependant resistor with a thermistor. By interchanging the positions of VR1 and the LDR, the circuit can be used to detect either light or dark, or heat or cold using a thermistor.

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. This may be good for a low impedance source such as the bridge circuit above, but not so good for a high impedance source.

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 low output impedance as it consists of two non-inverting buffers and one differential amplifier. This then forms the basis for most "Instrumentation Amplifiers".

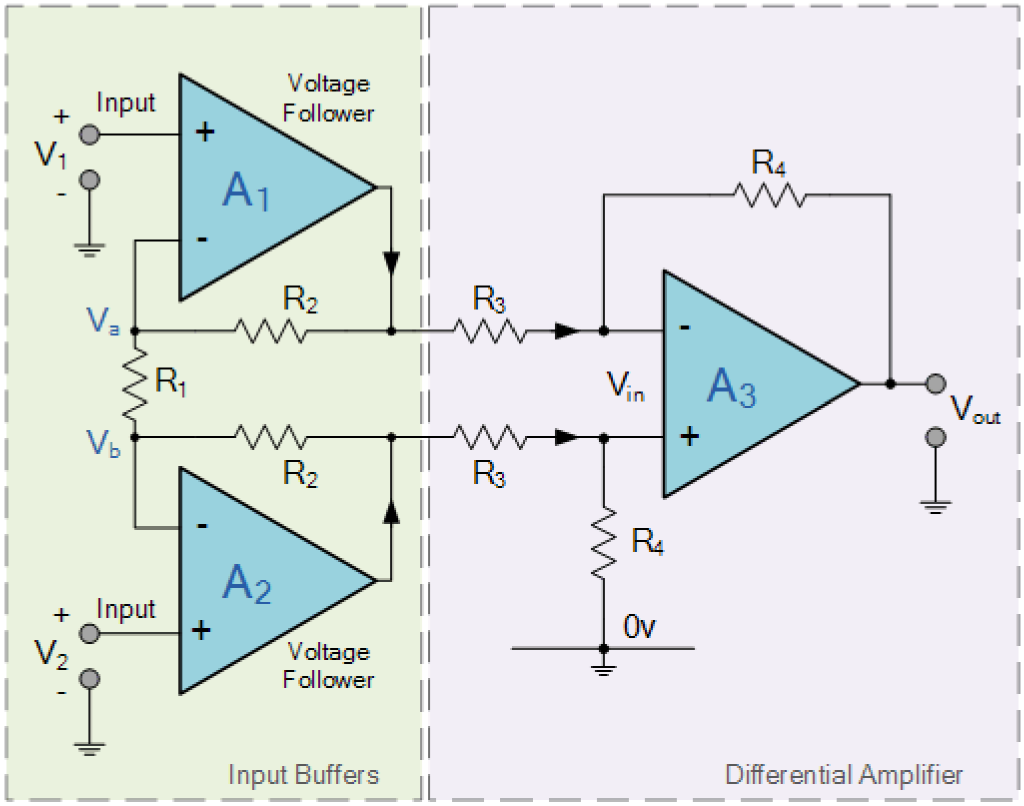
Instrumentation Amplifier

Instrumentation Amplifiers (in-amps) are very high gain differential amplifiers which have a high input impedance and a single ended output. Instrumentation amplifiers are mainly used to amplify very small differential signals from strain gauges, thermocouples or current sensing devices in motor control systems.

Unlike standard operational amplifiers in which their closed-loop gain is determined by an external resistive feedback connected between their output terminal and one input terminal, either positive or negative, "instrumentation amplifiers" have an internal feedback resistor that is effectively isolated from its input terminals as the input signal is applied across two differential inputs, V1 and V2.

The instrumentation amplifier also has a very good common mode rejection ratio, CMRR (zero output when $V_1 = V_2$) well in excess of 100dB at DC. A typical example of a three op-amp instrumentation amplifier with a high input impedance (Zin) is given below:

High Input Impedance Instrumentation Amplifier



The two non-inverting amplifiers form a differential input stage acting as buffer amplifiers with a gain of 1 + 2R2/R1 for differential input signals and unity gain for common mode input signals. Since amplifiers A1 and A2 are closed loop negative feedback amplifiers, we can expect the voltage at Vato be equal to the input voltage V1. Likewise, the voltage at Vb to be equal to the value at V2.

As the op-amps take no current at their input terminals (virtual earth), the same current must flow through the three resistor network of R2, R1 and R2 connected across the op-amp outputs. This means then that the voltage on the upper end of R1 will be equal to V1 and the voltage at the lower end of R1 to be equal to V2.

This produces a voltage drop across resistor R1 which is equal to the voltage difference between inputs V1 and V2, the differential input voltage, because the voltage at the summing junction of each amplifier, Va and Vb is equal to the voltage applied to its positive inputs.

However, if a common-mode voltage is applied to the amplifiers inputs, the voltages on each side of R1 will be equal, and no current will flow through this resistor. Since no current flows through R1(nor, therefore, through both R2 resistors, amplifiers A1 and A2 will operate as unity-gain followers (buffers). Since the input voltage at the outputs of amplifiers A1 and A2 appears differentially across the three resistor network, the differential gain of the circuit can be varied by just changing the value of R1.

The voltage output from the differential op-amp A3 acting as a subtractor, is simply the difference between its two inputs (V2 – V1) and which is amplified by the gain of A3 which may be one, unity, (assuming that R3 = R4). Then we have a general expression for overall voltage gain of the instrumentation amplifier circuit as:

Instrumentation Amplifier Equation

$$V_{OUT} = \left(V_2 - V_1\right)\left[1 + \frac{2R_2}{R_1}\right]\left(\frac{R_4}{R_3}\right)$$

In the next tutorial about Operational Amplifiers, we will examine the effect of the output voltage, Vout when the feedback resistor is replaced with a frequency dependant reactance in the form of a capacitance. The addition of this feedback capacitance produces a non-linear operational amplifier circuit called an Integrating Amplifier.