Unit 14

Electricity and Magnetism

This unit online, with its interactives:
science-playground.com/s/9a14

Comb your hair on a dry winter morning in Kathmandu and hold the comb over a few scraps of paper. The scraps jump up to it before it touches them. Put a compass on your desk, and its needle swings round to point north, though nothing touches it either. Hold a magnet near the compass and the needle swings again, toward the magnet, from several centimeters away.

In each case something pushes or pulls across empty space. Physicists say the comb, the magnet and the Earth each fill the space around them with a **field**: a region where a charge, or a magnet, feels a force. This unit is about two kinds of field. The first half is about the electric field of charges: how to draw it, how strong the force between two charges is (Coulomb's law), and the capacitor, a device that stores charge. The second half is about magnetic fields: the lines of force round a bar magnet, which you will plot yourself with a compass, the Earth's own field, and the two angles that say which way it points in Nepal.

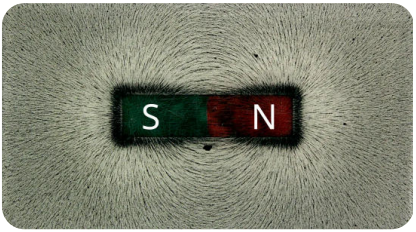


Figure 14.1 *Iron filings sprinkled round a bar magnet. Each filing becomes a tiny magnet and lines up with the field, so together they show its pattern: lines that leave one end, curve round and enter the other. You will plot the same lines with a compass in Practical 26.*
Photo: MikeRun , Vera Wurmsdobler, CC BY-SA 4.0

14.1 Electric field and lines of force

Rub a plastic ruler with a woolen cloth, or a balloon on your hair. Electrons move from one to the other, and both become **charged**: the one that gains electrons is nega-

tively charged, the one that loses them positively charged. You learned in Grade 7 that charges of the same kind repel each other and charges of opposite kinds attract.

The surprising part is that the force acts across a gap. The ruler doesn't have to touch the paper. We explain this by saying that every charge sets up an **electric field** in the space around it. Another charge placed in that field feels a force, pushed or pulled by the field where it is.

The electric field of a charge is the region around it in which another charge experiences an electrostatic force.

The field is strongest close to the charge and weakens with distance. In principle it reaches out for ever; in practice, a few meters from a charged comb it is far too weak to notice.

Testing a field with a test charge

How can we find out whether there is a field at a place, and how strong it is? Put a small positive charge there and see what force it feels. Such a charge is called a **test charge** (q_0). It must be small, so that it doesn't push the charges making the field out of place. By agreement, a test charge is always positive.

The force on the test charge depends on how big the test charge is: double it and the force doubles. So to describe the field itself, we divide the force by the test charge. This is the **electric field intensity** (or **electric field strength**), E:

$$E = \frac{F}{q_0}$$

Electric field intensity at a point is the force experienced by a unit positive charge placed at that point. Its SI unit is the **newton per coulomb (N/C)**. It is a vector: its direction is the direction of the force on a positive charge.

A field of 500 N/C at a point means a charge of 1 C there would feel a force of 500 N, a charge of 2 C a force of 1,000 N, and so on: $F = qE$. A **negative** charge in the same field feels a force of the same size in the **opposite** direction.

WORKED EXAMPLE

The force on a charge in a field

A drop of oil carrying a charge of -2 nC is in an electric field of 3,000 N/C pointing upward. Find the force on it.

Answer

q = 2 nC = 2×10^{-9} C, E = 3,000 N/C.

$$F = qE = 2 \times 10^{-9} \times 3000 = 6 \times 10^{-6} \text{ N}$$

6×10^{-6} N, downward. The drop is negative, so the force on it is opposite to the field. In 1909 the American physicist Robert Millikan used this idea, tiny charged oil drops held still by an electric field against gravity, to measure the charge of a single electron.

The field of a point charge

A **point charge** is a charge on a body so small, compared with the distances involved, that we can treat it as sitting at one point: a charged speck of dust, or a charged ball seen from far away. Using Coulomb's law (below), the field intensity at a distance r from a point charge Q comes out as

$$E = \frac{kQ}{r^2}$$

where $k = 9 \times 10^9$ N m^2/C^2 is Coulomb's constant. Twice as far from the charge, the field is a quarter as strong; three times as far, a ninth.

WORKED EXAMPLE

The field near a charged ball

A small ball carries a charge of $+5$ μC. Find the electric field intensity 30 cm from it.

Answer

Q = 5 μC = 5×10^{-6} C, r = 30 cm = 0.30 m.

$$E = \frac{kQ}{r^2} = \frac{9 \times 10^9 \times 5 \times 10^{-6}}{(0.30)^2} = \frac{45 \times 10^3}{0.09} = 5 \times 10^5 \text{ N/C}$$

5×10^5 N/C, pointing away from the ball (it is positive).

CAREFUL

Units first

Before using any formula with k, change charges to coulombs and distances to meters: 1 μC (microcoulomb) = 10^{-6} C, 1 nC (nanocoulomb) = 10^{-9} C, 1 cm = 0.01 m. Most wrong answers in this unit come from leaving a distance in centimeters. Remember to square the distance in meters: $(30\text{ cm})^2$ is 0.09 m^2, not 900.

Electric lines of force

A field can't be seen, but it can be drawn. In the 1830s, Michael Faraday, working in London, pictured the space round a charge as filled with lines, which he called **lines of force**. We still draw them today.

An electric line of force is the path along which a free, small positive charge would tend to move in an electric field. The tangent to a line of force at any point gives the direction of the field there.

Lines of force follow a few simple rules:

- They **start on positive charges and end on negative charges** (or go off to very far away, if there is no negative charge nearby).
- The **direction** of the line at any point is the direction of the force on a positive test charge there; an arrow on each line shows it.
- They **never cross**. If two lines crossed, the field at the crossing would point two ways at once, which is impossible.
- Where the lines are **close together** the field is **strong**; where they are spread out, it is weak.
- They leave or enter the surface of a conductor at **right angles** to it.

Field patterns round point charges

Round a single positive point charge, the lines spread straight out in every direction, like the spokes of a wheel. Round a negative point charge they are the same shape, but they point **inward**. A positive test charge placed near the positive charge is pushed away, along a line; near the negative charge it is pulled in.

The picture is flat, but the real field is in three dimensions: the lines spread out in all directions, like the spines of a hedgehog. The farther from the charge, the farther apart the lines are, which is the picture's way of saying the field gets weaker.

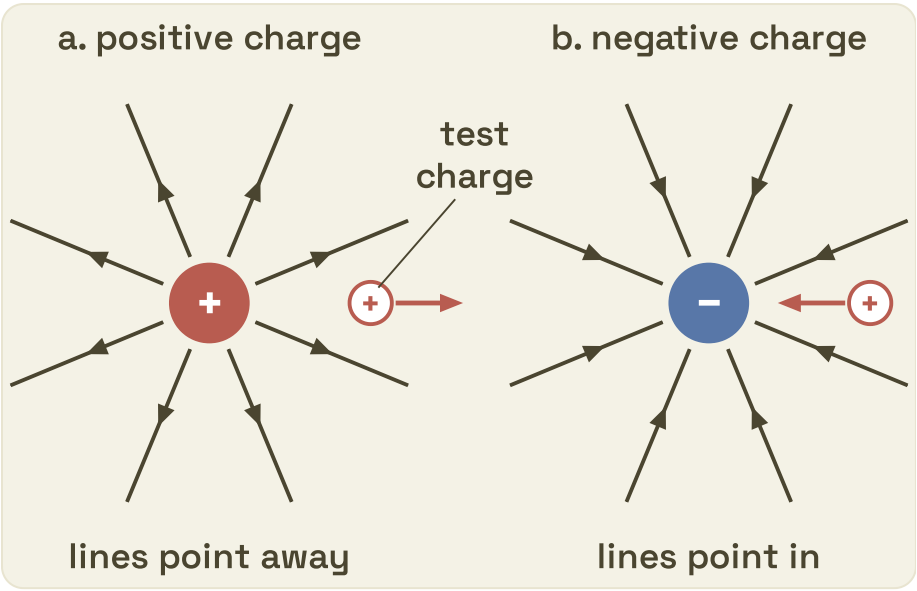


Figure 14.2 *The field round a single point charge. a. Round a positive charge, the lines of force point straight outward; a small positive test charge (red arrow) is pushed away. b. Round a negative charge, they point inward, and the test charge is pulled in. The lines crowd together near the charge, where the field is strongest.*

Check 1

Which way do the lines of force point round a negative point charge?

a outward, away from the charge

b inward, toward the charge

c in circles round the charge

d there are no lines round a negative charge

Like and unlike charges

When two charges are near each other, their fields add, and the lines bend. Between a **positive and a negative charge** (unlike charges), many lines run straight from one to the other, and the rest curve round to join them: the lines seem to pull the two together, and the charges **attract**.

Between **two positive charges** (like charges), no line joins them. The lines from each bend away from the other, as if squeezed apart: the charges **repel**. Exactly halfway between two equal like charges, the two fields are equal and opposite and cancel. A test charge there would feel no force at all. Such a point, where the field is zero, is a **neutral point**.

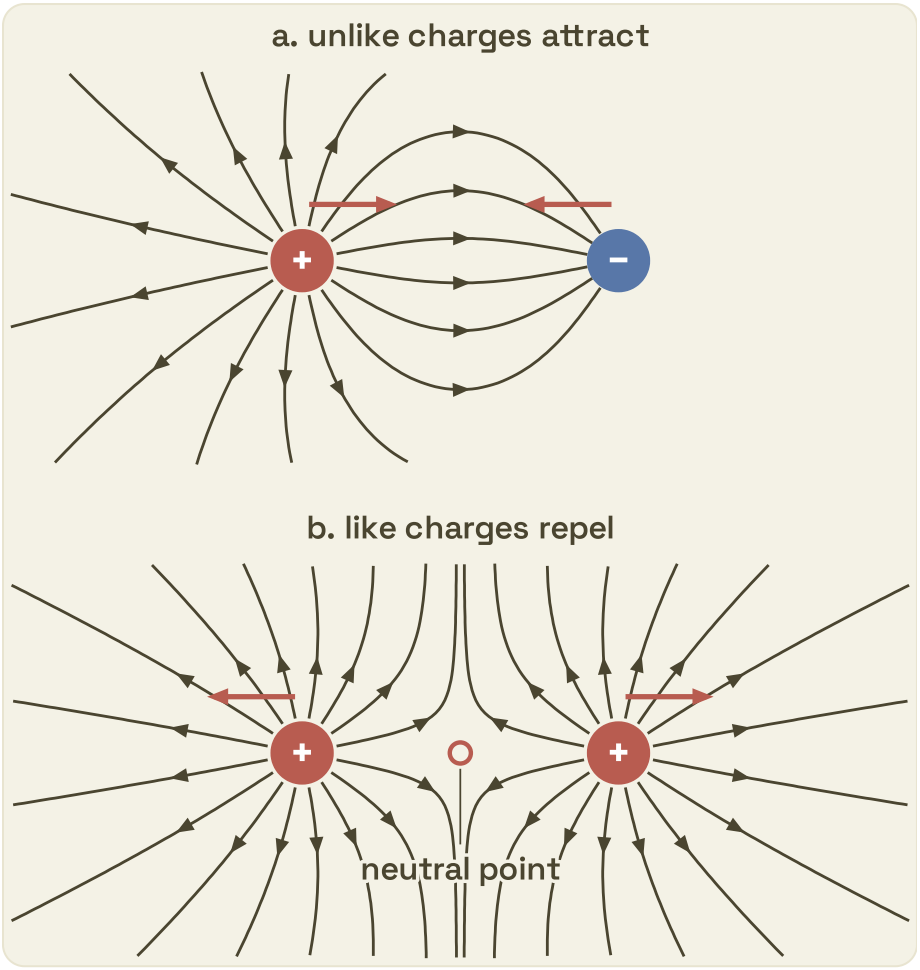


Figure 14.3 *Lines of force between two charges, worked out from the field. a. A positive and a negative charge: lines run from + to −, and the charges pull toward each other (red arrows). b. Two positive charges: no line goes from one to the other, the lines bend apart, and the charges push away from each other. Halfway between them is a neutral point, where the field is zero.*

So the direction of the electrostatic force follows from the kinds of charge: **like charges repel and unlike charges attract**. The force on each charge lies along the line joining them: away from the other charge for like charges, toward it for unlike ones.

Coulomb's law

How big is the force between two charges? In 1785 the French engineer Charles-Augustin de Coulomb measured it with a **torsion balance**: a light rod hanging from a thin wire, with a small charged ball at one end. A second charged ball pushed the first, the rod turned, and the wire twisted. How far it twisted told him the size of the force, and he could change the charges and the distance between the balls.

He found two things:

1. The force is **directly proportional to the product of the charges**: $F \propto q_1 q_2$. Double one charge and the force doubles; double both and it becomes four times as big.
2. The force is **inversely proportional to the square of the distance** between them: $F \propto \dfrac{1}{r^2}$. Double the distance and the force falls to a quarter.

Together these make **Coulomb's law**:

> The force of attraction or repulsion between two point charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them, and it acts along the line joining them.

$$F \propto \frac{q_1 q_2}{r^2} \quad \Rightarrow \quad F = \frac{k\, q_1 q_2}{r^2}$$

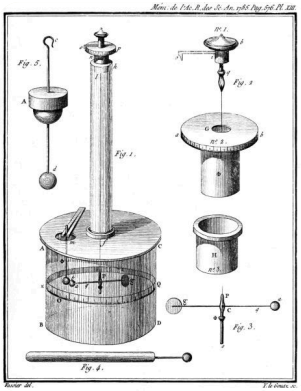


Figure 14.4 *Coulomb's torsion balance, from his paper of 1785. The rod hangs from a fine wire in the tall tube. A charged ball on the rod is pushed away by a second charged ball, and the angle the wire twists through measures the force.*
Photo: Charles-Augustin de Coulomb, Public domain

Here q_1 and q_2 are the charges in coulombs, r the distance between them in meters, F the force in newtons, and k is **Coulomb's constant**. In air or a vacuum,

$$k = 9 \times 10^9 \text{ N m}^2/\text{C}^2$$

(more precisely, 8.99×10^9; the rounded value is used in every calculation in this book). It is often written as $k = \dfrac{1}{4\pi\varepsilon_0}$, where $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/(N m^2) is a constant called the permittivity of free space.

The value of k tells us what one coulomb means. Put $q_1 = q_2 = 1$ C and $r = 1$ m into the law: $F = 9 \times 10^9$ N. So:

One coulomb is the charge which, placed 1 m from an equal charge in a vacuum, repels it with a force of 9×10^9 N.

That is the weight of about 900,000 tonnes, more than ninety thousand loaded trucks. A coulomb is a huge charge for static electricity: a rubbed comb carries a few nanocoulombs at most. Yet a coulomb flows through a torch bulb every few seconds, because the electrons in a current come with an equal positive charge in the metal around them, so they make no field outside the wire. One coulomb is the charge of about 6.25×10^{18} electrons; one electron carries 1.6×10^{-19} C.

The widget shows two more facts of the law. The forces on the two balls are always **equal in size and opposite in direction**, even when one charge is much bigger: this is Newton's third law. And the force depends only on the **product** of the charges: +1 μC and +4 μC push each other exactly as hard as +2 μC and +2 μC.

WORKED EXAMPLE

Two positive charges

Two small balls with charges of +3 μC and +4 μC are 20 cm apart in air. Find the force between them.

Answer

$q_1 = 3 \times 10^{-6}$ C, $q_2 = 4 \times 10^{-6}$ C, r = 20 cm = 0.20 m.

$$F = \frac{kq_1q_2}{r^2} = \frac{9 \times 10^9 \times 3 \times 10^{-6} \times 4 \times 10^{-6}}{(0.20)^2} = \frac{0.108}{0.04} = 2.7 \text{ N}$$

2.7 N, a repulsion (both charges are positive).

WORKED EXAMPLE

Finding a charge

Two equal charges 10 cm apart in air repel each other with a force of 0.9 N. Find each charge.

Answer

$q_1 = q_2 = q$, r = 0.10 m, F = 0.9 N.

$$F = \frac{kq^2}{r^2} \quad \Rightarrow \quad q^2 = \frac{Fr^2}{k} = \frac{0.9 \times 0.01}{9 \times 10^9} = 10^{-12} \text{ C}^2$$

q = 10^{-6} C. **Each charge is 1 μC.** (They repel, so both are positive or both negative; the force alone can't tell which.)

WORKED EXAMPLE

Finding a distance

A charge of $+2\ \mu\text{C}$ attracts a charge of $-8\ \mu\text{C}$ with a force of 1.6 N. How far apart are they?

Answer

For the size of the force, use the sizes of the charges; the signs only say it is an attraction.

$$r^2 = \frac{kq_1q_2}{F} = \frac{9\times10^9\times2\times10^{-6}\times8\times10^{-6}}{1.6} = \frac{0.144}{1.6} = 0.09\ \text{m}^2$$

r = 0.3 m, that is, 30 cm.

WORKED EXAMPLE

Changing the distance and the charges

Two charges attract each other with a force of 12 N. What will the force be if (i) the distance between them is doubled; (ii) one charge is tripled and the distance halved?

Answer

i. $F \propto \frac{1}{r^2}$: doubling r divides F by $2^2 = 4$. **The new force is 3 N.**

ii. Tripling one charge multiplies F by 3; halving r multiplies it by $2^2 = 4$. **The new force is $12 \times 3 \times 4 = 144$ N.**

YOUR TURN

Two charges of $+6$ nC and -2 nC are 3 cm apart. Find the force between them, and say whether it is a push or a pull.

Answer

r = 0.03 m, so $F = \frac{9\times10^9\times6\times10^{-9}\times2\times10^{-9}}{(0.03)^2} = \frac{1.08\times10^{-7}}{9\times10^{-4}} = 1.2\times10^{-4}$ N. **1.2×10^{-4} N, an attraction** (unlike charges).

From Coulomb's law to the field of a point charge

Now you can see where $E = \frac{kQ}{r^2}$ comes from. Put a test charge q_0 at a distance r from a charge Q. Coulomb's law gives the force on it, and dividing by q_0 gives the field:

$$F = \frac{kQq_0}{r^2} \quad \Rightarrow \quad E = \frac{F}{q_0} = \frac{kQ}{r^2}$$

The test charge cancels out, as it should: the field belongs to Q, not to whatever we use to test it.

Electricity and gravity

Coulomb's law looks just like Newton's law of gravitation, $F = \frac{Gm_1m_2}{r^2}$, which you met in Grade 9 Science. Both forces fall off as the square of the distance. But they differ in important ways.

Gravitational force	Electrostatic force
Acts between masses.	Acts between charges.
Always attracts.	Attracts or repels, depending on the kinds of charge.
$G = 6.67 \times 10^{-11}$ N m^2/kg^2: very weak.	$k = 9 \times 10^9$ N m^2/C^2: very strong.
Doesn't depend on what lies between the bodies.	Weaker when an insulator such as water or glass lies between the charges.
Holds planets, stars and galaxies together.	Holds atoms, molecules and solid bodies together.

Between two protons, the electrostatic push is about 10^{36} times as strong as the gravitational pull. Gravity rules the sky only because big bodies have almost exactly as much positive charge as negative, so their electric forces cancel, while their masses always add. Why gravity is so weak, and the fields of both forces side by side, are in Going Further: Why is gravity so weak?.

WORKED EXAMPLE

Inside a hydrogen atom

In a hydrogen atom the electron is, on average, about 5.3×10^{-11} m from the proton. Each carries a charge of 1.6×10^{-19} C. Find the force between them.

Answer

$$F = \frac{ke^2}{r^2} = \frac{9 \times 10^9 \times (1.6 \times 10^{-19})^2}{(5.3 \times 10^{-11})^2} = \frac{2.30 \times 10^{-28}}{2.81 \times 10^{-21}} = 8.2 \times 10^{-8} \text{ N}$$

About 8.2×10^{-8} N, an attraction. It sounds small, but the electron's mass is only 9.1×10^{-31} kg, so this force gives it an acceleration of about 9×10^{22} m/s^2: it is this pull that keeps the electron bound to the atom.

DID YOU KNOW?

Why salt dissolves in water

Coulomb's law with $k = 9 \times 10^9$ is for charges in air or a vacuum. Put the same charges in water, and the force between them is about **80 times weaker**: the water molecules, each a little positive at one end and negative at the other, turn to face the charges and partly cancel their fields. That is why common salt, whose sodium and chloride ions hold each other tightly in a crystal, falls apart into ions in water, and why water conducts when salt is dissolved in it (Unit 8, Electrolysis).

Check 2

The force between two charges is F. If both charges are doubled and the distance between them is also doubled, the force becomes:

a F/4
b F
c 2F
d 4F

Check 3

What is the SI unit of electric field intensity?

a coulomb per newton
b newton per coulomb
c newton meter
d coulomb

14.2 Capacitor

A camera's flash fires in a thousandth of a second, brighter than anything a small battery could light directly. The battery charges a component inside it for a few seconds, and that component lets all its charge go at once into the flash tube. The component is a **capacitor**.

A capacitor is a device that stores electric charge. It is made of two conductors, usually metal plates or foils, close together but separated by an insulator.

The insulator between the plates is called the **dielectric**: air, paper, plastic, mica, ceramic or a thin layer of oxide. In the circuit symbol, the two plates are two short parallel lines.

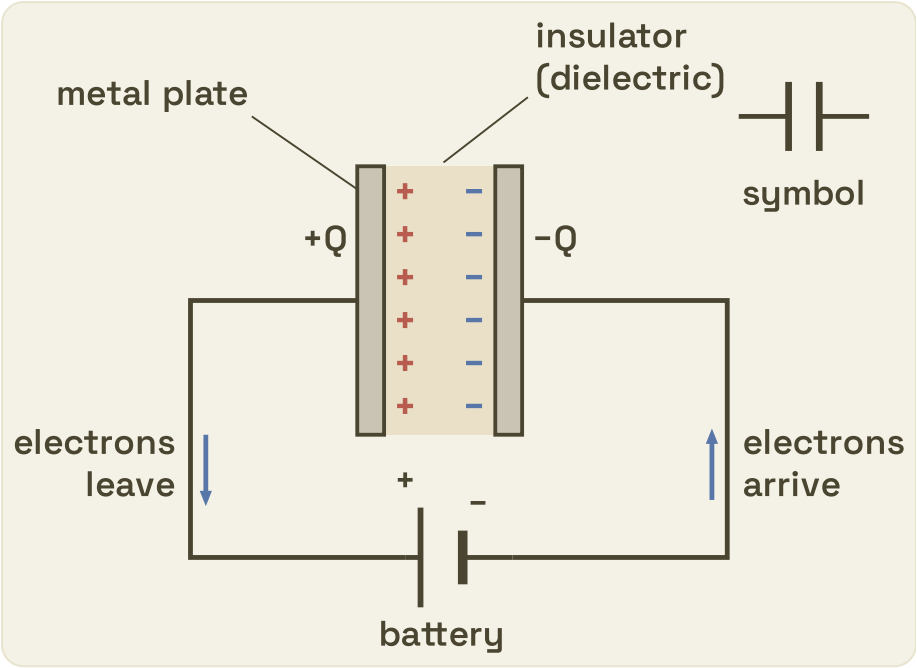


Figure 14.5 *A charged capacitor. Two metal plates face each other across a thin insulator, the dielectric. The battery has pulled electrons off the left plate and pushed the same number onto the right plate, so the left plate has a charge +Q and the right plate −Q. Inset: the circuit symbol.*

Charging and discharging

Connect the two plates to a battery. The battery pulls electrons off the plate joined to its positive terminal and pushes them round the circuit onto the other plate. No electrons cross the gap; the dielectric stops them. So one plate becomes positive, the other

equally negative. As the charges build up, the plates push back against the battery more and more, and the flow slows down. When the voltage across the capacitor equals the battery's voltage, the flow stops: the capacitor is **charged**.

Disconnect the battery, and the charges stay where they are, held by their attraction across the gap. The capacitor is storing charge. Now join its plates through a bulb: the extra electrons on the negative plate flow round to the positive plate, the bulb glows for a moment, and the capacitor **discharges**.

Notice that a charged capacitor's plates hold equal and opposite charges, +Q and −Q. When we say a capacitor "stores a charge Q", we mean the charge on either plate, not the total, which is zero.

Capacitance

The widget shows that the charge a capacitor stores depends on two things: the voltage across it, and the capacitor itself. For any one capacitor, the charge is **directly proportional to the voltage**: double the voltage and it stores twice the charge. So the ratio of charge to voltage is fixed for each capacitor. That ratio is its **capacitance**, C:

$$C = \frac{Q}{V} \qquad \text{so} \qquad Q = CV$$

The capacitance of a capacitor is the ratio of the charge on either plate to the potential difference between the plates. It tells how much charge the capacitor stores for each volt across it.

The unit of capacitance

The SI unit of capacitance is the **farad (F)**, named after Michael Faraday. One farad is one coulomb per volt:

A capacitor has a capacitance of one farad if a potential difference of one volt across it puts a charge of one coulomb on its plates.

A farad is enormous. A capacitor of 1 F made of two flat plates 1 mm apart in air would need plates of about 113 km² each: nearly 16,000 football fields. So capacitances are usually given in smaller units:

Unit	Symbol	Value
microfarad	μF	10^{-6} F
nanofarad	nF	10^{-9} F
picofarad	pF	10^{-12} F

A capacitor's capacitance and the highest voltage it can safely take are printed on it, such as "470 µF 25 V". Above that voltage, the dielectric can break down and let charge spark across.

WORKED EXAMPLE

The charge on a capacitor

A capacitor marked 470 µF is connected to a 12 V battery. How much charge does it store?

Answer

$C = 470\ \mu\text{F} = 470 \times 10^{-6}$ F, $V = 12$ V.

$$Q = CV = 470 \times 10^{-6} \times 12 = 5.64 \times 10^{-3}\ \text{C}$$

5.64 mC (millicoulombs) on each plate.

WORKED EXAMPLE

Finding the capacitance

A capacitor stores 2 mC when there is 20 V across it. Find its capacitance. How much would it store at 5 V?

Answer

$$C = \frac{Q}{V} = \frac{2 \times 10^{-3}}{20} = 10^{-4}\ \text{F} = 100\ \mu\text{F}$$

At 5 V: $Q = CV = 10^{-4} \times 5 = 5 \times 10^{-4}$ C = 0.5 mC. **100 µF; 0.5 mC at 5 V**, a quarter of the charge for a quarter of the voltage.

YOUR TURN

What voltage puts a charge of 9 mC on a 1,000 µF capacitor?

Answer

$V = \dfrac{Q}{C} = \dfrac{9 \times 10^{-3}}{1000 \times 10^{-6}} = 9$ V. **9 V.** (Check it in the widget.)

What makes the capacitance bigger

A capacitor holds more charge for each volt when:

- its **plates are bigger**: there is more room for the charges to spread out;
- its **plates are closer together**: the attraction across the gap holds more charge;

- a **better dielectric** lies between them: an insulator such as mica or ceramic weakens the field between the plates (as water weakens the force between ions), so more charge is needed to reach the same voltage.

So a real capacitor is often two long strips of metal foil with a thin plastic film between them, rolled up into a small cylinder. The biggest capacitances, thousands of farads, are in **supercapacitors**, whose "plates" are porous carbon with an enormous surface, and whose gap is only a few molecules wide.

A capacitor is not a cell

A capacitor and a cell both give out charge, but they work in very different ways.

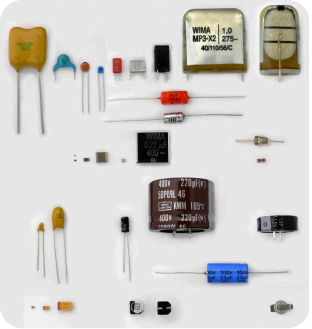


Figure 14.6 *Capacitors of many kinds. The small discs near the top left are ceramic capacitors, of picofarads to nanofarads; the big brown cylinder in the middle is an electrolytic capacitor of 220 µF, made for up to 400 V. Each has its capacitance and highest safe voltage printed on it, or written in a short code.*

Photo: Fabian ~ (Fabian R at de.wikipedia), CC BY-SA 3.0

Capacitor	Cell
Stores charge, as + and − charges on two plates.	Makes charge flow by chemical reactions inside it.
Its voltage falls steadily as it discharges.	Its voltage stays nearly steady until it is almost used up.
Can charge and discharge in a fraction of a second.	Takes minutes or hours to charge (if it can be recharged at all).
Stores little energy for its size.	Stores much more energy for its size.

Uses of capacitors in daily life

Almost every electrical device has capacitors in it. Some of their uses:

- **Camera flash.** A capacitor of a few hundred microfarads is charged to about 300 V over a few seconds, then empties through the flash tube in about a thousandth of a second.
- **Ceiling fans and water pumps.** Under a ceiling fan's cover, wired to its motor, is a small capacitor, usually of a few microfarads, that helps the motor start turning and run smoothly. When a fan hums but won't turn, or turns slowly, a worn-out capacitor is often the cause, and it is cheap to replace. Pumps, washing machines and fridges use bigger ones.
- **Phone chargers and power supplies.** A charger turns the mains' alternating current into direct current, which comes out in bumps. Large capacitors fill up at each bump and give charge back between them, smoothing the bumps into a steady voltage.
- **Radio and television tuning.** A capacitor and a coil together pick out one station's frequency; changing the capacitance changes the station.
- **Touchscreens.** A phone's screen has a grid of transparent conductors. Your finger, which conducts, changes the capacitance where it touches, and the phone works out where from those changes. This is why a touchscreen doesn't respond to a plastic pen or a gloved finger.
- **Computer memory.** Each bit in a computer's main memory (DRAM) is a tiny capacitor, charged for 1 and empty for 0. They leak, so the computer tops them all up every 64 milliseconds.
- **Defibrillators.** A defibrillator charges a capacitor to well over a thousand volts and then empties it through the chest of a person whose heart has stopped beating properly, to make it beat in time again.
- **Keeping electronics safe.** Small capacitors soak up sudden spikes of voltage that would harm a circuit, and they keep a clock or memory alive for a moment when the power flickers.

The energy a charged capacitor stores, and why it is half of what the battery gave it, is in Going Further: How do magnets push without touching? Grade 10 Optional Science goes on to the cells that store energy by chemistry, the secondary cells.

CAREFUL

A charged capacitor can bite

A big capacitor can stay charged for a long time after the device is switched off and unplugged. The capacitors inside a television, a microwave oven, a camera flash or a fan's regulator can give a painful or dangerous shock. Never open such a device. Electricians discharge a capacitor safely before working on it.

A STORY FROM SCIENCE

The jar that held electricity

In October 1745 the German churchman Ewald von Kleist tried to "store" electricity in a medicine bottle partly filled with alcohol, with a nail through its cork, charged from a machine that made charge by rubbing. Holding the bottle, he touched the nail and got a violent shock. A few months later, in Leiden in the Netherlands, Andreas Cunaeus and then the professor Pieter van Musschenbroek did the same with a jar of water held in the hand. Musschenbroek wrote in January 1746 that he would not take such a shock again for the kingdom of France. The **Leyden jar**, later made as a glass jar coated with metal foil inside and out, was the first capacitor: the two foils were the plates, the glass the dielectric. Within the year, the French physicist Jean-Antoine Nollet sent its shock through a line of 180 soldiers holding hands, before the king, and in the 1750s Benjamin Franklin used Leyden jars in his experiments that showed lightning is electricity.

Check 4

What is the job of the insulator between the plates of a capacitor?

a to let electrons flow from one plate to the other

b to keep the charges on the two plates apart, while letting their attraction hold more charge

c to make the capacitor conduct electricity

d to produce charge by chemical reactions

Check 5

1 μF is equal to:

a 10^{-3} F

b 10^{-6} F

c 10^{-9} F

d 10^{-12} F

14.3 Magnetic lines of force around a bar magnet

A magnet, too, fills the space around it with a field. **A magnetic field** is the region around a magnet in which another magnet, or a piece of iron, experiences a magnetic force. A compass needle is a small magnet free to turn, so it lines up with the field wherever it is placed: its north-seeking end, the **N pole**, points the way the field points.

Just as for electric fields, a magnetic field is drawn with **magnetic lines of force** (also called **magnetic field lines**).

A magnetic line of force is the path along which a free, isolated north pole would tend to move in a magnetic field. The tangent to it at any point gives the direction of the magnetic field there, which is the direction the N pole of a compass needle points.

No real north pole exists on its own (cut a magnet in two and each half has its own N and S), but a small compass is close enough: its N end is pushed along the line, its S end the other way, and the needle settles along the line.

Properties of magnetic lines of force

- Outside a magnet, they go **from the N pole to the S pole**. Inside the magnet, they go from S to N, so every line is a **closed loop**. (This is one difference from electric lines of force, which start and end on charges.)
- The **tangent** at any point gives the direction of the field there.
- They **never cross** each other: the field at a point can point only one way.
- They are **crowded together where the field is strong**, near the poles, and spread out where it is weak.
- In a **uniform field**, such as the Earth's field over a small table far from any magnet, they are straight, parallel and evenly spaced.
- They tend to **shorten**, like stretched rubber bands, which is why unlike poles pull together, and they **push sideways** on each other, which is why like poles push apart.

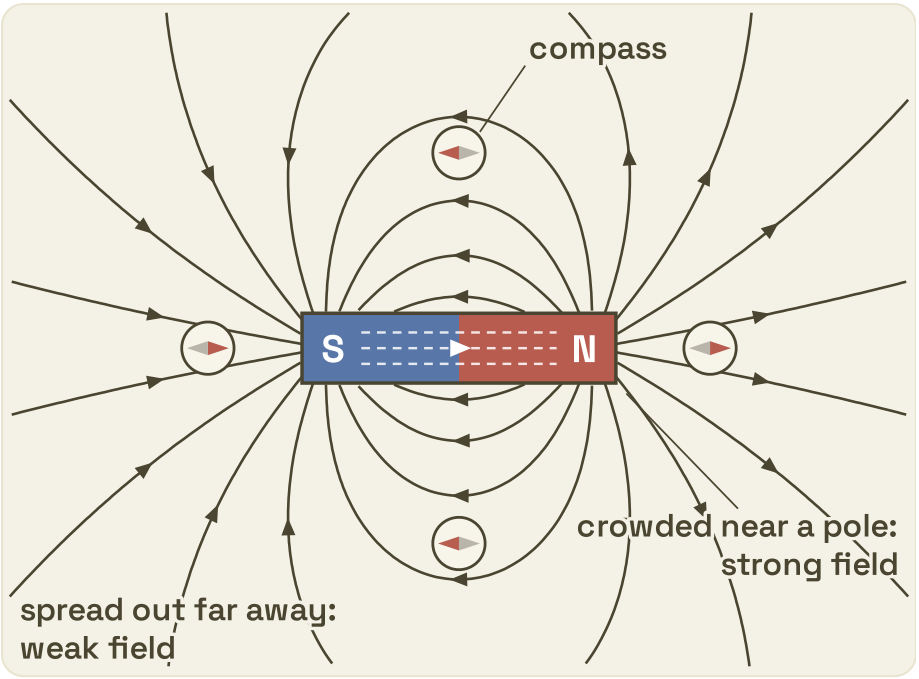


Figure 14.7 *Magnetic lines of force round a bar magnet, worked out from its field. Outside the magnet, the lines leave the N pole and curve round into the S pole; inside it (dashed), they run from S back to N, so each line is a closed loop. A compass placed anywhere settles along the line through it, its N end (red) pointing along the arrow.*

CAREFUL

Lines inside the magnet

Many drawings, and many exam answers, show the lines only outside the magnet, going from N to S, and stopping at the poles. That is fine for showing the pattern, and it is what the practical shows, since a compass can't go inside the magnet. But the lines don't stop: inside the magnet they continue from S to N, so each is a closed loop. If an exam asks for a property of magnetic lines of force, "they form closed loops, from N to S outside the magnet and from S to N inside" is the full answer.

Plotting the lines with a compass

You can draw the lines round a magnet for yourself with a small **plotting compass**, a compass about 1–2 cm across. The idea is simple: a compass needle always lies along

a line of force, so if you mark where its two ends are, then move the compass on so its tail sits where its head was, the marks follow the line step by step.

Neutral points

On the table, the compass feels two fields at once: the magnet's, and the Earth's, which is weak but the same everywhere on the table and points north. Close to the magnet, the magnet's field is far stronger, and the lines curve round from N to S. Far away, the Earth's field wins, and the lines run north. In between, at a few points, the magnet's field is exactly as strong as the Earth's and points exactly the opposite way. There the two cancel.

A neutral point is a point in a magnetic field where the resultant field is zero: the field of the magnet is equal and opposite to the Earth's horizontal field. A compass placed there doesn't point in any particular direction.

Where are they? Wherever the magnet's field points **south**, opposite to the Earth's.

- **N pole pointing north:** to either side of the magnet's middle, its field runs from the N end back to the S end, which is southward. So the two neutral points lie **east and west of the magnet**, on the line through its center at right angles to it. For the magnet in the widget, about 12.5 cm from the center.
- **N pole pointing south:** beyond each end, along the magnet's axis, its field points south (away from the N pole, beyond the N end; toward the S pole, beyond the S end). So the two neutral points lie **on the axis, beyond both poles**, north and south of the magnet. For the same magnet, about 16.5 cm from the center.

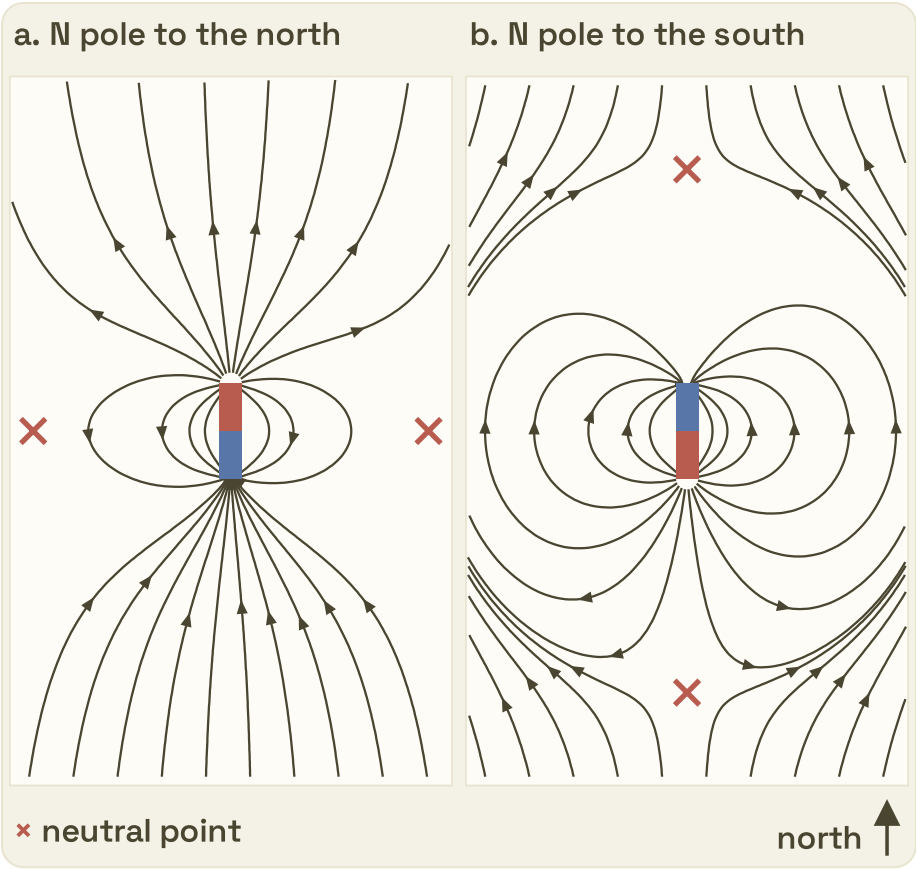


Figure 14.8 *The lines of force of a bar magnet on a table together with the Earth's field, worked out for a 6 cm magnet (its N pole red, its S pole blue), and its two neutral points (×). a. N pole pointing north: the neutral points are east and west of the magnet. b. N pole pointing south: they are on the magnet's axis, beyond its ends. Far from the magnet, in both, the lines run straight to the north.*

Check 6

A compass is placed at a neutral point near a bar magnet. Its needle:

a points north–south

b points toward the magnet's N pole

c doesn't settle in any particular direction

d spins round and round

Check 7

A bar magnet lies on a table with its N pole pointing north. Where are its neutral points?

a beyond its N pole and beyond its S pole, on its axis

b east and west of it, on the line through its middle at right angles to it

c at its two poles

d there are none

14.4 Magnetic field pattern of the Earth

A compass points north because the Earth itself is a magnet, as you learned in Grade 8. In 1600 the English doctor William Gilbert showed it with a **terrella**, a ball of lodestone, a naturally magnetic rock: a small compass needle moved over its surface behaved just as a compass does on the Earth, pointing toward its poles and tilting down near them. He concluded that the Earth is one great magnet.

Today we know the field comes from slow currents of molten iron in the Earth's outer core, about 2,900 km below us. These currents work like a dynamo, and the field they make looks, outside the Earth, very nearly like the field of a huge bar magnet placed at the Earth's center.

The pattern has these features:

- The lines of force **come out of the Earth in the southern hemisphere** and **go back in, in the northern hemisphere**. Outside the Earth they run from the geographic south to the geographic north. This is why a compass's N end points north: it points along the lines.
- So the pole of the Earth's magnet in the far north, which attracts the N pole of every compass, is magnetically a **south pole**, and the one in the far south a **north pole**.
- The **magnetic axis** doesn't line up with the geographic axis. The two make an angle of about 10°, so the Earth's magnetic poles are not at its geographic poles.
- Near the **magnetic equator**, the lines run parallel to the ground. Near the magnetic poles, they plunge steeply into the ground (in the north) or rise steeply out of it (in the south). In between, as in Nepal, they slope.
- The field at the Earth's surface is weak: from about 25 μT (microteslas) near the magnetic equator to about 65 μT near the magnetic poles. In Kathmandu it is about 49 μT. A fridge magnet is about a hundred times stronger, close up.

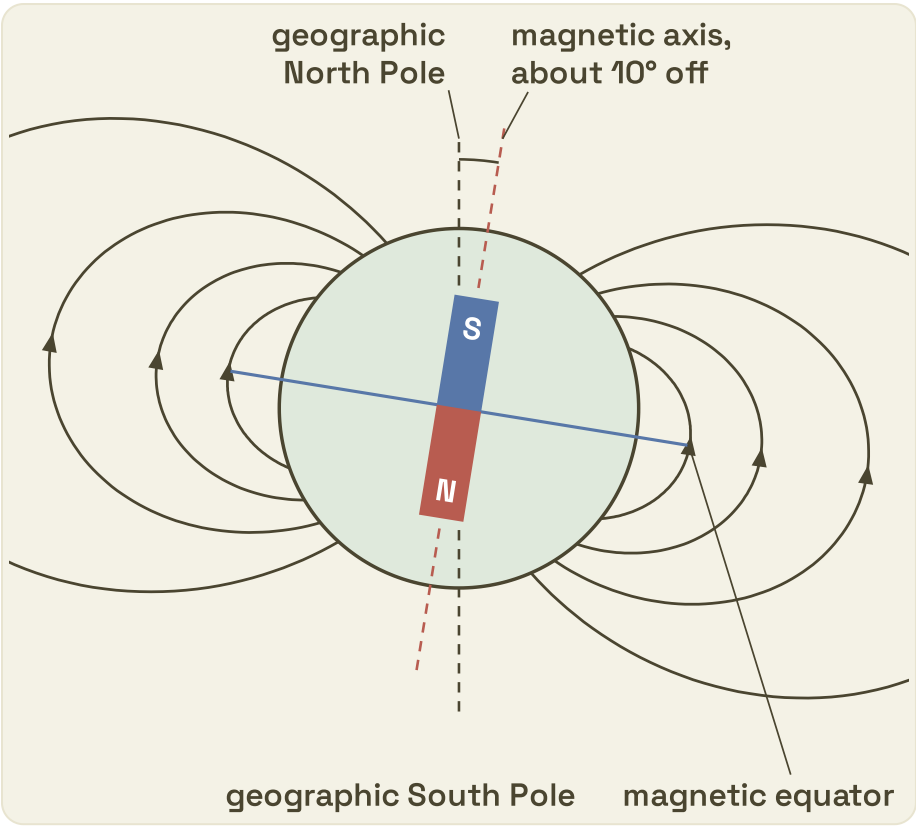


Figure 14.9 *The Earth's magnetic field, drawn as the field of a bar magnet at its center. Outside the Earth, the lines of force leave the southern half and enter the northern half. So the magnet inside has its* ***S pole toward the geographic north****. Its axis, the* ***magnetic axis****, is tilted from the axis the Earth spins on by about 10° (9.2° in 2026). The* ***magnetic equator*** *runs round the Earth at right angles to the magnetic axis.*

CAREFUL

The pole in the north is a south pole

The point in the far north that compasses point to is called the **North Magnetic Pole**, because it is in the north. But magnetically it is a **south pole**: it attracts the N pole of a compass, and unlike poles attract. If an exam asks what kind of magnetic pole lies near the geographic North Pole, the answer is a south pole.

The field helps living things too. Pigeons, migrating birds, sea turtles and salmon sense the Earth's field and use it to find their way, sometimes across thousands of kilometers.

DID YOU KNOW?

“The magnetic pole” means two places

There are two ways to say where the magnetic pole in the north is. One is the **dip pole**, where a free needle stands straight up and down; in 2026 it was at about 85.5° N, north of Siberia, and in recent decades it has moved tens of kilometers a year, from northern Canada toward Siberia. The other is the end of the magnetic axis of the bar magnet that best matches the whole field, the **geomagnetic pole**, at about 81° N. The two differ because the real field is not exactly a bar magnet’s. Both are near, but not at, the geographic North Pole. The figures in this book are computed from IGRF-14, the International Geomagnetic Reference Field, the model of the Earth’s field that the world’s observatories agree on.



Figure 14.10 *The northern lights, or aurora, above a fjord in northern Norway. Charged particles from the Sun are steered by the Earth’s field down the lines of force near the magnetic poles, where they strike the air high above the ground and make it glow. The field also shields the rest of the Earth from most of these particles.*
Photo: Ximonic (Simo Räsänen), CC BY-SA 3.0

DID YOU KNOW?

The field turns over

The Earth’s field has not always pointed the same way. Lava, as it cools, keeps a record of the field it cooled in, locked into its tiny magnetic crystals. Rocks of different ages show that the field has **reversed** hundreds of times, the north and south magnetic poles changing places. The last full reversal was about 780,000 years ago. Nobody can yet say when the next will be; it would take thousands of years to happen.

Check 8

Which statement about the Earth's magnetic field is correct?

a The lines of force go into the Earth near the geographic South Pole.

b The magnetic pole near the geographic North Pole is a south pole.

c The magnetic axis lines up exactly with the Earth's axis of rotation.

d The field is strongest at the magnetic equator.

14.5 Angle of dip and angle of declination

A compass tells you which way is north, roughly. But the Earth's field at a place points in a particular direction in space, and two angles are needed to describe it: one says how far it is turned from true north, and the other how steeply it slopes into the ground. They are two of the **elements of the Earth's magnetism**, which you met in Grade 8.

Two meridians

Imagine a vertical plane at a place, passing through the Earth's geographic North and South Poles. It is the **geographic meridian** (or true meridian) of the place. The line where it meets the ground runs true north–south, the direction a map's grid lines and the Pole Star show.

Now imagine the vertical plane that a freely hanging compass needle settles in, the plane containing the Earth's field at that place. It is the **magnetic meridian**. Its line on the ground is the direction a compass needle points.

The two are not usually the same, because the Earth's magnetic poles are not at its geographic poles.

Angle of declination

The angle of declination (or **magnetic declination**) at a place is the angle between the geographic meridian and the magnetic meridian there. It is the angle by which a compass needle points away from true north.

It is called **east** declination if the compass points east of true north, and **west** if it points west of it. It changes from place to place, and slowly, from year to year. Near the magnetic poles it can be tens of degrees; in some places it is zero, and there a compass points exactly to true north.

In Nepal the declination is small. Computed from the international model of the Earth's field, IGRF-14 (not measured in a survey), in 2026 it is about 0.1° E at Biratnagar, 0.4° E at Kathmandu, 0.6° E at Pokhara and 1.1° E at Mahendranagar: a

compass anywhere in Nepal points less than a degree and a half east of true north. In Kathmandu, the tip of a compass needle 10 cm long sits less than half a millimeter from where it would be if it pointed to true north.

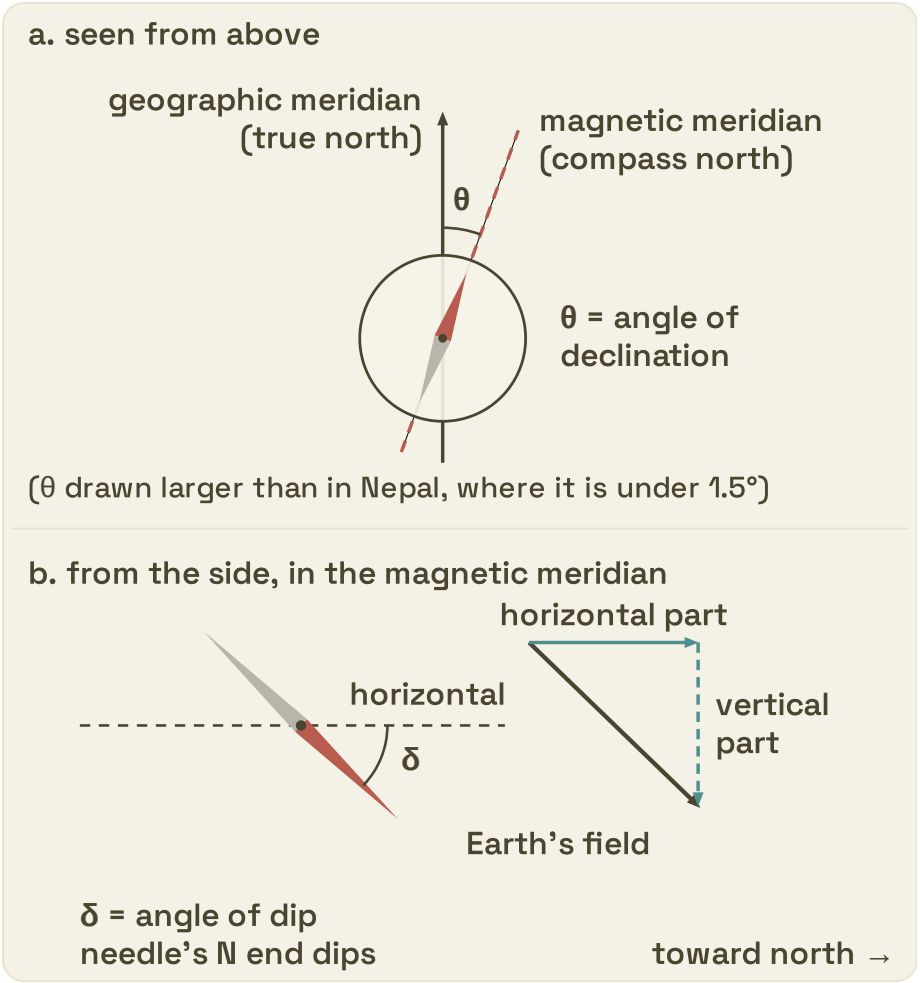


Figure 14.11 *a. Seen from above: the angle of declination, θ, between the geographic meridian (true north) and the magnetic meridian (where a compass points). It is drawn far larger than it is in Nepal. b. Seen from the side, in the magnetic meridian: a magnetic needle free to turn up and down settles along the Earth's field, its N end dipping below the horizontal by the angle of dip, δ. Beside it, the Earth's field split into a horizontal part and a vertical part.*

Angle of dip

A compass needle turns only in a horizontal plane, so it shows only the direction of the field along the ground. But the Earth's field also slopes. Hang a magnetized needle so that it can turn freely in a vertical plane, set in the magnetic meridian, and it doesn't rest level: in Nepal, its N end dips down by more than 40°.

The angle of dip (or **angle of inclination**) at a place is the angle that the Earth's magnetic field there makes with the horizontal, in the magnetic meridian. It is the angle by which a freely suspended magnetic needle, turning in the magnetic meridian, dips below the horizontal.

It changes with latitude, roughly as the lines of force in the figure slope:

Where	Angle of dip
At the magnetic equator	0°: the needle rests level
Between the magnetic equator and the magnetic north pole (Nepal, India, Europe)	the N end dips down, more the farther north
At the magnetic north pole	90°: the needle stands straight up and down, N end down
South of the magnetic equator (Australia, South Africa)	the S end dips down

In 2026, computed from the same model (IGRF-14), the angle of dip is about 42° at Biratnagar, 44° at Kathmandu, 45° at Pokhara, 46° at Mahendranagar and 47° at Jumla. The magnetic equator passes just south of India's southern tip, across Sri Lanka.

> CAREFUL
> **42° or 44°?**
>
> Some books give the angle of dip at Kathmandu as 42°. That was right around the year 2000 (41.6° by the international model): the Earth's field slowly changes, and by 2026 it is about 44°. Either may come up in an exam: 42° is the older figure, 44° today's.

Because the dip grows steadily from the magnetic equator toward the poles, it gives a rough idea of how far north or south one is, a fact sailors once used when they couldn't see the stars. A navigator with a dip needle could tell, on a cloudy night, roughly how far north of the magnetic equator the ship was.

DID YOU KNOW?

The field's two parts

The Earth's field at a place slopes down at the angle of dip, δ. It can be split into a **horizontal part**, H, along the ground in the magnetic meridian, which turns a compass, and a **vertical part**, V, straight down, which a compass doesn't feel. They make a right-angled triangle with the whole field, so

$$\tan\delta = \frac{V}{H}$$

In Kathmandu in 2026, H is about 35 μT and V about 34 μT, almost equal, so δ is a little under 45°. At the magnetic equator V = 0 and δ = 0°; at the magnetic poles H = 0 and δ = 90°, and an ordinary compass there has nothing to turn it.

Uses of the angle of declination and the angle of dip

- **Using a compass with a map.** Maps are drawn to true north, compasses point to magnetic north. Walkers, surveyors and soldiers add or subtract the declination to turn a compass bearing into a true one. In Nepal the correction is under 1.5°, often small enough to ignore over short distances, but near the magnetic poles it can be tens of degrees.
- **Ships and aircraft.** Compasses and navigation systems correct for the declination at every place along the route. Airport runways are numbered by their magnetic direction, rounded to the nearest 10° and divided by 10: Kathmandu's Tribhuvan International Airport's single runway points about 21° and 201° from magnetic north, so its two ends are numbered **02** and **20**. When the declination drifts, runways somewhere in the world have to be renumbered and their signs repainted.
- **Phones.** A phone has a tiny magnetic sensor. Its map app works out the declination for where the phone is, from a model of the Earth's field, and turns the magnetic reading into true north.
- **Finding latitude.** The angle of dip changes steadily with distance from the magnetic equator, so it was once used to estimate latitude.
- **Searching for minerals.** Iron ore and some other rocks change the field above them a little, changing the dip and declination there. Geologists map these small changes to find buried ore and to study the rocks below.
- **Studying the Earth.** Observatories record the declination and dip continuously, to follow the slow changes in the Earth's field, to warn of magnetic storms from

the Sun, and to keep the world's model of the field up to date, which is renewed every five years.

Finding the angle of declination

To find the declination at a place, you need two directions: true north and magnetic north. A compass gives magnetic north directly. True north can be found from the Sun, using a vertical stick.

At an observatory, the declination is measured much more precisely, with an instrument called a **declinometer**: a magnetometer that finds the magnetic meridian, mounted on a telescope that finds true north from the stars or the Sun.

Finding the angle of dip

The angle of dip is measured with a **dip circle** (or **dip needle**). It is a magnetic needle on a horizontal axle through its center, so that it can turn up and down in a vertical plane, in front of a vertical circular scale marked 0° at the horizontal and 90° straight up and down. The circle and needle stand on a base that turns on a horizontal scale, so the whole plane of the needle can be turned to face any direction, and a spirit level and leveling screws keep the base level.

It is used like this:

1. **Level the base**, using the leveling screws and the spirit level, so that the vertical scale is truly vertical.
2. **Set the circle in the magnetic meridian.** Turn the circle on the horizontal scale until the needle stands straight up and down (reads 90°). The needle's plane is then at right angles to the magnetic meridian: in that direction the needle feels only the field's vertical part. Note the reading on the horizontal scale, then turn the circle through exactly 90°. Now the needle swings in the magnetic meridian.
3. **Read the angle of dip** at both ends of the needle and take their mean. To cancel small errors of the instrument, turn the circle through 180° and read both ends again, and average all the readings.

Why does step 2 matter? In any other vertical plane, the needle feels only part of the field's horizontal part, but all of its vertical part, so it dips **more steeply** than the true angle of dip. In a plane at right angles to the meridian it would stand straight up and down, reading 90° anywhere off the magnetic equator. Only in the magnetic meridian does the needle show the true dip. So the reading is never smaller than the true dip; the smallest reading, when the circle is turned slowly round, is the angle of dip.

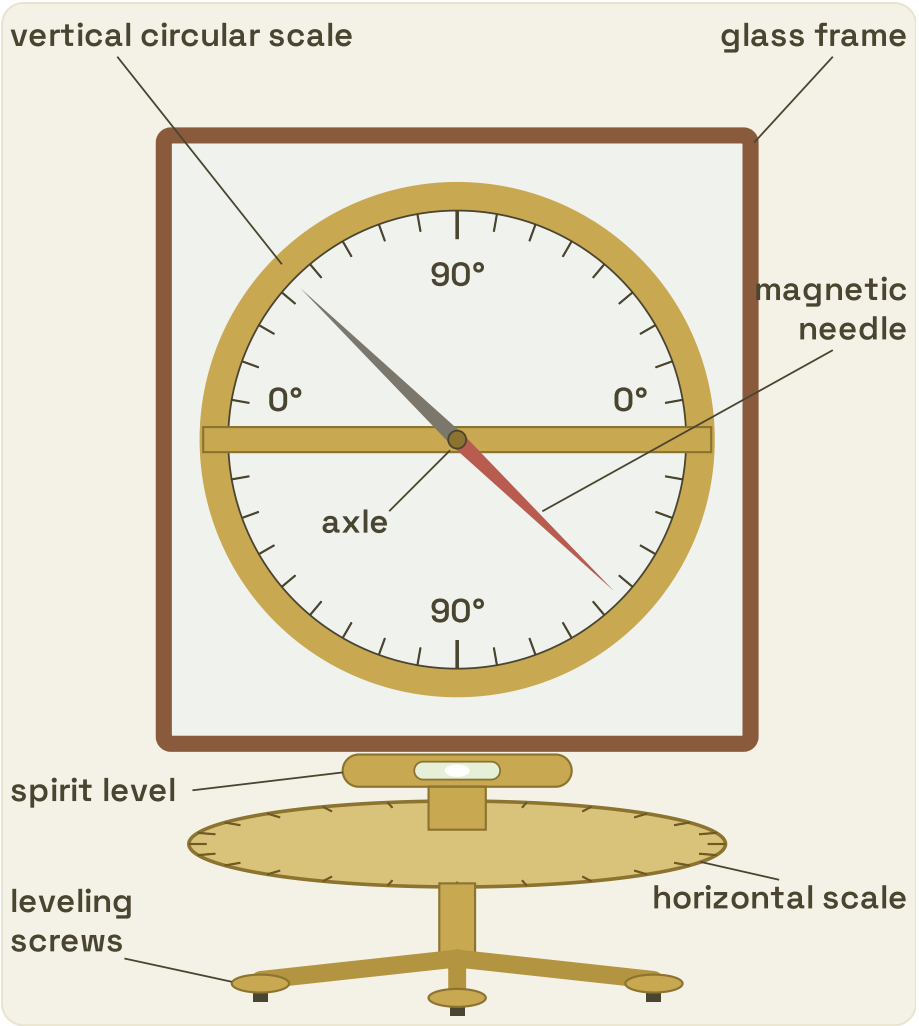


Figure 14.12 *A dip circle. The magnetic needle turns on an axle at the center of a vertical circular scale, inside a glass frame. The frame turns on a horizontal circular scale, so the needle's plane can be set in the magnetic meridian, and the spirit level and leveling screws set the base level. The needle is shown at Kathmandu's angle of dip, 44°.*



Figure 14.13 *An old dip circle in the University of Vienna's collection of historical physics instruments. The magnetic needle hangs on its axle inside the vertical scale, in a glazed wooden frame; the whole frame turns on the round scale below, and the three feet are leveling screws.*
Photo: W. Blaschnek, CC BY 4.0

WORKED EXAMPLE

Dip off the meridian

A dip circle is set up in Kathmandu, but by mistake its plane is turned 60° from the magnetic meridian. The true angle of dip is 44°. What will it read?

Answer

In the plane of the circle, the needle feels the field's vertical part, V, but only part of the horizontal part: H cos 60°. True dip: tan 44° = V/H = 0.966.

$$\tan\delta' = \frac{V}{H\cos 60^\circ} = \frac{0.966}{0.5} = 1.93 \quad \Rightarrow \quad \delta' = 62.6^\circ$$

It reads about 63°, far more than the true 44°. The farther the circle is from the magnetic meridian, the steeper the needle dips.

Check 9

At the magnetic equator, the angle of dip is:

a 0°
b 45°
c 90°
d equal to the angle of declination

Check 10

Why is a dip circle set in the magnetic meridian before the angle of dip is read?

a so that the needle points to true north
b so that the Earth's field can't affect it
c because in any other plane the needle feels less of the horizontal field and dips too steeply
d because the needle can only turn in the magnetic meridian

Check 11

In Nepal, a compass points:

a about 45° east of true north
b exactly to true north everywhere
c less than 1.5° east of true north
d about 10° west of true north

IN SHORT

- An **electric field** is the region round a charge in which another charge feels a force. Its **intensity** is the force on a unit positive charge, $E = F/q_0$, in N/C; for a point charge, $E = kQ/r^2$.
- **Electric lines of force** start on positive charges and end on negative charges, never cross, and are crowded where the field is strong. They point outward from a positive point charge and inward to a negative one.
- **Like charges repel, unlike charges attract**, along the line joining them. **Coulomb's law:** $F = \dfrac{kq_1q_2}{r^2}$, with $k = 9 \times 10^9$ N m²/C²: the force is proportional to the product of the charges and inversely proportional to the square of the distance.
- A **capacitor** stores charge on two conductors separated by an insulator (dielectric). **Capacitance** $C = Q/V$, in farads (F); 1 μF = 10^{-6} F, 1 nF = 10^{-9} F, 1 pF = 10^{-12} F. Uses: camera flash, fan motors, smoothing in chargers, tuning, touchscreens, computer memory, defibrillators.
- **Magnetic lines of force** go from N to S outside a magnet and from S to N inside it, forming closed loops; they never cross and are crowded near the poles. They can be plotted with a compass. At a **neutral point**, the magnet's field cancels the Earth's horizontal field.
- The **Earth's field** is like that of a bar magnet at its center with its S pole toward the geographic north, its axis tilted about 10° from the axis of rotation.
- The **angle of declination** is the angle between the geographic and magnetic meridians (about 0.4° E at Kathmandu). The **angle of dip** is the angle the Earth's field makes with the horizontal (0° at the magnetic equator, 90° at the poles, about 44° at Kathmandu), measured with a **dip circle** set in the magnetic meridian.

Exercise

1. Choose the correct option

a. Electric lines of force round an isolated positive point charge:

- **a** point straight outward in all directions
- **b** point straight inward
- **c** form closed circles round the charge
- **d** run parallel to one another

b. If the distance between two point charges is made three times as large, the force between them becomes:

a three times as large
b one third
c one ninth
d nine times as large

c. The value of Coulomb's constant k in air is:

a 6.67×10^{-11} N m^2/C^2
b 9×10^{-9} N m^2/C^2
c 9×10^{9} N m^2/C^2
d 1.6×10^{-19} N m^2/C^2

d. Two charges of +2 μC and +3 μC are placed 1 m apart. The force between them is:

a 0.054 N, attractive
b 0.054 N, repulsive
c 5.4 N, repulsive
d 54 N, attractive

e. A capacitor is a device used to:

a produce electric charge by chemical reactions
b store electric charge
c measure electric current
d increase the resistance of a circuit

f. A 10 μF capacitor is connected to a 6 V battery. The charge on each plate is:

a 0.6 μC
b 1.67 μC
c 16 μC
d 60 μC

g. Outside a bar magnet, magnetic lines of force go:

a from the N pole to the S pole
b from the S pole to the N pole
c from the middle of the magnet to its ends
d round the magnet in circles that don't touch it

h. With a bar magnet's N pole pointing geographic south, the neutral points lie:

a east and west of the magnet's middle
b on the magnet's axis, beyond its two ends
c at the two poles of the magnet
d anywhere along a circle round the magnet

i. The pole of the Earth's magnet that lies near the geographic North Pole is:

a a north pole
b a south pole
c neither a north nor a south pole
d a north pole in summer and a south pole in winter

j. The angle between the geographic meridian and the magnetic meridian at a place is called the:

a angle of dip
b angle of declination
c angle of inclination
d magnetic axis

k. The angle of dip at a place is measured with a:

a compass box
b declinometer
c dip circle
d galvanometer

2. Give reasons

a. A small positive charge is used as a test charge.

b. Electric lines of force never intersect each other.

c. Salt dissolves easily in water, though its ions attract each other strongly in a crystal.

d. A capacitor can store charge, but it doesn't let a steady direct current flow through it.

e. It is dangerous to open a television or a microwave oven even after it has been unplugged.

f. Magnetic lines of force are crowded near the poles of a bar magnet.

g. A compass placed at a neutral point doesn't point in any particular direction.

h. The N pole of a compass needle points toward the geographic north.

i. A dip needle rests horizontal at the magnetic equator but vertical at the magnetic poles.

j. A dip circle must be set in the magnetic meridian to measure the angle of dip.

3. Differentiate between

i. Electric field and electric field intensity

ii. Electric lines of force and magnetic lines of force

iii. Gravitational force and electrostatic force

iv. Capacitor and cell

v. Geographic meridian and magnetic meridian

vi. Angle of declination and angle of dip

4. Answer the following questions

a. What is an electric field? Define electric field intensity and write its SI unit.

b. What is a line of force? Write any four properties of electric lines of force.

c. Draw the electric lines of force round (i) an isolated positive point charge, (ii) an isolated negative point charge.

d. Draw the lines of force between (i) two equal unlike charges, (ii) two equal like charges. Mark the neutral point in (ii).

e. State Coulomb's law and write its formula. What is the value of Coulomb's constant in air?

f. Define one coulomb using Coulomb's law.

g. How does the force between two charges change if (i) one charge is doubled, (ii) both charges are halved, (iii) the distance between them is halved?

h. What is a capacitor? Define capacitance and write its SI unit.

i. Define one farad. Why are capacitances usually given in microfarads, nanofarads or picofarads?

j. Explain how a capacitor is charged by a battery and how it is discharged.

k. Write any four uses of capacitors in daily life.

l. What is a magnetic line of force? Write any four properties of magnetic lines of force.

m. Describe how you would plot the magnetic lines of force round a bar magnet using a plotting compass.

n. What is a neutral point? Draw the lines of force of a bar magnet placed with its N pole pointing (i) north, (ii) south, and mark the neutral points.

o. Describe the Earth's magnetic field pattern, with a labeled diagram.

p. Define the angle of declination and the angle of dip. Write the values of each at Kathmandu.

q. Write any three uses of the angle of declination and the angle of dip.

r. Describe how the angle of dip is measured with a dip circle.

s. **Think:** A student sets up a dip circle in Pokhara and reads 70°. She is sure the instrument is level. What has she most probably done wrong, and how can she check?

5. Numerical problems

a. Find the electric field intensity at a point 20 cm from a point charge of $+8\ \mu C$.

b. A charge of $4\ \mu C$ placed in an electric field experiences a force of 0.02 N. Find the electric field intensity there. What force would a charge of $-10\ \mu C$ feel at the same point?

c. Two point charges of $+5\ \mu C$ and $-4\ \mu C$ are 30 cm apart in air. Find the force between them.

d. Two equal charges repel each other with a force of 3.6 N when they are 5 cm apart in air. Find each charge.

e. How far apart must two charges of 1 μC each be placed in air so that the force between them is 0.1 N?

f. Two charges are 6 cm apart and attract each other with a force of 16 N. At what distance would the force be 4 N?

g. Two small balls, each of mass 0.9 g and each carrying a charge of 0.1 μC, are 3 cm apart. Compare the electrostatic force between them with the weight of one ball ($g = 10\ m/s^2$).

h. A capacitor of 220 μF is charged by a 9 V battery. Find the charge stored on it.

i. A capacitor stores a charge of 0.6 mC when it is connected to a 12 V supply. Find its capacitance in microfarads.

j. A camera flash has a capacitor of 150 μF, charged to 300 V. (i) How much charge does it store? (ii) If the flash empties it in 1 ms, what is the average current through the flash tube?

k. A ceiling fan's capacitor of 2.5 μF is connected to the mains, whose voltage reaches 325 V at its peak. Find the largest charge on the capacitor.

l. **Think:** At a place, the horizontal part of the Earth's field is 30 μT and the vertical part $30\sqrt{3}$ μT (about 52 μT). Find the angle of dip there. Is the place nearer the magnetic equator or a magnetic pole than Kathmandu?

Found a mistake? Please tell us.