Chapter 9 Electricity

Electricity powers our homes, businesses, and industries, providing lighting, heating, and the energy that fuels our gadgets such as game consoles and smartphones. Magnetism underpins the functionality of motors that propel vehicles, the generators that produce electricity, and medical devices like MRI machines. Electromagnetic waves make modern wireless communication and the internet possible. In this chapter, we explore what is the basic and fascinating science behind electricity, electronics, wireless communications, power tools and machines.

1. Electricity

Learning Objective

- Coulomb's Law
- Understanding electric field and electric potential
- Understand relation Ohm's law
- Articulate the difference between circuit in series and circuit in parallel

Glossary

- Charge
- Static electricity
- Coulomb's Law
- Electric field
- Dipole field
- Electric potential
- Potential difference
- Electric potential energy
- Voltage (same as potential difference)
- Conductor, insulator, semiconductor
- Electricity
- Resistance, resistor
- Electric Current vs. Conventional current
- Ohm's Law
- Circuit in parallel
- Circuit series

1. Electricity

If we turn our attention to something so essential, so integral to our daily lives, yet often taken for granted, it's electricity. Picture the world for a moment without it. Silent cities, motionless machines, and a night sky unlit by the familiar glow of homes and streets. Electricity isn't just the spark that turns on our lights. It's the lifeblood of our modern world. From the soft chime of your morning alarm to the comforting hum of the evening refrigerator, it plays a symphony in the background of our lives. Think of it as a silent conductor, orchestrating every technological advancement and modern comfort we enjoy. Beyond our physical homes and communities, it also powers ideas and innovations. With every surge of electricity, new possibilities emerge. Electric cars? Virtual Reality? Global communication networks? All borne from the dance of electrons. It deserves our attention to understand how it works and how we get here.

I. Mass Particles, Atom, Ions and Charged Bodies

All matter on Earth is composed of atoms. Each atom consists of three primary particles: protons with positive charges, electrons with negative charges, and neutrons, which are neutral. Within an atom, the number of electrons and protons are equal, rendering the atom neutrally charged by definition. Neutrons often outnumber protons and they cluster in the atom's core, known as the nucleus. Different atoms have varying numbers of protons in their nuclei: a carbon atom has 6 protons (not 4 as you mentioned), while an oxygen atom has 8. Although electrons are much lighter than protons and neutrons, they remain bound to the atom due to the attraction between opposing charges. When an atom gains or loses electrons, it becomes charged, and we refer to it as an ion. For instance, when an oxygen atom gains 2 electrons, it becomes a negatively charged ion. Conversely, when a silver atom sheds an electron, it becomes a positive ion.

Everyday objects comprise an unfathomable number of atoms — literally trillions upon trillions. Electrons can be added or removed from these objects. Consider rubbing a balloon against your hair: it adheres because the balloon acquires extra electrons, becoming negatively charged, while your hair becomes positively charged, exemplifying the attraction of opposite charges.

II. Electrostatic Force and the Coulomb's Law: The Dance of Electric Forces

Electrostatic force, like gravity, is a natural, fundamental force that emerges when electric charges are present. It ranks among the four primary forces of physics, which also includes gravity, the strong nuclear force, and the weak nuclear force.

Electrostatic forces can either attract or repel. Like charges repel each other, while opposite charges attract. Coulomb's Law quantifies the interaction between charges.
It states that the force (F) between two point charges, q1 and q2, is directly proportional to their product (q1*q2) and inversely proportional to the square of their distance (r) apart.

The is, the first proportion is:

F ← directly proportional to the products of the 2 charges

And the second proportion is:

$F \sim \frac{1}{r^2}$ ← inversely proportional to distance apart squared

Expressed together, the Coulomb' Law is:

$$F = k\frac{q_1 \times q_2}{r^2}$$

Where k is Coulomb's constant, approximately equal to 8.99×10^9 N·m^2/C^2

The Coulomb's Law above describes the strength or magnitude of the between 2 point charges either attract or repel quantitatively. It explains everything electric phenomenon form statics shock to what holds an atom together. It also offers insights into the interactions between differently shaped and sized as all charge bodies are are a collections of point charges.

III. Electric Field and Potential

Electric Field Vs Electric Force
When a charge is placed in a region, it produces an electric field around itself. Another charge placed within this field will experience a force due to the field. This mechanism allows two charges to exert force on each other from a distance. The force is calculated by multiplying the charge by the electric field it encounters.

If we imagine multiple charges scattered in a region rather than just one, each charge generates its own electric field. The overall space will then contain superimposed electric fields from each of these charges. When another charge is introduced to this space containing the superimposed field, it experiences a force. This force's magnitude and direction might vary depending on its location within the field.

Often, we're interested in understanding the motion and energy of a charged particle in a region of space. This leads us to map the electric field, which in turn helps us determine the force acting on that charged particle. Since force has both direction and magnitude, the field also indicates how a charge would move.

Fig. 1 below illustrates a region containing a pair of opposite charges separated by a certain distance. For our discussions, we assume these charges remain stationary. The space around them is filled with an electric field, represented by lines with arrows. These electric field lines form a distinct pattern, which provides insight into how a test charge, defined as a positive point charge, would move. For instance, if you place a test charge at Point **a**, it would move and follow the field line from Point **a** → **b** → **c**, eventually getting attracted to the negative charge on the right. As suggested by the arrows, at Point **a**, the test charge experiences a push upward, at **b**, a horizontal force, and at **c** a downward push. The arrows of the field line thus tell us the direction of a force along the line, tangentially. The density of these field lines indicates the strength (magnitude) of the electric field. As there are more lines in the vicinity of Point **a**, than in the vicinity of Point **b**, the electric field at Point **a** is stronger (more intense) than Point **b**. Meaning the test charge experiences a bigger force at Point **a** than at Point **b**.

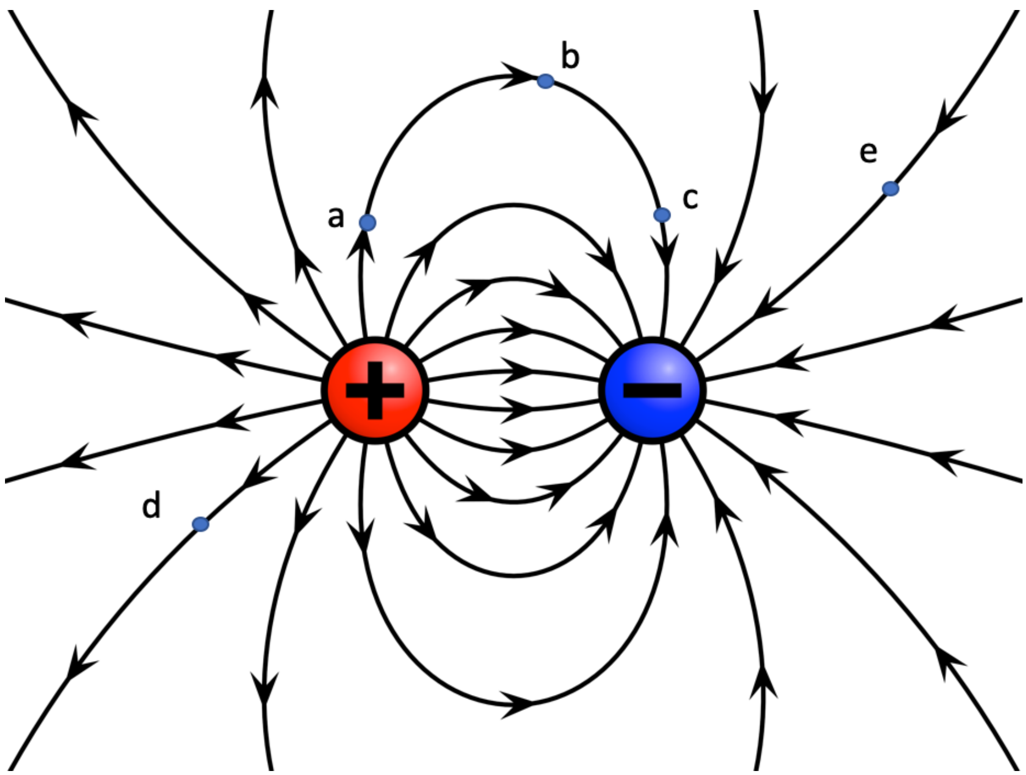

Fig. 1 Electric Field generated by a Pair of Opposite Charges: the Dipole Field. Note that the electric field radiates away from the positive charge, but converges into the negative charge.

The arrows indicate the force direction experienced by a test (positive point) charge placed at point in the field. The more dense are lines in the vicinity, the stronger is the field. Thus at Point **a**, the test charge experiences a horizontal push to East; while at **d**, it's forced to SW. The force at **a** is bigger than the force the test charge experiences at **d.** Field lines are invisible.

In a nutshell, field lines are lines a test charge will travel in if placed there. The more dense the lines, the stronger is the field. The arrow points away from a region of positive charge or toward a region of negative charge. The field tells you how much force a charge experiences and in what direction the force acting on the charge pushed there. That is all. Next we are going to apply the concept to the field patterns below.

If the charge placed in the field is a negative charge, then it follows the opposite direction indicated by the arrows, i.e., the force experienced by the negative charge is opposite to that the arrows.

Let's to apply the concept to the field patterns below.

Case 1: Electric Field Pattern of a Point Charge

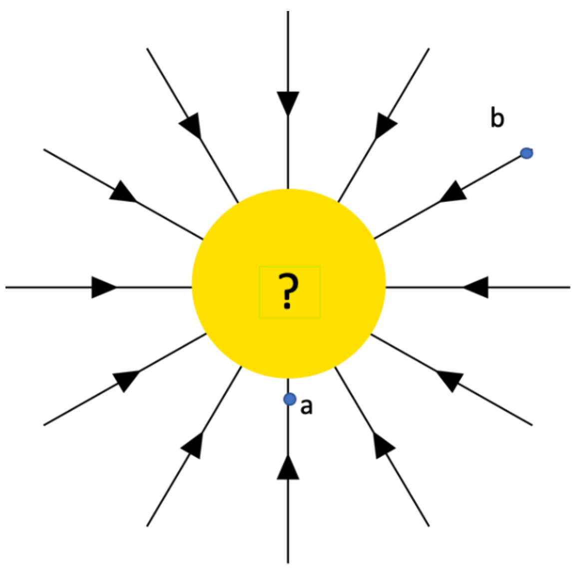

Fig. 2 Electric Field of a Point Charge.

What is the meaning of those lines pointing toward the unknown central charge radially? Those lines are electric field lines. Each field tells a test charge to travel straight into the charge at the center if placed there. Since the test charge is positive, the unknown charge at the center must be **negative.** Since the field pattern also tells us the strength of the field. Which point has a stronger field, at Point **a** or Point **b**? Point **a** has a stronger field because the density of field lines is higher in the vicinity there at Point **b**. Since the force is a product of the field and the magnitude of charge placed there, the force experienced by the charge is also stronger at Point **a** than Point **b.** What if you put an electron at Point **a** instead? The electron moves away from the center due south, opposite to the arrow indicated there. The field pattern indicates that a negative charge moves radially away, as though pushed by an outward radial force.

Note how that field concept above is related to Coulomb's law: the closer are two charges, the stronger is the electrostatic force. If a positive charge is placed at Point **a**, which is closer to the center, it experiences a force bigger in magnitude there than if it is at Point **b**. The charge moves toward the center because it is attracted to negative charge.

Case 2: Electric Field Pattern of Two Parallel Plates.

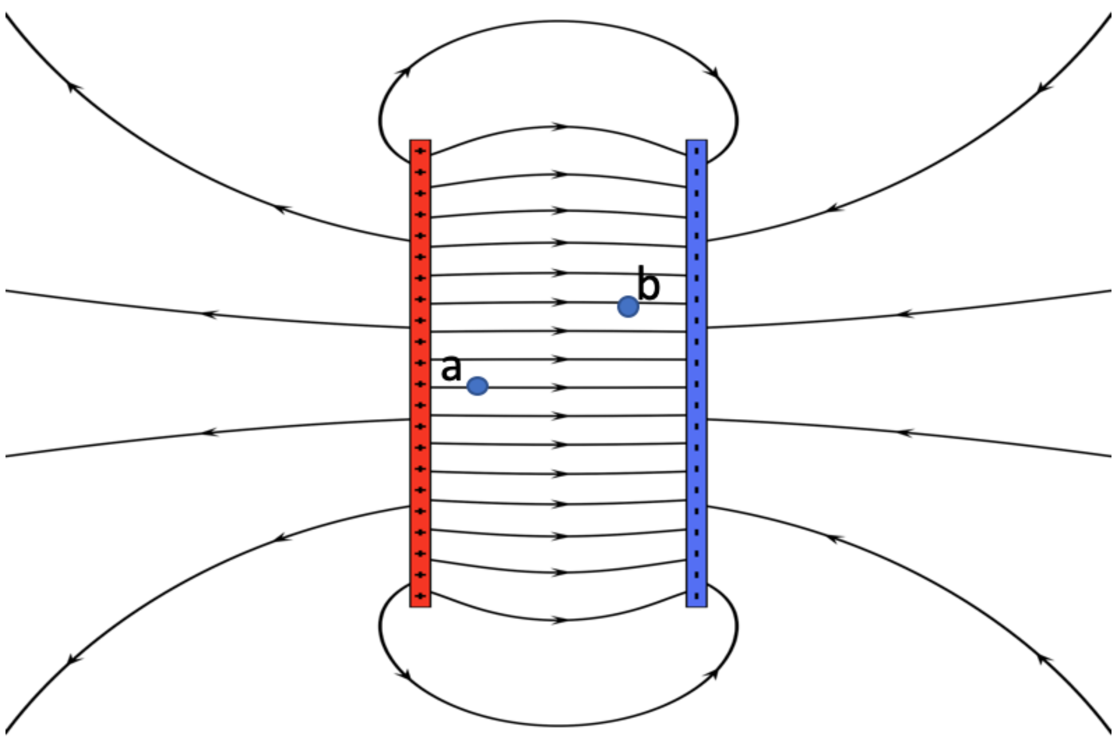

Fig. 3. Electric Field of Parallel Plate Capacitor, Side View. Two parallel plates, each holding equal amounts of opposite charges are held separated by a gap, generate a field pattern that is very uniform between the two plates except at the top and the bottom edge.

Which point has a stronger field, at Point **a** or Point **b** illustrated above? Since the line density is the same everywhere, the field at Point **a** is the same as at Point **b**. If you put a charge there, the force the charge experienced is the same no matter where between the two plates. In what direction will the charge move at these two points? It chare move straight to the right if it is positive. Where has the weaker electric field, inside or outside capacitor? Obviously, it’s in the outer region.

In a nutshell, a field pattern allows us to predict the motion of a charge once in it.
By inspecting the field pattern, we can know where a charge will move to and how much force it experiences no matter how complicated the field pattern looks.
Inspect the figure below. It looks complicated. Yet we should know exactly what those lines mean and what region has a strong field or a weak field. If you place a test charge between the square and the L-shaped charged bodies, you know it’ll be sent up northwest in a weak field; but if you place it near southeast of the positive charge in the center, the test charge will SE in a stronger field. How much force the test charge experienced depends on the magnitude of charges it carries.

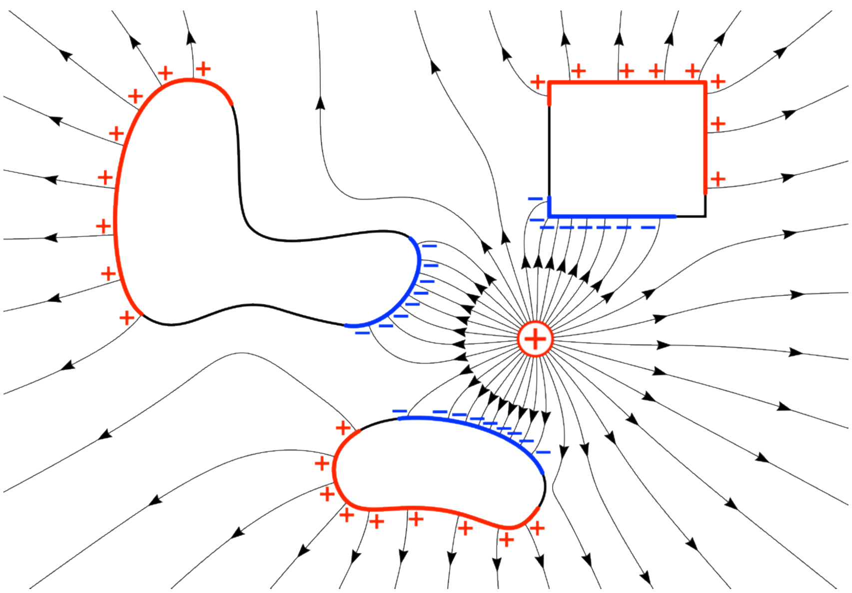

Fig. 4 A Complicated yet Easy to Understand Field Pattern.

Electric Field Definition.
Formally, an electric field is defined as the force per unit positive charge experienced by a stationary positive charge placed in the field. The electric field is also associated with a direction. The magnitude of electric field is

$E = F/q$ ← Field is force to be experienced by a unit charge

$F = qE$ ← The force acts on the charge placed there!

The actual force acts upon a charge in a field depends on the magnitude of electric charge carried by the charge and the field. The unit of charge is C (Coulomb). The unit for field is N/m. Example: A positron has a charge 1.6×10^{-19}C is placed in a field $E = 1\ 10^{15}$ N/C. What is the force acting on it?

$F = qE = (1.6 \times 10^{-19}\ \cancel{C}) \times (1.0\ 10^{15}\ N/\cancel{C}) = 1.6\ 10^{-4}\ N$

If a charge is 10 times the positron is placed there, then the force is 10 times larger.

Electric Potential and Potential Energy

The electric field pattern reveals not only the force and direction a charge will experience but also its potential energy. By understanding both motion and energy, we gain a comprehensive insight into the behavior of a charged body. Armed with this knowledge, we can manipulate it for practical applications.

Think of the electric field as similar to the gravitational field of the Earth, but instead of affecting masses, it affects charges. The gravitation field causes an object to fall or roll from higher levels to lower levels. If you go against the gravity, like climbing a hill, your potential energy increases as you go up. Similarly, a positive charge forced to move against the electric field, i.e., against the direction of the arrows of the field lines, it gains potential energy too.

Water upstream has more potential energy than water downstream. In analogous, we can treat electric field lines acts a channel for streaming charges, with the arrows pointing downstream. A positive charge placed in the field upstream has more potential energy than placed downstream. In fact, a positive charge placed upstream flows naturally downstream, following the field lines, as water flows from high places downward. Before the charge is placed in the field, the field is said to have potential. Upstream the potential is higher, downstream the potential is lower. Fig. 5 illustrates how potential are designated in an electric field with field lines that runs straight from top to bottom. The elevation is divided into equal distanced levels, appeared as dashed lines in Fig.5, to mark the height. Each point on the line has the same potential. The higher the level upstream, the higher is the potential. If a positive charge is placed at a level, where it attains potential energy, it naturally moves from the high level to levels below it. When the charge reaches the lower level, it has lower energy. Where does the energy go? It turns into kinetic energy of the charge, moving faster at downstream than up stream.

Water upstream has more potential energy than water downstream. Analogously, electric field lines can be thought of as channels for streaming charges, with the arrows pointing toward the directions downstream. A positive charge placed upstream in the field possesses more potential energy than one placed downstream. Indeed, a positive charge introduced upstream will naturally flow downstream, adhering to the field lines, just as water flows downward from higher elevations. Before a charge is introduced into the field, the field itself possesses potentials, not energy. This potential is higher upstream and lower downstream. Fig. 5 illustrates how potentials are designated in an electric field with field lines running straight from top to bottom. The elevation is segmented into equidistant levels, depicted as dashed lines in Fig. 5, to represent different heights, thus different potentials. Each point on a dashed line has the same potential, and the higher the elevation or level, the greater the potential. When a positive charge is positioned at a certain level, as shown in the figure, and acquires potential energy, it naturally descends to the levels beneath. As the charge moves to a lower level, its energy diminishes. So, where does this energy go? It is converted into the kinetic energy of the charge, which consequently moves faster downstream than upstream. The key take away is that as long as there is a difference in potential, the difference can drives a charge. The potential give a charge the energy. The difference in potential energy is converted the gains in kinetic energy of the charge. For a negative charge, it moves from low potential to high potential, opposite to the behavior of a positive charge.

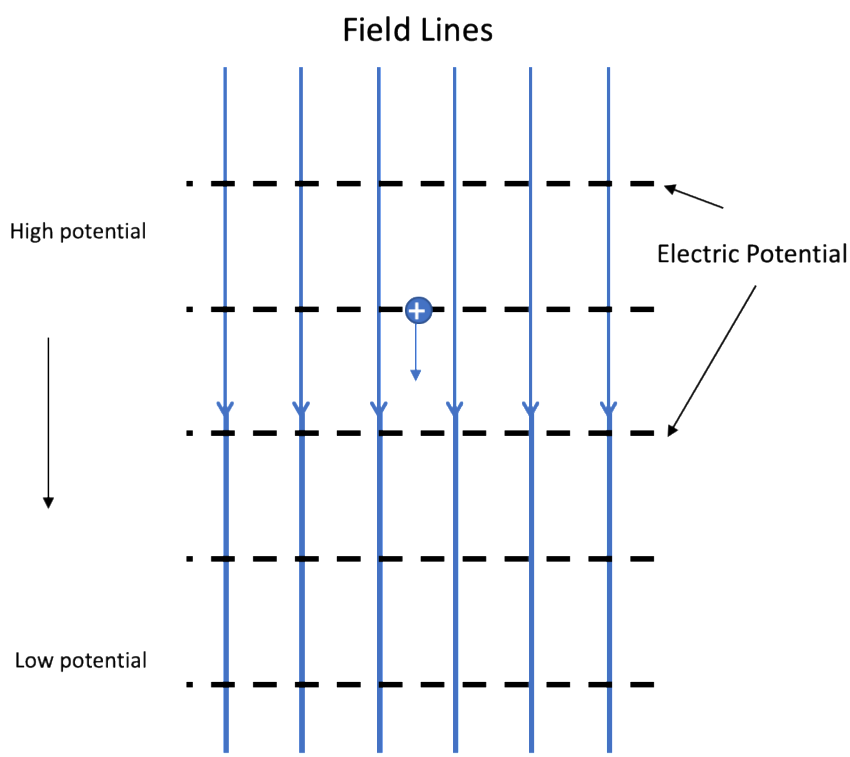

Fig. 5. Potentials (Dashed Lines) in a Uniform Electric Field (Blue Lines with Down Arrows). A positive (+) charge placed at a higher potential naturally moves to lower potential levels. Upon placement within a potential level, the charge acquires potential energy. As it descends to a lower potential level, its potential energy decreases. This reduction in potential energy translates into a gain in the charge's kinetic energy.

Keep in mind that the electric field is not the same as a gravitational field. Gravity is based on the concept of high and low. For a charged object, the electric force is much stronger than gravity. Therefore, for an electron, the electric potential difference has a more significant influence than the difference in heights. If we were to reorient Fig. 5 as Fig. 6, see below, the potential would no longer be defined by height, but by a distance angled 45° from the horizontal. The charge's behavior in Fig. 6 would mirror that in Fig. 5. Regardless of orientation, a positive charge will always follow the electric field lines, moving from areas of higher electric potential to those of lower potential.

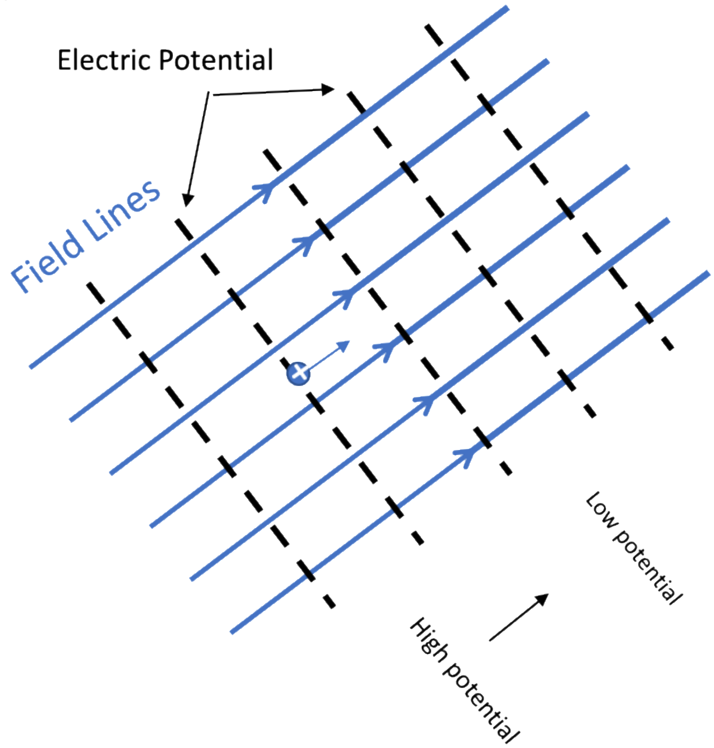

Fig. 6 Electric Field and Electric Potential in an Orientation not Vertical. The behavior of the positive charge will behave exactly the exam.

Electric Potential Definition

Electric potential at a point in space is defined as the electric potential energy per unit charge that would be present at that location. The unit of is 1.0 J/C or V (volt).

Often, potential is represented by the letter V and potential energy by the letter U.

$V = U/q$ ← Potential energy per unit charge at point, before a charge is put there.

$U = qV$ ← Potential energy of the charge when place at the point with a potential

Example: The potential of a charge $q = 2 \times 10^{-6}$C is placed at a location V = 10 volts. What is the potential energy of the charge there?

$U = qV = 2 \times 10^{-6}\cancel{C} \times 10\ (J/\cancel{C}) = 2\times10^{-6}\ J$

If a charge 2C charge is placed there, then U = 2C x 10V = 20 J
(An exaggeration, a point charge can't carry that much charge! But billions of billions of them can).
Comparing Fig. 5 and Fig. 6 with Fig. 3, we immediately recognize that fields and potentials are generated by a pair of parallel plates filled with opposite charges, commonly referred to as a capacitor. But what do potential lines look like around a point charge?

Fig. 7 below depicts the field and potential in the space surrounding a point charge. The radial lines with arrows represent electric field lines, while the concentric rings represent potential lines in 2D. In a 3D perspective, these field lines resemble spikes of a sea urchin, and the concentric rings transform into concentric spherical surfaces, akin to the layers of an onion. Every point on a ring, equidistant from the center, has the exact same potential. Therefore, each ring is termed an equipotential surface. The potential is higher in the inner layers (closer to the center) compared to the outer layers. The outermost ring in Fig. 7 has the lowest potential.

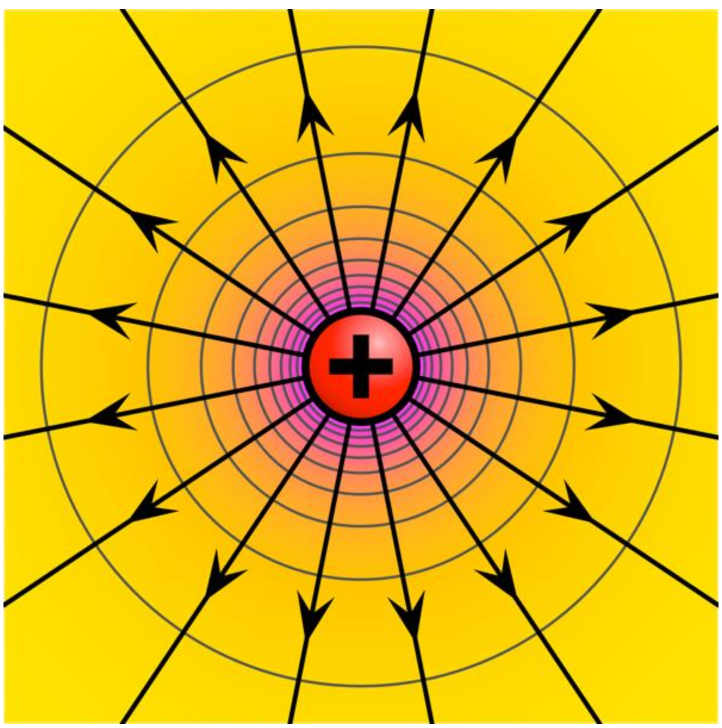

Fig. 7 Electric Field and Potential of a Positive Charge. T The electric field lines radiate outward, guided by arrows. Potential is marked by concentric rings. Every point on a ring has the same potential. The inner rings have a higher potential than the outer ones: red regions have more potential than yellow. The outermost ring has the lowest potential. A

positive charge in the inner core will move outward from high potential to the lower potentials; while a negative charge from the outer area will move inward towards the positive charge at the center.

Fig. 8 depicts the electric field and potential surrounding a negative charge. The field lines converge radially inward, while the potential rings are organized similarly to those around a positive charge. As indicated by the arrow's the outer potential rings upstream have a higher potential than those in the inner region downstream. A positive charge placed on the outermost ring will move inward to a region of lower potential. Conversely, a negative charge on an outer ring will move outward to a region of higher potential.

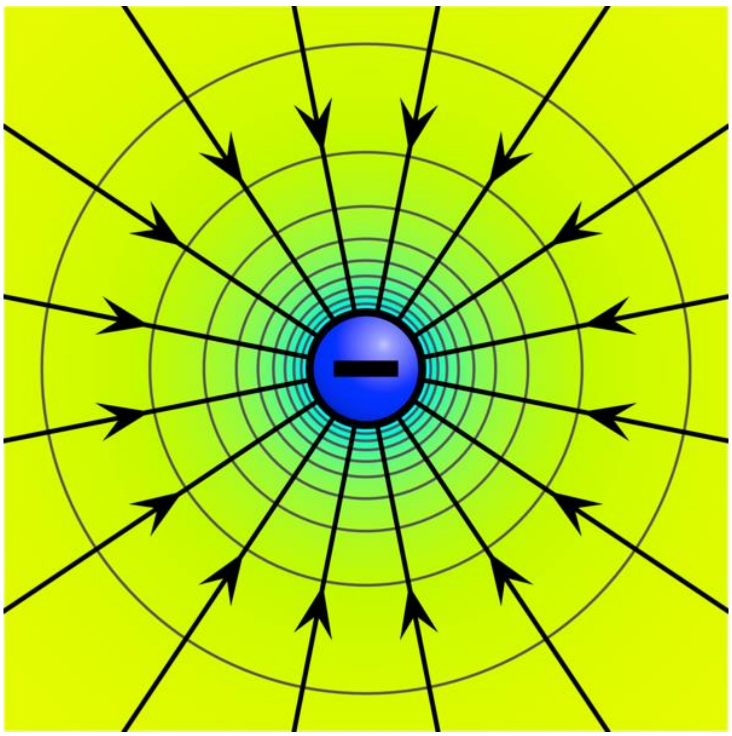

Fig. 7 Electric Field and Potential of a Negative Charge. The field lines converges inward toward the center, and the concentric rings represent potentials. As indicated by the arrows, the potential rings in the outer region (upstream) have a higher potential than those in the inner region (downstream).

By now, we should understand how both positive and negative charges behave within a space permeated by electric fields and electric potential surfaces. In essence, a positive charge moves in the direction of electric field lines and feels a stronger force where the line density is greater. Conversely, a positive charge is driven from areas of high potential (upstream) to areas of lower potential (downstream). A negative charge, on the other hand, moves in the opposite direction; what is upstream for a positive charge becomes downstream for a negative one.

Charge Movement Inside Solid Materials

Materials consist of atoms, either of the same type (element) or different types. In solids, these atoms are anchored in place, forming patterns that can be either regular (as in crystals) or random (as in glass). Electrons within atoms move at extremely high speeds. Materials like oxygen or non-metals tightly hold onto their electrons, preventing them from moving between atoms; these materials are known as insulators. On the other hand, materials that allow electrons to wander freely from one atom to another are referred to as metals. There are also materials that permit electron movement but not as freely as metals; these are called semiconductors.

For practical applications, we require materials that can conduct electrons. While conductors have freely moving electrons, they don't inherently generate electricity. By "electricity," we mean the directional movement of charges. In a conductor, electrons move randomly, effectively preventing any collective movement in one specific direction, resulting in no practical electricity. Harnessing the power of these random electrons requires channeling their movement in specific directions desired. As we learned in the previous section, potential differences can be utilized to drive charges. To make them move in preferred manner, we need to introduced electric field or potential difference to serve as a source of energy.

IV. Voltage, Electric Current, and Resistance

Electrons in conductors, which move freely, can be channeled into an electric current from one end of the conductor to the other by imposing a potential difference across the ends, thereby creating an electric field within the conductor. One method to achieve this is by connecting the conductor to a capacitor illustrated in Fig. 3. The negative plate of the capacitor has a lower potential than the positive plate, allowing electrons to flow from the negative to the positive terminal, generating electricity. However, the capacitor can't maintain the charges on its plates indefinitely, they move away too, diminishing the potential difference. Once its potential difference diminishes, the flow of electrons, or electric current, ceases.

Voltage.

Voltage is a concept born out of the need for a consistent source of potential difference. Batteries were developed to fill this role. In a battery, the positive terminal has a higher potential than the negative one. Through chemical reactions, i.e., redox reactions, a battery accumulates positive charges on one terminal and negative charges on the other. When an electric component, like a light bulb, is connected to these terminals, electrons flow from the negative terminal to the positive terminal via the conductor. This flow, or current, is due to the potential difference between the battery's terminals. The term "voltage" denotes this potential difference. Essentially, to establish an electric current, a voltage must be applied.

Common batteries come with voltages of 1.5V, 3V, 6V, 9V, or 12V, where "V" stands for "Volt." One volt signifies one unit of potential energy per unit of charge. Charges are quantified in Coulombs (C), with the typical unit being 1.0 C. Energy, on the other hand, is measured in Joules (J), commonly represented as 1.0 J. So, a 1.5 Volt battery is:

1.5 V = 1.5 J/C,

Meaning the batter can provide 1.5 Joule of energy for every Coulomb of charges passing through the terminals.

Similarly a 6V = 6 J/C provides 6 Joules of energy for each Coulomb of charge passing through the battery, providing 4 times more energy per Coulomb of charges than the 1.5V battery. In essence, a 12V battery has a positive terminal that's 12V higher in potential than the negative terminal. For every Coulomb of electrons that move between the terminals through a conductor, 12 Joules of energy is gained. This is why cars need a 12 V battery for a jump start; they require more energy than, say, a flashlight.

In addition to batteries, potential differences can be maintained using power supplies, generators, or solar panel to drive an electric current.

Electricity

Electricity, when referring to current, is defined as the flow of electric charge. Specifically, current represents the amount of charge passing through a cross-sectional area of a conductor per unit of time. Charge is measured in Coulombs (C). Thus, when 1 Coulomb of charge flows through a cross-section of a conductor in one second, this flow rate is defined as a current of one Ampere (**A**). In other words, 1 Ampere is equivalent to a flow rate of 1 Coulomb per second (1 C/s). Household electrical systems typically operate at currents ranging from fractions of an Ampere for smaller devices to several Amperes for larger appliances. For instance, a typical hairdryer might draw between 15-20 A, which can sometimes trip a circuit breaker if it draws more current than the circuit is designed to handle.

Conventional current

Electricity was discovered before electrons were identified. Early scientists defined electric current as the movement of positive charges from the positive terminal to the negative terminal when a voltage is applied. In reality, within conductors, it is the electrons that move, not positive charges. However, in solutions, positively charged ions do indeed move from the positive to the negative terminal. This convention has been preserved to this day. Typically, "electric current" refers to the movement of positive charges from a region of high potential to a region of low potential, not the flow of electrons. But in this text, we describe electric current in terms of the movement of negatively charged electrons, flowing from regions of low potential to high potential. We'll use the term "conventional current" to denote the movement of positive charges.

Heat

As you may be aware, a hair dryer produces heat. This is an effective use of electricity to generate heat for purposes such as drying clothes or cooking food. Heat is produced when electrons, moving through a conductor, collide with host atoms, causing them to vibrate. This vibration is what we perceive as heat. Some materials vibrate more intensely than others, making them better at generating heat.

Resistance and Heat.

When electrons in a solid collide with the constituent atoms, their movement is significantly hindered. In the absence of these atoms, electrons could approach the speed of light. However, when obstructed by atoms, it might take electrons several minutes to travel just one meter, making their movement more akin to drifting than speeding. This hindrance is termed "resistance," which is measured in **Ohms**, named after Georg Simon Ohm, the German physicist who formulated Ohm’s Law. The symbol for the unit Ohm is , the Greek letter omega.

Materials vary in their resistance. Greater resistance can lead to more heat generation. Due to the varying levels of resistance across materials, they are termed "resistors." Resistors can be composed of metals, carbon powder, thin films deposited on ceramics, or mixtures of conductors and ceramics, among others.

The measurement

Direct Current Vs Alternating Current

Direct current (DC) flows consistently in one direction, typical of batteries. In contrast, alternating current (AC) changes direction periodically, as is standard in household power outlets. AC is the chosen method for long-distance power distribution because of its efficiency. Meanwhile, DC is common in batteries and powers devices like laptops and smartphones. For a current to alternate directions, the terminals need to swap from positive to negative repeatedly. While batteries simply can't achieve this, specific generators are designed for the task. Inverters can also convert DC to AC. For instance, to power a TV, which runs on AC, using a car's DC power source, you'd need an inverter for conversion.

V. Ohms’ Law

Ohm's Law is a foundational concept in electronics. It describes the relationship between the conventional current (I), voltage (V), and resistance (R) of a conductor. The law asserts:

A.) The electric current passing through a resistor is directly proportional to the voltage applied across it:

means increase the voltage, the current also increases.

B.) The conventional current is inversely proportional to the resistance:

means as resistance increases, current decreases.

Combining these relationships, we get:

Conversely,

This indicates that the voltage across a resistor is the product of the current through it and its resistance.

Example 1: 10V is applied across a 100 Ohms () resistor, how much is the conventical current passing through it?

I = V/R = = 0.1 A

Example 2: 10V is applied across an unknown resistor, the current meter reads 1.0 mA passing through. What is the unknown resistance?

Rearranging the equation V = , divide both sides by I. 1.0 mA is one milliAmps

R = V/I = 10V/0.001A = 10,000

It means the large resistance resistor can seriously limit the flow of current.

VI. Simple Circuit in Series and in Parallel

Electricity is most effectively harnessed when it flows in a closed path or loop, known as a circuit. At its core, a circuit is an interconnected set of components that orchestrates the movement of electrons from one point to another. From powering electronic devices to facilitating power distribution systems, circuits are indispensable. Their complexity can range from the simple configurations found in everyday electric devices to the sophisticated setups integral to cutting-edge technologies.

A basic circuit must contain three essential components:

- A **voltage source** that provides the potential difference (or voltage) which propels the flow of electric current.

- A **circuit element** like a resistor or a bulb that utilizes the electricity.

- **Conductors or wires** that link the circuit element to the voltage source.

Consider the example depicted in Fig. 8. This simple circuit features a battery as the voltage source and a resistor. They are interconnected by wires, forming a single loop. Incorporated into this setup is a switch—a set of conductors designed to connect or disconnect the circuit. It's crucial for electricity to traverse a closed path to ensure its flow. When the switch is open, it breaks the path, preventing the flow of electricity.

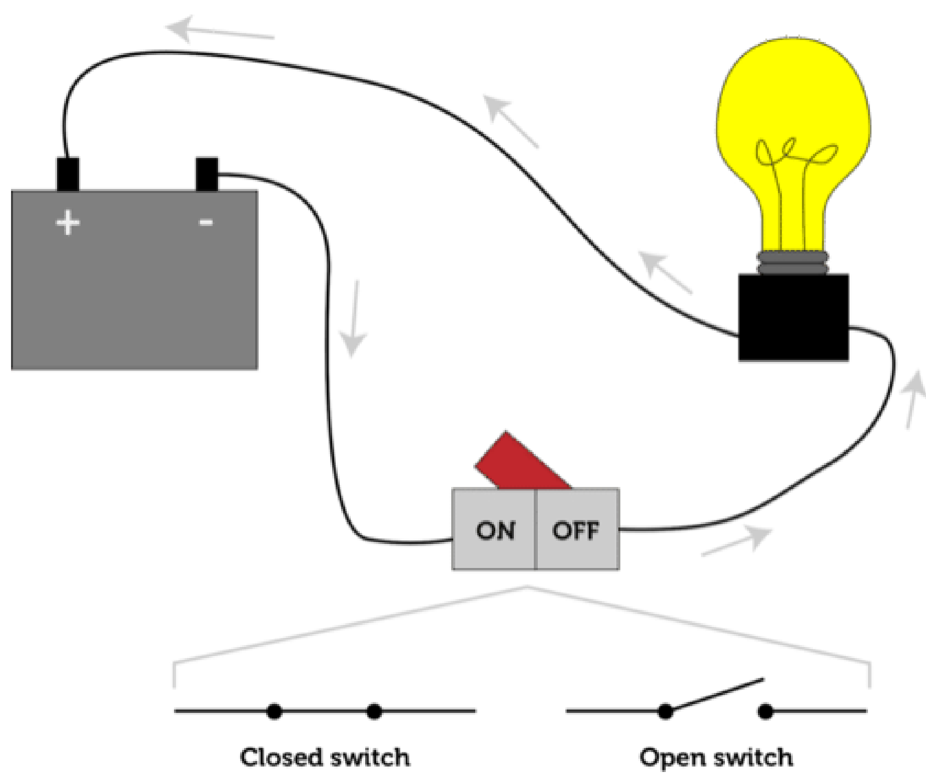

Fig. 8 A Simple Circuit. The circuit consist of a battery, a resistor (bulb), conductors, and a switch. **Credit:** Christopher AuYeung; **Source:** CK-12 Foundation; **License:** CC BY-NC 3.0

Other circuit elements

Besides resistor, there are other elements used in a circuit. They are

- **Capacitor:** a component that store and release electric charge as depicted in Fig. 3
- **Inductor:** a components that store energy in a magnetic field, basically a conducting coil.
- **Switch:** control the flow of current by opening or closing the circuit.
- **Diode:** allow current to flow in one direction only.
- **Transistor:** acts as amplifiers or switches in electronic circuits.
- **Integrated Circuits (ICs):** miniaturized circuits containing multiple components on a single chip.

Multi-loop circuit

A circuit can be constructed in multiple loops instead of a single loop, see Fig. 9

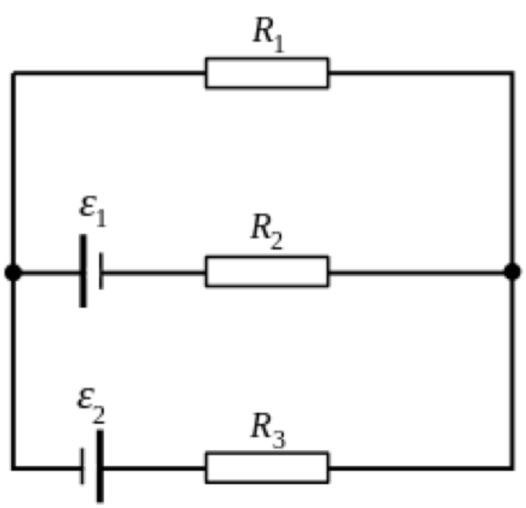

Fig. 9 Multi-loop Circuit. This circuit has there loops, 2 batteries (E1 and E2), and 3 resistors (R1, R2, R3). There are three branches of electricity current, each passing through a resistor. Each branch may have an electric current that is different from the other branches.

"In principle, there are no limits to the number of elements or batteries you can incorporate into a circuit, as long as they meet the design needs.

Circuit in Series
A circuit is said to be in series when its components are connected end-to-end, ensuring the same current flows through all of them. An example of this is a single string of Christmas lights, as shown in Fig. 10. The battery is represented two bars on the left, the long bar positive, the short bar negative. The current of electrons will travel from the minus terminal of the batter to R3, R2, and R1 back to the battery in circulation.

In such a series circuit, if one bulb goes out, the entire circuit breaks; in other words, electricity stops flowing through the loop, causing all the bulbs to go out. If the lights in our house were connected in series and one bulb went out, all the lights would go dark. To prevent this inconvenience, our homes are wired with multiple loop circuits, which are more intricate than the setup shown in Fig. 9

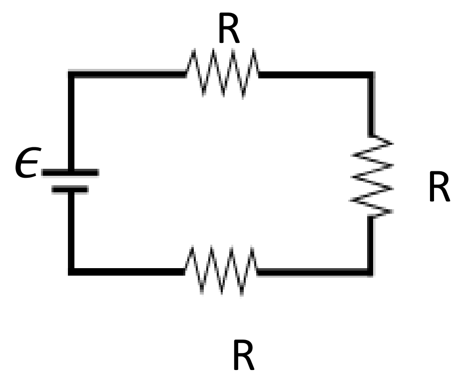

Fig. 10 A Circuit in Series. A circus in series containing a battery and resistors R1, R2, and R3, the zigzag line symbolizes a resistor. E is the

Parallel circuit. Fig. 9 is also a parallel circuit, that has 3 parallel branches. If resistors R1, R2, and R3 are light bulbs, then each branch has its own electricity. If R1 breaks, R2 and R3 can still lit. Basically our home uses parallel circuits to ensure all devices work independently.

Very Large-Scale Integration (VLSI) Circuits
Circuits above are rather simple. Modern society uses much more complex and very-scale integration (VLSI) circuits . Modern electronics, from our smartphones to space missions, heavily rely on very-large-scale integration (VLSI) circuits. These circuits pack billions of transistors onto a single chip, such as the microprocessors powering your phone. At their core, they're built upon foundational principles of circuits arranged in series or parallel configurations. By introducing an electric field through a potential difference source like a battery or capacitor, we can harness and direct the flow of electrons in these circuits. This control allows us to achieve various outcomes: generating heat, producing light, driving motors, and even powering advanced Artificial Intelligence platforms like Chat GPT. Despite

the immense complexity of VLSI circuits, their fundamental operation remains rooted in these basic electrical concepts.

Exercises:

1) An atom comprises of a) proton, b) electron c) nuclear d) all of above
2) A positive charge and a negative charge would repel each other
   a) True b) false
3) The current direction is the moving direction of positive charges
   a) True b) false
4) The electric potential is defined as the amount of electric potential energy per unit charge
   a) True b) false
5) The difference between conductors and insulators is that freely moving charges or charges are restricted.
   a) True b) false
6) The power is electric energy consumed per unit time
   a) True b) false
7) The resistance is directly proportional to the length of a resistor
   a) True b) false
8) The cross-sectional area is larger, the resistance of the resistor is smaller
   a) True b) false
9) The series connection and parallel connection both have advantages and disadvantages.
   a) True b) false
10) the resistance depends on a) substance, b) temperature, c) geometry d) all of above

Problems:

1) There are 1.6*10^24 Coulomb charges on a comb, calculate how many electrons on the comb.
2) For a device with a resistance of 10 ohm, if the voltage across is 15 v, find the current passing through it.
3) For a hair dryer with 120 voltage, and 10.0 ampere passing through it, what is the power of it?
4) There are 3 resistors with 24 ohms in series connection, what is the equivalent resistance?
5) There are 3 resistors with 24 ohm each in parallel connection, what is the equivalent resistance?
6) The conveyor belt is connected with a power source of 60 voltage, and could deliver 1000 watts, what is the current required?
7) A washing machine with 200 ohms resistance allows for 30 amperes current passing through it, what is the required voltage?
8) Calculate the electric force between a proton and an electron if they are 1.0 meter apart.
9) The electric lift could deliver 3000 watts and with a resistance of 500 ohm, what is the required voltage and current?
10) If a power source of 240 voltage is connected with 3 resistors of 60 ohms each which are in parallel connection, what is the current through each of them?