TOPIC D
FIELDS

SUBTOPIC D.2
ELECTRIC AND MAGNETIC FIELDS

Index

D. Fields / D.2 Electric and magnetic fields

The big picture

? Guiding question(s)

- Which experiments provided evidence to determine the nature of the electron?
- How can the properties of fields be understood using both an algebraic approach and a visual representation?
- What are the consequences of interactions between electric and magnetic fields?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

During a storm, lightning can be spectacular, and dangerous. Being struck by lightning can be life threatening.

How is lightning produced? What happens when lightning strikes the Earth? And why is lightning so powerful?

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Figure 1. A lightning strike.

Credit: Natalya Mamaeva, Getty Images

You may have experienced an electric shock when you touched a metal door handle. How is this similar to being struck by lightning?

Figure 2. The electric shock you get when touching a metal door handle 'looks' similar to lightning.

Credit: komta, Getty Images

In 1752, Benjamin Franklin carried out his kite experiment to try to understand the nature of lightning. He flew a kite near thunder clouds. Electric charge flowed through a conducting wire into a Leyden jar, which stored the charge.

Franklin was able to observe the flow of electric charge from the cloud to the Leyden jar, verifying the connection between lightning and electricity.

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Safety note: This is an extremely dangerous experiment and should not be reproduced.

Figure 3. Franklin's kite experiment to understand lightning.

Source "Benjamin Franklin Lightning Experiment 1752 (https://commons.wikimedia.org/wiki/File:Benjamin_Franklin_Lightning_Experiment_1752.jpg)" is in the public domain

Prior learning

Before you study this subtopic make sure that you understand the following:

- Field forces, including gravitational force, and electric charge (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).
- Electricity, electric potential difference and current (see subtopic B.5 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44361/)).
- Gravitational fields and Newton's universal law of gravitation (see subtopic D.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/)).

D. Fields / D.2 Electric and magnetic fields

Electric charge

D.2.1: Direction of forces between the two types of electric charge   D.2.3: Conservation of electric charge   D.2.5: Transfer of electric charge

Learning outcomes

By the end of this section you should be able to:

- Recognise that electric charge is quantised and conserved.

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- Explain that electric charge can be transferred between bodies by friction, contact and electrostatic induction.
- Describe how a build-up of electric charge can be discharged by grounding (earthing).

The forces acting on electric charges are gigantic, compared to the forces of gravity. But the solar system and most of our day-to-day experiences are governed by gravitational forces. The reason is that much of the time, objects are electrically neutral. Every so often, however, these charges become imbalanced. When this occurs, we are able to glimpse the incredible forces acting on positive and negative charges. In this section you will learn more about positive and negative charges, how we learned about them, and what still remains a mystery.

Quantisation and conservation of electric charge

Electric charge, q, is a property of matter (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)). Electric charge has discrete values. This means that it can only be equal to multiples of a base value, which is the charge of an electron, e (1.60×10^{-19} C). We say that electric charge is quantised**.**

We can express this charge as:

$$q = Ne$$

where N is an integer number.

The electric force acts between electric charges. The electric force is a field force because it acts at a distance (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

Charged objects have a charge imbalance – either more electrons than protons (negatively charged) or more protons than electrons (positively charged). Neutral objects have equal numbers of positive and negative charges, which cancel each other out. For a neutral object to become charged, it needs to gain or lose electrons.

Electric charge cannot be created or destroyed. It can only be moved from one place to another.

The total electric charge of an isolated system is conserved.

When we are talking about electrical circuits and charging and discharging, we say that only negative charge flows.

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Transfer of electric charge by friction

If you run a plastic comb through your hair and then hold it near small pieces of paper, the comb will pick up some of the small pieces (see section A.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-motion-id-44298/)).

When you run the comb through your hair, there is friction between the plastic teeth and your hair. Due to this friction, negative charges transfer from your hair to the teeth of the comb (**Figure 1a**):

- The comb has more negative charges than positive charges, so it is negatively charged.
- Your hair has fewer negative charges than positive charges, so it is positively charged.

The total electric charge of the system is conserved.

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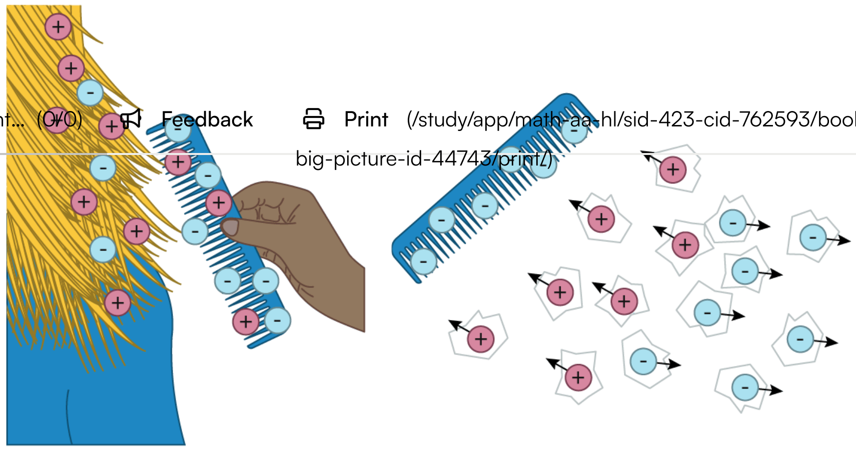

(a) (b)

Figure 1. (a) After combing, the comb has a negative charge and your hair has a positive charge. (b) The negatively charged comb repels the negative charges in the paper to the far end. Then the positively charged ends of the paper are attracted to the comb.

More information for figure 1

This image shows two illustrations side-by-side demonstrating static electricity. On the left side (a), a blue comb is being used to comb through yellow hair. The hair has pink circles representing positive charges and blue circles representing negative charges. The comb itself is covered with blue circles indicating negative charges.

On the right side (b), the comb from the first image is shown again, out of hair, surrounded by several small pieces of paper. These paper pieces have the same depiction of positive (pink) and negative (blue) charges. The negative charges are shown to be repelled to the farthest side of each piece of paper, while positive charges are closer to the comb. The negative charges on the comb and paper repel each other, causing the positive charges of the paper to attract the negatively charged comb.

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If you then bring the comb close to some small pieces of paper, the pieces of paper are attracted to the comb (**Figure 1b**). The teeth of the comb are negatively charged and the pieces of paper are neutral. The negative charges in the paper are repelled and pushed to the side of the paper farthest from the comb. This leaves the positive charges on the side of the paper nearest the comb, so the paper is attracted to the comb.

Transfer of electric charge by contact

Figure 2 shows a positively charged rod touching a neutral sphere.

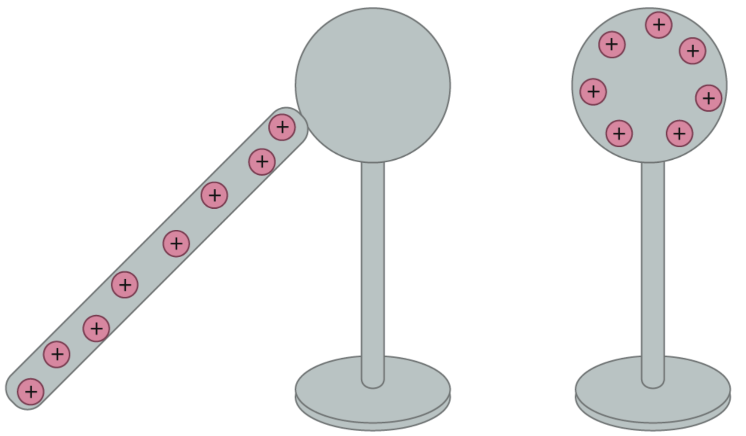

Figure 2. Electric charge transferred on contact.

More information for figure 2

The diagram shows two separate stages in the process of electric charging by contact. On the left, a positively charged rod with plus signs on it touches a neutral sphere on a stand. The neutral sphere is initially without any plus or minus signs, indicating it has no net charge. On the right side, the diagram shows the sphere after contact has been made and removed from the rod. The sphere now contains plus signs, indicating it has become positively charged due to the transfer of negative charges to the rod. Both the rod and the spheres are drawn as simple shapes without any color differentiation beyond light shading. The main components are labeled: the rod as "Charged rod," the initial sphere as "Neutral sphere," and the resulting sphere as "Charged sphere." The diagram visually represents the concept of charge transfer and conservation during the contact process.

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The negative charges in the neutral sphere are attracted to the positive charges in the rod. The negative charges are transferred from the sphere to the rod. This leaves an excess of positive charge in the sphere, and the sphere becomes positively charged. The amount of negative charges in the rod has increased, so

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the rod is now less positively charged. The total electric charge of the system is conserved.

The same process will take place if the rod is negatively charged. However, negative charges will transfer from the rod to the sphere, and the rod and the sphere will both become negatively charged.

Grounding (earthing)

When two objects are in contact, negative charges will transfer from the negatively charged object to the neutral object. This is known as electrical discharge. What if the neutral object is very large, for example, the Earth?

Negative charges will transfer from a negatively charged object to the neutral Earth, and the object becomes neutral. Because the Earth is so large, these negative charges do not have any measurable effect on the total charge of the Earth – it does not become noticeably negatively charged. However, conservation of electric charge still applies. Imagine pouring a glass of hot water into the ocean. The thermal energy of the hot water is not lost, but the overall temperature of the ocean does not measurably change.

If the object is positively charged, negative charges will transfer from the neutral Earth to the object. This again makes the object neutral. The Earth is a very large source of mobile electrons, so losing some negative charges will not have an observable effect, and the Earth remains neutral. In the same way, removing a small amount of thermal energy from the ocean does not measurably change the temperature of the ocean.

Electric current is the flow of electric charge. Electric charge can build up in electrical devices. If electric charges flow through a human body, this is dangerous and can be fatal.

To help prevent this, we often connect electrical devices to the Earth using a conducting wire. If we touch the device, any excess charge is transferred safely to the Earth and does not flow through our bodies. This is called grounding (earthing).

Clouds are made up of tiny water droplets that build up in the atmosphere. These droplets move around and bump into each other, which charges them by friction.

A cloud has a positively charged upper part and a negatively charged lower part. The negative charges are transferred through the air to other clouds or to the ground. This transfers a lot of energy, which is seen as lightning.

Lightning rods are tall conducting rods, usually on high buildings, that transfer electric charge safely to the ground if lightning strikes the building.

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Select whether each statement in **Interactive 1** is true or false.

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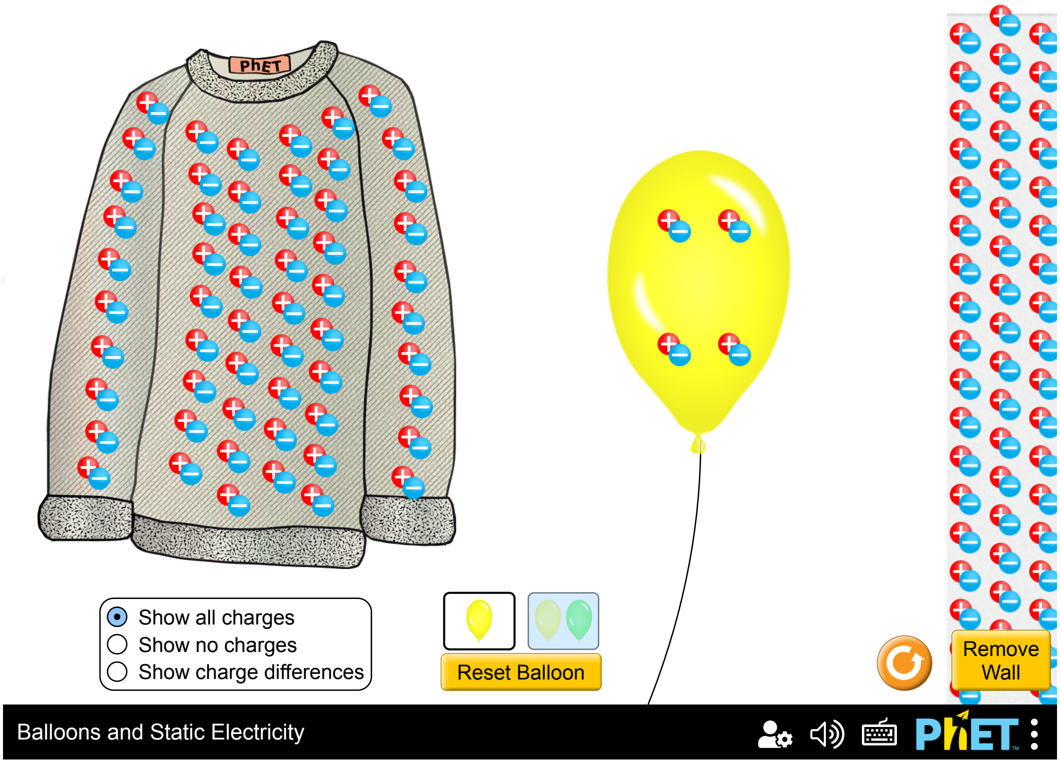
Interactive 1. Select whether each statement is true or false.

Transfer of electric charge by electrostatic induction

Look at the simulation in **Interactive 2**. When you rub the balloon with the jumper, the balloon gets negatively charged by friction, just like the plastic comb in the earlier example. (Note that in this interactive, the balloon sticks to the wall even when it is not charged. This would not actually happen in real life.)



Interactive 2. Charging a balloon.

More information for interactive 2

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Charging a Balloon is an interactive simulation that explores the principles of static electricity through the interaction of a balloon, a jumper, and a wall. Initially, the balloon and jumper have equal numbers of positive and negative charges, represented by red and blue symbols, evenly distributed to indicate electrical neutrality.

Users can manipulate the balloon by rubbing it against the jumper, and observing how negative charges transfer from the jumper to the balloon. This charge transfer leaves the jumper positively charged while the balloon becomes negatively charged. As a result, an electrostatic force emerges—opposite charges attract, drawing the balloon toward the jumper.

Users can also bring the balloon near a neutral wall to explore how charged objects influence their surroundings. The negative charges on the balloon repel the negative charges in the wall's surface, causing the wall to become slightly positively charged. This charge redistribution creates an attractive force, allowing the balloon to stick to the wall. The simulation visually represents charge movement, helping users understand how electrostatic forces shape interactions between objects. While the simulation allows the balloon to stick to the wall even when uncharged (a limitation noted in the instructions), it accurately demonstrates key electrostatic principles.

Throughout the interactive experience, users can experiment with different settings to deepen their understanding. Options include visualizing all charges, hiding charges, or displaying only charge differences. A reset button allows users to restart the process, and the ability to remove the wall enables focused exploration of the balloon-jumper interaction.

By engaging with the simulation, users gain a deeper understanding of static electricity, including charge transfer, attraction, and repulsion. The hands-on nature of the simulation reinforces key physics concepts, making abstract ideas more tangible and intuitive.

Look at the two images in **Figure 3.**

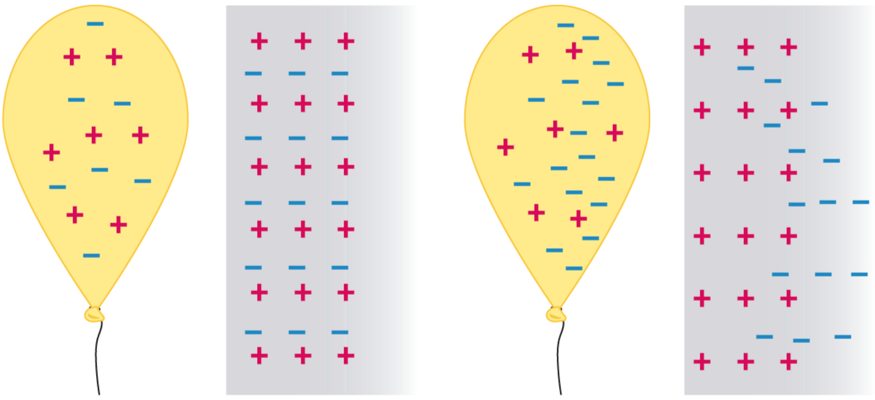

Figure 3. A neutral balloon has no effect on the wall. A negatively charged balloon temporarily induces a positive charge in the wall.

More information for figure 3

The image consists of two separate panels. The panel on the left shows a neutral balloon next to a wall. The balloon contains an equal mixture of positive and negative charges, indicated by symbols. The wall also shows an even distribution of positive and negative charges. In the panel on the right, a negatively charged balloon is depicted with a higher concentration of negative charges. This balloon induces a temporary positive charge on the wall next to it. The wall's charges are shown to realign, with positive charges moving closer to the balloon and negative charges moving further away.

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In the image on the left, both the balloon and the wall are neutral.

In the image on the right, a different negatively charged balloon approaches the neutral wall. This redistributes the charge in the wall. This happens because the negative charges in the balloon repel the negative charges in the wall, through the electric force. This part of the wall is now positively charged. The negatively charged balloon and the positively charged part of the wall experience a force of attraction. This is called electrostatic induction. Note that there is no contact between the two objects.

When the balloon moves away from the wall, the distribution of charge on the wall goes back to its original state, and the wall becomes neutral again.

What if we want the object to stay charged? **Figure 4** shows a negatively charged rod approaching a neutral sphere.

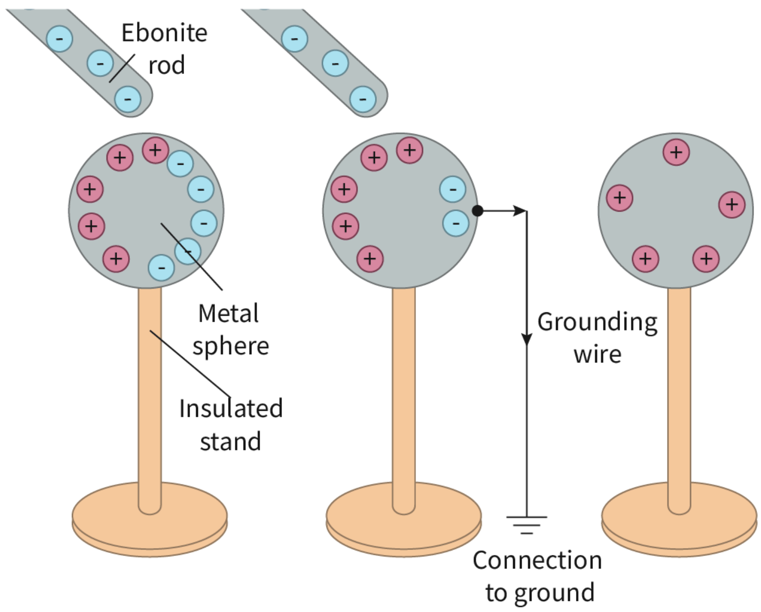

Figure 4. A grounding wire allows an induced charge to become permanent.

More information for figure 4

The diagram illustrates the process of electrostatic induction using three main components: an ebonite rod, a metal sphere on an insulated stand, and a grounding wire.

1. The image on the left shows an approach of the negatively charged ebonite rod (labeled with minus signs) towards a neutral metal sphere that is held on an insulated stand. The sphere initially contains both positive and negative charges distributed evenly.
2. The middle image shows the redistribution of charges as the negative rod comes near the sphere. The negative charges within the sphere are repelled, moving away from the rod, while positive charges cluster near the rod. A grounding wire is attached to the sphere in this phase, allowing the repelled negative charges to flow to the ground.

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3. The right image shows the final stage after the grounding wire is removed and the rod is taken away. The sphere retains an excess of positive charges, depicting the completion of the induction process, where the sphere stays permanently charged with positive charges.

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During electrostatic induction, the charge on the sphere is redistributed because the negative charges in the sphere are repelled from the rod. We ground the sphere using a grounding wire, and the negative charges are transferred to the Earth. Then we remove the grounding wire, which leaves the sphere with an excess of positive charges. When the rod is moved away, the sphere remains positively charged.

The same process will take place if the rod is positively charged, but the sphere will become negatively charged.

Table 1 shows the characteristics of each method of transferring charge.

Table 1. Methods of transferring charge and their characteristics.

Method of transferring charge	Characteristics
Friction	• There is contact and relative motion between the objects. • Negative charge transfers from one object to the other. • The two objects become charged with opposite charges.
Electrostatic induction	• There is no contact between the objects. • The charge of one object is redistributed. • If this object is connected to a grounding wire, negative charges are transferred to the Earth. • The two objects become charged with opposite charges.
Contact	• There is contact between the objects. • Negative charge transfers to the more positively charged object. • The two objects become charged with the same amount of charge.

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Worked example 1

Sphere A has a positive charge of 10 nC and sphere B has a negative charge of –5 nC. The spheres are brought into contact then separated again. What are possible values for the charge they have at the end of the process? The two spheres are electrically insulated from their surroundings.

	Sphere 1	Sphere 2
A	8 nC	—3 nC
B	8 nC	3 nC
C	7 nC	8 nC
D	7 μC	—2 μC

As the spheres are insulated from their surroundings, the total charge of the system (the two spheres) is conserved. Initially, the total charge is 10 nC – 5 nC = 5 nC . The only option that satisfies this condition is A: 8 nC + (–3 nC) = 5 nC. (Note that option D is in μC.)

Work through the activity to check your understanding of transferring electric charge.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Group activity

Watch **Video 1**, which shows some electrostatic electricity experiments.

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Video 1. Electrostatic electricity experiments.

More information for video 1

In this video, a series of science experiments are demonstrated using everyday objects, showcasing principles of physics and static electricity. Various items such as a PVC pipe, aluminum cans, beer cans, a plastic water bottle, a running faucet, a plastic comb, silver foil cupcake liners, and other household materials are used creatively to illustrate scientific phenomena.

In the first experiment, an aluminum can and a length of PVC pipe are placed on the counter, along with a white cloth on the right. The person performing the experiments wraps the cloth around one end of the pipe and rubs it several times to generate static electricity. The pipe is then placed next to the can, which makes the can roll towards the pipe. The pipe is continuously moved back and forth, and the aluminum can gets attracted to the pipe and keeps rolling towards it.

In the second experiment, two empty beer cans are placed side by side, with a small piece of white styrofoam under the second can. The tops of both cans are opened, and a red bendy straw is inserted into the pull tab of the first can. A pull tab is tied to the end of the straw and hung between the cans. The person demonstrating the experiment then rubs the PVC pipe with the cloth over the cans. As the cloth is rubbed against the PVC pipe, the string with the pull tab starts to oscillate between the cans. As the frequency of the rubbing is increased, the rate of oscillation also increases. The pull tab hits the cans and makes noises.

In the third experiment, a small plastic bottle filled with water, a pencil, and a pen are used. The pencil is placed on the top of the bottle in a balanced position. The pen is rubbed continuously with a cloth. The pen is then brought towards one end of the pencil, and the static energy from the pen attracts the pencil towards it, making the pencil move with the pen without physical contact. The pen is then used to gently move the pencil, causing it to rotate along its axis, demonstrating balance and rotational motion.

In the fourth experiment, a running faucet is shown. A plastic comb is rubbed continuously against a teddy bear made of fur fabric. The comb is then held next to the running water and moved back and forth. As the comb approaches the stream of water, the stream bends toward the comb, showcasing the effect of static electricity on water molecules. The comb is even shown to direct the flowing water into a glass tumbler.

In the fifth experiment, a bubble is shown to be formed on a surface. A PVC pipe is shown to be rubbed continuously with a cloth. The pipe is then brought towards the bubble. The bubble gets attracted to the pipe. The bubble is then manipulated with the pipe to move back and forth. Similarly, the experiment is repeated with two bubbles. The two bubbles are manipulated with the PVC pipe to move toward each other and merge to become one. The bubble is then shown to be manipulated to follow the pipe.

In the sixth experiment, a PVC pipe is charged by rubbing it continuously with a cloth. The pipe is brought over a stack of silver foil cupcake liners. The charged pipe is used to lift and flip over the cupcake liners one by one from the stack of cupcake liners. In another variation, three liners are stacked on top of a bamboo-lidded jar filled with water. The charged PVC pipe is again used to lift the liners, and one of the liners even gets glued to the pipe.

In the seventh experiment, a clear jar is displayed with its bamboo lid set aside. A hole is drilled into the center of the lid. A copper wire is taken, and one end of the wire is bent into a U shape. Two pieces of aluminum foil are

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attached to the U-shaped end of the wire. The other end of the wire is inserted in through the hole of the lid and twisted to secure it. The lid is used to cover the jar. A PVC pipe charged by rubbing continuously with a cloth is brought over the jar and moved. The aluminum foil inside the jar also moves.

In the eighth experiment, the head of a matchstick is cut off and tied with a thread. The matchstick is suspended inside a clear glass jar by taping the thread to the lid. A PVC pipe is charged by continuously rubbing against a cloth and brought over the jar. The matchstick inside the jar spins.

In the ninth experiment, salt is poured out onto the surface of a table. A balloon is rubbed on a person's head to generate static electricity. When the balloon is held over the pile of salt, it attracts and picks up some of the grains.

In the next experiment, a pencil is placed upright on a piece of clay. A square piece of paper with four creases dividing it into four quadrants is placed on the tip of the pencil. The centre of the crease sits on the tip of the pencil, balancing the piece of paper. A charged pen is brought near the paper, and it starts moving. The pen is used to manipulate the piece of paper to rotate on the tip of the pencil without the pen touching the paper.

In the final experiment, a balloon hangs from a wire against a black background. A charged PVC pipe is brought towards the balloon. The balloon moves away from the pipe. The same experiment is repeated with two balloons. A charged PVC pipe is brought between the balloons. The pipe makes the balloons move away in opposite directions.

Choose three experiments then answer the following questions as a group:

- What are the materials used?
- What happens in the experiment?
- What causes this to happen?

5 section questions

Question 1

SL HL Difficulty:

Lightning transfers a charge of 30 C from a cloud to the Earth. How many electrons have been transferred? Give your answer to 2 significant figures.

1 1.9×10^{20} ✓

2 1.875×10^{20}

3 1.9×10^{-20}

4 1.875×10^{-20}

Explanation

$q = N \times e$

$$\begin{aligned} N &= \frac{q}{e} \\ &= \frac{30}{1.6 \times 10^{-19}} \\ &= 1.875 \times 10^{20} \\ &= 1.9 \times 10^{20} \text{ electrons (2 s.f.)} \end{aligned}$$

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Question 2

SL HL Difficulty:

Object 1 is neutral. Object 2 is positively charged. Both objects are conductors. What is true about the charge of each object after the two objects come into contact?

	Charge of object 1	Charge of object 2
A	Positive	Positive
B	Negative	Negative
C	Positive	Negative
D	Negative	Positive

1 A ✓

2 B

3 C

4 D

Explanation

When the two objects are in contact, negative charges from object 1 (neutral) transfer to object 2 (positively charged). Object 1 becomes positively charged and object 2 becomes less positively charged but not neutral.

Question 3

SL HL Difficulty:

Two spheres, 1 and 2, are brought into contact.

More information

What is true about the transfer of electric charge between the spheres when they are in contact?

1 Negative charge moves from (2) to (1) ✓

2 Negative charge moves from (1) to (2)

3 Positive charge moves from (2) to (1)

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4 Positive charge moves from (1) to (2)

Explanation

Although both positive and negative particles carry charge, when charge is transferred between objects, it is always negative charges that flow. In this case object '2' is more negative (or less positive) than object '1'. The charges will move to create equal potential in each sphere (you will learn more about electric potential in D.2.6). In order to balance the charge here, negative charge flows from the more negative object to the less negative object, that is from sphere '2' to sphere '1'.

Question 4

SL HL Difficulty:

What happens during a lightning strike?

1 Charges move between the clouds and the ground. ✓

2 New charges are created from the clouds.

3 The clouds are neutral and they become charged after the lightning.

4 The ground becomes charged after the lightning.

Explanation

A lightning strike is a typical example of an electric discharge. Charges are moving, between clouds and the Earth. The total charge is redistributed. While the ground does receive an amount of negative charge, the Earth is so large and the charge diffuses so much that the ground near the lightning strike is effectively not charged.

Question 5

SL HL Difficulty:

True or false?

Charging with friction produces new charges, because we transfer energy to rub the two objects against each other.

False ✓

Accepted answers

False, F, false, f

Explanation

Electric charge cannot be created nor destroyed, and it is always conserved in a system. The energy we transfer is used to move charge from one object onto the other. This creates an imbalance between the positive and negative charge, since we redistribute the charges. However, the total amount of positive and negative charge remains the same when we consider all objects involved.

Coulomb's law

D.2.2: Coulomb's law

Learning outcomes

By the end of this section you should be able to:

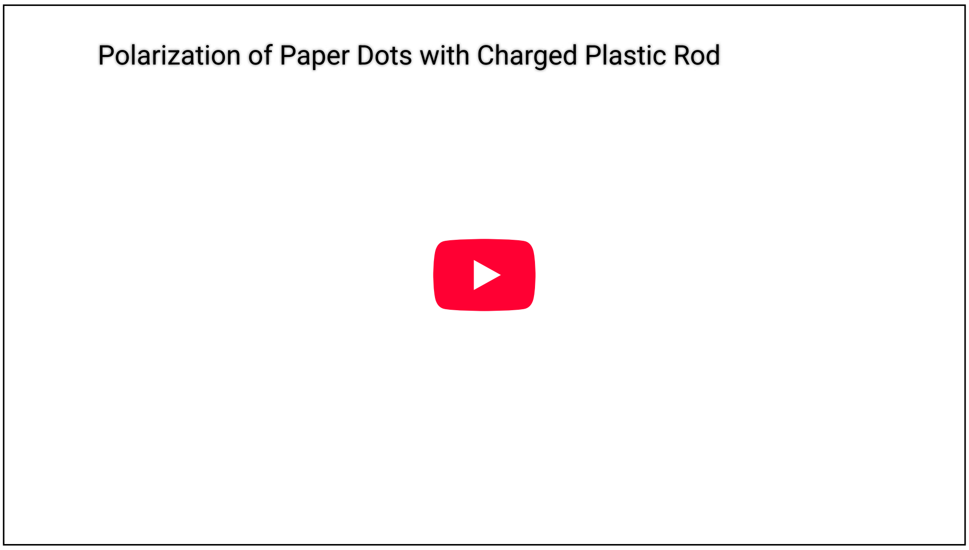
- Recognise that the electric force between electric charges can be attractive or repulsive.
- Understand Coulomb's law and use the equation:

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

- Know and use the equation for the Coulomb constant:

$$k = \frac{1}{4\pi\varepsilon_0}$$

Take an inflated balloon and rub it against your hair or some fabric. If you don't have a balloon, you could use a plastic rod like a ruler. Then, tear or find some tiny bits of paper (the left-over pieces from a hole-punch work well). Move the balloon or ruler close to the paper pieces. What happens? What is the origin of this force? **Video 1** illustrates what will happen to the paper pieces.



Video 1. Polarisation of paper dots.

The Coulomb's law equation

Like electric charges repel and unlike electric charges attract (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

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Investigate the electric force between two electric charges using the Coulomb's law simulation (https://www.physicsclassroom.com/Physics-Interactives/Static-Electricity/Coulomb-s-Law/Coulomb-s-Law-Interactive).

Try the following to see if and how the electric force between the electric charges changes:

- Move the electric charges around.
- Change the sign of the electric charges.
- Change the distance between the electric charges.
- Change the magnitude of each electric charge.
- Keeping the magnitude of the electric charges the same, determine the force for a certain distance. Double the distance and determine the new force.

Drag and drop the words in **Interactive 1** to complete the observations.

Drag the words into the correct boxes

The electric force between electric charges is ______ when the charges have the same sign and ______ when they have opposite signs.
The electric force always has a direction along the line connecting ______.
The electric force gets ______ as the magnitudes of the electric charges get larger.
The electric force gets ______ when the distance between the two electric charges gets larger.
When the distance is doubled, the electric force becomes ______ times smaller.

attractive | repulsive | larger | four | the two charges | smaller

Check

Interactive 1. Behavior of Electric Force Between Charges.

These observations are modelled by Coulomb's law, which gives the magnitude of the electric force between two point charges. A point charge is a charge whose volume is so small that it can be considered as negligible.

Table 1 shows the Coulomb's law equation.

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Table 1. The Coulomb's law equation.

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Equation	Symbols	Units
$F = k\frac{q_1 q_2}{r^2}$	F = electric force	newtons (N)
	k = Coulomb constant (8.99×10^9 N m^2 C^{-2})	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	q_1 and q_2 = magnitudes of the two point charges	coulombs (C)
	r = distance between the two point charges	metres (m)

The equation also applies to spherical charges of uniform density (or with density that varies only with radius). In that case the distance *r* is the distance between the centres of the spheres.

The equation cannot be applied to charges of other shapes – unless the distance between the charges is so large, compared with their size, that they can be considered as points.

Worked example 1

Two point charges are 3 m from each other. One charge has a magnitude of 5 μC and the other charge has a magnitude of 4 μC. Draw the two charges and the electric force between them, then determine the magnitude of the electric force.

Solution steps	Calculations
Step 1: Draw the two charges and the electric force.	 The charges are both positive, so they repel each other. The electric forces are equal and opposite to each other.

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Solution steps	Calculations
Step 2: Write out the values given in the question and convert the values to the units required for the equation.	$q_1 = 5\ \mu\text{C} = 5\times10^{-6}\ \text{C}$ $q_2 = 4\ \mu\text{C} = 4\times10^{-6}\ \text{C}$ $r = 3\ \text{m}$
Step 3: Write out the equation.	$F = k\dfrac{q_1 q_2}{r^2}$
Step 4: Substitute the values given.	$= 8.99\times10^9 \dfrac{5\times10^{-6}\times4\times10^{-6}}{3^2}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 19.98\times10^{-3}\ \text{N} = 0.02\ \text{N}\ (1\ \text{s.f.})$

The Coulomb constant

Imagine that we have two point charges a certain distance apart in air, with an electric force acting between them. If we were to put these charges in a water tank, keeping their distance the same, would the electric force remain constant or would it change?

Table 2 shows the equation for the Coulomb constant, k.

Table 2. The equation for the Coulomb constant.

Equation	Symbols	Units
$k = \dfrac{1}{4\pi\varepsilon_0}$	k = Coulomb constant (8.99×10^9 N m^2 C^{-2})	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	ε_0 = permittivity of free space (8.85×10^{-12} C^2 N^{-1} m^{-2})	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet

The Coulomb constant is dependent on ε_0 which is the permittivity of free space. This means we assume that the electric charges interact in a vacuum.

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If we want to calculate the electric force in another medium, then we need to substitute the permittivity of free space with the permittivity of that medium.

We define relative permittivity as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$

where ε_r is the relative permittivity of the medium, ε is the absolute permittivity of the medium and ε_0 is the permittivity of free space. The relative permittivities of some materials are shown in **Table 3**.

Table 3. The relative permittivities of some materials.

Material	Relative permittivity
Air	1.0005 ≈ 1
Body tissue	8
Olive oil	3
Paper	2
Water	4—88 (depends on temperature)

Study skills

The relative permittivity equation is not required by the IB. Note however that other permittivity values than ε_0 (the permittivity for a vacuum) will sometimes be used.

Worked example 2

Two point charges separated by a distance *r* in air are attracted to each other with an electric force *F*. What will the force between the point charges be if they are submerged in olive oil?

Solution steps	Calculations
Step 1: Write out the equations for Coulomb's law and Coulomb's constant.	$F = k\frac{q_1 q_2}{r^2}$ and $k = \frac{1}{4\pi\varepsilon_0}$ $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$

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Solution steps	Calculations
Step 2: Write out the equations for the electric force in air and in olive oil.	$F_{\text{air}} = \frac{1}{4\pi\varepsilon_{\text{air}}}\frac{q_1q_2}{r^2}$ $F_{\text{oil}} = \frac{1}{4\pi\varepsilon_{\text{oil}}}\frac{q_1q_2}{r^2}$
Step 3: Take the ratio of the two forces.	$\frac{F_{\text{air}}}{F_{\text{oil}}} = \frac{\frac{1}{4\pi\varepsilon_{\text{air}}}\frac{q_1q_2}{r^2}}{\frac{1}{4\pi\varepsilon_{\text{oil}}}\frac{q_1q_2}{r^2}} = \frac{\varepsilon_{\text{oil}}}{\varepsilon_{\text{air}}}$
Step 4: Substitute the values given and solve.	$\frac{F_{\text{air}}}{F_{\text{oil}}} = \frac{\varepsilon_{\text{oil}}}{\varepsilon_{\text{air}}} \Rightarrow \frac{F}{F_{\text{oil}}} = \frac{3}{1}$ $F_{\text{oil}} = \frac{F}{3}$

Making connections

Newton’s law of gravitation is covered in subtopic D.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/). There are similarities between Newton’s universal law of gravitation and Coulomb’s law.

Newton’s universal law of gravitation:

$$F = G\frac{m_1m_2}{r^2}$$

Coulomb’s law:

$$F = k\frac{q_1q_2}{r^2}$$

Compare the two equations. In what ways are they similar, and in what ways are they different? Click on ‘Show or hide solution’ to see an answer.

- Both equations describe forces between two objects. One equation describes a force between masses and the other equation describes a force between charges.

Both forces are proportional to the inverse square of the distance. (They are 'inverse square laws'.)

Both equations include a constant that affects the order of magnitude of the force. The gravitational constant (~10^{-11}) is 20 orders of magnitude smaller than the Coulomb constant (~10^{9}).

Both equations can be applied only to spherical or point objects.

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- The gravitational force is always attractive, while the electric force can be attractive or repulsive.
- Gravitational forces are affected by mass, while electric forces are affected by charge.

Work through the activity to check your understanding of Coulomb's law.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 10 minutes
- **Activity type:** Individual activity

Figure 1 shows two identical bodies connected by a spring (spring constant k = 180 N m^{-1}). The two bodies are on a horizontal surface, such as a frictionless table.

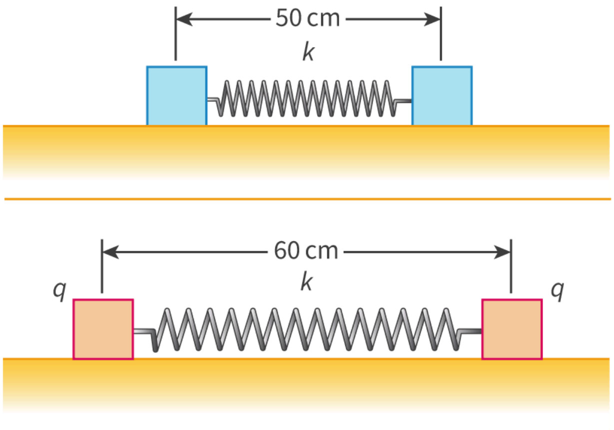

Figure 1. Two bodies are connected by a spring.

More information for figure 1

The image is a diagram depicting two scenarios of two bodies connected by a spring, placed on a horizontal surface. In the top part of the diagram, the bodies are shown with the spring at its natural length of 50 cm. The spring constant is noted as k. In the bottom part of the diagram, the two bodies are assigned positive charges q, causing them to repel and the spring to extend to a new length of 60 cm. The identical bodies are visually represented as blocks on a surface, with arrows indicating the initial and extended lengths of the spring. The spring constant k is noted in both scenarios.

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At the start, the bodies are neutral, so the spring is at its natural length, which is 50 cm. The two bodies are given an equal positive charge, *q*. The bodies repel each other so the spring extends. The new length of the spring is 60 cm. What is the charge *q* on each body? Click on 'Show or hide solution' to see the answer.

After the bodies repel each other, they are in equilibrium. Applying Hooke's law $(F = kx)$ for one of the bodies:

$$F = F_{\text{spring}}$$

$$\begin{aligned} F = k\frac{q_1 q_2}{r^2} \\ = F \\ = kx \end{aligned}$$

$$q_1 q_2 = q^2$$

$$8.99 \times 10^9 \frac{q^2}{0.6^2} = 180 \times (0.6 - 0.5)$$

$$q = \sqrt{\left(\frac{18 \times 0.6^2}{8.99 \times 10^9}\right)}$$

$q = 27\ \mu\text{C}$ for each body.

5 section questions

Question 1

SL HL Difficulty:

There is an electric force *F* between two point charges q_1 and q_2 that are separated by a distance *d*. What will the electric force be if the magnitude of one of the charges is doubled and the distance between the charges is doubled?

1 $\frac{F}{2}$ ✓

2 F

3 $2F$

4 $4F$

Explanation

$$\begin{aligned} F' &= k\frac{2q_1q_2}{(2d)^2} \\ &= k\frac{2q_1q_2}{4d^2} \\ &= \frac{1}{2}k\frac{q_1q_2}{d^2} \\ &= \frac{F}{2} \end{aligned}$$

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/electric-charge-id-46475/print/) Assign

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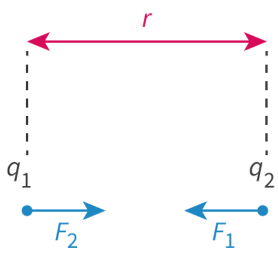
Question 2

SL HL Difficulty:

The diagram shows two point charges, q_1 and q_2:

$$q_1 = q \text{ and } q_2 = 4q$$



More information

The distance between the charges is r.

If $F_1 = F$ is the electric force exerted by q_1 on q_2, what is the electric force F_2 exerted by q_2 on q_1?

1 F ✓

2 $4F$

3 $\frac{F}{4}$

4 $16F$

Explanation

The two electric forces are an action—reaction pair, so according to Newton's third law, they are equal in magnitude but opposite in direction.

Question 3

SL HL Difficulty:

True or false?

The formula for Coulomb's law can be used for point charges.

True ✓

Accepted answers

True, T, true, t

Explanation

When point charges exert an electrostatic force at a distance, the magnitude of the force can be determined from Coulomb's law.

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view

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Question 4

SL HL Difficulty:

The force between two point charges in a vacuum at a distance *r* from each other is F. When these charges are put in an unknown medium, the force becomes $\frac{F}{5}$, if the distance is kept the same.

Which of the following statements is true?

1 The relative permittivity of the unknown medium is 5. ✓

2 The absolute permittivity of the unknown medium is 5.

3 The magnitudes of the charges increase by 5 times in the medium.

4 Coulomb's law is only valid in a vacuum, so it cannot be used to determine the electric force inside the unknown medium.

Explanation

The electric force is proportional to the Coulomb constant *k:*

$$\frac{F\ (\text{vacuum})}{F\ (\text{medium})} = \frac{k\ (\text{vacuum})}{k\ (\text{medium})} = \frac{\frac{1}{4\pi\varepsilon_o}}{\frac{1}{4\pi\varepsilon}} = \frac{\varepsilon}{\varepsilon_o}$$

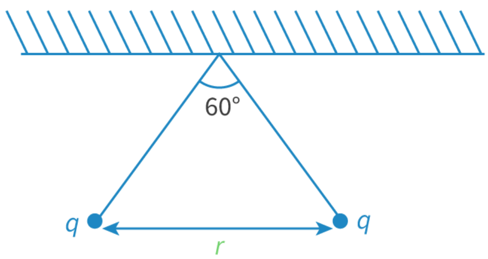
$$\frac{F\ (\text{vacuum})}{F\ (\text{medium})} = \frac{F}{\frac{F}{5}} = 5$$

$$\frac{\varepsilon}{\varepsilon_o} = 5 \Rightarrow \varepsilon_r = 5$$

Question 5

SL HL Difficulty:

The diagram shows two point charges, each with a charge of 1 μC. They are suspended from point A using two identical, non-conducting, massless strings. Each charge has a mass of 20 g. When they are at equilibrium, the angle formed by the strings at point A is 60°.



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More information

Determine the distance r between the point charges. Give your answer to 2 significant figures.

The distance is 1 0.28 m.

Accepted answers and explanation

#1 0.28

General explanation

Draw the forces on the particles.

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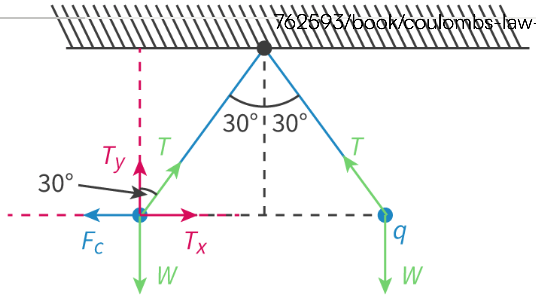

More information

The image is a diagram illustrating the forces acting on two particles in equilibrium. At the top, there is an object labeled 'A' suspended by two lines forming a symmetrical triangle. Both lines make an angle of 30 degrees with a vertical line running through 'A'. Each line has a force 'T' acting along its length. At the point where the lines meet at the middle, forces are shown with labels: 'T_y', 'T_x', and 'F_c'. The force 'T_y' is vertical, pointing upwards from the center. The force 'T_x' is horizontal, pointing left. The force 'F_c' is horizontal and points left as well. Below, each particle is subjected to an equal weight force 'W' acting downward vertically. These components visually depict the balance of forces, illustrating Newton's first law of motion.

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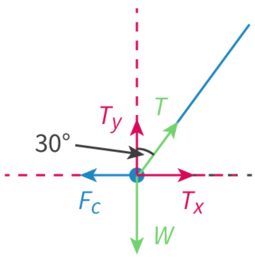
The particles are at equilibrium, so according to Newton's first law:

$$F_{\text{net}} = 0$$

Focus on one of the particles, since the forces are identical.



More information

The image is a diagram illustrating a set of vectors acting at a point. At the center, there's a blue circle with four different colored arrows pointing in various directions. The blue arrow, labeled 'Fc', points horizontally to the left. The green arrow, labeled 'W', points vertically downward. The red arrow, labeled 'T', is at a 30-degree angle pointing upward and to the right. The vector labeled 'Ty' is vertically upwards in red, and 'Tx' points horizontally to the right. The diagram indicates the angle between the green 'W' vector and the red vector 'T' as 30 degrees. The forces are identical, providing a focus for analysis.

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On the y-axis:

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$$\begin{aligned}F_{\text{net},y} &= 0 \Rightarrow T_y\\ &= W \Rightarrow T_y\\ &= mg \Rightarrow T_y\\ &= 20\times\ 10^{-3}\times 9.8 \Rightarrow T_y\\ &= 0.196\ \text{N}\end{aligned}$$

Also:

$$\begin{aligned}T_x &= T_y\times\tan 30 \Rightarrow T_x\\ &= 0.113\ \text{N}\end{aligned}$$

On the x-axis:

$$\begin{aligned}F_{\text{net},x} &= 0\ \Rightarrow F_c\\ &= T_x \Rightarrow F_c\\ &= 0.113 \Rightarrow k\frac{q\times q}{r^2}\\ &= 0.113\end{aligned}$$

$$8.99\times10^9\frac{10^{-6}\times10^{-6}}{r^2} = 0.113$$

$$r^2 = \frac{8.99\times10^{-3}}{0.113}$$

$$r = 0.28\ \text{m}\ (2\ \text{s.f.})$$

D. Fields / D.2 Electric and magnetic fields

Electric fields

D.2.4: Millikan's experiment and quantisation of electric charge D.2.6: Electric field strength D.2.7: Electric field lines D.2.8: Field line density and field strength D.2.9: Uniform electric field strength between parallel plates

Learning outcomes

By the end of this section you should be able to:

- Understand electric field strength and use the equations $E = \dfrac{F}{q}$ and $E = \dfrac{V}{d}$.
- Describe the electric field lines around a point charge, between two point charges, inside and outside a charged sphere and between parallel charged plates.
- Recognise the relationship between electric field strength and electric field line density.
- Describe Millikan's oil drop experiment.

In subtopic D.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44096/) we saw that gravitational forces could act in three dimensions, and these regions were known as gravitational fields. An important skill in Physics is recognising that some ideas are replicated across different parts of the physical world, and 'fields' is one of those concepts. All the knowledge gained about gravitational fields can be applied to electric fields, with a few novel twists! Let's find out more.

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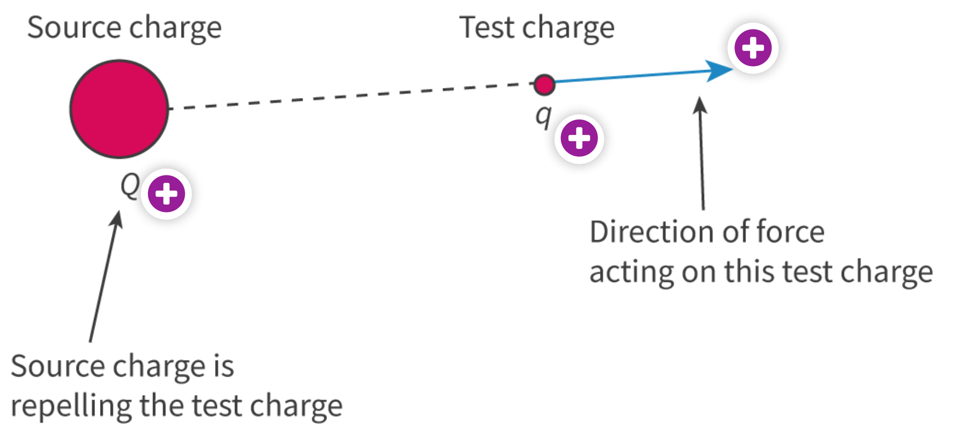
Electric field strength

Imagine we have a positive point charge Q that creates an electric field around it. This is called a source charge. In order to test how strong the electric field is we bring a small positive charge q inside the field. This is called the test charge. The test charge feels an electric force F because of the electric field around the source charge.

Click on the hotspots in **Interactive 1** to find out about the charges and the electric field.



Interactive 1. Charges and the Electric Field.

More information for interactive 1

An interactivity focuses on exploring the concept of electric field strength by illustrating the interaction between a source charge and a test charge. It presents a scenario where a positive point charge, referred to as the source charge, creates an electric field around it. A smaller positive charge called the test charge, is placed within this field to observe the effects of the electric force.

The source charge is represented by a big pink circle which is connected by dotted lines to the test charge represented by a small pink circle. The source charge is represented by "Q" and the test charge is represented by "q". There is a blue colored arrow mark starting from test source "q" with the tip of the arrow pointing away from the test source and it represents the direction of the force.

There is a text below the source charge which states "Source charge is repelling the test charge" with an arrow in between the text and "Q". There is another text below the blue-colored arrow which states "Direction of force acting on this test charge" with another arrow in between.

The interactivity has three hotspots named hotspot 1, hotspot 2, and hotspot 3, each represented by a purple circle with a plus sign inside. Clicking on these hotspots reveals more information about the sources and forces acting on the electric field.

The location of the hotspots and the text for each hotspot are as follows:

Hotspot 1 at the arrow indicating the force direction, which reads, "F, The magnitude of the electric force depends on the distance from the source charge. The direction of the electric force depends on the sign of the source charge."

Hotspot 2 near the test charge (q) which reads, "q, This is the test charge, which is used to detect an electric field. It is very small compared to the source charge."

Hotspot 3 near the source charge (Q) which reads, "Q, This is the source charge. It creates an electric field that exerts a force on other charges in the field. The source charge also feels the electric force, but we do not usually draw it. We assume that the source charge does not move."

The diagram visually represents how the source charge repels the test charge due to their like charges, and an arrow indicates the direction of the force acting on the test charge.

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We define the strength of the electric field as the force per unit charge that is experienced by a small positive test charge. The equation for electric field strength is shown in **Table 1**.

Table 1. Equation for electric field strength.

Equation	Symbols	Units
$E = \frac{F}{q}$	E = electric field strength at a certain point	newtons per coulomb (N C^{-1})
	F = electric force at this point	newtons (N)
	q = magnitude of the test charge	coulombs (C)

Worked example 1

What is the magnitude of the force experienced by a 2.6 μC charge in an electric field of 4.5 kN C^{-1}.

12 mN

$$\begin{aligned} F &= Eq \\ &= 2.6 \times 10^{-6} \times 4500 \\ &= 1.17 \times 10^{-2} \\ &= 12 \text{ mN} \end{aligned}$$

Electric field lines and electric field strength

Electric field lines are used to show the direction of an electric field. **Figure 1** shows the electric field lines for a positive point charge and a negative point charge.

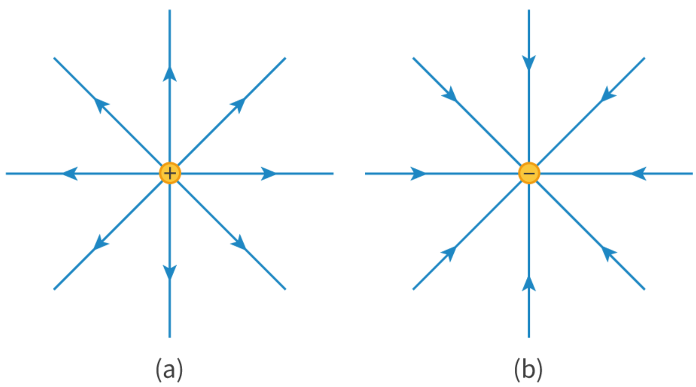

Figure 1. The shape of an electric field around a point charge.

More information for figure 1

Student view

The image features two diagrams showing electric field lines around point charges. Figure (a) depicts a positive charge with arrows radiating outward, indicating the direction of the electric field moving away from the charge. Figure (b) shows a negative charge with arrows pointing inward, indicating the electric field is directed towards the charge. Both diagrams illustrate the radial symmetry of electric field lines, which helps visualize how the field behaves at different points around the charges.

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When drawing electric field lines, we follow the following conventions:

- The field lines show the direction of the electric force on a **positive** charge. The field lines are directed radially outwards for a positive point charge and inwards for a negative point charge. The electric field is a **radial field**. A positive charge placed on a field line will move along the line in the direction of the arrow.
- The field lines are closer together (higher density) where the electric field strength is greater and further apart (lower density) where the electric field strength is weaker. Close to the point charge there are more lines per unit of area, showing that the electric field is stronger there.
- The field lines cannot cross each other. Since electric field strength is a vector quantity, two lines at the same point would add and give the total strength at this point. We cannot say that they cross at the centre, since this is where the source of the field is.

The electric field strength for the electric field around a point charge (radial field) can be written as:

$$\begin{aligned} E &= \frac{F}{q} \Rightarrow E \\ &= \frac{k\dfrac{Qq}{r^2}}{q} \Rightarrow E \\ &= k\frac{Q}{r^2} \end{aligned}$$

Worked example 2

Which diagram, A, B, C or D, best describes the change of electric field strength with distance for a point charge? Explain why.

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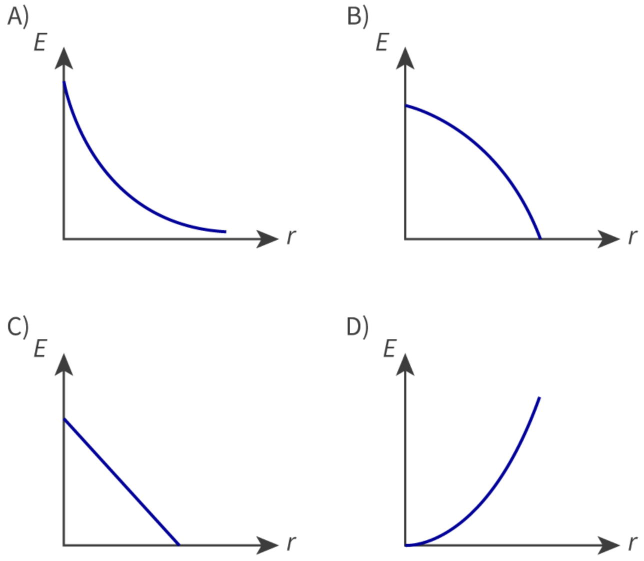

Figure 2. Electric field strength and distance.

More information for figure 2

The image displays four diagrams labeled A, B, C, and D, each showing a graph of electric field strength (E) versus distance (r) for a point charge.

Diagram A: The graph depicts a decreasing curve with a steep slope that flattens as it moves from the top left to the bottom right, indicating that the electric field strength decreases rapidly at first and then more slowly with increasing distance.

Diagram B: This graph also shows a decreasing curve but starts at a lower initial electric field strength compared to A. The curve is less steep, describing a gradual decline in electric field strength with increasing distance, from the top left to near the bottom right.

Diagram C: The graph presents a straight line with a negative slope moving diagonally from top left to bottom right, showing a consistent decrease in electric field strength proportional to distance.

Diagram D: This graph depicts an upward curve starting near the bottom left and moving to the top right, showing an electric field strength that actually increases with distance, contrary to typical expectations for a point charge.

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Electric field strength decreases as we move away from the source of the field, and electric field strength decreases less quickly further away from the source, so A is correct.

Electric field strength decreases as distance from the source increases, so D is wrong.

Student
view

The equation for electric field strength $E = k\frac{Q}{r^2}$ shows that electric field strength depends on distance squared, so the graph cannot be a straight line, so C is wrong.

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In graph B, electric field strength decreases slowly close to the source and faster further away from the source. According to the equation, it should be the other way around.

Use the simulation in **Interactive 2** to investigate the electric field lines for two point charges.

Move the positive charge into the black space. What do the electric field lines look like? Move yellow sensors into the electric field to see the electric field strength. Repeat with the negative charge.

Now move two charges into the black space and look at the electric field lines between them. Look at two positive charges, two negative charges, and a positive charge and a negative charge.

Interactive 2. Simulation of how charges and electric fields behave.

More information for interactive 2

Simulation of how charges and electric fields behave, is an interactive tool that allows users to explore the behavior of electric fields and equipotential lines generated by point charges. The black background displays a grid where charges can be placed, with arrows representing the direction and relative strength of the electric field. Users can add positive and negative charges and observe how the field lines form around them. The field vectors change dynamically based on the position and magnitude of the charges.

Users can place a single positive charge in the space and observe how the electric field radiates radially outward symmetrically, demonstrating that field lines move away from positive charges. Similarly, placing a single negative charge results in field lines pointing inward, indicating that electric fields are directed radially inwards for a negative charge. The strength of the field at different locations

Student view

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can be analyzed using yellow sensor points, which provide real-time feedback. The length of the red arrow attached to the yellow sensor point shows the magnitude of the electric field.

Adding multiple charges allows users to visualize interactions between fields. When two positive charges are placed near each other, their electric fields repel, creating a region of reduced field intensity between them. Similarly, two negative charges exhibit repulsion with field lines bending away from each other. In contrast, placing a positive and a negative charge close together forms a dipole, where field lines originate from the positive charge and curve toward the negative charge, illustrating attraction.

The length of the red arrow attached to the yellow sensor point becomes zero at certain points, it indicates that the electric field at that point is zero. A ruler feature provides distance measurements between charges, allowing users to analyze how field strength changes with distance. Additional options in the interface include toggling the electric field display, showing only direction indicators, and enabling a grid for precise placement of charges. By allowing real-time manipulation and observation, the simulation provides an intuitive way to understand fundamental electrostatic concepts. Users can experiment with charge configurations, analyze field interactions, and explore electric potential, reinforcing principles such as Coulomb's law, superposition of fields, and the nature of equipotential surfaces.

Figure 3 shows the electric field lines for two like point charges and two unlike point charges.

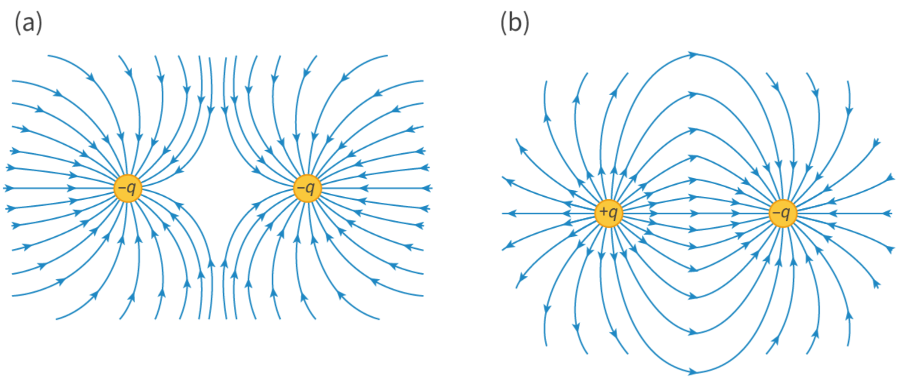

Figure 3. The electric field lines for a system of like charges (a) and unlike charges (b).

More information for figure 3

The image is a diagram illustrating electric field lines for two scenarios. On the left, labeled (a), are two like charges indicated by '-q', with each having radial lines pointing outward, showing repulsion between them. On the right, labeled (b), are two unlike charges, '+q' and '-q'. Here, the field lines originate from the positive charge and terminate at the negative charge, illustrating the attraction between opposite charges. The arrows denote the direction of the electric field.

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Consider a spherical conducting body with radius R. It is touched by a negatively charged rod and the sphere becomes negatively charged with charge Q. Where does this charge go? Does it spread throughout the sphere?

Like charges repel each other, so the charges will try to go as far away from each other as possible. The charges end up spread uniformly on the surface of the sphere.

Figure 4 shows the charges and the electric field lines.

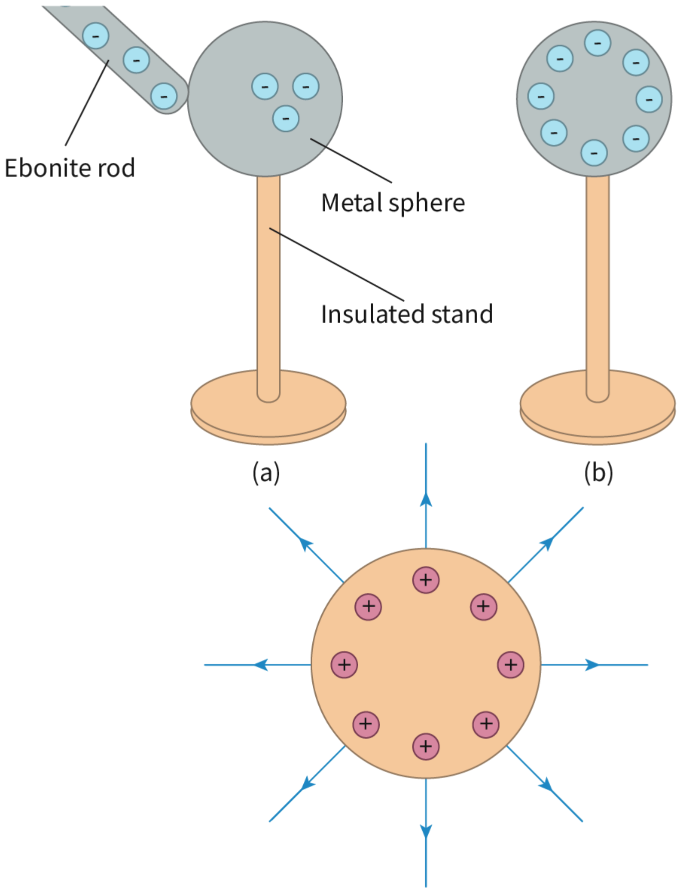

Figure 4. The charges transferred to the sphere are distributed on the surface of the sphere. The same will be true for positive charges.

More information for figure 4

This diagram illustrates the distribution of charges on a metal sphere mounted on an insulated stand. There are two main parts labeled (a) and (b), showing different stages or perspectives. In part (a), an ebonite rod is shown transferring negative charges to the sphere, resulting in a few negative charges depicted on the sphere. In part (b), the charges have redistributed evenly on the surface. Below the two stages, a cross-sectional view of the sphere is shown with positive charges on its surface and electric field lines emanating outward, indicating that the charges are only present on the exterior and not within the sphere. This visual representation emphasizes that excess charges reside on the outer surface, and the electric field inside the sphere is zero.

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Figure 4 shows you that the inside of the sphere does not contain excess charges. This tells us that the electric field strength inside the sphere is zero.

The electric field outside the sphere is similar to the electric field of a point charge.

The electric field strength at a distance *r* from the centre of the spherical body is:

$$E = 0 \text{ for } r < R$$

and

$$E = k\frac{Q}{r^2} \text{ for } r > R$$

Worked example 3

Which graph, A, B, C or D, shows the electric field inside and outside a sphere?

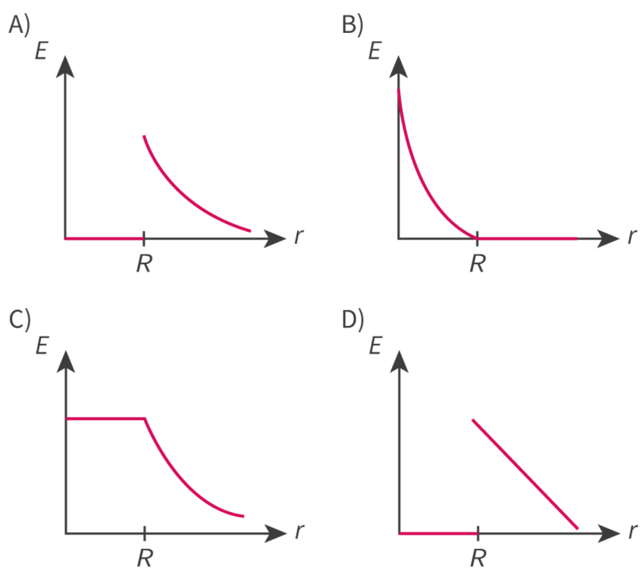

Figure 5. Graphs of *E* against *r*.

More information for figure 5

The image contains four graphs labeled A, B, C, and D, each depicting the relationship between electric field (E) and radius (r).

- **Graph A:** The Y-axis represents the electric field (E), and the X-axis represents the radius (r). The graph shows a curve starting at the origin with E decreasing non-linearly as r increases beyond a marked point R.

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- **Graph B:** The Y-axis is marked with E, and the X-axis with r. The curve descends steeply initially and then flattens out beyond R, indicating E decreases rapidly as r increases.
- **Graph C:** Similarly marked axes as others. The graph starts with a horizontal line indicating constant E up to point R, beyond which it decreases steeply.
- **Graph D:** The Y and X axes show E and r respectively. The graph shows a linear but negative slope indicating a steady decrease in E as r increases from the origin.

Each graph visualizes how the electric field varies around a sphere, with differences indicating variable behavior inside or outside the sphere.

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The electric field strength inside the sphere ($r < R$) should be zero, so B and C are wrong.

Outside the sphere, the electric field strength varies in a similar way to the electric field strength of a point source, so A is the correct option.

Figure 6 shows two parallel plates with equal and opposite charge.

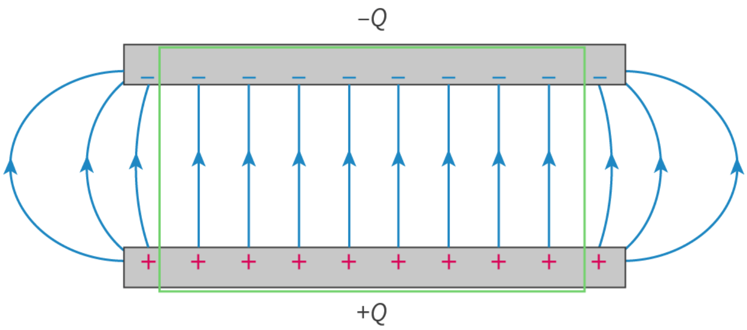

Figure 6. The shape of an electric field between two parallel plates.

More information for figure 6

The diagram illustrates the electric field between two parallel plates with equal and opposite charges. The top plate is labeled as having a negative charge (-Q), and the bottom plate is labeled as having a positive charge (+Q). Between the plates, inside a green rectangle, are multiple parallel blue arrows pointing from the positive plate to the negative plate. These arrows represent the electric field lines, which are straight and evenly spaced, indicating a uniform field between the plates. Outside the green rectangle, the field lines curve, showing the non-uniform field outside the region between the plates.

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Let us look at the area inside the green rectangle. The electric field lines are parallel to each other at equal distances from each other.

- The direction of the electric field lines is from the positively charged plate to the negatively charged plate. If both plates are positive (or both negative), the field lines go from the most positive plate to the least positive plate.
- The electric field lines have the same density at all points, so the electric field has the same electric field strength at all the points between the plates within this area.

A field that has a constant field strength at all points is called a uniform field.

The electric field strength between two parallel plates can be determined using the equation in **Table 2**.

Table 2. Equation for electric field strength.

Equation	Symbols	Units
$E = \frac{V}{d}$	E = electric field strength between the plates	newtons per coulomb (N C^{-1}) or volts per metre (V m^{-1})
	V = electric potential difference between the plates	volts (V)
	d = distance between the plates	metres (m)

Worked example 4

A fly catcher has two parallel metal electrodes, one at 20 kV, the other –20 kV, separated by 2.0 cm. What is the electric field strength in between the two electrodes?

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Solution steps	Calculations
Step 1: Write down known values.	$V = 20\text{ kV} - (-20\text{ kV}) = 40\text{ kV}$ $d = 2\times10^{-2}\text{ m}$
Step 2: Select an equation and input values.	$E = \frac{V}{d} = \frac{40\times10^{3}}{2\times10^{-2}}$
Step 3: Give answer with units to the correct number of significant figures.	$E = 2\times10^{6}\text{ Vm}^{-1}$

Note that at the edges of the plates, the electric field has a different pattern. The electric field in these areas is not uniform, since the field lines are not parallel and they do not have the same density at all points. This is called the **edge effect**.

Think back to The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/). We can think of the clouds and the Earth as forming a system that resembles parallel plates (**Figure 7**). The electric potential difference between the clouds and the ground can be in the order of hundreds of million volts.

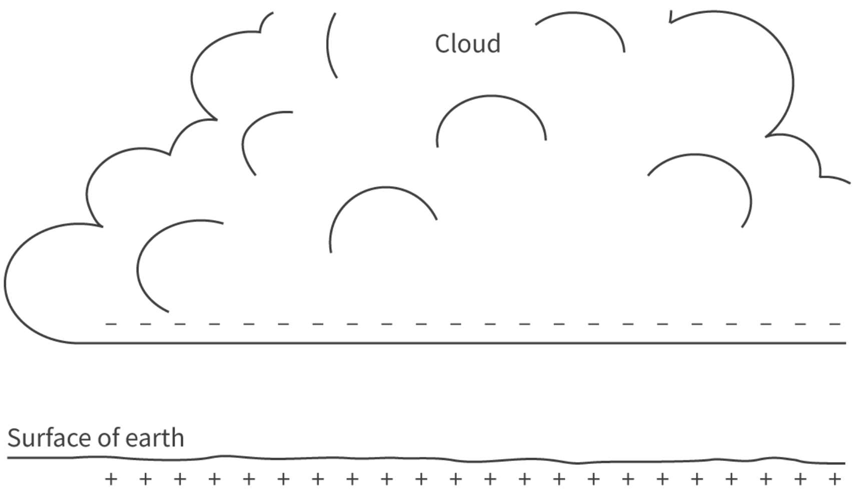

Figure 7. The electric field between clouds and the ground is similar to the one between parallel plates with opposite charge.

More information for figure 7

The image is a diagram illustrating the electric field between clouds and the ground, similar to the field between parallel plates with opposite charges. The top part of the image shows a cloud labeled as "Cloud," with its base represented by a dashed line indicating negative charge. Below, the "Surface of earth" is labeled, depicted with plus signs lined across it to indicate a positive charge. The

Student view

illustration visually presents how an electric field forms between the two, analogous to the field produced between oppositely charged parallel plates. Arrows within the electric field region indicate the direction of flow from the cloud to the Earth's surface.

[Generated by AI]

Making connections

The gravitational field close to the surface of the Earth is assumed to be uniform. This is why you apply g = 9.81 m s^{-2} in all kinds of situations. Visualising the gravitational field as we would see it from a point in space, it looks like the electric field of a negative point charge.

However, when we zoom in , the electric field lines are almost parallel to each other (**Figure 8**).

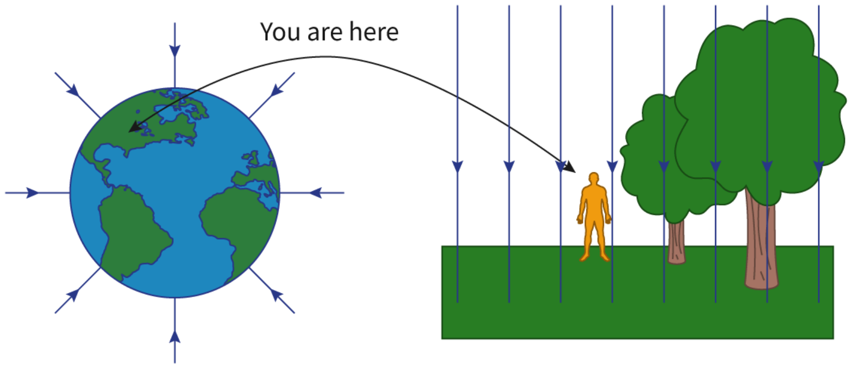

Figure 8. The electric field lines around the Earth are radial when considered from far enough away, but parallel to the ground when you zoom in.

More information for figure 8

The diagram illustrates the electric field lines around Earth, showing how they are radial when observed from a distance but appear nearly parallel to the ground when viewed close up. On the left side, Earth is depicted with radial electric field lines extending outward. On the right side, a close-up view shows these lines as parallel, with additional features including a human figure standing on a grassy ground and a tree. The lines are shown as arrows pointing from the top toward the ground, indicating the direction of the electric field.

[Generated by AI]

Worked example 5

The diagram shows two parallel plates separated by a distance d = 40 cm. There is an electric potential difference of 200 V between the plates.

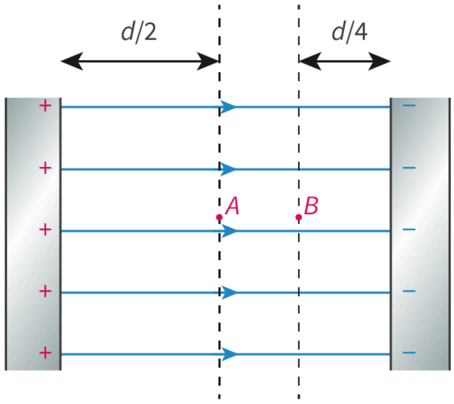

Figure 9. Two oppositely charged parallel plates.

More information for figure 9

The diagram illustrates two parallel plates positioned vertically. The left plate is positively charged, indicated by red '+' symbols, and the right plate is negatively charged, shown by blue '-' symbols. The plates are separated by a distance labeled 'd'. Between the plates, there are several horizontal blue arrows pointing from the positive to the negative plate, indicating the direction of the electric field. Two points, A and B, are marked within this field. Their positions are specified with respect to the plates: point A is located at a position labeled 'd/2' from the left plate, and point B is labeled 'd/4' further to the right of A towards the negative plate.

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Determine the magnitude of the electric force on an electron at point A and at point B.

$$\begin{aligned} E &= \frac{V}{d} \\ &= \frac{200}{0.4} \\ &= 500\ \text{NC}^{-1} \end{aligned}$$

$$E = \frac{F}{q}$$

$$F = E \times q$$

The charge is equal to the charge of an electron:

$$e = -1.6 \times 10^{-19}\ \text{C}$$

Magnitude of the force (ignoring the minus sign on the charge):

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$$F = 500 \times 1.6 \times 10^{-19}$$
$$= 8 \times 10^{-17}\ \text{N}$$

The force will be the same at both points. The field in this area between the two plates is uniform, so the field strength is constant, which means that the force on a given charge will be constant.

Millikan's oil drop experiment

In 1909, Millikan and Fletcher carried out the oil drop experiment, which provided evidence for the quantisation of electric charge.

Millikan created many small, lightweight oil drops, and focused on one of them, observing it with a microscope. He let this drop fall in air until it reached its terminal velocity. Equating the gravitational force on the drop with the force of air resistance, he could calculate the mass of the drop. **Figure 10** shows the oil drop experiment.

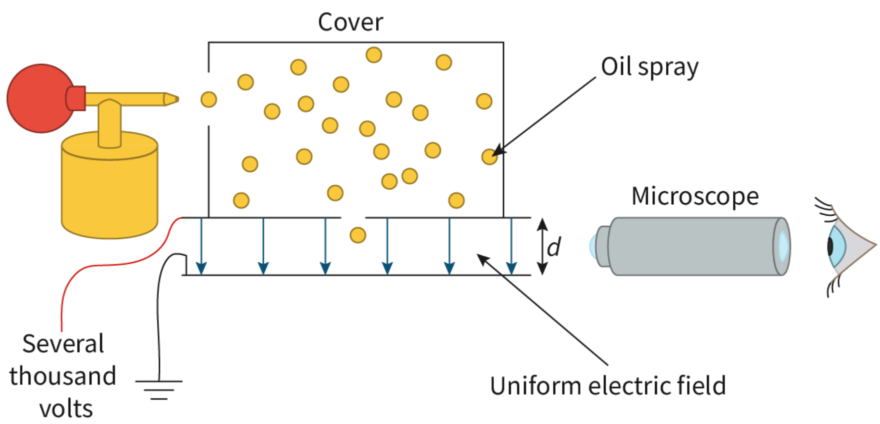

Figure 10. The oil drop experiment.

More information for figure 10

The diagram illustrates the setup of Millikan's oil drop experiment. It shows an oil spray apparatus on the left emitting small, spherical oil droplets inside a chamber with a cover. The chamber has arrows pointing downward, indicating a uniform electric field. Below the chamber is a label indicating 'uniform electric field'. There is a labeled distance 'd' between the plates creating the electric field. The diagram is annotated with labels pointing to each component: 'Cover', 'Oil spray', 'Microscope', 'Uniform electric field', and 'Several thousand volts' for the electric field. On the right, a microscope and an eye are depicted, showing the observation setup. The microscope line of sight is aimed at one of the oil droplets inside the chamber. The chamber is connected to a voltage source marked as 'Several thousand volts', indicating the electric field power source needed for the experiment.

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Nature of Science

Aspect: Experiments

The ingenious design of the Millikan oil drop experiment is an example of physicists using their creativity and problem-solving skills to devise an experiment to test a particular hypothesis. Many experiments that are done in schools are done with specialist equipment which is designed to test exactly the thing being studied, but when scientists are formulating their initial theories, they must also design and in some cases manufacture the necessary equipment to test their theory, as well as come up with the theory and the methodology.

Millikan allowed the drop to enter a region of a uniform electric field created by two oppositely charged parallel plates. By varying the electric potential difference between the plates, he made the drop stand still. By equating the electric force with the gravitational force on the drop, he was able to determine the charge of the drop.

Repeating this process for many oil drops with different masses, Millikan concluded that the charge on all the drops was an integer multiple of a specific value. This is evidence that charge is quantised. The base value is the charge of one electron, e. Millikan was able to determine the charge of an electron to within 1% of today's accepted value.

Worked example 6

A negatively charged oil drop of mass $m = 5.0 \times 10^{-14}$ kg is at rest between two oppositely charged parallel plates. The electric potential difference between the plates is $V = 2.0$ kV, and the distance between the plates is $d = 1.0$ cm.

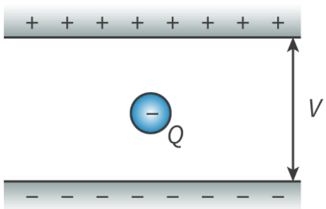

Figure 11. An oil drop at rest between two oppositely charged parallel plates.

More information for figure 11

The diagram illustrates a negatively charged oil drop positioned at rest between two parallel plates. The plate on the top has a positive charge, represented by a series of plus signs, while the plate on the bottom is negatively charged, indicated by minus signs. The oil drop is depicted as a blue circle in the center, marked with a negative sign and labeled 'Q' to represent its charge. An arrow labeled 'V' points from the bottom plate to the top plate, signifying the electric potential difference between the plates.

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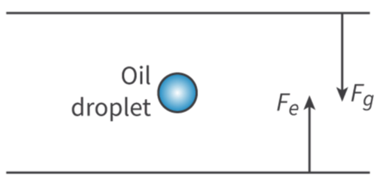
Determine the charge of the oil drop, and estimate the number of excess electrons the oil drop contains. (Assume buoyancy is negligible.)

Solution steps	Calculations
Step 1: Identify and draw the forces on the oil drop.	
Step 2: Write down expressions for the electric force and the gravitational force.	Electric force: $F_e = E \times q$ and $E = \frac{V}{d}$ $F_e = \frac{V}{d}q$ Gravitational force: $F_g = mg$
Step 3: Apply Newton's 1st law.	Because the oil drop is at rest: $F_{\text{net}} = 0$ $F_e = F_g$ $\frac{V}{d}q = mg$
Step 4: Substitute the values given.	$\frac{2000}{0.01}q = 5.0 \times 10^{-14} \times 9.8$
Step 5: Calculate the charge and write it with the appropriate unit.	$q = 2.45 \times 10^{-18}\ \text{C}$
Step 6: Estimate the number of excess electrons.	$\frac{q}{e} = \frac{2.45 \times 10^{-18}}{1.6 \times 10^{-19}}$ $= 15.3\ (3\ \text{s.f.})$ ≈ 15

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Although we ignored buoyancy in the worked example above, buoyancy is not negligible in the oil drop experiment, and Millikan allowed for it in his calculations. Why does neglecting buoyancy give a result that is higher than the actual charge on the drop?

Ignoring the upwards force of buoyancy causes an overestimate of the upwards electrostatic force on the drop. As a result, the drop appears to be more charged than it really is.

Work through the activity in the next section to check your understanding of the electric field between uniform parallel plates.

5 section questions

Question 1

SL HL Difficulty:

The electric field strength created by a point charge *Q* has a magnitude *E* at a distance *r*. At what distance from the source does the electric field strength reduce to half its original magnitude *E*?

1 $\sqrt{2}r$ ✓

2 $2r$

3 $4r$

4 $\frac{r}{2}$

Explanation

The electric field strength for a point charge is given by:

$$E = k\frac{Q}{r^2}$$

If r' is the distance where the field strength reduces to half its original magnitude, then:

$$\frac{E}{2} = k\frac{Q}{r'^2}$$

$$\begin{aligned}\frac{E}{\frac{E}{2}} &= \frac{k\frac{Q}{r^2}}{k\frac{Q}{r'^2}} \Rightarrow 2\\ &= \frac{r'^2}{r^2} \Rightarrow r'\\ &= \sqrt{2}r\end{aligned}$$

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view

Question 2

SL HL Difficulty:

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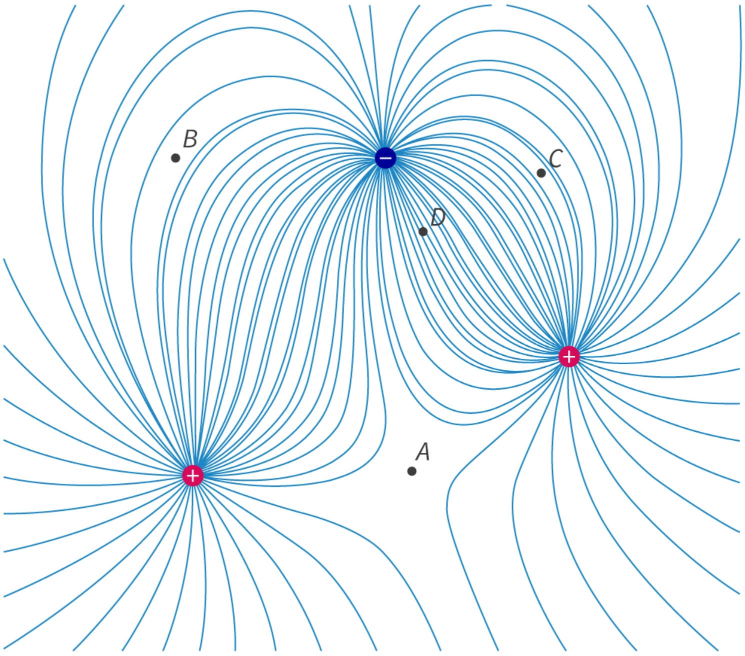
The diagram shows the electric field lines for three point charges.



More information

At which of the points, A, B, C or D, is the strength of the electric field the greatest?

1 D ✓

2 A

3 B

4 C

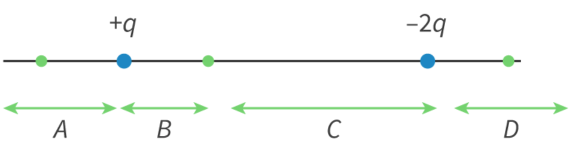
Explanation

The density of the electric field lines shows the strength of the field. At D, the lines are the most dense, so the electric field is the strongest here, compared to A, B and C.

Question 3

SL HL Difficulty:

Two charges are oppositely charged with $+q$ and $-2q$ respectively.



More information

Student view

In which area, A, B, C or D, could the total electric field strength be zero?

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1 A

2 B

3 C

4 D

Explanation

In order for the total electric field strength to be zero, the electric field strength vectors from the positive and the negative charges need to be equal and opposite.

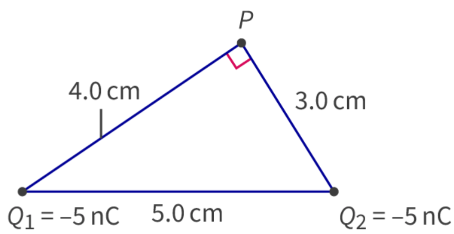
At B and C, the directions of the two electric fields are to the right. The two vectors sum to the right.

At A and D, the directions of the electric fields are in opposite directions. D is closer to the charge with the greater magnitude and further away from the charge with the smaller magnitude. The electric field strength from the negative charge is larger than the electric field strength from the positive charge. At A, the two vectors are opposite to each other but can also be equal, since A is closer to the weaker charge and further away from the stronger charge.

Question 4

SL HL Difficulty:

Two point charges are 5.0 cm from each other. They each have a negative charge of (—)5.0 nC. Point P forms a right-angled triangle with the two point charges, with the right angle at P.



More information

Determine the magnitude of the resultant electric field strength at point P. Give your answer to an appropriate number of significant figures.

The total electric field strength is 1 57000 ✓ N C^{-1}.

Accepted answers and explanation

#1 57000

57 000

57,000

Student view

General explanation

The total electric field strength at point P is the result of two field strengths, one from each source.

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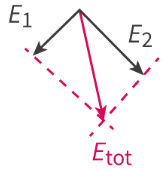

More information

The image is a vector diagram illustrating the relationship between two electric field vectors, labeled E1 and E2, and their resultant vector, Etotal. E1 and E2 are represented as arrows pointing towards the intersection point, forming an angle between them. The resultant vector, Etotal, is depicted as a red dashed arrow pointing downward from the intersection, completing the triangle. The background suggests that these vectors are part of a physics question related to electric field strength and vector addition. No specific values or angles are provided, only the vector labels are visible.

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$$
\begin{aligned}
E_1 &= 8.99\times10^9 \frac{5\times10^{-9}}{\left(4\times10^{-2}\right)^2} \\
&= 28093.75\ \mathrm{N\ C^{-1}}
\end{aligned}
$$

$$
\begin{aligned}
E_2 &= 8.99\times10^9 \frac{5\times10^{-9}}{\left(3\times10^{-2}\right)^2} \\
&= 49944.44\ \mathrm{N\ C^{-1}}
\end{aligned}
$$

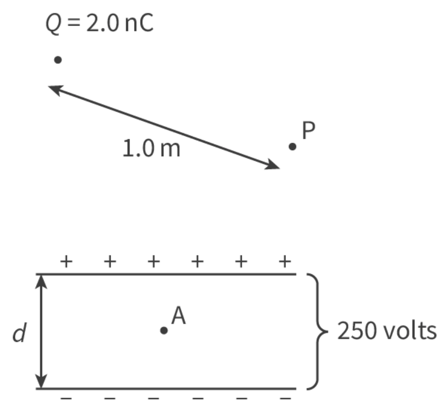
$$
\begin{aligned}
E_{\text{tot}} &= \sqrt{{E_1}^2 + {E_2}^2} \\
&= \sqrt{28\,093.75^2 + 49\,944.44^2} \\
&= 57\,303.59\ \mathrm{N\ C^{-1}} \\
&= 57\,000\ \mathrm{N\ C^{-1}}\ (2\ \text{s.f.})
\end{aligned}
$$

Question 5

SL HL Difficulty:

An electric field is created around a point charge with a charge of Q = +2.0 nC. Point P is at a distance of 1.0 m from the point charge.

Determine the distance, d, between two parallel plates, which have an electric potential difference of 250 V, so that the electric field strength at point A between them is equal to the electric field strength at point P. Give your answer to an appropriate number of significant figures.



More information

The distance should be 1 14 ✓ m.

Student view

Accepted answers and explanation

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#1 14

General explanation

Electric field strength at P:

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{8.99\times10^9 * 2\times10^{-9}}{1^2} \\ &= 17.98 \text{ N C}^{-1} \\ E &= \frac{V}{d} \end{aligned}$$

so:

$$\begin{aligned} d &= \frac{V}{E} \\ &= \frac{250}{17.98} \\ &= 13.9 \\ &\simeq 14 \text{ m (2 s.f.)} \end{aligned}$$

D. Fields / D.2 Electric and magnetic fields

Activity: Capacitors

D.2.9: Uniform electric field strength between parallel plates

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view

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Capacitors are used to store charge, and thus electric energy, for short amounts of time. Capacitors have two charged plates with a uniform electric field between them (**Figure 1**).

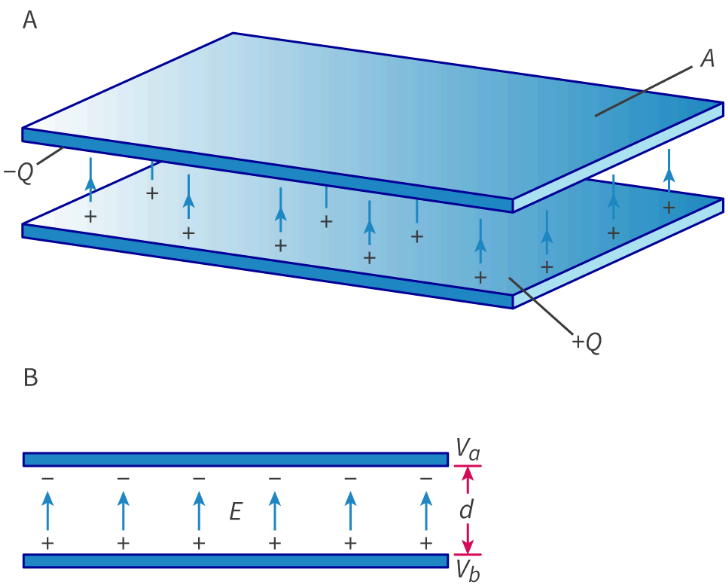

Figure 1. Diagram of capacitors.

More information for figure 1

The diagram illustrates a basic capacitor with two parallel plates labeled as A. The top plate has a negative charge indicated by "−Q" and the bottom plate has a positive charge indicated by "+Q". Between these plates, small plus and arrow symbols display the uniform electric field direction from positive to negative. Below this, a side view of the capacitor shows the distance between the plates marked as "d" with voltages "V_a" and "V_b" at the top and bottom, respectively. The electric field is represented by "E" between the plates.

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(Note that an understanding of capacitors and capacitance is not required in the IB physics course, however this is a good example of charges on parallel plates)

A uniform electric field is created $\left(E = \frac{V}{d}\right)$ between the plates. This electric field is created because of the accumulation of charges on each plate.

Student view

Use the simulation in **Interactive 1** to explore how capacitors work. Note that the space between the plates is empty. The battery provides the electric potential difference that drives the charges to the two plates. Capacitance is the quantity that describes how much charge can be stored on the plates for a given electric

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potential difference between them.

1. Select all the boxes for ‘View’ and ‘Meters’.
2. Put the negative terminal (black) of the voltmeter on the bottom plate, and the positive terminal (red) on the top plate.
3. The battery is at 0 V. Is there any charge on the plates? Is there an electric field?
4. Move the battery slider up (positive potential difference) and see how the following quantities vary:
    - capacitance
    - plate charge
    - stored energy.
5. Move the battery slider down (negative potential difference) and see how the quantities above change.
6. Calculate the electric field strength for each electric potential difference.
7. Record four sets of values using a table like **Table 1**.

Table 1. Example results table.

Electric potential difference, *V*	Capacitance, *C*	Plate charge, *Q*	Stored energy, E_p	Electric field strength, *E*

- What do you observe about the capacitance when you change the electric potential difference?
- The relationship between capacitance, charge and electric potential difference is $C = \frac{Q}{V}$. Find the capacitance for each electric potential difference using this equation. Do the values match the capacitances given in the simulation?
- Calculate the energy stored for each electric potential difference using the equation:

$$E = \frac{1}{2}QV$$

Do the values match the stored energies given in the simulation?

D. Fields / D.2 Electric and magnetic fields

Magnetic fields

D.2.10: Magnetic field lines

Learning outcomes

By the end of this section you should be able to:

- Describe the magnetic field lines around a bar magnet, a current-carrying wire, a circular coil and an air-core solenoid.
- Determine the direction of the magnetic field based on the direction of current in a current-carrying wire using the right-hand rule.

Student view

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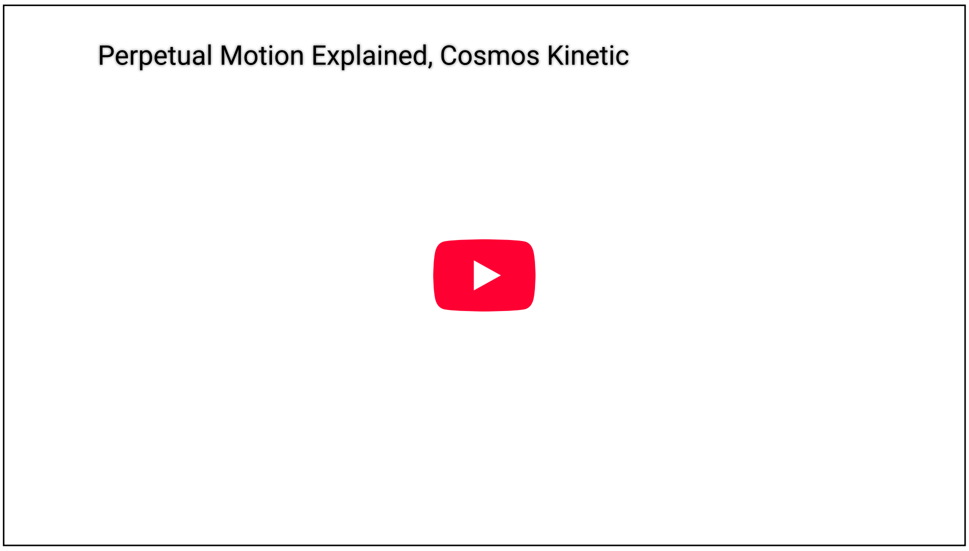
Some desk toys are advertised as ‘perpetual motion toys’ (**Video 1**). If you give an initial push to this toy, it will keep moving for a long time. How is this achieved? Why does the toy not lose energy due to air resistance?



Video 1. Perpetual motion toys.

More information for video 1

The video shows a desk toy swinging gently after being given an initial push. The toy has a metallic structure with 3 rings and 3 orbiting spheres around a central point. It seems like the toy keeps moving on its own for a long time, which gives the impression of a "perpetual motion" machine. As the video continues, it reveals the secret behind this endless motion—a magnet hidden inside the base of the toy. This magnet is key to how the toy works.

The magnet creates a magnetic field, which can push or pull on the metal parts of the toy without any physical contact. This invisible force adds small amounts of energy to the toy at just the right time to keep it spinning. This is why the toy doesn’t seem to slow down due to air resistance or friction—the magnetic field keeps giving it little boosts to make up for any lost energy. The toy actually needs a battery to power this system, so it isn’t truly a perpetual motion device, but it cleverly uses physics to keep going.

Later in the video, you see the toy spinning in a darker setting, and laser lights are used to show its continuous movement. The lights make the motion even more noticeable, helping to track how the parts rotate smoothly and steadily. This part of the video shows how consistent the motion looks thanks to the magnetic support.

Overall, this toy is a fun and smart demonstration of magnetic force, energy transfer, and motion. It shows how magnets can apply forces at a distance and how small amounts of energy can keep something moving, balancing out the effects of resistance in the environment.

The answer lies in a hidden magnetic field that pulls and pushes the metal parts. The toy needs a battery for it to work. Magnets, like electric charges, can exert forces at a distance, through magnetic fields (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Magnetic field lines

Magnets can be permanent magnets, such as bar magnets, or temporary magnets, such as electromagnets. Magnets always have a north pole and a south pole (see section A.2.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/field-forces-id-44733/)).

Figure 1 shows the magnetic field lines around a bar magnet.

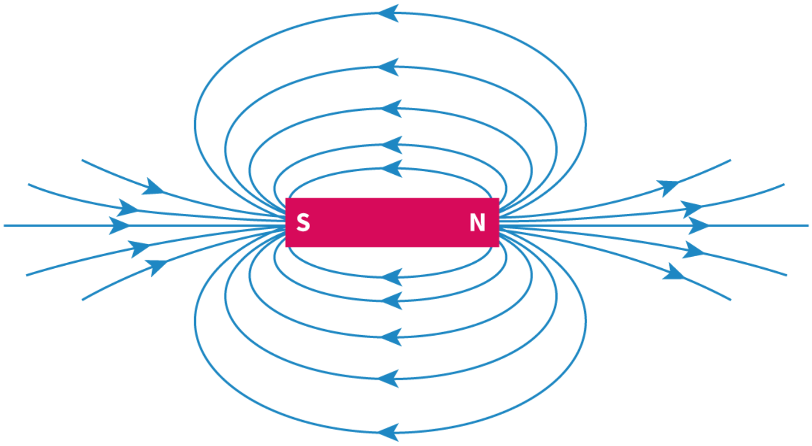


Figure 1. Magnetic field around a bar magnet.

More information for figure 1

The diagram illustrates the magnetic field lines surrounding a bar magnet, represented by a rectangular box. The magnet is labeled with 'S' for the south pole on the left and 'N' for the north pole on the right. Curved lines, symbolizing magnetic field lines, originate from the north pole and curve around to enter the south pole, forming closed loops. These lines are evenly spaced and demonstrate the direction of the magnetic field from north to south externally and continue through the magnet internally. Arrows on the field lines indicate their direction from north to south outside the magnet, emphasizing the concept of closed loops. The diagram visually depicts the nature of magnetic fields as continuous loops, underlining that these fields do not start or stop anywhere along the path but only change direction at the poles.

[Generated by AI]

The magnetic field lines originate from the north pole of a magnet and are directed towards the south pole of the magnet. This means that the magnetic field lines always have a closed shape, starting and ending on the poles of the magnet. In other words, they form closed loops.

As with electric field lines, the density of the magnetic field lines shows the strength of the magnetic field and the field lines cannot intersect.

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/activity-capacitors-id-46478/print/) Assign

When a current flows in a straight wire, a magnetic field is created around it. The magnetic field is there for as long as the current is flowing. **Figure 2** shows the magnetic field lines for a current-carrying wire.

Student view

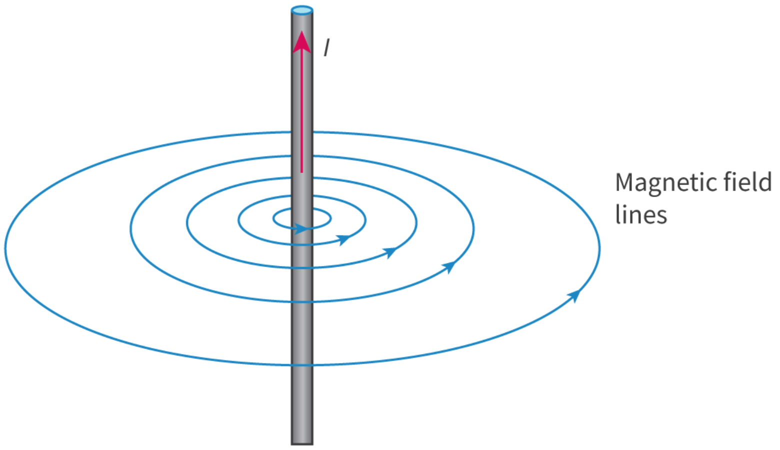


Figure 2. Magnetic field around a straight wire.

More information for figure 2

This image is a diagram illustrating the magnetic field lines around a straight, vertical wire carrying an electric current. The wire is depicted in gray and extends vertically from the bottom to the top of the image. Surrounding the wire are a series of concentric circles representing magnetic field lines. These circles are thinner and more closely spaced near the wire, indicating a stronger magnetic field, and become wider and spaced farther apart as they move away from the wire, indicating a weaker magnetic field. The field lines are drawn with arrows indicating the circular direction around the wire. A label on the right side reads "Magnetic field lines."

[Generated by AI]

The magnetic field lines are circular. They are more dense close to the wire and less dense further away from the wire. This means that the magnetic field becomes weaker as you increase the distance from the wire.

Use the simulation in **Interactive 1** to explore how changing the magnitude and direction of the current affects the magnetic field lines. Drag the black slider to vary the current.

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Interactive 1. Explore how the current in a wire and its direction affect the magnetic field around the wire.

Credit: Chris Hamper

More information for interactive 1

The interactive simulation visually represents how an electric current influences the magnetic field lines around a current-carrying conductor. It allows users to manipulate the magnitude and direction of the current while observing real-time changes in the surrounding magnetic field. By adjusting parameters such as the magnitude and direction of the current, users can visualize how these factors influence the surrounding magnetic field lines. As the current in a wire is increased, the field lines become more concentrated, and their direction changes when the current direction is reversed.

At the center of the interactive tool, a black slider is provided to control the current passing through the conductor. This slider enables users to adjust both the magnitude and direction of the current. The key components of the interface include:

1. Current Indicator: Displays the magnitude and direction of the current. Positive values represent one direction (e.g., upward or out of the screen), while negative values indicate the opposite direction (e.g., downward or into the screen).
2. Magnetic Field Lines: Represented as circular loops around the conductor, these lines change dynamically in response to the current adjustments.
3. Field Strength and Direction: The density of the magnetic field lines indicates the field strength. A stronger current results in denser lines, signifying a stronger magnetic field. Additionally, the arrows on the field lines indicate the direction of the magnetic field, which reverses when the current's direction is flipped.

As the slider is moved to increase the current, the magnetic field becomes stronger. This is visualized by the increased density of the field lines around the conductor. A higher current leads to a more pronounced magnetic effect, making the field lines more noticeable and tightly packed.

As the slider is moved to decrease the current magnitude, the field lines become less dense, indicating a weaker magnetic field. At zero current, no magnetic field is present, and the field lines disappear entirely.

Moving the slider to the opposite direction (negative values) reverses the direction of the current. This causes the magnetic field lines to flip, changing the orientation of the arrows that indicate field direction. According to the Right-Hand Rule, if the current was originally flowing upwards, reversing it makes the field circulate in the opposite direction.

For example, if the current is set to 1 A, the magnetic field strength at a specific point can be calculated and shown. Increasing the current to 2 A will result in the magnetic field strength doubling, reinforcing the proportional relationship between current and magnetic field strength.

From this simulation, users will understand the strength of the magnetic field depends directly on the magnitude of the current. A larger current produces a stronger magnetic field, while a smaller current results in a weaker field.

The direction of the magnetic field follows the Right-Hand Rule: if the thumb points in the direction of the conventional current, the curled fingers represent the direction of the magnetic field lines.

Reversing the current reverses the direction of the magnetic field, confirming the direct relationship between current flow and magnetic field orientation.

This simulation provides an engaging way to explore fundamental electromagnetism concepts, helping users develop a strong intuition about how electric currents generate magnetic fields.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

You may have noticed that if you change the magnitude of the current, you change the strength of the magnetic field. If you reverse the current, you reverse the direction of the magnetic field.

A circular coil is a single loop of wire. When current flows in a circular coil, a magnetic field is created. **Figure 3** shows the magnetic field lines for a coil.

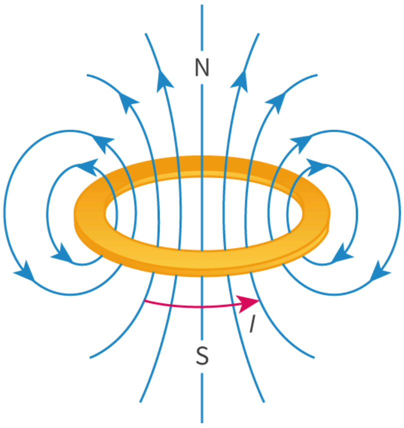


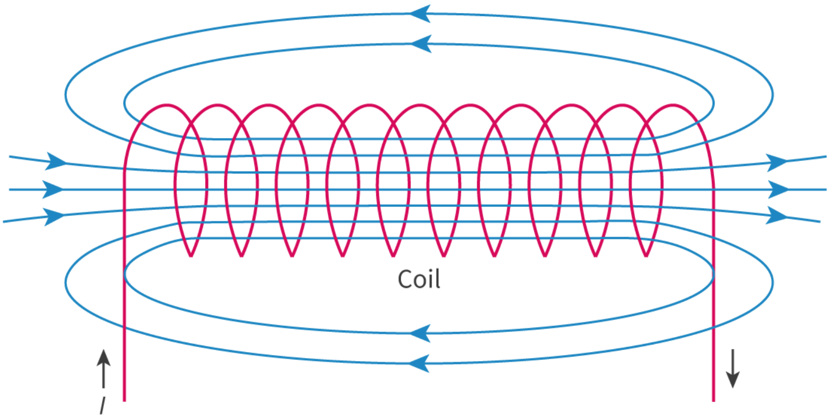
Figure 3. Magnetic field around a circular coil.

More information for figure 3

The image is a diagram illustrating the magnetic field surrounding a circular coil. The coil is depicted as a yellow ring, and magnetic field lines are shown as blue arrows. These lines emanate from the central axis of the coil, spreading outward and looping back around the coil, forming closed loops. The direction of current flow in the coil is indicated by a red arrow marked 'I', moving in a clockwise direction. The diagram also features labels 'N' and 'S', denoting the north and south poles of the magnetic field, illustrating the field's orientation as it emerges and returns to the coil. The field lines are symmetrically distributed, showing the typical pattern of magnetic flux around a coil.

[Generated by AI]

A solenoid is a coil of wire with many loops. Some solenoids have an iron core. **Figure 4** shows the magnetic field lines for a solenoid with an air core.



Student view

Figure 4. Magnetic field around a solenoid.

More information for figure 4

The diagram illustrates the magnetic field around a solenoid with an air core. The solenoid is depicted as a coil of wire with loops, and the magnetic field lines are shown as arrows. Inside the solenoid, the magnetic field lines are parallel and closely spaced, indicating a uniform field. Outside, the lines diverge and curve around the solenoid, suggesting varying field strength and direction. The text 'Coil' is labeled inside the solenoid. Arrows outside the solenoid indicate the direction of the magnetic field.

[Generated by AI]

The shape of the magnetic field is different inside and outside the solenoid. Inside the solenoid, the magnetic field is uniform. Outside the solenoid, the magnetic field strength and direction of the magnetic field vary.

The magnetic field of a solenoid is similar to the magnetic field of a bar magnet (**Figure 5**).

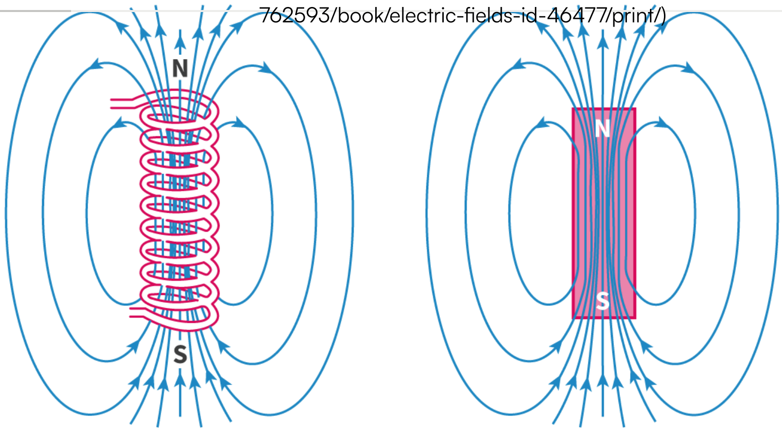


Figure 5. Comparison of the magnetic fields around a solenoid and a bar magnet.

More information for figure 5

The image consists of two side-by-side diagrams comparing magnetic fields. The left diagram illustrates a solenoid, which is depicted as a coil of wire through which current flows, generating a magnetic field with arrows indicating the direction of the field lines. The arrows start at one end of the solenoid marked 'N' and loop around to the other end marked 'S'. The right diagram shows a bar magnet, with the magnetic field similarly depicted with arrows looping from the 'N' (north) end of the magnet to the 'S' (south) end. Both diagrams visually represent the similarity in field patterns, with concentric loops emanating from both structures, indicating the trajectory of magnetic force lines.

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Creativity, activity, service

Strand: Creativity
Learning outcome: Identify own strengths and develop areas for growth

The Earth also has a magnetic field. The magnetic field of the Earth interacts with charged particles ejected from the Sun and gives rise to the Northern and Southern Lights — the Aurora Borealis and Aurora Australis, respectively. These amazing displays of light have inspired artists, musicians and authors for hundreds if not thousands of years. Take a look at some photos of the Auroras. How might they influence or inspire you in your chosen field? Poetry? Visual arts?

The right-hand rule

The right-hand rule can be used to determine the direction of a magnetic field.

For a straight current-carrying wire, your thumb should be in the direction of the current, I. Your curled fingers will then show the direction of the magnetic field around the wire, B (**Figure 6**).

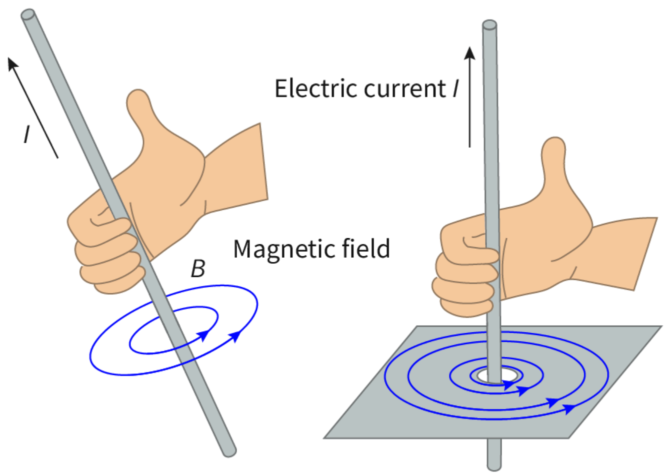

Figure 6. The right-hand rule for a straight wire.

More information for figure 6

The image illustrates the right-hand rule for both a straight wire and a circular wire. On the left, a hand is shown holding a straight wire with the thumb pointing upwards, representing the direction of the current (I). The curled fingers around the wire indicate the circular direction of the magnetic field (B) around the wire.

On the right, a hand is shown holding a straight wire perpendicular to a flat surface. The thumb points upwards to show the direction of current (I) through the circular wire, and the curled fingers around the wire indicate the circular magnetic field lines around the wire on the surface.

[Generated by AI]

Student
view

Overview
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For a circular coil, your curled fingers should be in the direction of the current. Your thumb will then show the direction of the magnetic field inside the coil (**Figure 7**)

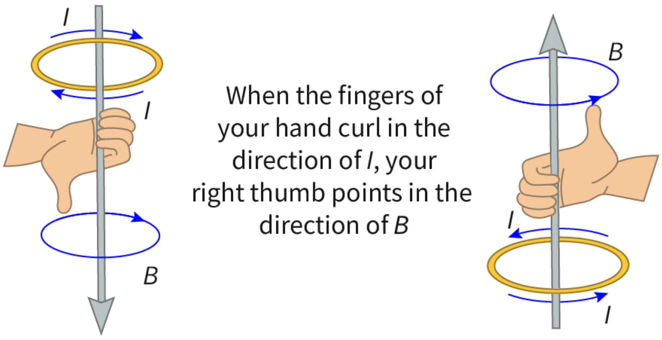


Figure 7. The right-hand rule forthe magnetic field produced by a current in a loop.

More information for figure 7

The image illustrates the right-hand rule used to determine the direction of the magnetic field around a current-carrying wire. Two hands are depicted: on the left, a hand is shown with fingers curled in the direction of the current (I) encircling a vertical wire. The thumb points upwards, indicating the direction of the magnetic field (B). On the right, a similar illustration shows fingers curled in the opposite direction around another wire, with the thumb pointing downwards. The text alongside emphasizes the concept: "When the fingers of your hand curl in the direction of I, your right thumb points in the direction of B." The arrows around the wires and the fingers visually depict the flow of current and the resultant magnetic field direction.

[Generated by AI]

For a solenoid, your curled fingers should also be in the direction of the current. Your thumb will then show the direction of the magnetic field inside the solenoid (**Figure 8**).

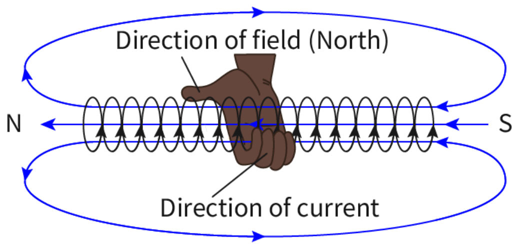


Figure 8. The right-hand rule for a solenoid.

More information for figure 8

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The diagram illustrates the right-hand rule for determining the direction of the magnetic field inside a solenoid. It shows a hand with fingers curled in the direction of the current. The thumb points towards the magnetic field's direction labeled as "North." The solenoid is represented as a series of loops, with arrows indicating the current's path and the resulting magnetic field lines around the solenoid. The current travels through the loops from left to right, and the magnetic field circulates around them, shown by loops and arrows indicating its direction, moving from North to South outside the solenoid and in the opposite direction inside.

[Generated by AI]

Study skills

In physics, we often need to represent something in three dimensions as two dimensions. To represent a vector (magnitude and direction) pointing ‘out of the page’ or ‘out of the screen’, we use a circle with a point at its centre (like the tip of an arrow moving towards you) (**Figure 9**). To represent a vector that is pointing ‘into the page’ or ‘into the screen’, we use a circle with an ‘x’ (like the end of an arrow moving away from you).

Figure 9. Symbols for vectors going out of and into the page.

Figure 10 shows this notation for a straight current-carrying wire.

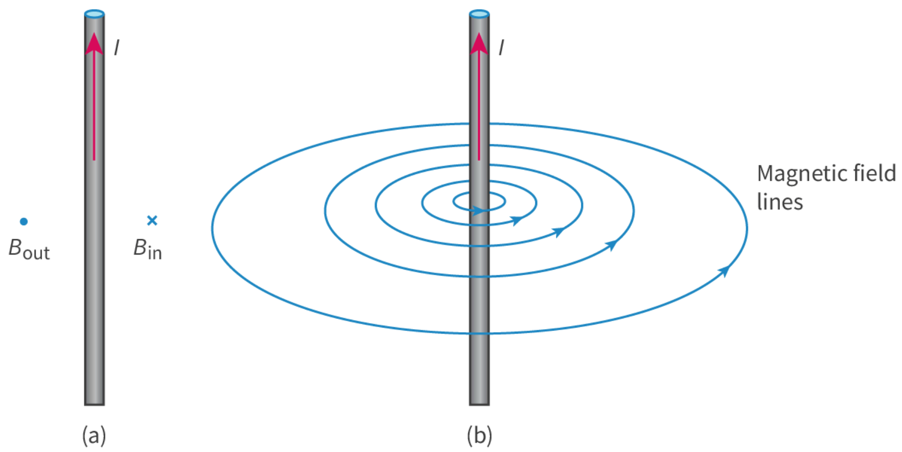


Figure 10. Magnetic field around a current-carrying wire, illustrated using the above symbols.

More information for figure 10

The image consists of two parts labeled (a) and (b) demonstrating the magnetic field around a current-carrying wire. In part (a), the wire is shown with an upward current denoted by the letter "I" and magnetic field symbols labeled "B_out" and "B_in". These symbols suggest the direction of the magnetic field with regards to the wire, with dots representing outward direction and crosses indicating inward direction.

Student view

Part (b) displays the wire again with the current "I" flowing upwards, surrounded by concentric circular lines labeled as "Magnetic field lines". These lines indicate the magnetic field encircling the wire, showing a circular pattern around it with arrows illustrating the direction of the field.

[Generated by AI]

The magnetic field forms circles that are going out of the page on the left of the wire and going into the page on the right of the wire, as you are looking at it.

Work through the activity to check your understanding of magnetic field lines.

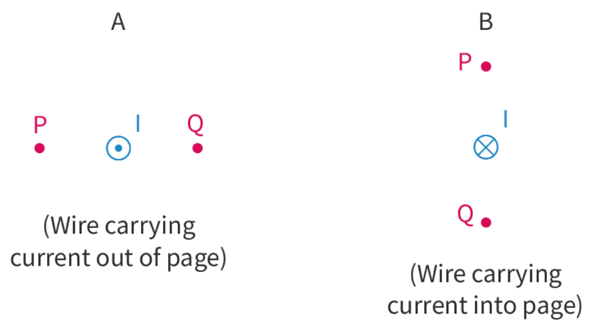
Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

For each of the diagrams in **Figure 11**, determine the direction of the magnetic field at the points indicated. Use the right-hand rule to help you. Click on ‘Hide or show solution’ to see the answers.

1.

2.



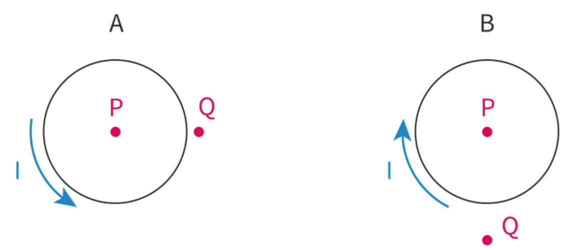
More information

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

The image is a diagram illustrating two different wire configurations. Configuration A shows three points labeled P, I, and Q. The points P and Q are depicted as red circles, while I is a blue circle with a dot in the center, labeled as 'Wire carrying current out of page.' Configuration B mirrors this setup but includes a blue circle with a cross, indicating 'Wire carrying current into page.' The elements P and Q are similarly positioned as red circles in both configurations. The diagram visually distinguishes between the two types of current direction using these labeled circles.

[Generated by AI]

3.

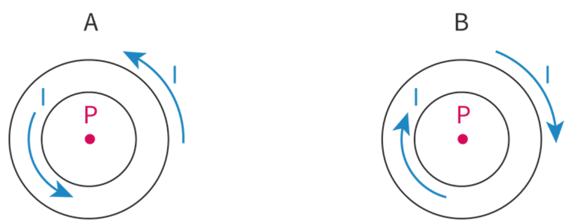


More information

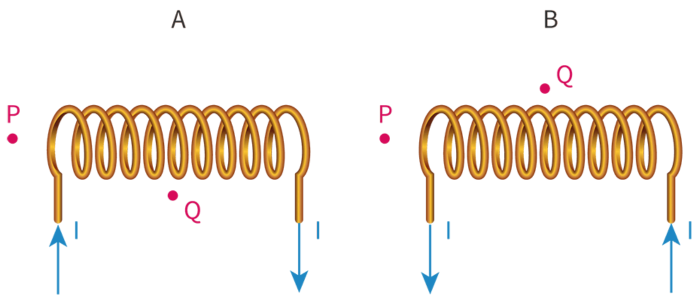
The image shows two circular diagrams side by side. Each diagram contains a circle with arrows and additional shapes inside. The arrows seem to indicate a flow or cycle between the inner shapes, indicating a process or sequence. The left diagram has the circular arrows surrounding a central point, while the right diagram has a similar structure but with variations in the arrangement of shapes and arrows. Each component in both diagrams appears to be interconnected, suggesting a relationship or flow of information between them. However, there is no text visible within the diagrams to offer more specific details about their meaning.

[Generated by AI]

4.



5.



Student view

Overview
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More information

The image is a diagram depicting magnetic fields around two current-carrying wires. The wires are shown as coils with arrows indicating the direction of current flow. The magnetic field lines are represented as circular loops around the wires, illustrating how the magnetic field circulates due to the current. The top part of the diagram includes labels and markings indicating specific areas of interest within the magnetic fields. The left wire has an upward-pointing arrow labeled "Current In," while the right wire has a downward-pointing arrow labeled "Current Out." Both wires are connected at the bottom, forming a complete circuit. The diagram emphasizes the direction and pattern of the magnetic field lines surrounding the wires and highlights the areas where they interact.

[Generated by AI]

Figure 11. Marked locations in the magnetic fields around current-carrying wires.

1A P out of page
Q into page

1B P into page
Q out of page

2A P down page
Q up page

2B P towards right
Q towards left

3A P vertically downwards

3B P vertically upwards

4A P out of page

4B P into page

5A P towards right
Q towards left
(since N pole is at right-hand end of coil)

5B P towards left
Q towards right
(since N pole is at left-hand end of coil)

5 section questions

Question 1

SL HL Difficulty:

Student
view

Overview
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The magnetic field lines for a bar magnet form 1 closed ✓ loops. They come out of the 2 north ✓ pole and go into the 3 south ✓ pole. A wire has a magnetic field around it when there is an electric 4 current ✓ flowing in it.

Accepted answers and explanation

#1 closed

#2 north

#3 south

#4 current

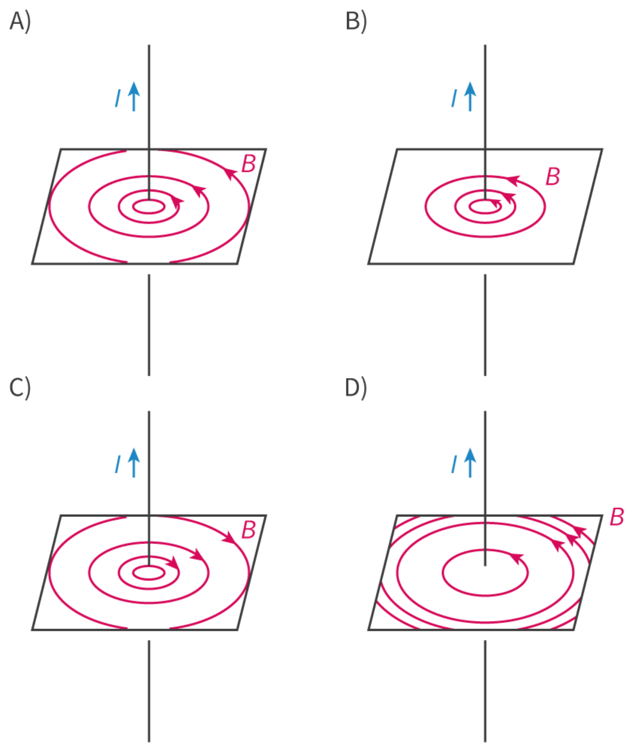
General explanation

Magnetic field lines are always unbroken and so they form closed loops. The lines show the direction of the force acting on a north pole in that location, so they always point from North to South. When current flows in a wire, it creates a magnetic field around the wire.

Question 2

SL HL Difficulty:

In which diagram, A, B, C or D, is the magnetic field around a straight wire shown correctly?



More information

1 A ✓

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

2 B

3 C

4 D

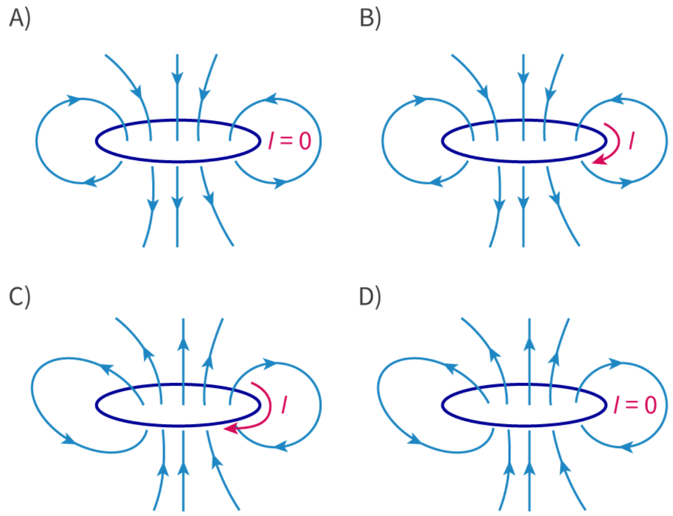
Explanation

The direction of the magnetic field lines should be counter-clockwise for the direction of the current, according to the right-hand rule. The magnetic field becomes weaker as the distance from the straight wire increases, so the field lines become less dense.

Question 3

SL HL Difficulty:

In which diagram, A, B, C or D, is the direction of the magnetic field lines shown correctly for a circular coil of wire?



More information

1 B ✓

2 A

3 C

4 D

Explanation

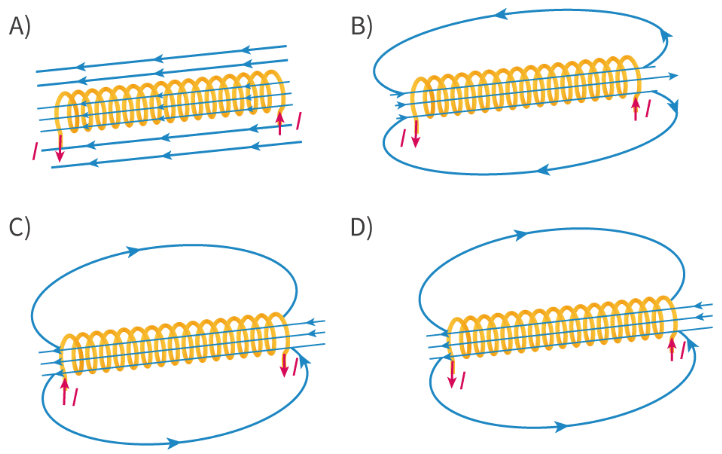
When current is zero (as in options A and D), there will be no magnetic field. By using the right-hand rule on one section of the loop of wire, you can deduce which direction the magnetic field will act inside the coil, thus finding the fields lines in B are moving in the correct direction for the current.

Student view

Question 4

SL HL Difficulty:

In which diagram, A, B, C or D, is the direction of the field lines shown correctly for a solenoid?



More information

1 D
2 B
3 C
4 A

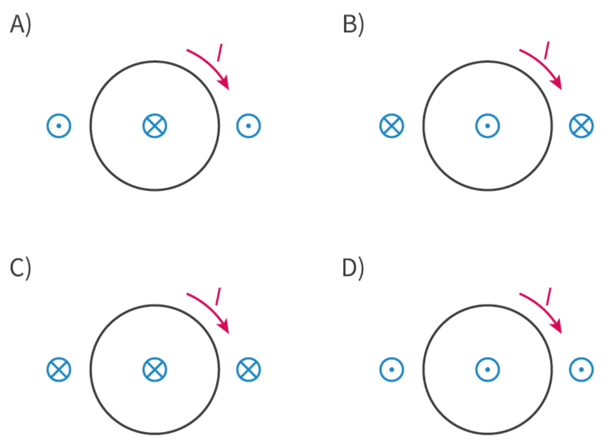
Explanation

According to the right-hand rule, B and C are wrong. The magnetic field at A is uniform outside the solenoid. This is wrong as the magnetic field is only uniform inside the solenoid.

Question 5

SL HL Difficulty:

In which diagram, A, B, C or D, is the direction of the magnetic field lines shown correctly for a circular current-carrying wire?



More information

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762593/c

1 A

2 B

3 C

4 D

Explanation
Using the right-hand grip rule, where our fingers represent the current (*I*) and our thumb represents the magnetic field (*B*), we can see that the field in the middle of the loop is into the page. As magnetic field lines must form closed loops, these downward field lines curve back up, around the edges of the loop, so that the field direction outside the loop is upwards, or out of the page.

D. Fields / D.2 Electric and magnetic fields

Electric potential energy (HL)

D.2.11: Electric potential energy of a system (HL) D.2.12: Electric potential energy for a system of two charged bodies (HL)
D.2.13: Electric potential as a scalar quantity (HL) D.2.14: Electric potential as the work done per unit charge (HL)

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/electric-potential-energy-hl-id-46480/print/) Assign

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand the concept of electric potential energy and use the equation:

$$E_{\mathrm{p}} = \frac{kq_1q_2}{r}$$

- Understand the concept of electric potential and use the equation:

$$V_{\mathrm{e}} = \frac{kQ}{r}$$

We have seen that when we do work against a force, we gain potential energy. Think of lifting a heavy mass against the gravitational force. The mass has gravitational potential energy. But how about when we do work against an electrostatic force – do we still gain potential energy? If so, which kind? Let’s find out!

Student
view

Overview
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Electric potential energy

Imagine that you and a friend each have a charge and that you move these charges towards each other. Whether the forces are attractive or repulsive depends on whether the charges are like or unlike.

Figure 1 shows two charges with the same positive charge being pushed towards each other.

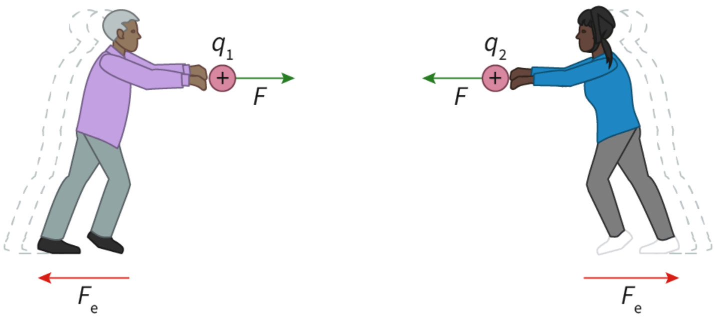

Figure 1. Two people pushing two positive charges q_1 and q_2 towards each other.

More information for figure 1

The image depicts two people facing each other, each pushing a circular object labeled q1 and q2 with a positive plus sign. The person on the left pushes q1 to the right, while the person on the right pushes q2 to the left. Both circular objects have arrows labeled 'F' pointing towards the center between the two charges, indicating the applied force. Red arrows labeled 'Fe' point outward from each person, indicating the repulsive force exerted due to the like charges. The dotted silhouettes indicate potential positions or movement.

[Generated by AI]

As you and your friend move closer together, you both start to feel a force that makes your charges repel. The larger the charges, the larger the force. You are both strong enough to overcome that force and keep pushing the charges closer. When you are at a certain distance apart, you both stop and hold your charges there. You still need to apply a force to each charge or they will start accelerating apart.

Because you have moved the charges by applying forces to them, you have done work. The forces applied are towards each other and you are moving towards each other, so the work done by each of you is **positive**. In other words, you have both given some energy to the charges. The closer you bring the charges, the more energy you have given to them. Now you are standing at a certain distance from each other. Where did this energy go?

Figure 2 shows two unlike charges.

Student
view

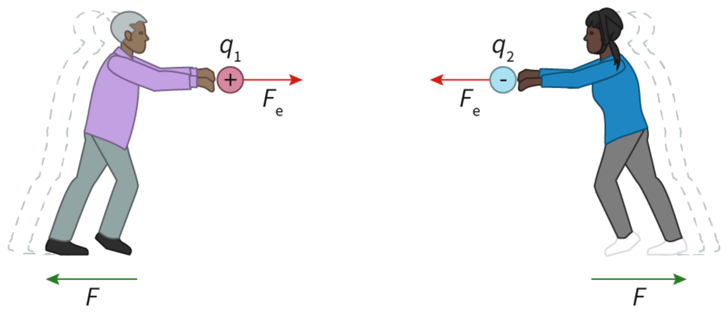

Figure 2. Two people pushing unlike charges towards each other.

More information for figure 2

The image shows two individuals facing each other, each holding a charge. The person on the left is holding a red sphere labeled as a positive charge 'q1' with an electric force 'Fe' pointing to the right. The person on the right is holding a blue sphere labeled as a negative charge 'q2' with an electric force 'Fe' pointing to the left. Both individuals have arrows labeled 'F' pointing away from each other, indicating the force applied to move the charges together. The arrows suggest that each person is exerting force to overcome the attractive electric force between the charges. The dotted lines behind the individuals depict their movement towards each other while maintaining the force on the charges.

[Generated by AI]

While you are approaching each other, your charges are attracted to each other. The larger the charges, the more they will attract each other. You need to constantly apply a force as you move them or they will start accelerating towards each other. This means that the forces you apply are directed away from each other, while you are moving towards each other. The work done is **negative**. In other words, you are gaining energy from this process. The closer you bring them, the more energy you gain. Where did this energy come from?

Since energy is conserved, the work done on these charges, whether positive or negative, is stored in the system. We call this electric potential energy, E_p.

We can say that:

The electric potential energy for a system is the work needed to assemble that system from infinite separation.

Note the following:

- Infinite separation means a distance between the charges where the force between them is negligible. For point charges, a few metres is an 'infinite' distance.
- The electric potential energy belongs to the system of charges, not to each individual charge. For a single charge, far from other charges, there is no external electric field to interact with, so there is no force, and no work is needed to move it around.

The equation to calculate the electric potential energy for a system of two charged bodies is shown in **Table 1**.

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Table 1. Equation for electric potential energy.

Equation	Symbols	Units
$E_\mathrm{p} = k\frac{q_1 q_2}{r}$	E_p = electric potential energy of the system	joules (J)
	k = Coulomb constant $(8.99\times10^9\ \mathrm{Nm^2\ C^{-2}})$	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	q_1 and q_2 = magnitudes of each charge	coulombs (C)
	r = distance between the charges	metres (m)

Worked example 1

Two point charges of 5.0 nC and 7.0 nC have an electric potential energy of 21 μJ. Determine the separation between the charges.

Solution steps	Calculations
Step 1: Identify the quantities and convert their units to SI.	$q_1 = 5.0\ \mathrm{nC}$ $= 5\times10^{-9}\ \mathrm{C}$ $q_2 = 7.0\ \mathrm{nC}$ $= 7\times10^{-9}\ \mathrm{C}$ $E_p = 21\ \mu\mathrm{J}$ $= 21\times10^{-6}$ $= 2.1\times10^{-5}\ \mathrm{J}$
Step 2: Write out and rearrange the formula.	$E_\mathrm{p} = k\frac{q_1 q_2}{r}$ $r = \frac{kq_1 q_2}{E_\mathrm{p}}$
Step 3: Substitute in the values.	$r = 8.99\times10^9\frac{5\times10^{-9}\times7\times10^{-9}}{2.1\times10^{-5}}$ $= 149.83\times10^{-4}\ \mathrm{m}$
Step 4: State your answer to the appropriate number of significant figures.	$r = 1.5\times10^{-2}\ \mathrm{m}$ or $1.5\ \mathrm{cm}\ (2\ \mathrm{s.f.})$

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Electric potential

Electric potential energy always belongs to a system of charges. What if you want to study just one of the charges? Then we need a new concept – the electric potential, V_e.

The electric force is an **interaction** between charges, but the electric field is a **property** of the space (caused by the presence of the charges).

Electric potential energy refers to the system of charges and electric potential is a property of the space around one charge.

Imagine that you have a charge and you are moving it around. When there is no electric field, then you do not need to do any work on the charge to move it around.

If you enter a region where an electric field exists, then you start to feel a force on the charge. This makes it more difficult to move the charge, since you need to apply a force on the charge to move it. You have to do work to move the charge.

In places where the field is stronger, you need to do more work to move the charge. The electric potential is higher at certain points and lower at other points.

We can say that the electric potential at a point is the **work done per unit charge** to bring a small, positive test charge from infinity to that point.

The equation to calculate the electric potential at a distance r from a source charge Q is shown in **Table 2**.

Table 2. Equation for electric potential.

Equation	Symbols	Units
$V_e = k\frac{Q}{r}$	V_e = electric potential at a certain point	volts (V)
	k = Coulomb constant ($8.99\times10^9\ \mathrm{Nm^2\ C^{-2}}$)	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	Q = magnitude of charge	coulombs (C)
	r = distance from charge	metres (m)

The electric potential is a scalar quantity but it can be positive or negative, depending on the charge of the source charge, Q. A positive charge gives rise to a positive electric potential. This means that you have to do positive work to bring a small positive test charge close to the (positive) source charge. A negative charge gives rise to a negative electric potential. This means that you have to do positive work to separate a small positive test charge from a (negative) source charge.

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Electric potential is defined as being zero at an infinite distance from the source charge.

Worked example 2

Determine the magnitude of the charge of a source charge that creates an electric potential of 0.16 mV at a distance of 1.0 mm.

Solution steps	Calculations
Step 1: Identify the quantities.	$V_e = 0.16\ \text{mV}$ $= 16 \times 10^{-5}\ \text{V}$ $r = 1.0\ \text{mm}$ $= 1 \times 10^{-3}\ \text{m}$
Step 2: Write out the equation and rearrange to make Q the subject.	$V_e = k\frac{Q}{r}$ $Q = \frac{V_e r}{k}$
Step 3: Substitute in the values.	$Q = \frac{16 \times 10^{-5} \times 10^{-3}}{8.99 \times 10^9}$
Step 4: State your answer in the appropriate number of significant figures.	$Q = 1.8 \times 10^{-17}\ \text{C}\ (2\ \text{s.f.})$

Work through the activity in the next section to check your understanding of electric potential energy and electric potential.

5 section questions

Question 1

HL Difficulty:

The electric potential energy of two point charges at a distance *r* from each other is —10 mJ.

Which of the following statements is correct?

1. In order to separate the two charges an infinite distance, 10 mJ of energy is needed. ✓
2. In order to bring the two charges from infinity to distance *r*, 10 mJ of energy is needed.
3. The electric potential energy of each charge is —5 mJ.
4. The electric potential energy of each charge is 5 mJ.

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Explanation

A negative electric potential energy means that work needs to be done to separate the charges, since negative electric potential energy means there is one positive charge and one negative charge. Electric potential energy belongs to the system and not to each charge.

Question 2

HL Difficulty:

Determine the electric potential at a distance of 2.0 m from a point charge of $Q = +6.0 \text{ nC}$. Give your answer to an appropriate number of significant figures.

The electric potential is 1 27 ✓ V.

Accepted answers and explanation

#1 27

General explanation

$$\begin{aligned} Q &= +6.0 \text{ nC} \\ &= 6.0 \times 10^{-9} \text{ C} \end{aligned}$$

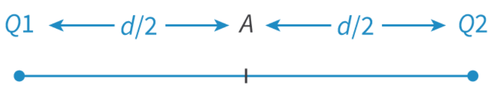
$$r = 2.0 \text{ m}$$

$$\begin{aligned} V_e &= k\frac{Q}{r} \\ &= 8.99 \times 10^9 \frac{6.0 \times 10^{-9}}{2} \\ &= 26.97 \text{ V} \\ &= 27 \text{ V (2 s.f.)} \end{aligned}$$

Question 3

HL Difficulty:

Point A is at an equal distance from two identical point charges, $Q1$ and $Q2$.



More information

If V_e is the electric potential due to each charge at point A, what is the total electric potential at point A?

1 $2V_e$ ✓

2 V_e

3 0

4 $\sqrt{2}V_e$

Student view

Explanation

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Electric potential is a scalar quantity. The electric potentials due to each charge are positive, so:

$$\mathrm{V_e + V_e = 2V_e}$$

Question 4

HL Difficulty:

True or false?

Electric potential energy is the energy of a charge inside an electric field.

False ✓

Accepted answers

False, F, false, f

Explanation

Electric potential energy belongs to the system of charges, not to the individual charges.

Question 5

HL Difficulty:

The hydrogen atom has a proton in the nucleus and one electron orbiting the nucleus. Determine the magnitude of the electric potential energy of the hydrogen atom in electronvolts (eV), assuming that the orbit of the electron has a radius of 5.29×10^{-11} m. Give your answer to an appropriate number of significant figures.

The electric potential energy is 1 −27.2 ✓ eV.

Accepted answers and explanation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/magnetic-fields-id-46479/print/) Assign

#1 27.2

-27.2

27.2

General explanation

$r = 5.29 \times 10^{-11}$ m

The proton and the electron have a charge magnitude of $|e| = 1.6 \times 10^{-19}$ C but the electron is negative and the proton is positive.

$$E_\mathrm{p} = k\frac{q_1 q_2}{r}$$

$$\begin{aligned} E_\mathrm{p} &= 8.99 \times 10^9 \frac{-1.60 \times 10^{-19} \times 1.60 \times 10^{-19}}{5.29 \times 10^{-11}} \\ &= -4.35 \times 10^{-18} \text{ joules} \end{aligned}$$

Converting joules to electronvolts:

$$\begin{aligned} \frac{-4.35 \times 10^{-18}}{1.6 \times 10^{-19}} &= -27.1875 \text{ eV} \\ &= -27.2 \text{ eV (3 s.f.)} \end{aligned}$$

Student view

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D. Fields / D.2 Electric and magnetic fields

Activity: Electric potential energy

D.2.11: Electric potential energy of a system (HL)

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/activity-electric-potential-energy-id-46711/print/) Assign

Activity

Activity

- **IB learner profile attribute:**
  - Knowledgeable
  - Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Student view

Using the simulation, see how changing the charges affects the size and direction of the electric potential energy.

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Task 1: Set q_1 to −4 μC and q_2 to +8 μC. How can you move the person on the left so that they do positive work? How can you move them so they do negative work?

Task 2: Set q_1 to +4 μC and q_2 to +8 μC. How can you move the person on the right so that they do positive work? How can you move them so they do negative work?

Task 3: How can you change the magnitude, polarity and position of the charges so that the system has maximum positive potential energy? How many ways are there of achieving this?

Don't worry about where the charges are on the ruler, only their position relative to each other.

Task 4: How can you change the magnitude, polarity and position of the charges so that the system has maximum negative potential energy? How many ways are there of achieving this?

Task 5: How can you change the magnitude, polarity and position of the charges so that the system has zero potential energy?

The position of the charges is less important here. Think about the magnitude of the charges instead!

Task 6: Set q_1 back to −4 μC and keep q_2 at +8 μC. Position q_1 at 5 cm, and q_2 at 7 cm. What is the electrical potential energy of the system in this configuration?

Try using the equation:

$$E_{\mathrm{p}} = k\frac{q_1 q_2}{r}$$

Task 7: Now move q_1 to the position 0 (cm). What is the new potential energy of the system? How much work has been done to move q_1 to this new position?

To find the work done, calculate the difference in electric potential energy in the system between q_1 at 5 cm and q_1 at 0 cm.

$$\begin{aligned}\text{Work done} &= \Delta E_{\mathrm{p}} \\ &= k\frac{q_1 q_2}{r_2} - k\frac{q_1 q_2}{r_1} \\ &= kq_1 q_2\left(\frac{1}{r_2} - \frac{1}{r_1}\right)\end{aligned}$$

Task 8: What is the electric potential at x = 0 (cm) due to the field around q_2? What is the electric potential x =7 (cm) due to the field around q_1? What do you notice about these two values? Would you expect them to be the same, or different? Why?

Try using the equation:

$$V_{\mathrm{e}} = k\frac{q}{r}$$

Student view

Equipotential surfaces (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Understand the concept of equipotential surfaces and the relationship between electric field lines and equipotential surfaces.
- Know and use the equation for work done moving a charge in an electric field:

$$W = q\Delta V_{\mathrm{e}}$$

- Understand that electric field strength is the electric potential gradient and use the equation:

$$E = -\frac{\Delta V_{\mathrm{e}}}{\Delta r}$$

Figure 1 shows a meteorological map with numbered lines on it. The numbers correspond to air pressure, which is an important factor in weather patterns, but what do the lines represent?

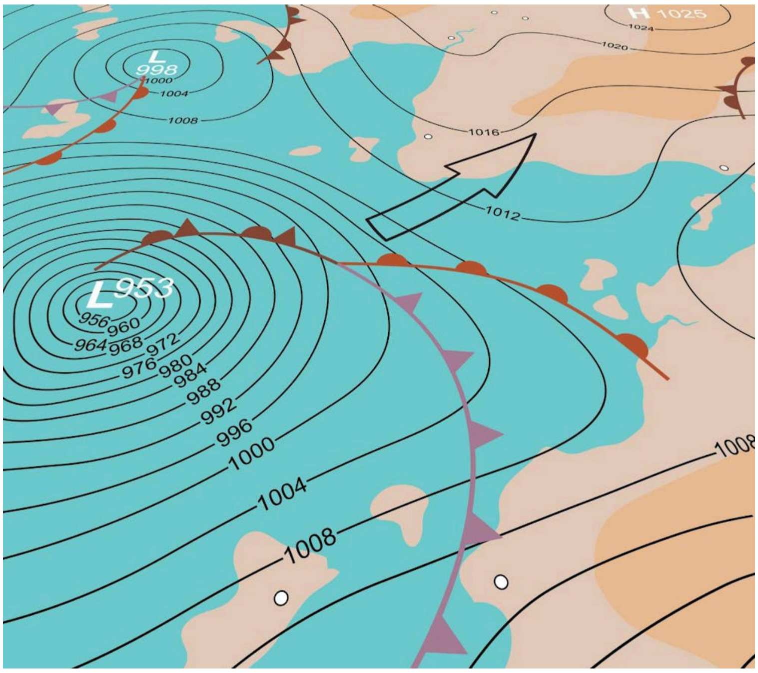

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Figure 1. A meteorological map showing isobars for air pressure.

Credit: AdrianHillman, Getty Images

More information for figure 1

The image is a meteorological map featuring numerous isobars—contour lines that represent areas of equal atmospheric pressure. These lines are numbered with specific pressure values. For example, in the center-left, a low-pressure system is indicated by concentric circles with a central label "L953". Surrounding this central pressure, the isobars are labeled "956", "960", "964", "968", up to "1008" as they extend outwards, indicating increasing pressure. In the top left, another pressure system is labeled "L998". On the right side of the map, there are higher pressure areas labeled with "H1025". Arrows and symbols such as triangles and semi-circles on lines are used, possibly to represent fronts and wind directions. The map uses different colors, including shades of blue and orange, for representing different meteorological elements, though these are not crucial for the understanding of the pressure data.

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Figure 2 shows an island with a hill. What do the lines on the right-hand diagram represent?

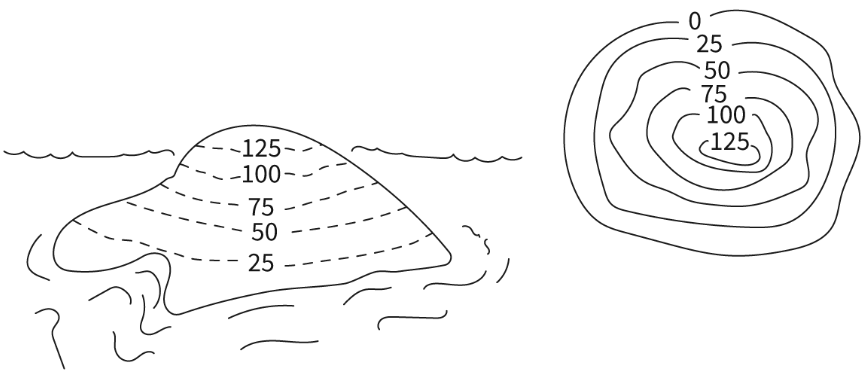

Figure 2. An island with a hill.

More information for figure 2

The left side of the image shows a side view of an island emerging from the sea, with contour lines representing elevation: 25, 50, 75, 100, and 125 meters above sea level. The right side shows a topographic map of the same island. This map uses concentric, irregular circular lines to represent the same elevations. Both views illustrate how contour lines on a map correspond to the physical shape of an island, with lines close together indicating steeper elevations.

[Generated by AI]

In **Figure 1**, the lines represent regions with the same air pressure. In **Figure 2**, the lines represent areas of the island with the same elevation (height above sea level). How does this link to electric potential?

International Mindedness

The contour system in cartography is internationally accepted and enables us to travel to different areas of the world and understand maps. A mountaineer, for example, could travel to mountains in the Himalayas, Andes, the Ethiopian Highlands and the Dolomites

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and would be able to read a map and gain valuable information about, for example, the steepness of a gradient or the height of a peak. What other diagrams or graphs have international relevance like this? What conventions are followed internationally in other areas of science?

Equipotential surfaces

Look at this simulation (https://ophysics.com/em9.html).

Select 'Equipotential View'. Set $Q1$ to a positive value (not maximum) and $Q2$ to zero. Move the pink pointer to see the electric potential at different places around the circles. What do you notice?

Select '3D View'. What do you notice? Increase the value of $Q1$. What happens to the circles? Change the value to a negative value. What happens to the circles?

You will have seen that the electric potential is the same at all points around a particular circle.

These circles are called equipotential lines when they are drawn in two dimensions. In three dimensions, they are known as equipotential surfaces.

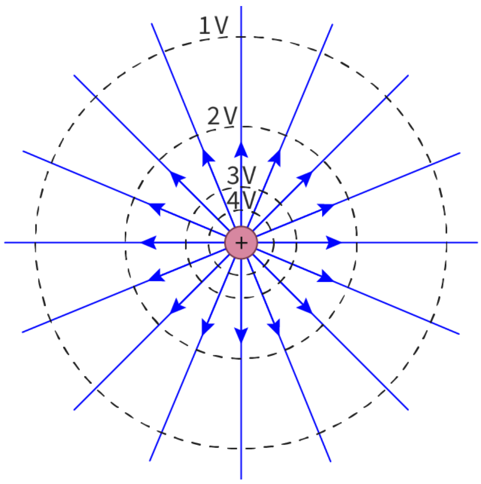

Figure 3. Electric field around a positive point charge.

More information for figure 3

The image depicts the electric field around a positive point charge. At the center of the image, there is a bright red circle marked with a '+' sign indicating the positive charge. Surrounding the charge are concentric dashed circles labeled with voltages: 1V, 2V, 3V, and 4V, representing equipotential lines. Radial blue arrows emanate outward from the charge, illustrating the direction of the electric field. Each arrow starts from the center and points perpendicularly through the equipotential lines, indicating the flow of electric field from the positive charge outward. The spacing between the equipotential lines decreases as they get closer to the charge, showing the decrease in potential difference as one approaches the charge.

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Figure 3 shows the direction of the electric field and the equipotential circles. What do you observe?

You will see that the electric field vectors are at 90 degrees to the equipotential lines. We can say that:

The equipotential lines are always perpendicular to the electric field lines.

Figure 4 shows some examples of electric fields and equipotential lines.

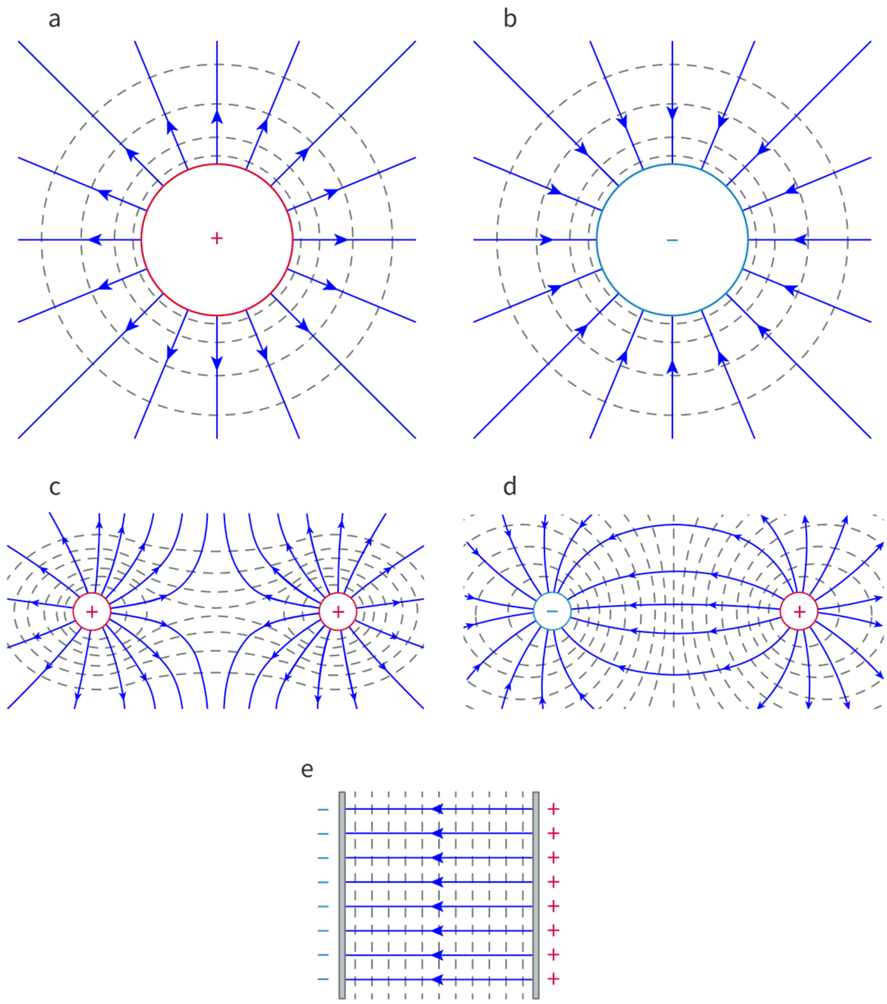

Figure 4. Equipotential lines (dashed lines) and field lines a) around a positively charged sphere, b) around a negatively charged sphere, c) around two positive point charges, d) around a negative and a positive point charge and e) between two oppositely charged plates.

More information for figure 4

The illustration shows five scenarios displaying electric fields (solid lines) and equipotential lines (dashed lines):

1. Image (a): A positively charged sphere at the center. The electric field lines radiate outward symmetrically from the sphere, and the equipotential lines are concentric circles around it.
2. Image (b): A negatively charged sphere at the center. The electric field lines radiate inward symmetrically towards the sphere, with equipotential lines as concentric circles around it.
3. Image (c): Two positive point charges side by side. Each charge has electric field lines radiating outward, while the equipotential lines form ovals between and around the charges.

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4. Image (d): A negative and a positive point charge adjacent to each other. The electric field lines describe a pattern curving from the positive to the negative charge. The equipotential lines create ovals and intersect between the charges, showing the interaction between the fields.
5. Image (e): Two oppositely charged plates with electric field lines moving directly from the positive to the negative plate. The equipotential lines run parallel to the plates.

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Work done

Moving a charge inside an electric field requires a force, so it requires some work to be done on the charge (see section D.2.5a (/study/app/math-aa-hl/sid-423-cid-762593/book/electric-potential-energy-hl-id-46480/)). But how much work?

Figure 5 shows a positive point charge, its electric field and the equipotential lines.

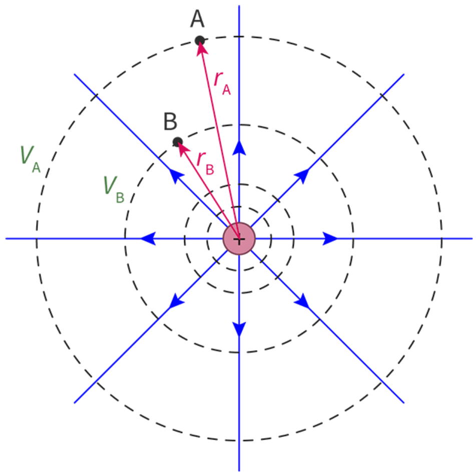

Figure 5. Positive point charge, showing two positions at displacements r_A and r_B from the charge, where the electric potentials are V_A and V_B respectively.

More information for figure 5

This diagram illustrates a positive point charge located at the center with two designated positions, rA and rB, at different distances from the charge. The charge is surrounded by circular equipotential lines, typically represented as blue lines. Electric field lines radiate outward from the charge, depicting the direction of the electric field. Position rA is marked as being further away compared to position rB, indicating different potentials, VA and VB, respectively. The distances from the charge, rA and rB, are crucial for understanding the variation in electric potential and field strength, which decreases with increased distance from the charge.

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Suppose you move a test charge q from point A to point B, closer to the source charge Q.

When you do that, you are changing the electric potential energy of the system, because you are changing the distance between the test charge and the source charge.

The amount of work you have to do depends on how much the electric potential energy of the system changes.

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The change in electric potential energy is:

$$\begin{aligned}\Delta E_{\mathrm{p}} &= k\frac{Qq}{r_{\mathrm{B}}} - k\frac{Qq}{r_{\mathrm{A}}}\\ &= q\left(k\frac{Q}{r_{\mathrm{B}}} - k\frac{Q}{r_{\mathrm{A}}}\right)\\ &= q\left(V_{\mathrm{e_B}} - V_{\mathrm{e_A}}\right)\end{aligned}$$

The equation to determine the work done to move a charge q is given in **Table 1**.

Table 1. The equation for work done to move a charge q.

Equation	Symbols	Units
$W = q \times \Delta V_{\mathrm{e}}$	W = work done	joules (J) or electronvolts (eV)
	q = magnitude of charge	coulombs (C)
	ΔV_{e} = difference in electric potential	volts (V)

Table 1 mentions a unit of energy called the electronvolt. This unit is used for amounts of energy that are much smaller than a joule, such as the change in energy when a single electron moves from one place to another in an electric field. It is not strictly an SI unit, but it is commonly used in physics.

The electronvolt (eV) is the positive work done in moving an electron through a potential difference of one volt. Compare this with the joule, which is the work done in moving one coulomb of charge through one volt.

The work done in moving charge Q through potential difference V is $W = QV$, so:

$$\begin{aligned}1\ \mathrm{eV} &= \text{magnitude of the charge on one electron} \times 1\ \mathrm{V}\\ &= 1.6 \times 10^{-19}\ \mathrm{C} \times 1\ \mathrm{J\ C^{-1}}\\ &= 1.6 \times 10^{-19}\ \mathrm{J}\end{aligned}$$

Study skills

Table 2 summarises the scenarios you may encounter and whether the field does positive work or negative work.

Table 2. Types of work done by the field in different scenarios.

Charges	Increasing separation	Decreasing separation
Like charges (repel)	Positive work is done by the field.	Negative work is done by the field.

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Charges	Increasing separation	Decreasing separation
Opposite charges (attract)	Negative work is done by the field.	Positive work is done by the field.

Negative work done **by** a field is equivalent to **positive** work being done **on** the field.

Worked example 1

The diagram shows equipotential lines for a positive point charge.

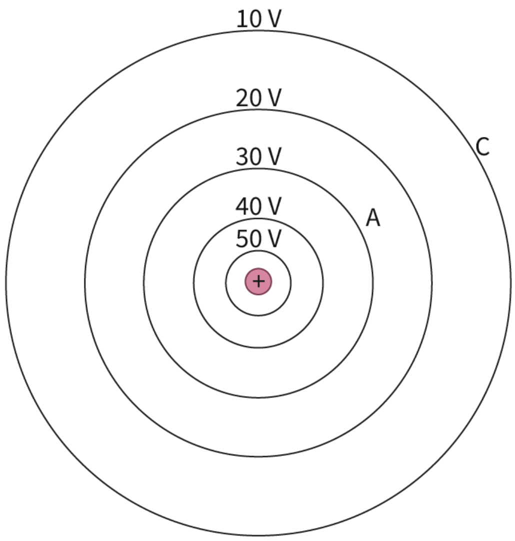

Figure 6. Equipotential lines for a positive source charge.

More information for figure 6

The diagram depicts concentric circles representing equipotential lines around a central positive charge source, marked with a plus sign at the center. Each circle is labeled with voltage values, starting with the innermost circle labeled as 50 V, followed by 40 V, 30 V, 20 V, and 10 V as they expand outward. Point A is located on the 30 V equipotential line, while point C is on the 10 V equipotential line. These lines indicate positions of equal electrical potential surrounding the positive charge.

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A positively charged particle of 2 pC is at point A (on the 30 V equipotential line). The particle has a mass of 5×10^{-16} kg.

Determine the speed of the particle when it reaches point C (the 10 V equipotential).

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	Difference in potential, $\Delta V = 10 - 30 = -20$ (V) Mass, $m = 5\times10^{-16}$ kg $q = 2$ pC $= 2\times10^{-12}$ C $m = 5\times10^{-16}$ kg $V_{e_A} = 30$ V $V_{e_C} = 10$ V
Step 2: Determine the work done.	$W = q\times\Delta V_e$ $W = 2\times10^{-12}\,(30 - 10)$ $= 4\times10^{-11}$ joules The source charge is positively charged. The particle is also positively charged. The force between them is repulsive, moving the particle away from the source charge, from A to C. The electric force has the same direction as the motion of the particle. The work done is positive.
Step 3: Determine the kinetic energy.	$E_{K_C} - E_{K_A} = W_{tot}$ The speed of the particle at A is zero, so $E_{K_A} = 0$. The only force is the electric force between the particle and the source charge. $E_{K_C} = 4\times10^{-11}$ J
Step 4: Determine the speed of the particle at C.	$\frac{1}{2}m{v_C}^2 = 4\times10^{-11}$ $\frac{1}{2}\times5\times10^{-16}\times{v_C}^2 = 4\times10^{-11}$ ${v_C}^2 = \frac{8}{5}\times10^5$ $= 1.6\times10^5$ $v_C = 400$ ms^{-1} (1 s.f.)

To move a charge depends on the change in electric potential energy between two points. It also depends on the magnitude of the charge. In a gravitational field, it is harder to move a heavy bag and easier to move a lighter bag. In the same way, the larger the charge, the more work needs to be done on the charge to move it. Since electric forces can be attractive or repulsive, this work will be provided either by what is moving the charge or by the electric field.

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What will happen if a charge is moved along an equipotential line or surface?

The electric potential difference between any two points on an equipotential line is zero $(\Delta V_\mathrm{e} = 0)$ as all the points are at the same electric potential. This means that the work done is zero.

Worked example 2

The diagram shows equipotential lines in an electric field. A particle with charge q = 4 nC starts from point B, follows the path indicated and stops at point C.

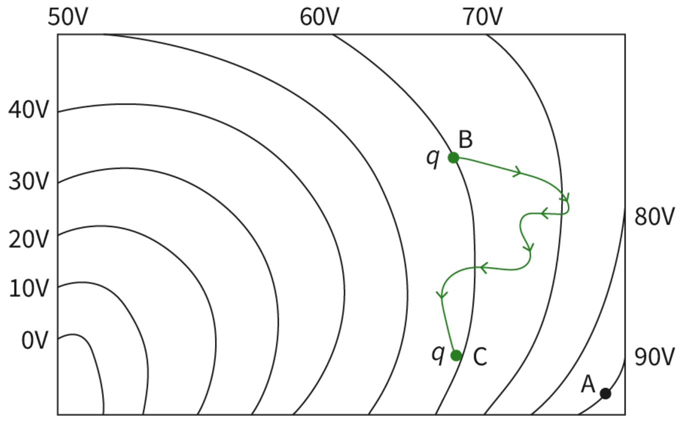

Figure 7. Equipotential lines in an electric field.

More information for figure 7

The diagram illustrates equipotential lines in an electric field, labeled with voltage values from 0V to 90V. Each line represents a constant voltage, with the lines closer to the center being lower in voltage. The voltages increase outward, with clearly labeled lines at increments of 10V, from 0V at the innermost line to 90V at the outermost.

A particle with charge q starts at point B and moves along a path to point C, crossing several equipotential lines. Point A is located on the 90V line, point B on the 70V line, and point C on the 50V line. The path from B to C includes changes in direction as the particle crosses these lines, indicating areas where the electric potential changes.

The diagram is significant for understanding the work done on the particle as it moves between points of different electric potentials.

[Generated by AI]

Determine the work done on the particle.

The work done is zero:

$$W = 0 \text{ J}$$

$$W = q \times \Delta V_\mathrm{e}$$

The work done depends on the initial and final values of the electric potential for the motion. The particle starts from the equipotential with $V_\mathrm{e} = 60$ V at point B and stops at the same equipotential line at point C. This means that the change in electric potential is zero $(\Delta V_\mathrm{e} = 0)$

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so the work done is also zero. It does not matter what the magnitude of the charge is or what the shape of the path followed is.

Electric field strength

Suppose we have two equipotential lines separated by a small distance Δr, and we want to move a charge between them.

The work done is:

$$W = q \times \Delta V_{\mathrm{e}}$$

where ΔV_{e} is the electric potential difference between the lines.

When positive work is done moving a (positive) test charge, the charge will always move in the opposite direction to the field direction:

$$W_{\text{field}} = -q \times \Delta V_{\mathrm{e}}$$

If we assume that the lines are very close together, and the electric field is approximately constant, we can calculate the work done as:

$$\text{Work} = \text{Force} \times \text{Distance}$$

$$W = F_{\mathrm{e}} \times \Delta r$$

But:

$$E = \frac{F_{\mathrm{e}}}{q}$$

So:

$$W = E \times q \times \Delta r$$

Equating the two expressions for work, we get:

$$-q \times \Delta V_{\mathrm{e}} = E \times q \times \Delta r$$

Solving for electric field strength, E, gives the equation in **Table 3**.

Table 3. Equation for electric field strength.

Equation	Symbols	Units
$E = -\frac{\Delta V_{\mathrm{e}}}{\Delta r}$	E = electric field strength	newtons per coulomb (N C^{-1})
	ΔV_{e} = difference in the electric potential	volts (V)
	Δr = distance	metres (m)

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This tells you that the magnitude of the electric field strength is an expression of how large the 'jump' of the electric potential is between two adjacent equipotentials.

Figure 8 shows a graph of electric potential, V_e, versus distance, r. The negative value of the slope (gradient) of the curve gives you the electric field strength. This is known as the electric potential gradient.

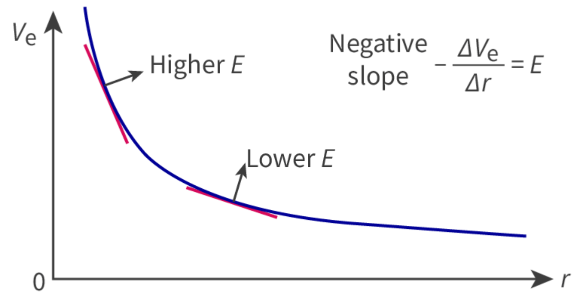

Figure 8. The electric potential gradient is the negative slope of the graph of V_e against r.

More information for figure 8

The image is a graph depicting the relationship between electric potential (Ve) and distance (r). The horizontal axis (X-axis) represents distance "r," while the vertical axis (Y-axis) represents electric potential "Ve." The graph is a curve that slopes downward from left to right, illustrating that the electric potential decreases with increasing distance.

Key components and annotations in the graph:

1. Higher Electric Field (E) - Indicated on the left side of the graph, where the slope is steep, meaning the electric potential gradient is high, and the electric field strength is greater.
2. Lower Electric Field (E) - Indicated on the right side of the graph, where the slope is less steep, meaning the electric potential gradient is lower, and the electric field strength is smaller.
3. Negative Slope Formula - In the middle of the graph, the formula "-ΔVe/Δr = E" is shown, indicating that the negative gradient of the potential curve represents the electric field strength.

Overall, the graph visually explains the concept of electric potential gradient and its correlation to electric field strength across different distances from the source.

[Generated by AI]

The magnitude of the gradient is equal to the electric field strength. Closer to the source, where r is small, the gradient is steep and the electric field strength is greater. Further away from the source, the gradient is less steep and the electric field strength is smaller.

As the gradient of the electric potential versus distance graph line is negative, the electric field is positive.

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Theory of Knowledge

The natural sciences often rely on mathematics as a tool for knowledge production. The process of moving a charge a small distance is related to a mathematical concept known as 'integration'. To what extent does knowledge production in Physics depend on the application of mathematics?

Spend 5 minutes using your knowledge of this subtopic to prepare a 60-second verbal response to this TOK question.

Figure 9 shows a charged, hollow conducting sphere of radius R and graphs of electric field strength E versus distance from the centre of the sphere r, and electric potential V versus distance r.

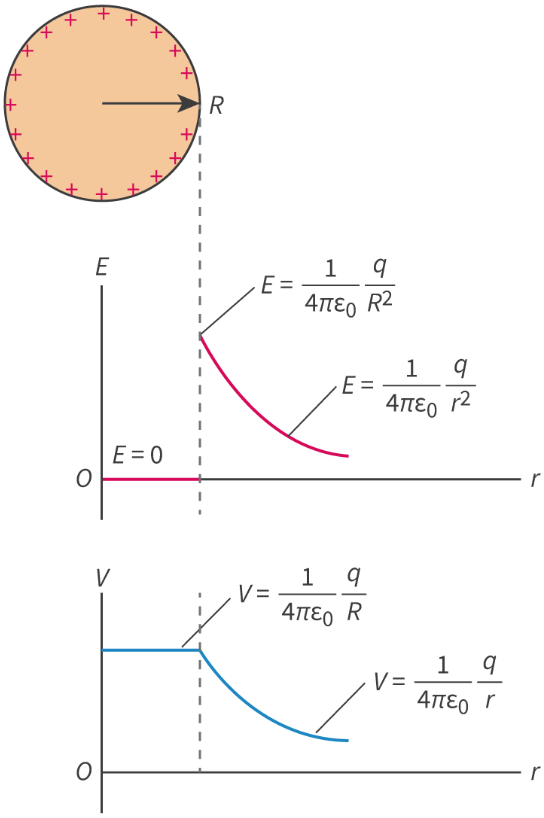

Figure 9. The electric potential inside and outside a charged sphere.

More information for figure 9

The image consists of a diagram with a charged, hollow conducting sphere and two graphs. The sphere is depicted at the top with a radius labeled as 'R' and has positive charges on its surface.

Below the sphere are two graphs:

1. **Electric Field Graph (E vs. r):**
2. X-axis: Represents the distance 'r' from the center of the sphere.
3. Y-axis: Represents the electric field strength 'E'.
4. A curve shows the electric field is zero inside the sphere (E = 0 for r < R). Outside the sphere, the electric field decreases as r increases, with the equation E = (1 / (4πε$_0$)) * (q / r^2) depicted.

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5. At r = R, E becomes constant, calculated by $E = (1 / (4\pi\varepsilon_0)) * (q / R^2)$.
6. **Electric Potential Graph (V vs. r):**
7. X-axis: Represents the distance 'r' from the center of the sphere.
8. Y-axis: Represents the electric potential 'V'.
9. Inside the sphere, V is constant and given by $V = (1 / (4\pi\varepsilon_0)) * (q / R)$.
10. Outside the sphere, V decreases with distance, represented by the equation $V = (1 / (4\pi\varepsilon_0)) * (q / r)$.

[Generated by AI]

Inside the hollow sphere, the electric potential is constant, so the electric potential gradient is zero. This tells us that the electric field strength is also zero. Outside the sphere, the electric field strength is equal to the gradient of the blue line at a particular point.

Work through the activity in the next section to check your understanding of equipotential lines.

Activity

- **IB learner profile attribute:**
  - Inquirer
  - Knowledgeable
  - Thinker
  - Reflective
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Self-management skills — Breaking down major tasks into a sequence of steps
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Looking back at the simulation (https://ophysics.com/em9.html) you explored earlier, you will be able to see the potential surfaces and the equipotential lines that are formed from two charges.

By default, you can see two charges at a certain distance in a three-dimensional view. The red surface is indicating the potential.

Start by setting both charges to zero. The shape of the red surface is flat, because there is no electric potential.

Now set Q_1 to a positive value and leave Q_2 at zero. Press to rotate the view and have a good look at the shape of the red surface.

- What is the shape of the potential around the charge? Describe it in your own words.
- How is the height of the surface connected to the value of the charge?

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- Why is there a hole at the top of the 'hill'? In other words, why is it open at the top? Think of the denominator in the formula $V_e = k\frac{Q}{r}$.
- What happens if you set the value of Q_1 to be negative?

Now set both charges to have a positive value. What changes in the shape of the red surface?

Repeat for a positive and a negative value for Q_1 and Q_2.

Finally, try to vary the distance between the charges. Does the shape change?

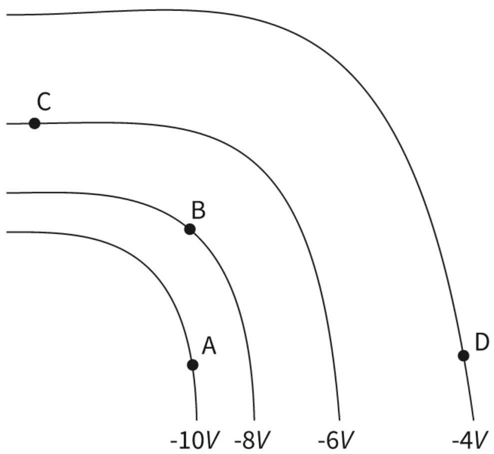
Write down your observations and verify that you can connect them to the things you learned in this subtopic. These observations will also help you with the activity in the next subtopic.

5 section questions

Question 1

HL Difficulty:

The diagram shows some equipotential lines. Charge +*q* is moved between the equipotential lines.



More information

Which movement requires the greatest work to be done on the charge?

1 Moving from A to D ✓

2 Moving from C to D

3 Moving from A to C

4 Moving from D to A

Student view

Explanation

$W = q \times \Delta V_e$

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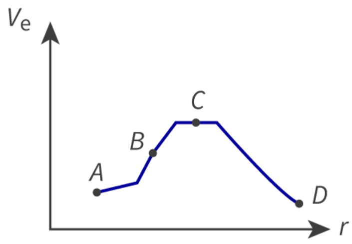
Moving from A to D gives the largest difference in electric potential $(-4-(-10))$ so the work done is the greatest.

Question 2

HL Difficulty:

The graph shows how electric potential in a field varies with distance. At which point, A, B, C or D, is the magnitude of the electric field strength at a minimum?



More information

1 C

2 A

3 B

4 D

Explanation

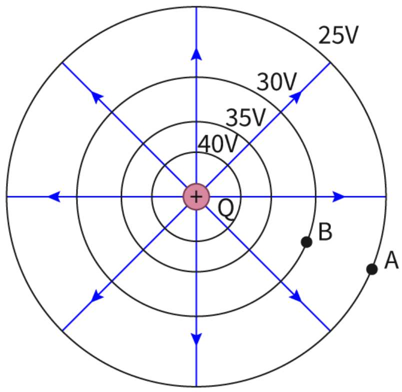
The electric field strength is equal to the gradient of the graph line, so at C, the gradient is zero, so the electric field strength is zero. You are asked for the magnitude of the electric field strength, so the correct option is C.

Question 3

HL Difficulty:

Determine the work done by the electric field when a charge q of 2 mC is moved from A to B. Give your answer to an appropriate number of significant figures.

Student view



More information

The magnitude of work done is 1 0.01 ✓ J

Accepted answers and explanation

#1 0.01

-0.01

General explanation

$$q = 2 \text{ mC}$$
$$= \Delta V_{\text{e}}$$
$$= 30 - 25$$
$$= 5 \text{ V}$$

When the charge is moved from A to B, the charges are repelling each other. So, the force does positive work, and the force of the electric field does negative work.

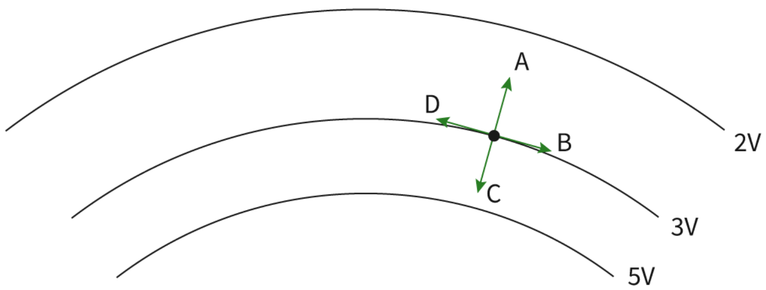
$$W_{\text{field}} = -q \times \Delta V_{\text{e}}$$

$$W_{\text{field}} = -2 \times 10^{-3} \times 5$$
$$= -0.01 \text{ J (1 s.f.)}$$

Question 4

HL Difficulty:

The diagram shows some equipotential lines. Which arrow, A, B, C or D, shows the direction of the electric field correctly?



More information

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1 A

2 B

3 C

4 D

Explanation

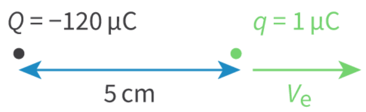
The field lines show the direction of the electric field. Field lines are perpendicular to equipotential lines, so A and C are possible.

The value of the electric potential decreases in the direction of A, which means that the gradient is negative in that direction. $E = -\frac{\Delta V_e}{\Delta r}$, so a negative gradient means a positive electric field strength. A is the correct option.

Question 5

SL HL Difficulty:

Charge *Q* = —120 µC is not free to move. Charge *q* = +1.0 µC with a mass of *m* = 15 g is at a distance of *r* = 5.0 cm from *Q*.



More information

Charge *q* moves away from *Q* with an initial speed of 50 m/s. What is the maximum distance that charge *q* will reach? Give your answer to two significant figures.

The maximum distance is 1 0.38 m.

Accepted answers and explanation

#1 0.38

0.381

0.3817

General explanation

$$Q = -120\ \mu\text{C}$$
$$= 1.2\times10^{-4}\ \text{C}$$

$$q = +1.0\ \mu\text{C}$$
$$= 1\times10^{-6}\ \text{C}$$

$$m = 15\ \text{g}$$
$$= 15\times10^{-3}\ \text{kg}$$

$$r = 5.0\ \text{cm}$$
$$= 0.05\ \text{m}$$

$$v_{\text{initial}} = 50\ \text{m s}^{-1}$$

Student view

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The work done by the electric field is negative, as the charges are attracted to each other. This slows down charge q as it moves away from charge Q.

$$E_{\mathrm{k,final}} - E_{\mathrm{k,initial}} = -q\Delta V_{\mathrm{e}}$$

The maximum distance d will be reached when the charge stops momentarily, so when $E_{\mathrm{k,final}} = 0$

$$-\frac{1}{2}m{v_{\mathrm{o}}}^2 = -q\left(V_{\mathrm{final}} - V_{\mathrm{initial}}\right)$$

The electric potential at any point is given by:

$$V_{\mathrm{e}} = k\frac{Q}{r}$$

$$-\frac{1}{2} \times 15\times10^{-3} \times 50^2 = -1 \times 10^{-6} \times (8.99\times10^9 \times \frac{-120\times10^{-6}}{r} - 8.99\times10^9 \times \frac{-120\times10^{-6}}{0.05})$$

$$-18.75 = -1 \times 10^{-6} \times 8.99 \times 10^9 \times -120\times10^{-6}\left(\frac{1}{r} - \frac{1}{0.05}\right)$$

$$-17.380 = \frac{1}{r} - \frac{1}{0.05}$$

$$r = 0.38\ \mathrm{m}\ (2\ \mathrm{s.f.})$$

D. Fields / D.2 Electric and magnetic fields

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-46482/print/) Assign

- Electric charge is quantised and is conserved for an isolated system.
- Objects can be charged through friction, conduction and induction.
- Grounding allows objects to lose their excess charge and become neutral.
- Point charges as well as spherical charges interact with electric forces that obey Coulomb's law.
- The electric field strength is a measure of the force per unit of positive charge inside an electric field.
- Magnets interact with each other through forces at a distance.
- Magnetic field lines always form closed loops.
- A current-carrying wire that is straight, forming a circular coil or a solenoid gives rise to a magnetic field.
- Field lines are directed from more positively to less positively charged bodies.

Higher level (HL)

- The electric potential energy of the system is the work that was done to assemble the system of charges.
- Lines that connect all points with the same electric potential are called equipotential lines.
- The work involved when a charge moves between two points is independent of the path followed and depends only on the potential difference between the points.

Table 1 summarises the concepts covered in this subtopic.

Student view

Table 1. Summary of the concepts covered in this subtopic.

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Electric force	**Electric field strength**	**Electric potential energy**	**Electric potential**
Between two point charges $F = k\frac{q_1 q_2}{r^2}$	Around a point charge $E = k\frac{Q}{r^2}$	For a system of two point charges $E_\text{p} = k\frac{q_1 q_2}{r}$	Around a point charge $V_\text{e} = k\frac{Q}{r}$
Always $F = E \times q$	By definition $E = \frac{F}{q}$ For parallel plates $E = \frac{V}{d}$	Negative when charges attract each other	Constant inside a conducting sphere
Vector	Vector	Scalar	Scalar

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Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. : States that the force between two charges is proportional to the product of their charges and inversely proportional to the square of the distance between them.

2. : A 3D region where charges experience an electrostatic force.

3. : The work done in bringing a small positive test charge from infinity to a point in an electric field.

4. :The work done per unit charge in bringing a small positive test charge from infinity to a point in an electric field.

Electric field | Coulomb's law | Electric potential | Electric potential energy

Check

Interactive 1. Key Concepts in Electrostatics.

D. Fields / D.2 Electric and magnetic fields

Checklist

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-id-46483/print/) Assign

What you should know

At the end of this subtopic you should be able to:

- Recognise that electric charge is quantised and conserved.
- Explain that electric charge can be transferred between bodies by friction, contact and electrostatic induction.
- Describe how a build-up of electric charge can be discharged by grounding (earthing).
- Recognise that the electric force between electric charges can be attractive or repulsive.

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- Understand Coulomb's law and use the equation:

$$F = \frac{kq_1q_2}{r^2}$$

- Know and use the equation for the Coulomb constant:

$$k = \frac{1}{4\pi\varepsilon_0}$$

- Understand electric field strength and use the equations:

$$E = \frac{F}{q} \text{ and } E = \frac{V}{d}$$

- Describe the electric field lines around a point charge, between two point charges, inside and outside a charged sphere and between parallel charged plates.
- Recognise the relationship between electric field strength and electric field line density.
- Describe Millikan's oil drop experiment.

Higher level (HL)

- Understand the concept of electric potential energy and use the equation:

$$E_\text{p} = \frac{kq_1q_2}{r}$$

- Understand the concept of electric potential and use the equation:

$$V_\text{e} = \frac{kQ}{r}$$

- Understand the concept of equipotential surfaces and the relationship between electric field lines and equipotential surfaces.
- Know and use the equation for work done moving a charge in an electric field:

$$W = q\Delta V_\text{e}$$

- Understand that electric field strength is the electric potential gradient and use the equation:

$$E = -\frac{\Delta V_\text{e}}{\Delta r}$$

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D. Fields / D.2 Electric and magnetic fields

Investigation

Section Student… (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-46484/print/) Assign

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills – Combining different ideas in order to create new understandings
- **Time required to complete activity:** 1 hour
- **Activity type:** Individual activity

Your task

Charge can only be an integer multiple of a base value, which is the charge of a single electron, e (see section D.2.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/electric-charge-id-46475/)). In 1909, Millikan and Fletcher conducted an experiment that enabled them to measure this base charge with an accuracy of 0.6% of the value that is accepted today.

Use this simulation (https://www.thephysicsaviary.com/Physics/Programs/Labs/MillikanOilDropLab/) to investigate Millikan's oil drop experiment.

Oil drops are produced by spraying them inside a closed chamber. These drops fall under their own weight but also experience air resistance as they move. They reach a terminal velocity (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)).

- Spray to create some oil drops.

Note how some drops continue to fall down. For these drops the gravitational force (downwards) is larger than the electrostatic force (upwards). That is, $F_g > F_e$. Some drops rise through the chamber. For these drops the reverse is true, and $F_g < F_e$. Some drops will remain in place. For these drops, $F_g = F_e$.

- Click on the scope when you have created drops that hover in the same position.
- Record the radius of the drop.
- Calculate the volume of the drop.

Use the equation: $V = \frac{4}{3}\pi r^3$ to find volume.

- Using the density of oil value $\rho = 900\ \text{kg m}^{-3}$, calculate the mass of the drop.

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Use the equation: m = ρ × V to find the mass of the oil drop.

- Calculate the force of gravity acting on the drop.

Use the equation: $F_g = mg$ to find the mass of the oil drop.

- As there is no net force on this drop, we can say that $F_g = F_e$. Use this fact to find the charge on the drop.

Use the equation: $E = \frac{V}{d}$ to find E, the electric field strength between the plates, then use the equation $F_e = qE$ to find the charge, q, of the oil drop.

- Repeat this process for at least seven drops, and record the charge of each drop. For each of your values, also find the ratio $\frac{q}{q_e}$, and record it in a table like **Table 1** below.

Table 1. Sample results table.

Oil drop	Charge q of the oil drop	Ratio q/q_e
1		
2		
3		
4		
5		
6		
7		

As charge is discrete, the charge of the oil drops should appear as integer multiple values of the unit charge (e).

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$$q = N \times q_e \Rightarrow \frac{q}{q_e} = N$$

This means that if you divide the charge of each oil drop by the charge of an electron, you should get integer numbers. This will provide evidence that 'all' random charges have discrete values of charge.

Millikan followed a similar procedure to the one above. By determining the charges for lots of different oil drops, he was able to identify a pattern and calculate the base unit of the charge of an electron.

Reflection

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44743/).

- Which experiments provided evidence to determine the nature of the electron?
- How can the properties of fields be understood using both an algebraic approach and a visual representation?
- What are the consequences of interactions between electric and magnetic fields?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?

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- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic D.2 Electric and magnetic fields

Help us improve the content and user experience.

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