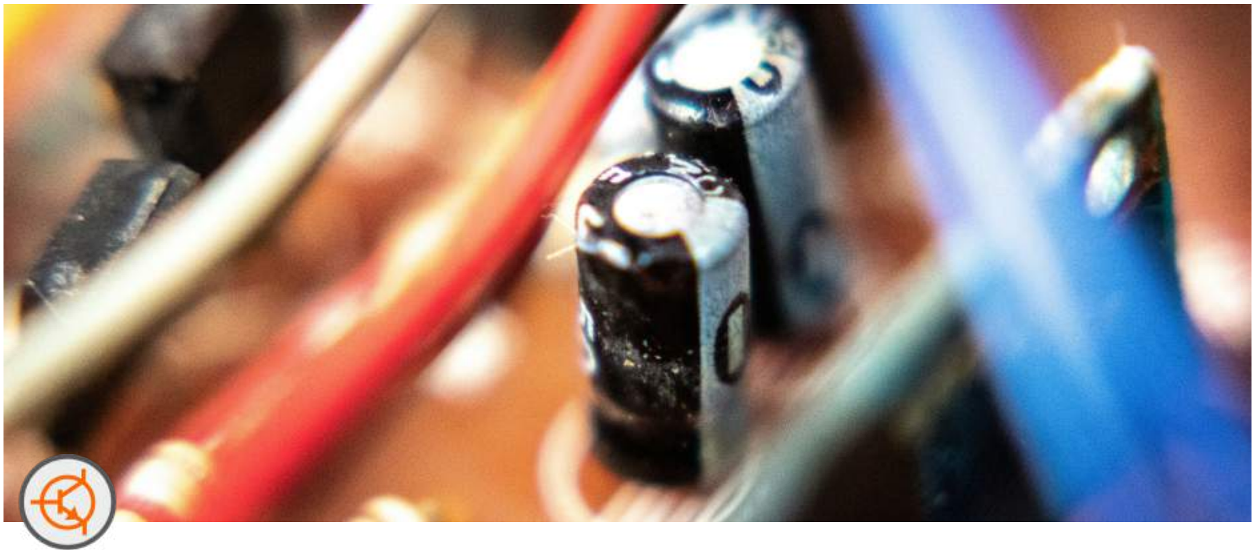

Your Introduction to Electronics

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The Fundamental Principles of Electrical Circuits

What is a circuit ?

The best way to start explaining the fundamental principles of electrical circuit is to understand what is a circuit exactly ? That is the first question we will be trying to answer.

A circuit is a closed cycle or pathway through which there is an electrical current flowing (An electrical current flowing is when electricity moves through a conductor of electricity). It consists of electrical components such as resistors, diodes, capacitors, transistors and other electronic devices connected together to preform a specific task.

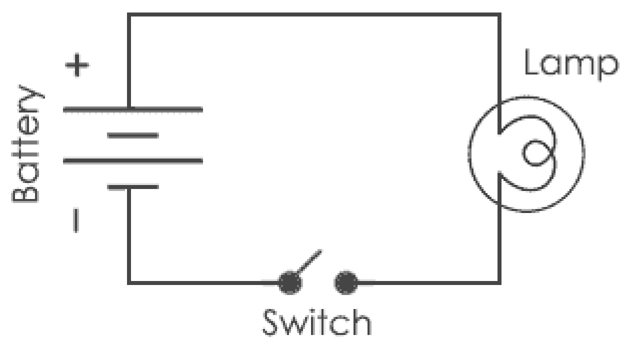


Figure 1: An example of a simple circuit

Direct current and Alternative current circuits.

Now that we understand what is a circuit, let's dive into the difference between the two main types of currents that flow in a circuit: Direct Current (DC) and Alternative Current (AC).

1. Direct current (DC)

Direct current circuits are electrical circuits where the electric current flows in one direction continuously without changing polarity. The voltage remains constant and the current flows from a power source like a battery or a DC power supply to a load (such as a lamp like previously in the example of Figure 2 or a any electronic device) and then back to the power source like shown in the Figure 3 below.

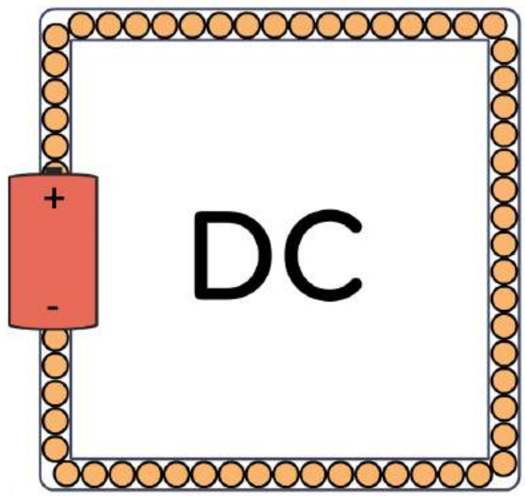


Figure 2: Current flow in a DC circuit

- ***Key Characteristics of DC:***

→ **Unidirectional Flow:** The flow of current flows in one direction.

→ **Used in Batteries:** DC circuits are often associated with batteries or other similar components where the output is a constant current.

→ **Steady Voltage:** in a DC circuit the voltage maintains a constant voltage over time.

→ **Widely Used in Electronics:** DC is used in a lot of electronic devices such as computers, smartphones... where a constant voltage output is required.

→ **Low Frequency:** DC systems typically operate at a low frequency or at zero frequency, because the flow of current remains constant and doesn't change directions periodically.

2. Alternative current (AC)

Alternative circuits use alternating current, which means the flow of current periodically changes direction like it is shown in Figure 4 below.

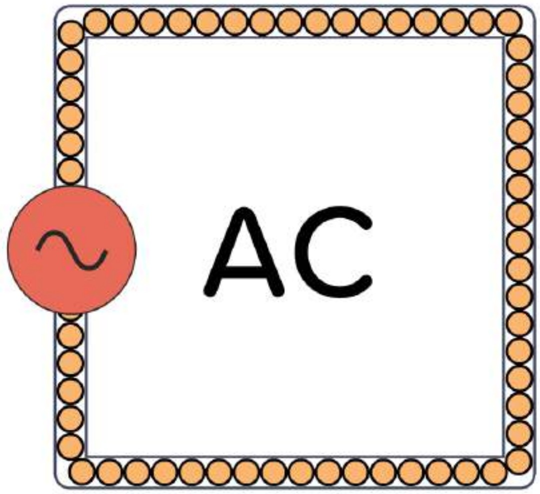


Figure 3: Current flow in DC circuit

- ***Key Characteristics of AC:***

→**Sinusoidal Waveform:** In AC circuits the voltage and current typically alternate between positive and negative values following a sinusoidal waveform.

→**Voltage Variation:** The voltage in AC circuits rises to a positive peak, crosses zero falls to a negative low and then returns to zero and repeats the cycle.

→**Minimal loss:** Most power generation and distribution worldwide use AC due to it's ability to be transmitted over long ranges with minimal energy loss.

→**Applications:** AC circuits can be found in various applications including residential and commercial power systems, lightning systems, electric motors, telecommunication and electronics.

Basic Electric Metrics

1. Standard Electrical Units of Measure

Every measurable thing has a unit of measurement, we use meters to measure how tall something is, Gram to measure the weight of something and Celsius to measure the temperature. So what do we use for electricity ?

We first have to understand what electricity is before we talk about how to measure it, electricity is in its basics the movement of electrons, the charge created by moving electrons is basically the power of electricity.

So what are the basic units of measurements for electricity ? The international standard units that are used in electricity are shown in the table below:

Electrical Parameter	Measuring Unit	Symbol of the unit	Description	Formula
Voltage	Volt	V and E	Unit of electrical potential	V = I × R
Current	Ampere	I and i	Unit of electrical current	I = V ÷ R
Resistance	Ohm	Ω	Unit of DC Resistance	R = V ÷ I
Conductance	Siemens	℧	Reciprocal of resistance	G = 1 ÷ R
Capacitance	Farad	F	Unit of capacitance	C = Q ÷ V
Charge	Coulomb	C	Unit of electrical charge	Q = C × V
Inductance	Henry	H	Unit of electrical charge	VL = -L(di/dt)
Power	Watts	W	Unit of inductance	P = V × I or I^2 × R
Impedance	Ohm	Z	Unit of Power	$Z^2 = R^2 + X^2$
Frequency	Hertz	Hz	Unit of frequency	ƒ = 1 ÷ T
Energy	Joules	J	Unit of energy	E = P × t

2. Multiples and Sub-multiples

We use multiples and sub multiples basically to avoid writing too many zero’s to define the position of the decimal point, for example resistance can be lower than 0.01 Ω or higher than 1.000.000 Ω.

Below is a table that gives the names and abbreviations of these multiples and submultiples:

Prefix	Symbol	Multiplier	Power of ten
Tera	T	1,000,000,000,000	10^12
Giga	G	1,000,000,000	10^9
Mega	M	1,000,000	10^6
Kilo	K	1,000	10^3
None	none	1	10^0
Centi	c	1/100	10^-2
Milli	m	1/1,000	10^-3
Micro	µ	1/1,000,000	10^-6
Nano	n	1/1,000,000,000	10^-9
Pico	p	1/1,000,000,000,000	10^-12

Foundational Understanding of Electricity

The next subject we will be delving into some basic laws that govern electricity and stating some basic knowledge in this field. It is essential to understand these laws to truly comprehend how electric circuits and systems actually work.

1. Ohm's Law

Ohm's law states that the voltage (V) across a conductor depends on the current (I) flowing through it and the resistance (R).

- V (voltage) = I (current) × R (resistance)

This can also be written as:

- I (Current) = V (Voltage) / R (Resistance)

or:

- R (Resistance) = V (Voltage) / I (Current)

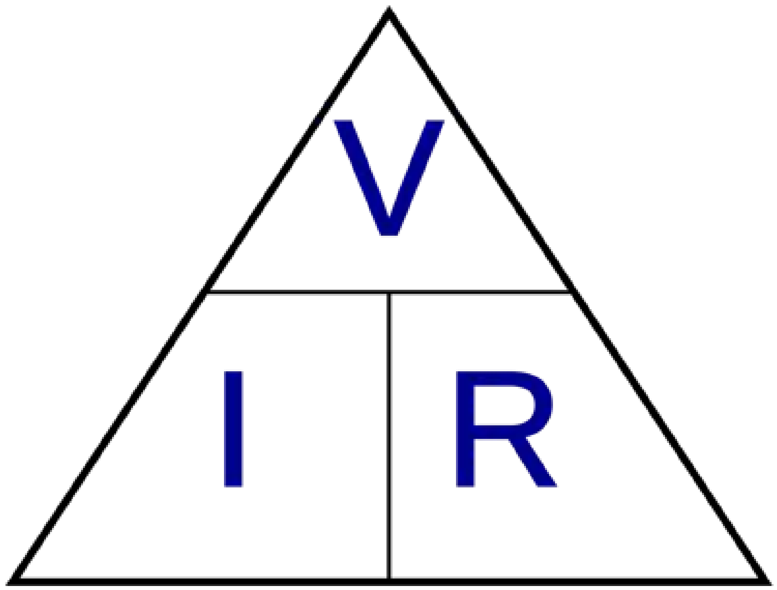


Figure 4: Ohm's law

2. Kirchhoff's Circuit Laws

Kirchhoff's circuit laws consist of two main principles:

Kirchhoff's current law (KCL): This law states that at any junction, or node in an electrical circuit, the total current (I) entering the node must be equal to the total current (I) leaving the node.

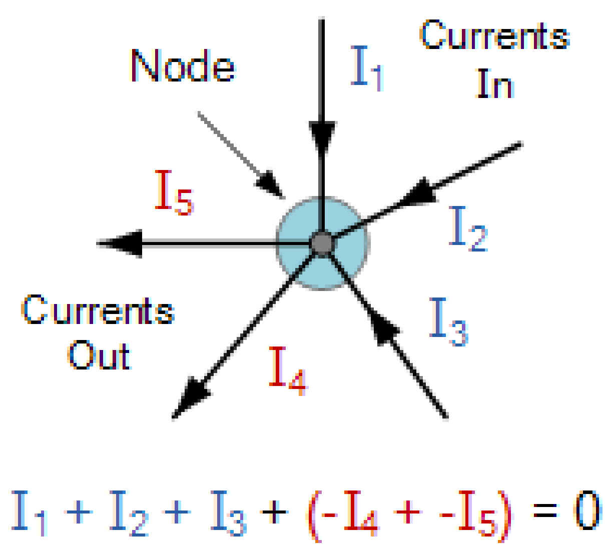


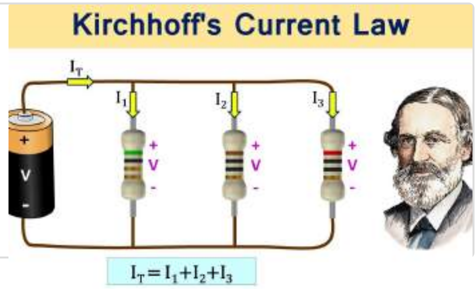
Figure 5: Kirchhoff's current law visualization

Figure 5 shows a node in a circuit where the sum of the currents on the two wires going into the node is equal to the current on the wire coming out.

Kirchhoff's Current Law (KCL) Explained

In our previous lesson, we examined Kirchhoff's Voltage Law. In this video, I will explain the Kirchhoff’s Current Law, which is as important as it is for us to analyze electrical circuits and one of

https://www.youtube.com/watch?v=pRm2e6qDbX8&ab_channel=ElectricalElectronicsApplications



Kirchhoff's Voltage Law (KVL)*: T*his law states that the total voltage around a closed loop in a circuit sums up to zero. Which means that the sum of voltage in a closed circuit is 0, let’s further explain this with an example:

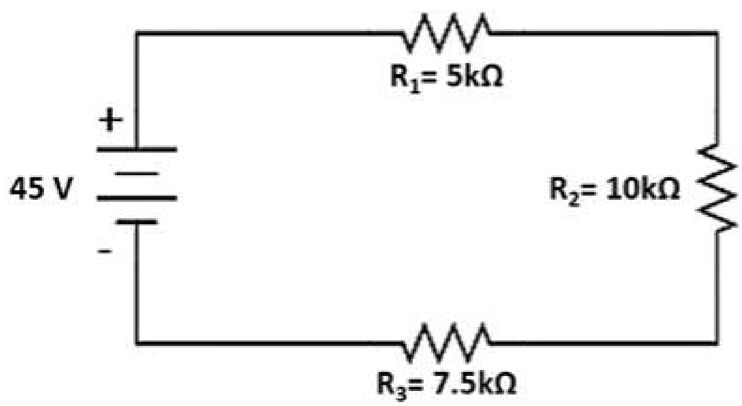


Figure 6.a: An example of an electrical circuit

Figure 6 shows a circuit that consists of a power source that has a voltage Vt= 45V and 3 Resistors with a resistance of R1=5kΩ, R2=10kΩ and R3=7,5kΩ, each of these resistors also have a voltage V1, V2 and V3 respectively.

In this circuit we need to find the Voltage of each of the resistors using Kirchhoff’s voltage law. To do this we first need to find the current’s value, and to do this we must assume the direction of the current then find it’s value, if the value is positive it means that the direction we chose is right, if it’s negative that means it’s the opposite direction, we will get back to this later.

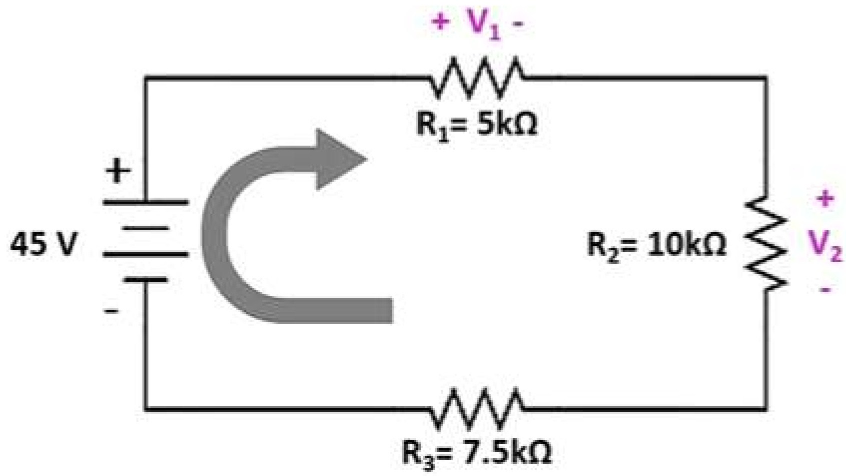


Figure 6.b: An example of an electrical circuit

After we choose the current's direction using Kirchhoff's law that tell us the total voltage around a closed loop in a circuit sums up to zero and ohm's law we can find the current in the below way:

$$-Vt + V1 + V2 + V3 = 0$$

$$-Vt + (I.R1) + (I.R2) + (I.R3) = 0$$

$$-45V + (I.5k\Omega) + (I.10k\Omega) + (I.7,5k\Omega) = 0$$

$$I.22,5k\Omega = 45V - - > I = 45V/22,5k\Omega$$

$$I = 2mA$$

Since the current is positive that means we chose the right current direction.

$$V1 = I.R1 = (2mA).(5k\Omega) = 10V$$

$$V2 = I.R2 = (2mA).(10k\Omega) = 20V$$

$$V3 = I.R3 = (2mA).(7,5k\Omega) = 15V$$

3. Series and parallel networks

In a circuit, the connections of the parts and their arrangement are crucial. As illustrated in Figure 11, two components (in this case, resistors) can be placed in two distinct ways. Figure 11(a) depicts a circuit where the current must follow a single path, passing through one component after another in series; Figure 11(b) depicts a circuit where the current splits and takes two parallel paths simultaneously.

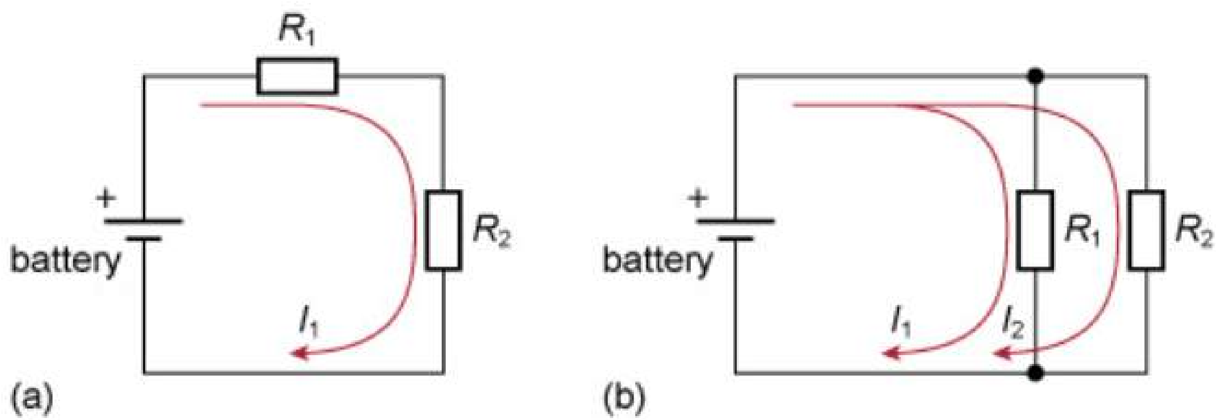


Figure 7: Electrical circuits with two resistors placed in (a) parallel and (b) series

By combining Ohm's and Kirchhoff's laws, we can conclude that:

- The total resistance ***R*** of ***n*** resistors in a series circuit is:

$$R = R1 + R2 + ... + Rn$$

- The total resistance ***R*** of ***n*** resistors in a parallel circuit is:

$$\frac{1}{\frac{1}{R1} + \frac{1}{R2} + ... + \frac{1}{Rn}}$$

4. Resistor's values from the coloured bands

If you ever pick up a resistor in real life you will notice these coloured bands going around it right in the middle, those colour bands show us the value of the resistor. Here is how it works.

→ **The First band(1st digit):** The first band represents the first digit of the resistance value. Each color corresponds to a number, these can be decoded in using the table in Figure 8.

→**The Second band(2nd digit):** The second band represents the second digit of the resistance value, just like the first band.

→ **The Third band(The Multiplier):** The third band represents the multiplier, which indicates how many zeros should be added to the two digits obtained from the first two bands to get the resistance value, each color represent a multiplier (See figure 8).

→**The Fourth band(The Tolerance**): The fourth band represents the tolerance, which indicates the range within which the actual resistance value of the resistor may vary from the specified value.

Colour	Band 1 First digit	Band 2 Second digit	Band 3 Multiplier	Band 4 Tolerance
Black	0	0	x 1 (x 1)	-
Brown	1	1	x 10 (x 10)	1%
Red	2	2	x 100 (x 100)	2%
Orange	3	3	x 1 000 (x 1k)	not used
Yellow	4	4	x 10 000 (x 10k)	not used
Green	5	5	x 100 000 (x 100k)	not used
Blue	6	6	x 1 000 000 (x 1M)	not used
Violet	7	7	-	not used
Grey	8	8	-	not used
White	9	9	-	not used
Gold	-	-	-	5%
Silver	-	-	-	10%

Figure 8: The four-band colour-coding scheme for resistors

Some Fundamental circuits:

In this section we will explore some circuits that are quite important in electronics, we will first look at the voltage divider then the Wheatstone bridge before we introduce a new component in the form of an operational amplifier (op-amp).

1. Voltage dividers:

A voltage divider is a basic electronic circuit that produces an output voltage (Vout) that is a fraction of its input voltage (Vin). It typically consists of two resistors connected in series (see figure below).

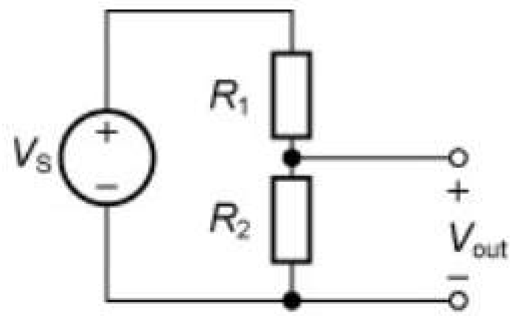


Figure 9: A voltage divider circuit

The ratio of the two resistors determines the voltage divider's output voltage. In particular, the voltage divider formula can be used to determine the output voltage (Vout):

$$Vout = Vs \times (\frac{R2}{R1 + R2})$$

Let’s show how did we get this formula using the previously studied laws of electricity:

first we assume that Vout is not connected to anything (for voltage dividers we always assume that negligible current flows through Vout). This means that, according to Kirchhoff’s first law, the current flowing through R1 is the same as the current flowing through R2. Ohm’s law allows you to calculate the current through R1. It is the potential difference across that resistor, divided by its resistance. Since the voltage Vs is distributed over two resistors, the voltage of R1 is

$$Vr1 = Vs - Vout$$

The current Ir1 according to Ohm’s law is :

$$Ir1 = \frac{(Vs - Vout)}{R1}$$

Similarly the current Ir2 is:

$$Ir2 = \frac{Vout}{R2}$$

Kirchhoff's current law tells us that Ir1=Ir2, so:

$$\frac{Vout}{R2} = \frac{(Vs - Vout)}{R1}$$

$$--> R1.Vout = R2(Vs - Vout)$$

$$--> R1.Vout + R2.Vout = R2.Vs$$

$$--> (R1 + R2).Vout = R2.Vs$$

$$--> Vout = Vs \times (\frac{R2}{R1 + R2})$$

2. The Wheatstone bridge:

The Wheatstone bridge is a basic electrical circuit that helps find unknown resistances. Comprising of four resistors configured in a diamond shape as it's shown in the figure below:

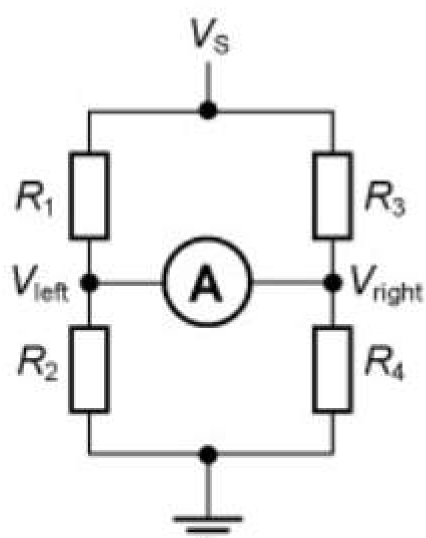


Figure 10: Example of a Wheatstone bridge

When the Wheatstone bridge is in balance, meaning there's no current flow and the galvanometer needle remains still, it signifies that the voltages Vleft and *V*right are equal. This condition indicates that there's no potential difference between the left and right sides of the bridge.

Understanding the Wheatstone bridge as two separate voltage dividers can help clarify its operation. On the left side, $R1$ and $R2$ form a voltage divider, while $R3$ and $R4$ constitute a voltage divider on the right.

Applying the voltage divider equation to each side gives us:

$$Vleft = \frac{R2.VS}{R1 + R2} \qquad Vright = \frac{R4.Vs}{R3 + R4}$$

So

$$\frac{R2}{R1 + R2} = \frac{R4}{R3 + R4}$$

And

$$R2(R3 + R4) = R4(R1 + R2)$$

Multiplying out brackets gives

$$R2.R3 + R2.R4 = R4.R1 = R4.R2$$

Which simplifies to

$$R2.R3 = R4.R1$$

And finally

$$\frac{R3}{R4} = \frac{R1}{R2}$$

So if R4 was unknown we can choose the resistances R1,R2 and R3 and then

$$R4 = \frac{R2.R3}{R1}$$

3. Operational Amplifier circuits

In electronics, operational amplifiers are a basic part. In this section we will focus on the 741 op-amp, a traditional amplifier.

The op-amp symbol below, as depicted in figure 15.a, has five terminals. The input and output are managed by the terminals V+ and V−, which typically result in an amplified signal on Vout. Transistors and a number of resistors are used in the construction of the op-amp. Entire set of transistors and resistors is crammed into the tiny package shown in Figure 15.b. Typically, the orientation of the package and, thus, the pin number are determined by a dot and a dent on top of it. These are also indicated on the configuration diagram seen in Figure 15.c.

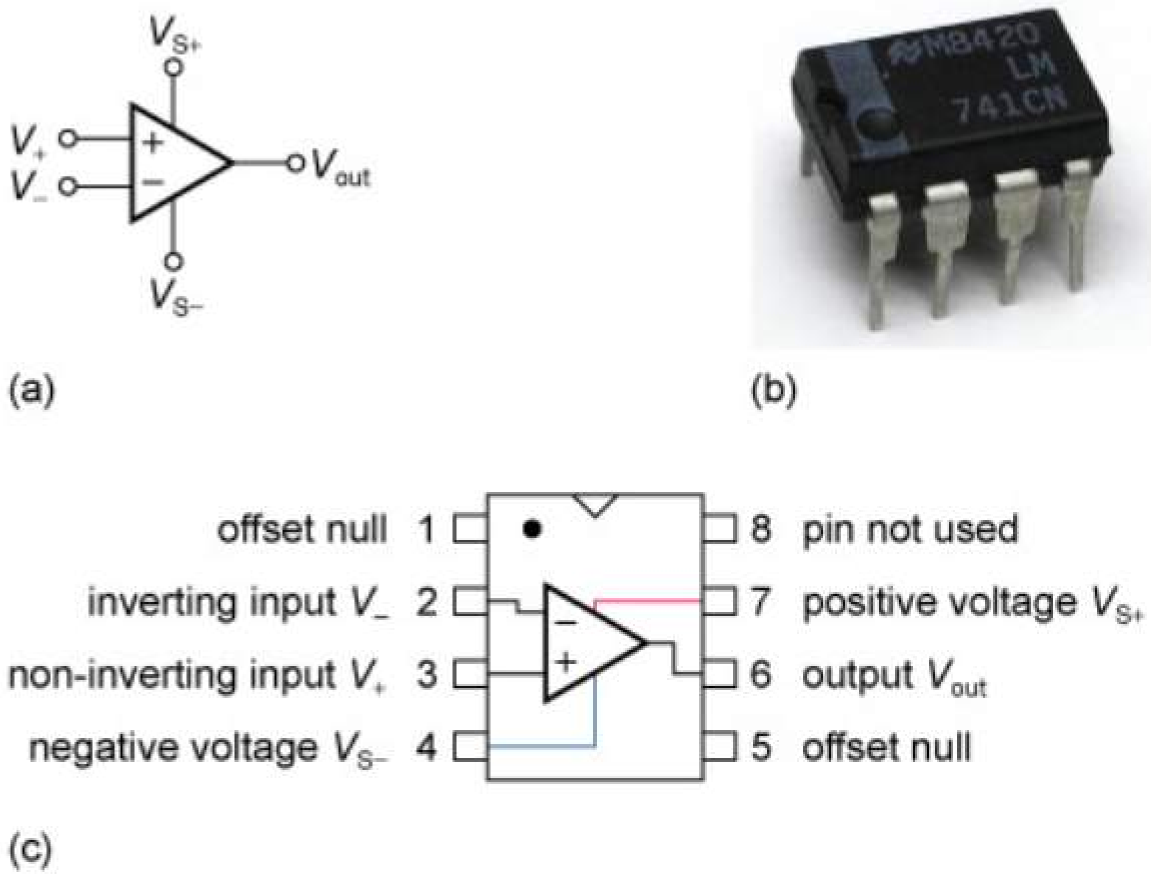


Figure 15: (a) Symbol for an op-amp; (b) the 741 op-amp package; (c) top view of an LM741 showing internal configuration and pin connections

So what is exactly an Operational amplifier ?

An Operational amplifier is simply an electrical circuit that takes a differential voltage input and gives out a single voltage as output.

Here’s a simple breakdown:

1. Differential Voltage input: It accepts two input voltages which are measured relative to a common reference point (often ground), and the difference between them is what matters to the op amp.
2. Single-Ended Voltage Output: After processing the difference between these two input voltages the op-amp produces a single output.

In conclusion, the op-amp “operates” on the difference between two input voltages and provides a single voltage based on the difference. It’s a fundamental component due to its versatility and many abilities such as Comparation, filtering, amplification, mathematical operations etc.

Classification of op amps

We can classify op amps into four categories:

1. **Voltage Amplifiers:**
    - **Input:** Voltage
    - **Output:** Voltage
    - **Operation:** Voltage amplifiers take an input voltage signal and amplify it to produce a proportional output voltage. They are widely used in audio amplifiers, signal conditioning circuits, and voltage regulators.
2. **Current Amplifiers:**
    - **Input:** Current
    - **Output:** Current
    - **Operation:** Current amplifiers receive an input current and amplify it to produce a proportional output current. They find applications in current-controlled systems, such as motor drivers, transducer interfaces, and current mirrors.
3. **Transconductance Amplifiers:**
    - **Input:** Voltage
    - **Output:** Current
    - **Operation:** Transconductance amplifiers convert a voltage input into a proportional output current. They are commonly used in applications

requiring voltage-to-current conversion, such as in filters, voltage-controlled oscillators, and automatic gain control circuits.

4. **Transresistance Amplifiers:**
    - **Input:** Current
    - **Output:** Voltage
    - **Operation:** Transresistance amplifiers take a current input and produce a proportional output voltage. They are useful in applications where current-to-voltage conversion is needed, such as in photodetectors, current-mode amplifiers, and current-to-voltage converters.

This next part will concentrate on voltage amplifiers because voltage amplification is the primary function for op amps.

Operational Amplifiers: Key Characteristics and Parameters

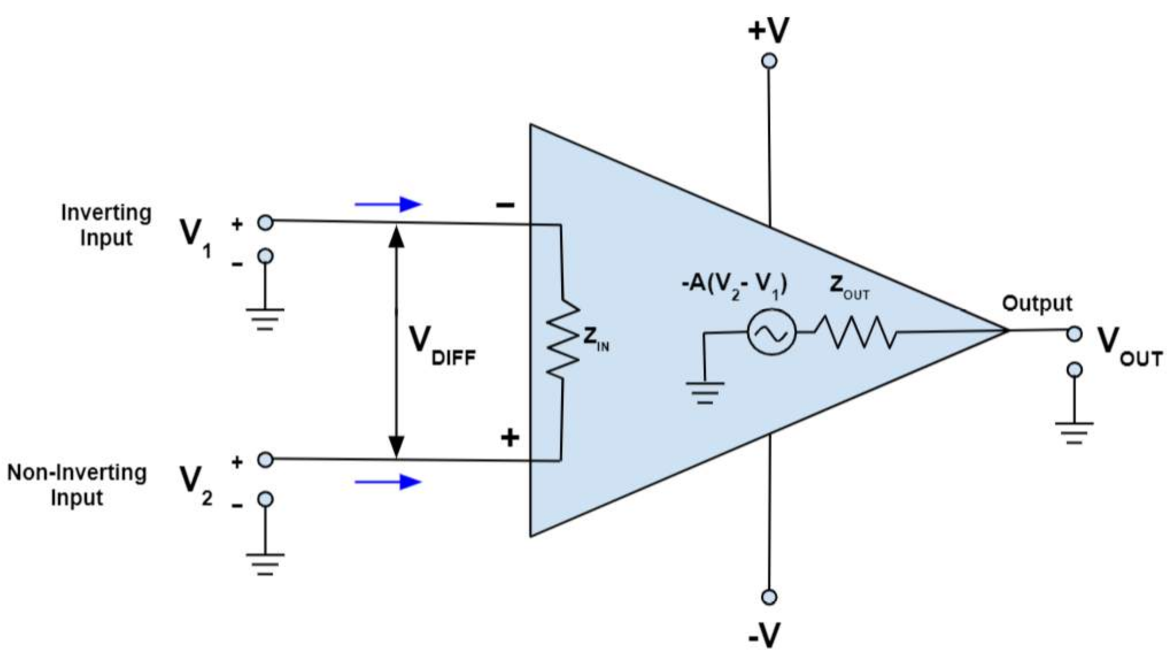


Figure 16: Operational amplifier schematic

***Open-loop gain ("A" in Figure 16)*:**

The open-loop gain is the amplification factor of an operational amplifier when there is no feedback in the circuit.

In most cases, the open-loop gain needs to be very large, often thousands or even tens of thousands, to be practical. However, in voltage comparators, even with small voltage differences, the output can be driven to either the positive or negative power supply rails.

High open-loop gains are advantageous in closed-loop configurations because they help maintain stable circuit behavior across changes in temperature, manufacturing processes, and variations in the input signal.

Input impedance("Zin" in Figure 16):

Input impedance refers to the resistance or opposition a circuit presents to the input signal. In the case of operational amplifiers, input impedance is measured between the negative and positive input terminals.

Op amps generally have high input impedance, ideally infinite, which means they don't draw much current from the source connected to their inputs. This minimizes loading effects on the input source.

While the ideal input impedance is infinity, in reality, there may be a small amount of current leakage. Additionally, input capacitance, not just resistance, can also influence the behavior of the circuit. Therefore, external components and feedback loops must be carefully designed to ensure proper circuit operation.

Output Impedance ("Zout" in Figure 16):

The output impedance of an operational amplifier ideally remains at zero, indicating it can deliver any required amount of current without influencing its output voltage. Nonetheless, real-world amplifiers possess a small output impedance. This impedance governs the amplifier's ability to supply current and its efficacy as a voltage buffer, influencing how well it can drive external loads.

Operational Amplifier Arrangements:

In this section we will discuss different arrangements and configurations in which operational amplifiers can be utilized. These configurations determine the functionality of the op amp.

1. **Voltage follower:**

The most basic operational amplifier (op amp) configuration is a voltage follower, sometimes referred to as a buffer amplifier or a unity-gain amplifier. The non-inverting input of the op amp is linked to the input voltage source, and the output is connected straight back to the inverting input wire. With this configuration, there is a voltage gain of 1, which means that the output voltage precisely matches the input voltage.

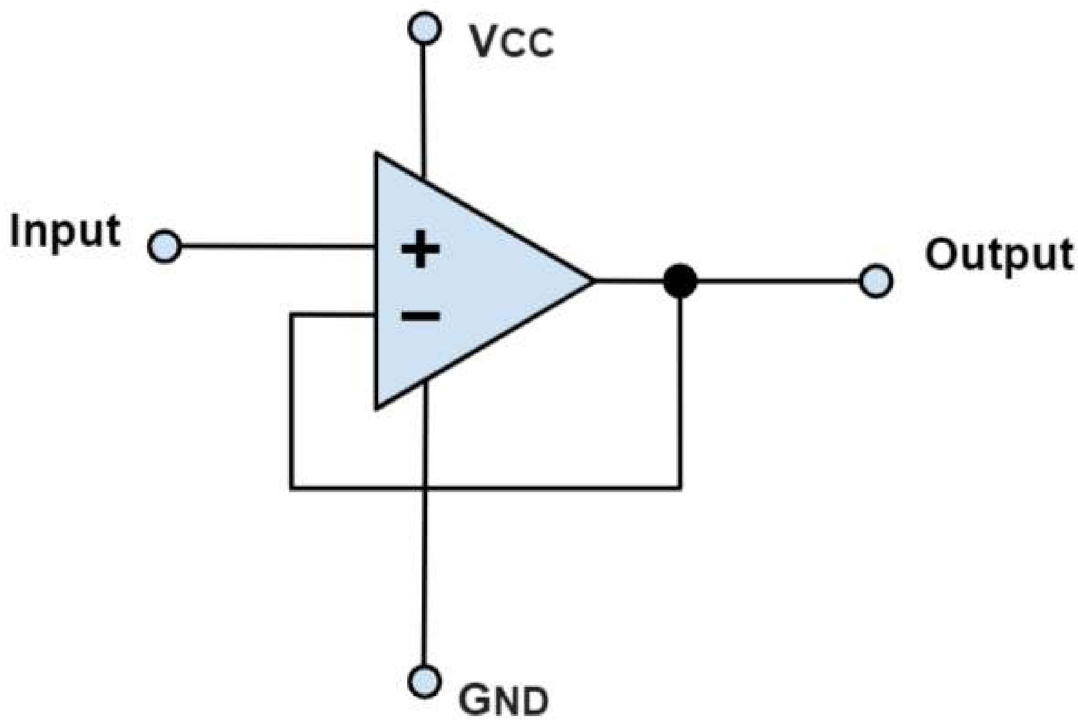


Figure 17: Voltage Follower

$$VOUT = VIN$$

2. **Inverting operational amplifier**

The fundamental arrangement of an inverting operational amplifier involves connecting the input signal to the device's inverting (-) input terminal and connecting the output's feedback to the inverting input. This is how it operates:

Input Signal: The input signal is linked to the operational amplifier's inverting (–) input terminal.

Feedback Resistor ("R2" in figure 18): A resistor is wired between the op amp's output and the input terminal that reverses.

Output: The feedback resistor feeds the op amp's output voltage back into the inverting input.

Amplification: The voltage differential at the op amp's inverting and non-inverting input terminals is amplified. The output voltage is the opposite of the input voltage in the inverting arrangement.

The output voltage falls with an increase in input voltage and vice versa.

Gain: The ratio of the feedback resistor to the input resistor determines the gain, or amplification factor, of the inverting amplifier.

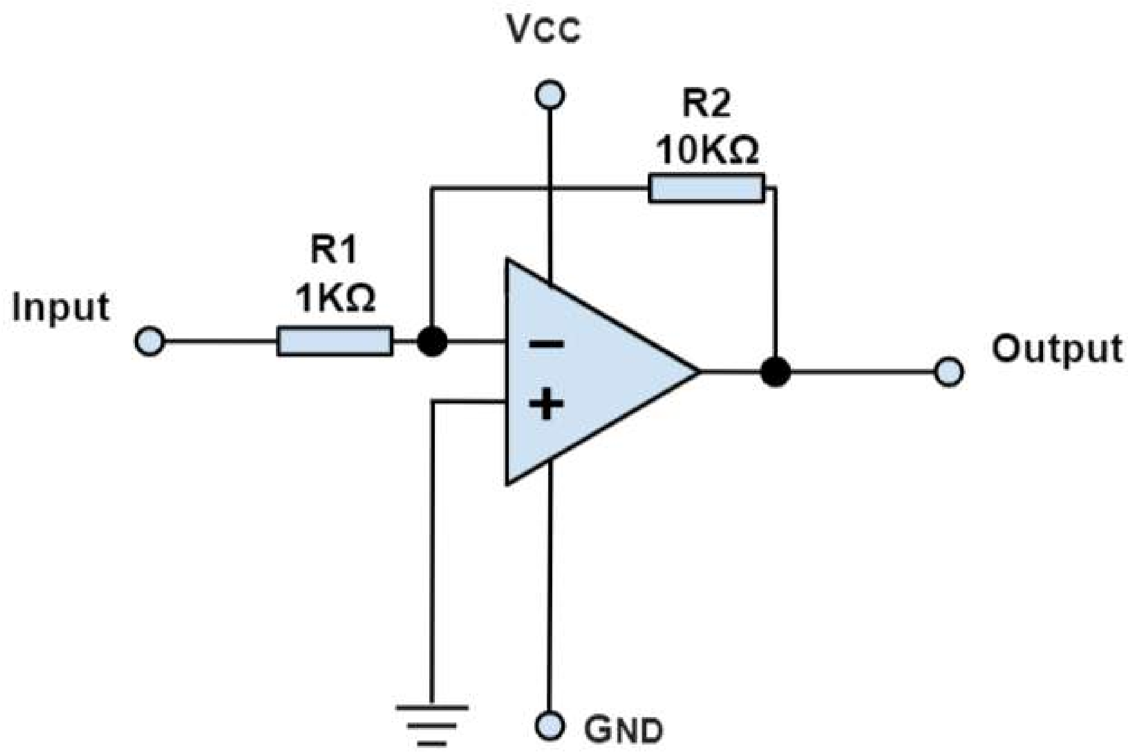


Figure 18: Inverting operational amplifier

$$VOUT = -(\frac{R2}{R1}).VIN$$

3. **Non-inverting operational amplifier**

The non-inverting operational amplifier configuration is another common setup used in electronics. In this configuration, the input signal is applied to the non-inverting input terminal of the op-amp, while the feedback resistor is connected between the output and the non-inverting input terminal.

Here's a quick breakdown:

Input Signal: The op-amp's non-inverting input terminal is linked to the input signal.

Feedback Resistor (R2): The output and the non-inverting input terminal are connected by a resistor.

Grounded Inverting Input: In this setup, the inverting input terminal is usually grounded.

Usability:

A positive gain is provided by the non-inverting arrangement (output is in phase with the input).

The voltage differential between the non-inverting and inverting input terminals is amplified by the op-amp.

The amplifier's gain is adjusted by the feedback resistor.

Low output impedance and high input impedance are offered by the non-inverting arrangement.

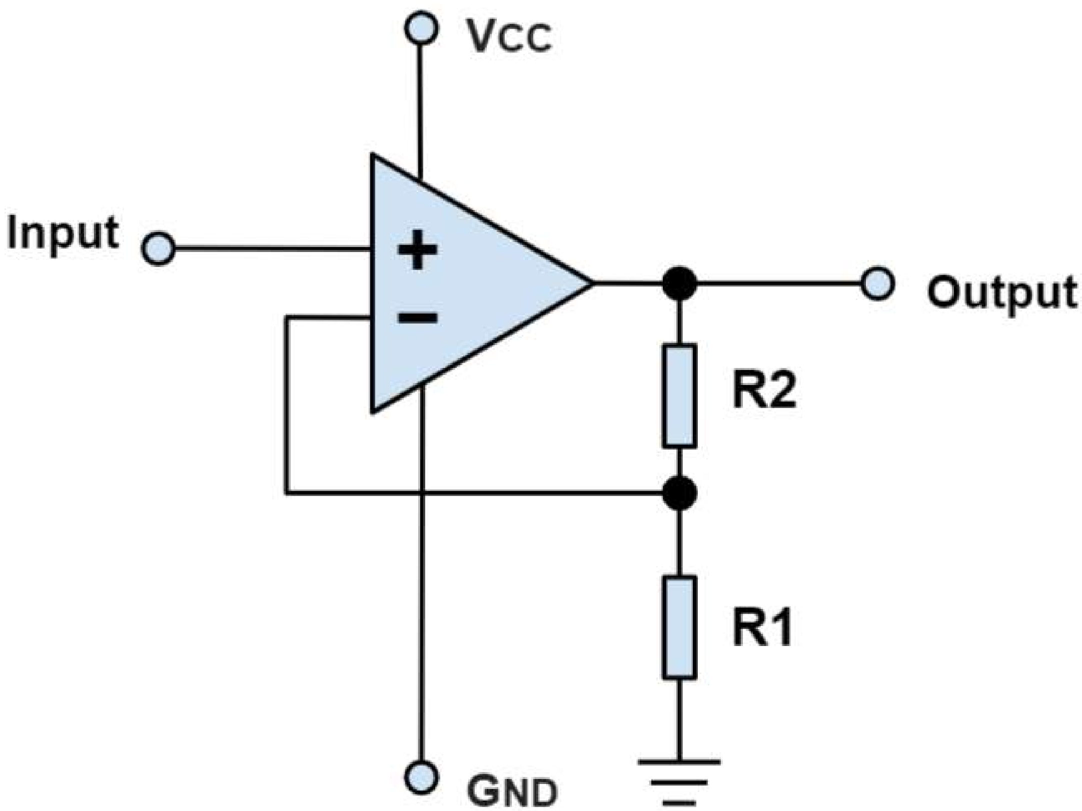


Figure 19 Non-inverting operational amplifier

4. **Voltage comparator**

When two voltage inputs are compared, an operational amplifier voltage comparator sends the output to the supply rail of the input that is higher. Since there is no feedback in this setup, it is regarded as an open-loop operation. One advantage of voltage comparators over the closed-loop topologies previously addressed is their significantly faster operating speed.

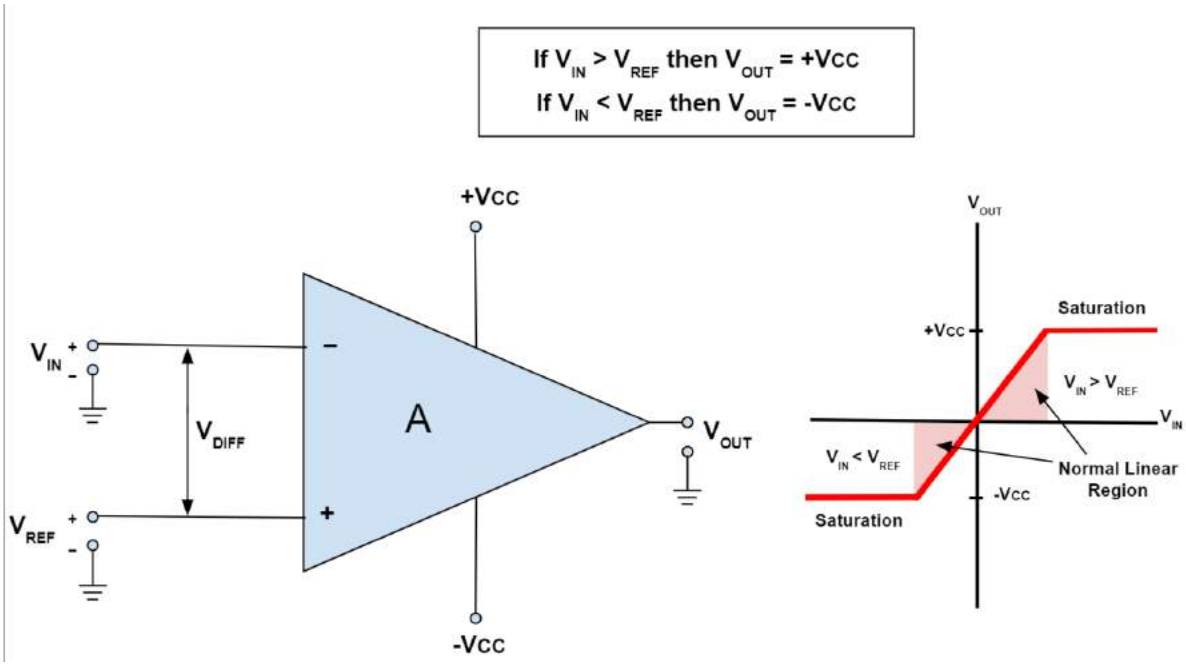


Figure 20: Voltage comparator