EEEM — INTRODUCTORY ELECTRONICS

UNDERGRADUATE ELECTIVE COURSE

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These lecture notes serve as supplementary reading material for unit one of this elective course for students without *a background in physics. It is advised that students also read Grob's* Basic electronics, *the suggested book for this course.*

CONTENTS

For more visit `vhbelvadi.com/notes`.

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COURSE OVERVIEW

Current (types), voltage, resistance, Ohm's law and basic circuit symbols — active and passive components, resistors, potentiometers, LDR, capacitors, inductors, transformers, relays, fuses — basic circuit analysis: series and parallel resistances, switches, power supplies, and connecting nodes.

Diodes, forward and reverse biased characteristics — LED, photodiode — regulating voltage, Bridge rectifier, Bipolar Junction Transistor — Displays: seven segment display, dot matrix display — amplification, OP AMP 741, open and closed loop configurations.

Wiring, earthing and UPS — communication systems (block diagram) — regulated power supply (block diagram) — multimeters, CROs — Basic digital electronics: the binary system, gates, SR latch, memory, and counters.

This course awards you 3 credits, 100 marks (50 + 50 from the final exam and internal assessments). The latter will consist of classwork for 40 marks, and laboratory work and homework for 20 marks. Regular attendance will carry 20 marks. These notes cover the first unit of the curriculum (in bold above).

0 PREREQUISITES

While no background in physics or mathematics is assumed while teaching this course, it helps if students have a good grip on the fundamental ideas of these subjects. This section provides an extremely brief overview of some such ideas whose knowledge will prove useful to students.

There are seven standard units of measurement in physics: lengths are measured in metres, time in seconds, current in ampere, mass in kilogram, temperature in kelvin, the amount of a substance in mole, and luminous intensity in candela. You are likely to encounter only the first three in this course, so we will focus on those for now.

Although these are **fundamental units**, they are not always the most convenient: measuring the thickness of a wire in metres, while not incorrect, makes little sense. It is for such circumstances that we employ multiples and submultiples of units. These are stated in multiples or fractions of ten, called **orders of magnitude**, with the following standard set of prefixes:

10^{-12}: pico (p)	10^{-9}: nano (n)	10^{-6}: micro (μ)	10^{-3}: milli (m)
10^{2}: centi (c)	10^{3}: kilo (k)	10^{6}: mega (M)	10^{9}: giga (G)

Keep in mind what these powers mean: 10^5 means 100000, i.e. the *number of zeroes* following the digit one is given by the magnitude of the power. Further, this can be split as $10^5 = 10^2 \cdot 10^3$ because $2 + 3 = 5$. This should be simple enough to verify for yourself. Therefore, given that 10^5 has no special name or prefix, we can choose to express it as $10^5 = 10^{-1} \cdot 10^6$ or 10^{-1} mega units.

The negative powers themselves refer to fractions: 10^{-1} simply means $\frac{1}{10^1} = 0.1$. Likewise $10^{-4} = \frac{1}{10^4} = 0.0001$. Note that, in this case, the magnitude of the power tells us the total number of digits following the decimal point, *including the digit one*.

Always express values in orders of magnitude and/or multiples or sub-multiples of units. Therefore, prefer 60 kA to 60 thousand amperes, or 5 μm to 5 millionths of a metre and so on. Beware of writing made-up symbols: a gram is represented by g, not gm; several grams are still g, not gms.

Handling orders of magnitude is an important, fundamental skill in physics: we know that 24000 can be written as 24000×10^0 since $10^0 = 1$ and makes no difference. But this can also be written as 2400×10 and 240×10^2 and so on. Likewise if we start off with 0.002 we can write this as 0.002×10^0 and, equivalently, as 0.02×10^{-1} or, more conveniently, as 2×10^{-3}. Keep an eye on the pattern with which the decimal point is moved: for any $x \times 10^y$, x must fall as y increases and vice versa.

NB Do not expect to understand an idea perfectly as soon as you read it. Understanding (not memorising) is important, however, and requires that you work towards it constantly. This means reading through your notes as often as necessary, thinking about these ideas as often as you can (possibly several times a day), and working out as many mathematical problems as possible.

1 FUNDAMENTAL PARAMETERS

Electronics is the study of the flow of electrons in the context of the development and application of devices. It is most often seen as the study of certain aspects of electricity that help in the construction of circuits and other technology that benefit us in our daily lives. However, electronics need not be restricted to physical circuitry: the movement of electrons in vacuum tubes too, for example, can be considered a part of electronics.

More accurately, as the name itself suggests, electronics may be considered the systematic study of how the flow and energy of electrons may be controlled to achieve various electric outputs using carefully planned circuits.

1.1 *Current*

It makes sense then that our study of electronics must begin with electrons themselves. Atoms are made up of three particles: extremely light, negatively electrons; heavier, positively charged protons; and neutral particles called neutrons that are almost as heavy as protons. Of these, the electron is a fundamental particle while the other two can be broken down further. Although not strictly accurate once can think of electrons as being 'in orbit' around a nucleus consisting of protons and neutrons. However, not all electrons are locked this way: electrons that are free to move are those particles that we can influence based on the simple idea that negatively charged particles are attracted by, and accelerate towards, a positive charge.

Keep in mind that charge flavours may just as effectively be perceived as relative: a negative charge region can, where convenient, be simply thought of as the lack of a positive charge and vice versa. A negative charged electron may, therefore, travel from a region where several electrons exist to one where few electrons exist. That is to say, although few electrons exist in the destination region, generally making it negatively charged, the region is still *more positive* than the source region and this difference in charge prompts the flow of electrons. We will revisit this idea shortly.

That charge flow constitutes current is a simple idea. To state it more specifically we use the term *charge carriers* to denote any charged particles whose flow constitutes current. Electrons are one example of charge carriers. The definition of **current** may then be given more accurately as—

> Current is the rate of flow of charge carriers in a conductor.

The rate of change of any quantity is the amount of change it undergoes in unit time. As a result, for charge q flowing through a *solid*, *metallic conductor* in time t the intensity of current I is given by

$$\mathrm{I} = \frac{q}{t}$$

with q measured in coulomb, t in seconds, and I in **ampere** (A). The unit of current has been named after André–Marie Ampere for his pioneering work in the field of electricity; the device used to measure currents is called an **ammeter**.

By historic convention, the direction of current flow is taken to be opposite to that of the flow of electrons. The direction of current flow in a circuit is, by itself, not of particular concern: current flow is assigned arbitrary directions and will correct itself during calculations with a negative sign (if the real current flow is opposite to the assumed direction) or a positive sign (otherwise).

1.2 *Potential difference and power*

Not unlike water, it is this mismatch in the charges between two points of a conductor that makes current flow between those two points. Specifically, given that electrons flow from a region of greater negative charge to a region of greater positive charge, current flows from a positive to the negative region precisely because there is greater positivity at one point than another.

However, the idea is scientifically more rigorous than just a difference in charge. The amount of work needed to move a unit positive charge from infinity to a point inside an electric field is called the electric potential at that point. Each point in a circuit has a different electric potential and it is this difference which prompts current flow. This is called the **potential difference** or, colloquially, the 'voltage' across two points of a circuit. Historically, thanks to the use of vacuum tubes, it was often called 'tension' (sometimes it still is, e.g. 'high tension wires' are wires with high voltage across them).

> Potential difference, or voltage, is the difference in electric potential energy per unit charge between two points in a circuit.

Naturally, as with any difference in general, to measure the potential difference we need to first decide on two convenient points of measurement. Oftentimes these are on either side of an electronic component in which case we say that we measure the potential difference *across* that component. By comparison, current is measured at a single point in the circuit.

Just like current is measured in ampere using a device known as an ammeter, voltage too has its own unit and measuring device: the **voltmeter** measures the potential difference across two points in a circuit in **volts** (V).

The combination of current and potential difference gives rise to another parameter called the electric **power** of a circuit which is given by the rate of transfer of electrical energy:

$$P = VI$$

Power is measured in **watt**, but, commercially, electric power is sold to homes in terms of the power used and the running time, known as a kilowatt hour.

1.3 *Resistance and Ohm's law*

Both current and voltage can be thought of as 'universal parameters' in electronics. They exist everywhere and are valid descriptions for every electric circuit as well as every component within an electric circuit. The natural question that follows from the description of two such parameters is the relationship between them.

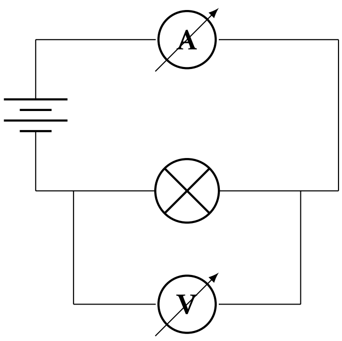


Figure 1: Ohm's law circuit

This key relationship was established by the German physicist Georg Ohm in 1827 when he was studying the currents and potential differences involved in a simple electric circuit. His discovery is known today as Ohm's law—

> The current flowing between two points of a conductor is directly proportional to the potential difference across those two points.

Mathematically, the relationship $V \propto I$ requires that a constant of proportionality (which we shall label R) be introduced to employ an equals sign:

$$V = IR$$

which is the mathematical form of Ohm's law. And the constant of proportionality is known as the **resistance** of that device across which the potential difference is being measured.

For a given device then, this third universal parameter, the resistance, is a constant. In reality, R varies with variations in, for example, temperature, but it is nonetheless considered a descriptive parameter that can be associated with any electronic device. Resistance is simply an opposition offered against the flow of current. It is measured in **ohm** (Ω) as a nod to Georg Ohm.

Resistance is a universal parameter when all its forms (impedance, conductance etc.) are considered since they represent different manifestations of the same notion. That every electronic device opposes current flow albeit to various extents is, however, a universal property.

Finally, note that, from the above equation, when $R = 0$, it might appear that all current flow ceases. However, this is incorrect. Having no resistance (although practically impossible) does not mean zero current flow but infinite current flow. This is easy to see mathematically as well, given that any number divided by zero gives us infinity.

$$\frac{V}{R} = I$$
$$\Rightarrow \frac{V}{0} = \infty$$

Practically, everything in a circuit, including the conducting wire itself, offers some degree of resistance; the resistance of most of these **circuit components** is negligible for all practical purposes. The resistance offered by a power supply, such as a battery, is known as its **internal resistance**.

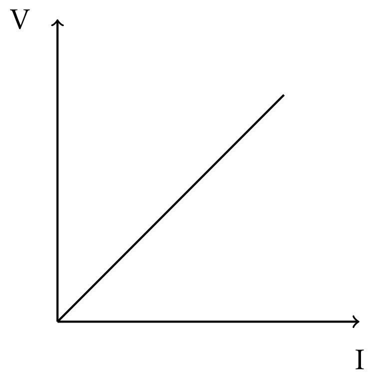


Figure 2: The nature of Ohm's law on a graph of voltage v. current.

Not all devices obey Ohm's law. Those which do are called **Ohmic devices** while those which do not are called **non-Ohmic devices**. The linear relationship of Ohm's law suggests that a graph of V against I is a straight line with slope R (see fig. 2). Non-Ohmic devices, on the other hand, have V–I graphs with a curved shape.

A linear relationship is an equation where the maximum power of the variable is one. Ohm's law is such relation and its graph is a straight line passing through the origin $(0, 0)$ of a graph of V against I, i.e. with voltage on the y-axis and current on the x-axis. By contrast, $P = IV$ where we can replace $V = IR$ to get $P = I^2R$ has the power two which means that a graph of P versus I is not a straight-line graph anymore and is a curve instead.

2 CIRCUIT BASICS AND POWER SUPPLY

We already came across an electronic circuit in fig. 1 and it carried four important symbols:

There are several other symbols which we will come across in context rather than listing them out all at once. The symbol for load is sometimes also called a lamp and is a stand-in for any circuit element which is fed by the rest of the circuit and across which the output of a circuit is taken. Think of this as the main object to power which a circuit is constructed.

2.1 *Circuit construction*

There are two important ideas to remember when drawing a circuit:

1. Two random points on a circuit, or two **nodes** (those points where a wire branches out), that are not separated by a circuit element are equivalent.

2. Every device influences V, I and R in some manner, however subtly. As a result the relative placement of devices is important even if their absolute positions in a diagram is not.

In fig. 1 observe that we have two nodes formed by connecting the voltmeter across the load. All points between the right node and the ammeter are equivalent. This is not true of the left node, however, since a battery exists in-between.

All circuit elements can be broadly classified into two types: **active devices**, which require their own power source to work and can control current flow, and **passive devices**, which do not require their own power source to function. All electric circuits *must* contain at least one active device (often this is a battery or other power source). Examples of active devices include diodes, transistors, amplifiers and batteries. Examples of passive components are, among others, resistors, capacitors and inductors.

A circuit is a planned structure built using various components, called **circuit elements**, which together help us achieve an intended end result. While circuits can be constructed only in specific forms, depending on their purpose they can be drawn in several ways and this can make it easy to be misled about a circuit by looking only at its overall appearance in a diagram; focus instead on the relative positions of components to deduce what a circuit does. For instance, these two circuits are the same:

Figure 3: An example of equivalent circuits with seemingly different structures

As noted in the two points above, the equivalence of these constructions becomes apparent when you realise that the nodes on any single side of the resistors, having no circuit elements between them, are equivalent to each other.

2.2 *Alternating and Direct Current*

The current we discussed in 1.1 was unidirectional, i.e. charges only ever flowed in one direction. The effect of this, of course, was that the voltage was also a constant. However, the downside of such a set-up is that with high voltage comes a high current flow if excellent conductors are used; however, if we wish to maintain a low, steady current flow, DC supplies would experience extreme amounts of resistance which could, in turn, generate a lot of heat and wear out the entire circuit. (The increase in resistance for high V and low I is a consequence of Ohm's law; in fact, this process of heat generation is nothing new given that this is precisely how bulbs work: a thin wire–a filament–glows when a current passes through it and experiences resistance.)

To transfer current across large distances then we need to send it as a small and stable quantity. Since the power of a circuit is $P = VI$ we can see quite easily that to ensure a small current flow, the voltage must be increased considerably. This way we can eliminate any loss of energy. For instance, to maintain a power of 100 W you could send in 10 A of current with 10 V across, or, better yet, maintain 10^3 V across so that you would have to send in a current of only 0.1 A while still maintaining a power of 100 W as desired. This reduced current flow would mean lower resistance and hence lesser energy loss through excess heat.

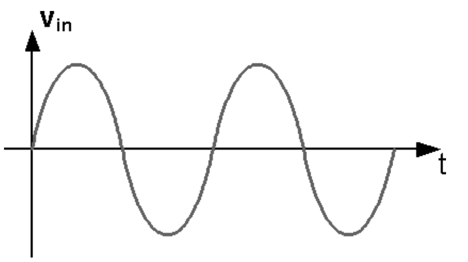


Figure 4: AC waveform. Courtesy, Communications Museum of Macao.

The solution to such a problem is to introduce an **alternating current**, a current flow defined by its alternately reversed directions as opposed to the unidirectionality of direct current. We shall simply refer to these as AC and DC henceforth.

An AC current flow is not defined by a straight-line equation but, rather, by a periodic one such as the sine wave shown in fig. 4. A sine wave is described by the equation $V(t) = V_m \sin 2\pi f$ on a fundamental level (there are more complex versions of this equation that describe more realistic scenarios). What this means is simply that the voltage V at any time t is given by the product of the **amplitude**, i.e. the maximum voltage V_m (the peaks of the waveform), and the sine of 2π times the frequency of the AC supply.

From the equation and, perhaps more so, from the waveform shown in fig. 4 it is apparent that AC voltage changes gradually over time. However this need not be the case: a square wave that flip-flops between two voltages (either 0 to V_m or $-V_m$ to $+V_m$, with one LOW and one HIGH voltage) is also considered alternating. Such instances are, in fact, the definition of logic circuits and are employed in computation where the LOW and HIGH voltages are interpreted as binary zeros and ones respectively.

This brings us to the doorstep of an important factor associated with AC, the **frequency**. If AC consists of several to-and-fro alternative motions of current, then one to and one fro motion can be thought of as a single cycle and AC can, in general, be thought of as a series of such cyclic to-and-fro motions. Therefore we are in a position to define the quantity 'cycles per second'. AC can be as low as 5 cycles per second or even 60 cycles per second. A cycle per second is called a **hertz** (Hz) after the German physicist Heinrich Rudolf Hertz; n cycles per second are then n Hz and, say, five cycles in three seconds is $5/3 \approx 1.7$ Hz. Further, the variation in AC means no single voltage may be specified with justification to represent the entire supply. This is why the root-mean-square value of AC voltage supply (given by $V_m/\sqrt{2}$ and being approximately 70.7% of the maximum) is stated instead. (Looking at this in terms of the square wave we discussed earlier, students with a computer science background—or anyone aware of the insides of a computer—may further recognise the frequency associated with such waves as nothing but the time period of a pulsating clock where the frequency is often referred to as the 'clock speed' of a processor.)

Observe that if n repetitions per second is the frequency of some phenomenon then $1/n$ is the time period of a single repetition. Frequency f and time t are therefore related as $f = 1/t$ or $t = 1/f$.

The reliability, energy efficiency and possible inductance (see 3.3) to vary V and I are all why AC is, today, the preferred means of supplying current to the public. India, China, and most of Asia and Europe have standardised a supply of ≈220 V AC at 50 Hz, while the USA, Taiwan, Saudi Arabia and a few others supply ≈120 V at 60 Hz.

One last point worth noting is that AC supply does not experience DC resistance alone. Besides this it also experiences reactance (see 3.2 and 3.3) and, together with DC resistance, the resistance of an AC circuit is called the **impedance** of that circuit.

3 PASSIVE DEVICES

We previously talked about what active and passive devices are. The remainder of this section will be dedicated towards studying an assortment of commonly used passive electronic devices. We will understand the purpose of each device, any special parameters that describe it, and its contribution to, and behaviour in, an electric circuit.

3.1 *Resistors*

A resistor is a passive electronic device whose job is to offer a well-defined amount of electrical resistance in a circuit. There are several types of resistors, including those which offer fixed resistance and those whose resistance can be varied.

The quintessential resistor is a small (few mm) cylindrical construction made of a helical carbon or metal-oxide film wrapping a ceramic core. This is also known as a **carbon composition resistor**. The turns of the helix and width of the film used determine the resistance that that device will offer.

The precise value of resistance, within acceptable experimental error, called **tolerance**, is mentioned on such resistors using coded bands of colour.

Carbon composition resistors can have four or five bands of colour. In the former case the first three bands give the value of resistance and the fourth gives the tolerance; in the latter case the first four bands give the value of resistance and the fifth gives the tolerance.

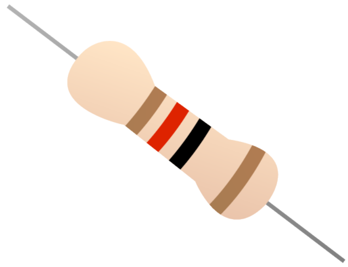


Figure 5: A generic resistor. Courtesy, Raspberry Pi.

Tolerance is specified by a gold band (±5%), a silver band (±10%) or, only in case of four-band resistors, a blank band (±20%). Other colours such as red (±2%), brown (±1%) and green (±0.5%) are also used in more accurate resistors. Tolerance bands are usually placed farther from the main bands.

The colour bands (found closer together in threes or fours) which specify the value of resistance carry integral weights from zero to nine in the following order: black, brown, red, orange, yellow, green, blue, violet, grey and white. There are several mnemonics used to recall this group of colours such as 'Better be right or your great big vacation goes wrong', 'Big, beautiful roses occupy your garden but violets grow wild', and 'B.B. Roy of Great Britain had a very good wife'. Whichever you choose to use as an aid, be sure to remember that the Bs stand for black, brown and blue, and the Gs stand for green and grey, in that order.

We will discuss more about the specific effects of resistors in a circuit in 4.1.

A commonly used resistor which can vary its resistance is known as a **rheostat**. (An instrument used to regulate potential difference, called a **potentiometer**, can also be used for the same purpose.) It consists of three terminals, one of which serves as a movable contact to increase or decrease the length of the resistor through which current must travel, thereby increasing or decreasing the resistance offered. The construction of a rheostat involves winding a wire around a cylinder, rather than using a carbon or metal-oxide film, as this allows us to vary the length of the resistor while the winding keeps the resistor (fairly) compact. Such resistors are called **wire-wound** resistors.

3.2 *Capacitors*

A capacitor is a device used to store electric charge. It is a two-terminal, passive component that consists of a pair of conductors separated by an insulator. It is sometimes also called a 'condenser'. Some capacitors can store more electric charge than others and this capacity to store electric charge is known as the **capacitance** of a capacitor. The circuit symbol for a capacitor looks quite like a capacitor itself: two parallel plates perpendicular to their connecting terminals on either side.

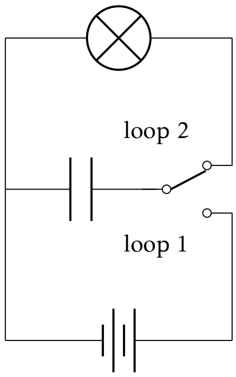


Figure 6: A circuit to charge and discharge a capacitor.

Figure 6 shows a capacitor forming two loops in a circuit with a load and with a battery. There is a three-terminal switch next to the capacitor that can be used to connect loop 1 and break loop 2 or vice versa. When loop 1 is connected, a **closed circuit** is formed with the battery, the capacitor and the switch. The negative of the battery (the shorter line on the left) is connected to one 'plate' of the capacitor while the positive is connected to the other. The fact that an insulator exists between the two plates of the capacitor means no charges can transfer easily from one plate to the other. With time, negative charges (electrons) from the negative of the battery accumulate on one plate of the capacitor leaving us with a **charged capacitor** where one plate is heavily negatively charged and the other, by comparison, is heavily positively charged. The capacitor now has some stored charge. Next, we flip the switch so that loop 1 is broken and loop 2 becomes a closed circuit (this is the exact moment shown in fig. 6) and the charges stored in the capacitor begin to flow, i.e. the negative plate with excess electrons will see a net movement of those electrons along the circuit towards the positive plate. In other words, this results in the flow of current flow through the load (if it is a lamp, the lamp will not light up). This naturally goes on until the capacitor has been **discharged** and the charges on either plate of the capacitor are neutralised. Most capacitors charge must faster than they discharge.

Can you think of a way of proving that a capacitor has been charged besides waiting for the bulb to glow? Hint: What is the potential difference across a charged capacitor versus that across a discharged one?

As a short hand it is worth remembering that if the charging battery applies V volts across the capacitor (as in loop 1), then the capacitor is charged up to a maximum of V volts. Such a capacitor is said to be 'fully charged'. It is understandable then that some charge Q will now be stored across the two plates of the capacitor as a result of charge accumulation. It is the ratio of these two quantities that gives us the capacitance C in mathematical form as

$$C = \frac{Q}{V}$$

When storing one coulomb of charge in a capacitor requires one volt to be applied across the capacitor, then its capacitance is said to be one **farad** (F), named after the English physicist Michael Faraday who contributed greatly towards our understanding of electromagnetism.

Key factors that affect capacitance are the size (area) of the plates, the distance between the plates, and the **dielectric** (insulating) material sandwiched between them. The plates are generally made of a good conducting metal foil or film while the dielectric is made from polyester, ceramic, glass or even simply a blanket of air. Capacitors with such a construction are called **parallel plate capacitors**. Modern designs such as multi-plate capacitors made nowadays consist of several plates arranged alternately in an attempt to increase

Do you need a DC or an AC source to charge a capacitor? Hint: DC sources are unidirectional and will charge one plate with electrons as expected; on the other hand an AC source keeps switching directions. What is the effect of such alternation?

the surface area used to store charge (nine plates are better than two).

There are several other types of capacitors too: ceramic capacitors which use ceramic dielectrics and electrolytic capacitors which use a semi-fluid electrolytic solution are two popular examples. In the former case, the capacitance is usually small and the capacitor has no polarity, i.e. no specific positive and negative terminal. In the latter case, where the capacitor looks like a cylinder and is capable of having a much larger capacitance, the device has a polarity and in all such cases the negative terminal is marked with a band in addition to which the positive terminal is built longer than the negative one. (The circuit symbol of a capacitor with defined polarity is slightly different; the negative pole of such a capacitor is marked using a curved line instead of a straight one—see fig. 8.) Keep an eye on this when building circuits in the lab as mixing up polarities can lead to capacitors swelling up, becoming extremely hot and exploding powerfully.

3.3 *Inductors and transformers*

An **inductor**, rarely also called a 'reactor' or simply a 'coil', is a passive, two-terminal electrical device that stores electrical energy in the form of a magnetic field. It is called a coil because it is just that, a coil of wire usually wound around a magnetic ring or cylinder called the **core** of the inductor.

The characteristic property of an inductor is its **inductance**, the ability of one conductor to use a varying current to create, or *induce*, a potential difference across another conductor that is not directly connected to it. It is hard to describe inductance without considerable mathematical rigour but here is a simple form:

$$\mathrm{L}\,\frac{\Delta \mathrm{I}}{\Delta t} = -\mathscr{E}$$

where L is the inductance, $\mathscr{E}$ is the electromotive force (emf, think of this as nothing but the potential difference generated specifically by the power source of a circuit) and $\Delta \mathrm{I}/\Delta t$ gives the rate of change of current (Δ in physics means 'change in'). The negative sign tells us that the generated emf is in a direction opposite to the initial current flow that generated it.

There are two ideas to take away from this: Firstly, the fact that the generated emf opposes the original current flow (this is known as Lenz's law) means inductors, in general, oppose changes in the direction of current; that is to say, inductors generally block off AC and allow DC to pass through. As a result, inductors are used to select certain frequencies of current and *choke* the others; this behaviour sees considerable use in radio and TV receivers to make channel selections and in any other instances where tuning is required. Secondly, inductance is measured in **henry** (for Joseph Henry, see below) and one henry is defined as the inductance when a current flow changing at the rate of 1 As^{-1} induces an emf of 1 V.

Michael Faraday (recall him from 3.2) and Joseph Henry both realised, around the early 1830s, that any change in the current flowing through a conductor, which gives rise to a magnetic field, creates a potential difference across the conductor. This is the idea that drives inductors. In essence, if we have a coil around which a magnetic field is generated due to current flow, any change in the current flow is opposed by the magnetic field which tries to prevent that change. So AC is blocked while DC, which does not change direction, is in agreement with the inductor and passes freely.

The fundamental idea behind inductors leads us to an extremely important electronic device used everywhere from small circuits to city-wide power grids: the transformer.

While the magnetic field generated by an inductor can create an emf across it, the same effect can be exerted on *another* circuit. When one inductor induces a current flow in another the phenomenon is termed **mutual inductance**. This is shown in fig. 7 where each coil is the circuit symbol of an inductor and the two coils together form the circuit symbol of a transformer. The unanswered question of course is why the term 'transformer' was chosen to represent such a mutually inductive dual-inductor set-up.

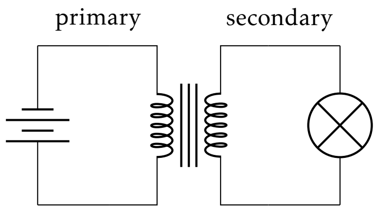


Figure 7: A basic transformer.

One key factor in all inductors is the number of turns, or **winding**, of the inductor coil. As a rule of thumb, the more the turns in an a coil the greater the inductance. Apply this logic to a transformer made up of two inductors of different sizes: not only will there be inductance but if the primary inductor is smaller than the secondary one, the low voltage supplied across the primary winding, by a battery, will end up *transforming* into a high voltage across the secondary circuit. Since the voltage has been stepped up such a transformer is called a **step-up transformer**. Likewise if the primary winding is greater than the secondary winding we have a **step-down transformer** and the voltage can be reduced.

You may have noticed transformers (they often look like grey boxes) on several power supply lines as they are used to maintain a high voltage and transmit low current over city power grids to minimise loss and the voltages are then stepped down using transformers before being sent into homes. Note that for inductance as mentioned above we need a constantly fluctuating magnetic field, which is introduced by a constantly fluctuating current, which means only AC can achieve such transformations with ease. This is an important reason why we prefer to transmit AC to homes almost universally.

3.4 *Other passive components*

The trio of resistor, capacitor and inductor form the main set of passive electronic components predominantly used in electronic circuits. However, there are other important but more simplistic devices that are used just as often and we have already come across a couple of them.

A circuit that is completely connected in a closed loop is known as a closed circuit. The opposite, when a circuit is not fully connected, is called an open circuit. A **switch** is an electronic circuit component that switches an electrical circuit between a closed and an open state. In effect, it makes or breaks a circuit. The opening of a circuit in particular can be by simple disconnection (as in fig. 8) or by connecting to another part of the circuit (as in fig. 6).

The simplest switch is a mechanical device with metallic contacts that can be kept ON or OFF (toggle switches) or held ON and released to switch OFF (push switches). There can also be an electronically operated interruption device called a **relay** which the circuit itself can turn on and off. Like a switch, a relay too uses contacts but need not be operated mechanically. Recall from 3.3 that a varying current generates a magnetic field; a relay is simply a coil and a metallic contact arranged such that a sufficient current produces a magnetic field that attracts or repels the contact thereby closing or opening a circuit. Relays can alternatively also be automated based on temperature or other parameters of our choice. The sole purpose of a relay being the automation of switching between circuit states, it finds great use in logic-based circuits where sections of a circuit may need to be opened or closed based on several other parameters and doing this job manually is often not efficient.

We can take the idea of automatic switches in a slightly different direction when compared to a relay; we can use a thin conductor (thinner than the other wires in the circuit) whose size is carefully determined so that if the current, and hence resistance and heat, exceeds a particular value the conductor melts thereby breaking the circuit. Such a set-up can be used to prevent damage to other electrical components in case of a sudden surge of power because the circuit will quickly be opened. In fact such a device is used in several circuits today, from small vehicles to entire homes, and is known as a **fuse**.

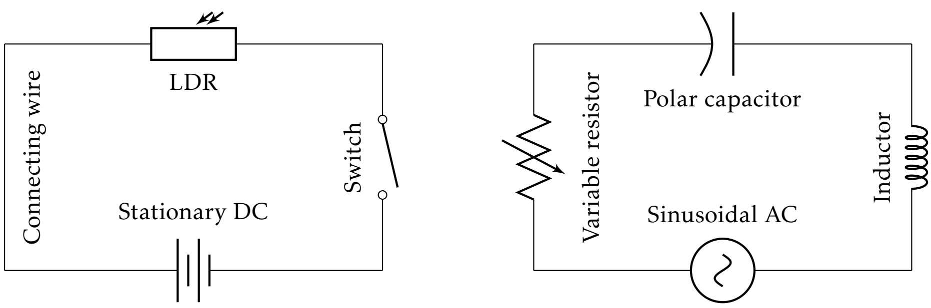


Figure 8: Dummy circuits, only to show various components.

Although not a passive component a battery is a key device that forms an integral part of every circuit. It is the only active component in some circuits and its function is to provide power to the circuit.

DC sources are marked on a circuit using an alternating series of short and long parallel lines with one end being short (negative) and the other being long (positive) to denote the two terminals of the battery. DC sources are made up of wet or dry electrolytes and some undergo irreversible chemical change during use (disposable) while others can be reused by reversing the direction of charge flow in much the same way as a capacitor (rechargeable).

An AC source on the other hand has no specific polarity since it constantly alternates direction. Most generic AC sources provide a sinusoidally varying voltage (recall the equation for $V(t)$ from p. 8) and such sources are represented by a circle with a sine waveform inscribed (see the right-hand circuit in fig. 8). In laboratories AC sources are commonly known as signal generators and can be used to generate any signal, not only sine waves. The AC supplied in urban power grids, though, is sinusoidal.

Some components like resistors and capacitors can be varied depending upon our needs in a circuit. Such variable devices are marked with the same symbol but with an overlaid arrow (see the resistor in fig. 8). There are still other variable devices that are not directly under our control but respond to other stimuli. Examples of these include **thermistors** and **Light-Dependent Resistors** (LDR) which are resistors whose resistances vary based on their exposure to heat and light respectively.

4 INTRODUCTION TO CIRCUIT ANALYSIS

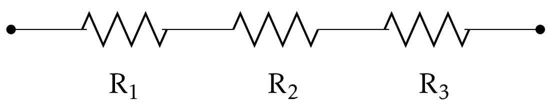
Having gone over the most important passive circuit components we are now in a position to understand how they work together. We will focus our attention on resistors specifically but also overview capacitors and inductors. Our aim is to try to answer two questions:

1. What effect does a collection of resistors have on a circuit as opposed to a single resistor? (Likewise for capacitors and inductors.)
2. How does current flow through and branch out in a complex network of wires and components, and how is voltage distributed across the same?

The first of these questions can be answered by studying two specific arrangements of resistors. The second was answered by the German physicist Gustav Kirchhoff in 1845 and are named after him.

4.1 *Resistances in series and parallel*

Consider the following train of resistors:



When three components are connected in this manner they are said to be connected in **series**. Observe that there are no branches in the circuit and that each resistor leads to the next one. As a result the current through each component is the same but the voltage across each component may be different.

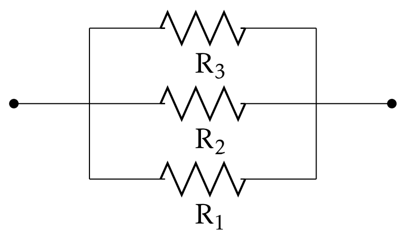
The equivalent resistance R_s of a series connection of n resistors is simply the sum of the individual resistances:

$$R_s = R_1 + R_2 + \cdots + R_n$$

While one may look at the same current flowing through all resistors to be an advantage, it can also be a disadvantage: if one of the resistors malfunctions, or if the connecting wire between two resistors is broken, the entire circuit falls apart. Sometimes this may be a required feature, sometimes it may not.

Remember that the resistances may not be in a *line* but so long as one resistor leads directly to another they are said to be connected in series.

There is a second way to connect resistances:



The difference between this circuit and the previous one is that a resistor is *not* connected directly to another resistor but to a node instead. In fact, all three resistors begin and end and the same two nodes. In such cases the resistors are said to be arranged in **parallel**.

The effective resistance R_p of n resistors in parallel is

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

which is *not* the same as a set of resistors connected in series. This formula, as well as the series formula, can both be verified experimentally.

Once again, the requirement is not that the resistors must look like they are placed in parallel to one another but that they must all have common start and end points. As a result of this arrangement, note that the potential difference across all parallel resistors is the same since it is across the same two points. However, at their starting node the current branches out as it passes through each resistor and converges again at the end node, which means the current through each parallel resistor may vary.

Both these formulae are easy to arrive at. We use Ohm's law ($V = IR$) and the fact that in a series connection the same I flows through all resistors:

$$\begin{aligned} I &= I_1 = I_2 = \cdots I_n \\ \Rightarrow V_1 + V_2 + \cdots V_n &= I(R_1 + R_2 + \cdots R_n) \\ &= IR_s \end{aligned}$$

Likewise for resistances in parallel the same V exists across all resistors:

$$V = V_1 = V_2 = \cdots V_n$$

$$\Rightarrow I_1 + I_2 + \cdots I_n = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}\right)$$

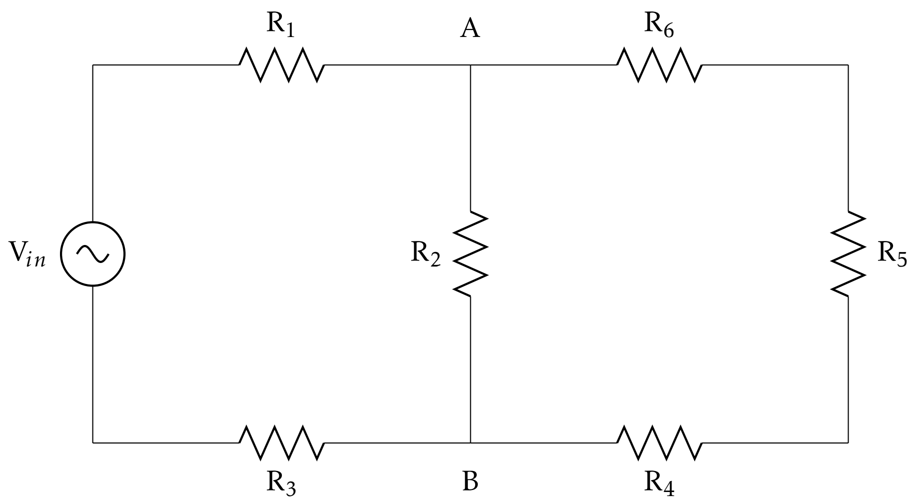
$$= VR_p$$

In case of series inductors too the same pattern of formulae holds. Inductors in parallel, however, see some complications. For capacitors in series, the reciprocal of the effective capacitance is the sum of reciprocals of each capacitance (analogous to parallel resistors), and the effective capacitance of parallel capacitors is, like series resistors, simply the sum of each capacitance.

Amidst all this discussion the net effect of a series and parallel combination of resistances must not be forgotten. The effective resistance of a series combination of resistors is always greater than the greatest individual resistance; and the effective resistance of a parallel combination of resistors is always lesser than the least individual resistance. For example, three resistors of $2\,\Omega$, $4\,\Omega$ and $5\,\Omega$ may be combined in series to get $R_s = 11\,\Omega$, which is greater than $5\,\Omega$, and in parallel to get $R_p = 1.05\,\Omega$, which is lesser than $2\,\Omega$. Resistors can be placed in series to increase the overall resistance and in parallel to achieve a resistance lower than any single resistor being combined.

4.2 *Kirchhoff's laws*

Kirchhoff developed two laws that hold universally to all circuits are often the first step to analyse any circuit. These laws help determine how current and voltage behave in a circuit. For our discussion let us consider this circuit:



We have two nodes or junctions, marked A and B, and **Kirchhoff's current law** deals with how current in a circuit behaves when it encounters a node:

> The total current entering a node is equal to the total current leaving that node.

Can you identify which resistors in the above circuit are arranged in series and which are in parallel?

This is a simple but powerful idea that can help us determine the magnitudes and directions of current flow in any circuit. In effect all we have to do is ensure that we do not have any nodes with all current going in or all current coming out. We can make this choice arbitrarily and, during calculation, if we assigned the wrong direction we end up with a negative current which simply means the direction of current must be reversed.

In the same vein **Kirchhoff's voltage law** describes how voltages behave in a circuit:

> In a closed loop, the total voltage around the loop is equal to the sum of all voltage drops within that loop.

We have two loops in our circuit: one with the source V_{in}, R_1, R_2 and R_3; and the second with R_4, R_5, R_6 and R_2. Kirchhoff's voltage law tells us that if we keep adding up the potential differences cross each component (calculable using $V = IR$) going in one direction (clockwise or anticlockwise) the sum will be zero. Mathematically, from our circuit,

$$V_{in} + V_{R_1} + V_{R_2} + V_{R_3} = 0$$

where V_{R_n} is the voltage across the n^{th} resistor.

Whenever you are required to analyse a circuit, begin by labelling the currents through each branch (both known and unknown) and then apply Kirchhoff's current law at each node to determine the magnitude and direction of unknown currents. Next, for each loop, determine the unknown potentials using Kirchhoff's voltage law.

END RESULTS

By the end of this unit you should be able to

1. Describe current flow, potential difference and resistance
2. Use Ohm's law effectively and differentiate between DC and AC
3. Explain the fundamental structure and working of resistors, capacitors, inductors, transformers, relays and switches
4. Identify series and parallel connections
5. Use nodes and loops to identify currents and potential differences across various components and determine as many unknowns as possible

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