Fields

A-level overview

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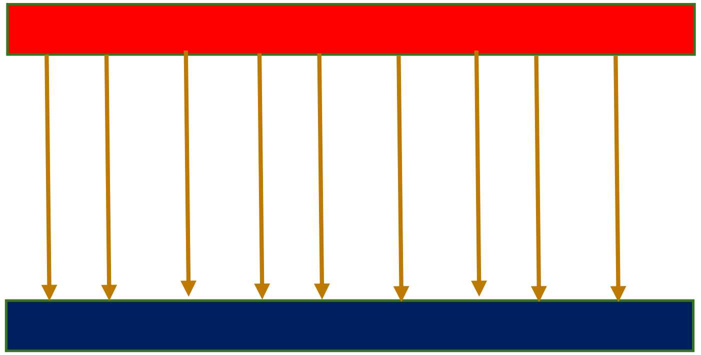
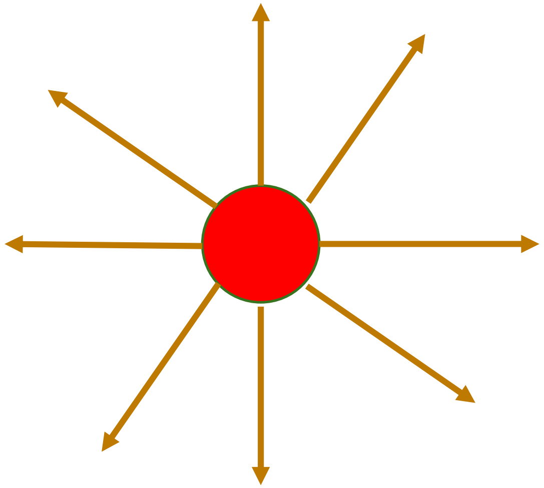
What is a Field

Name of field	Affects	Field strength	Measured in	Equation
Gravitational	masses	g	N/kg or m/s^2	$F = mg$
Electric	charges	E	N/C or V/m	$F = Eq$
Magnetic	moving charges (currents)	B	T or N/(Am)	$F = BIL$



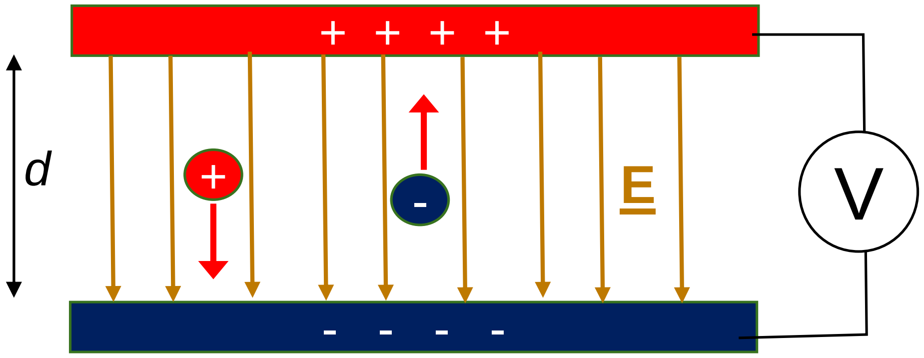
Uniform Field



Spherical field

Force	Field
Energy	Potential

Uniform electric fields



Electric field strength <u>E</u>

= force per unit positive charge

Force on charge: <u>F</u> = q<u>E</u>

+ charge has force in direction of <u>E</u>

- charge has force in opposition to <u>E</u>

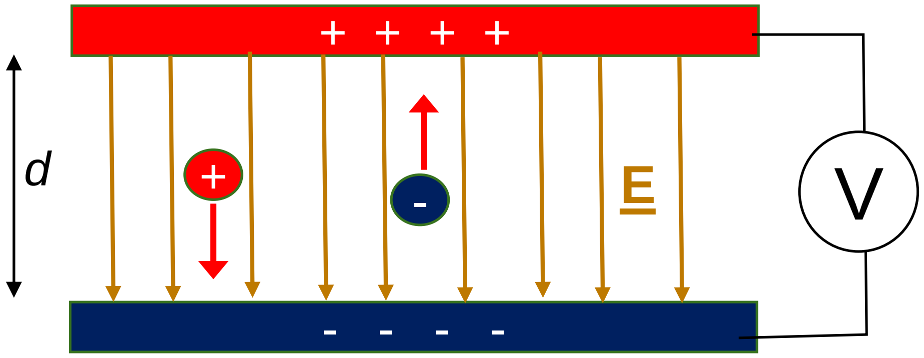
Units of electric field strength <u>E</u>

$NC^{-1} = Vm^{-1}$

Electric field between plates

$$E = \frac{V}{d}$$

Acceleration and work



Acceleration

$$a = \frac{F}{m} = \frac{qE}{m} = \frac{qV}{md}$$

Work done

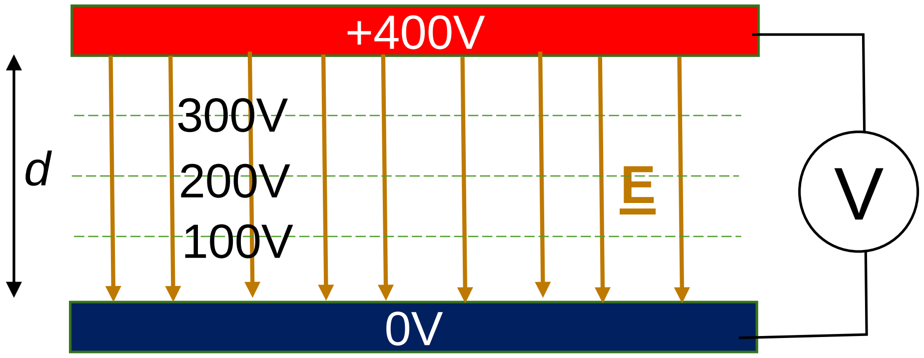
$$U = Fd = qEd = qV$$

Final speed

$$U = qV = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2qV}{m}}$$

Uniform electric fields - potential



Potential = Energy per unit charge

$$V = \frac{U}{q}$$

At height h above lower plate

Potential energy $U = Fh = Eqh$

Potential $\quad V = \frac{U}{q} = Eh$

Lines joining points of equal potential are equipotentials, which are perpendicular to field lines

The stronger the field, the closer the equipotentials are to each other

Uniform electric field practice

1. What is the electric field strength between the plates of a capacitor charged to 16V if the plates are 0.32mm apart?

2. Air begins to ‘break down’ and conduct when the electric field reaches about 1.5MV/m. How far apart must two contacts be kept if there must be no spark and there is 415V between them?

3. Calculate the force on an electron in the space between two metal sheets held 1.3cm apart if one is at -200V and the other is at +1200V.

Radial field - introduction

The gravitational field strength due to the Earth is 9.8Nkg^{-1} at the surface (6400km from the centre).

At a radius of 384 000km, the Moon orbits every 27.3 days.

Its centripetal acceleration is $a = \omega^2 r = \frac{4\pi^2}{T^2} r$ = 0.00272ms^{-2}

Increasing the distance by a factor of 60 reduces field by 3600.

So, we say that the gravitational field generated by Earth is

- proportional to the mass of the planet ($g \propto M$), and
- inversely proportional to the distance squared ($g \propto r^{-2}$)

Radial gravitational field

Gravitational field g (N/kg)

$$g = \frac{GM}{r^2}$$

$G = 6.67 \times 10^{-11}\ Nm^2kg^{-2}$; M is mass (kg); r is distance from centre (m)

g is directed towards the mass (inwards)

Force on a mass m at the location is given by

$$F = mg = \frac{GMm}{r^2}$$

This is known as Newton's law of gravitation

Multiple objects

Earth
$M_E = 6.0\times10^{24}$kg

$$g_E = \frac{GM_E}{r_E^2} \qquad g_M = \frac{GM_M}{r_M^2}$$

Moon
$M_M = 7.3\times10^{22}$kg

There is no net field at the point if

$$g_E = g_M \quad \text{so} \quad \frac{M_E}{r_E^2} = \frac{M_M}{r_M^2} \quad \text{so} \quad \frac{r_E}{r_M} = \sqrt{\frac{M_E}{M_M}} = 9.0$$

Orbits

Force on a satellite $F = \frac{GMm}{r^2}$ $G = 6.67 \times 10^{-11}\mathrm{Nm}^2\mathrm{kg}^{-2}$

Writing $F = ma$ **using** $a = \frac{v^2}{r}$**:**

Writing $F = ma$ **using** $a = r\omega^2 = \frac{4\pi^2 r}{T^2}$**:**

Gravitational field practice

1. Given that g=9.8Nkg^{-1} 6400km from the Earth's centre, calculate the mass of the Earth.

2. Given that the Earth orbits the Sun once every 365 days on an orbit with radius 1.50x10^{11}m, work out the mass of the Sun.

3. The Earth-Moon distance is 384 000km, M_E=6.0x10^{24}kg and M_M=7.3x10^{22}kg. Calculate $\underline{g}$ at a point 300 000km from the centre of the Earth on the Earth-Moon line.

Gravitational potential

Potential = Energy per unit of mass: $V_g = \frac{U}{m}$

Near to the Earth's surface,

we use the ground as our U=0 reference,

assume a uniform field, and therefore use $U = mgh$ so $V_g = gh$

At greater distances,

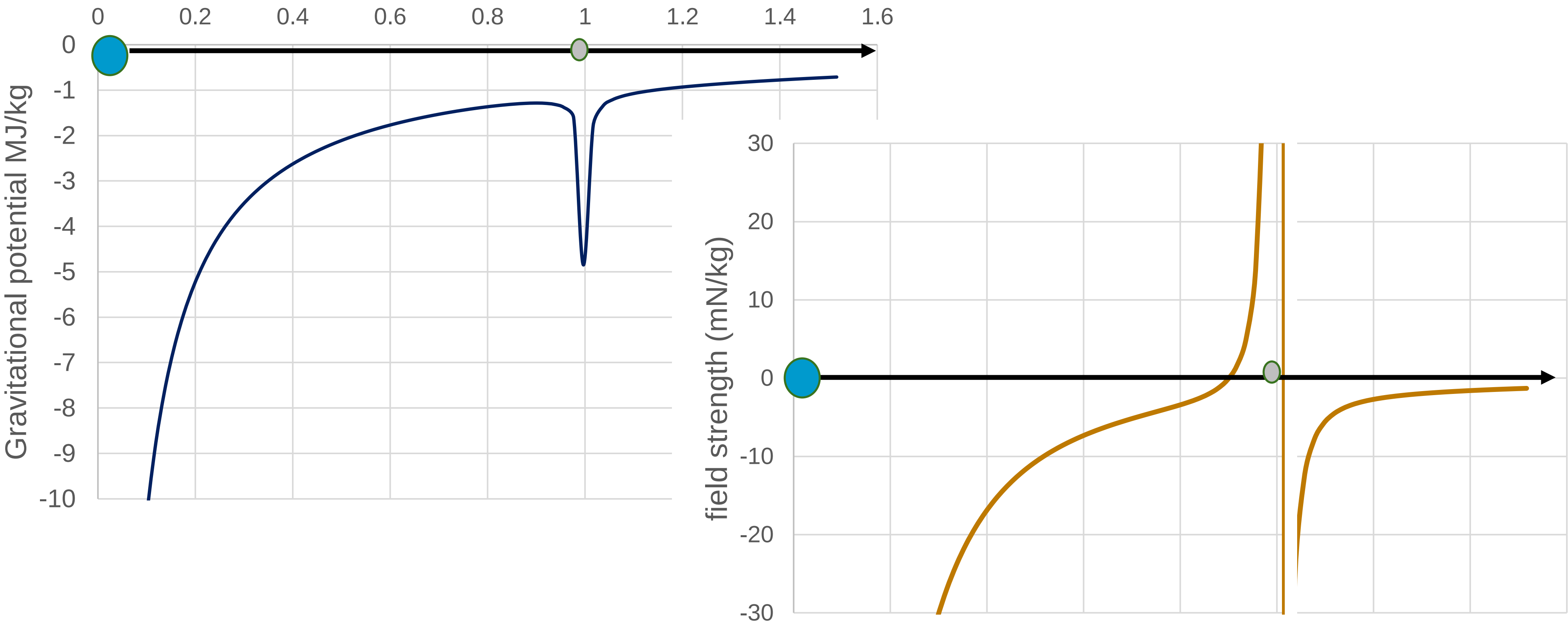
we take our U=0 reference at infinity

gravitational potentials and energies near the planet are lower, hence negative

$$V_g = -\frac{GM}{r} \;\; so \;\; U = -\frac{GMm}{r}$$

potentials are scalars, and can be added if there is more than one mass nearby

Gravitational potential and field



Gradient of potential graph gives field $g = -\frac{\Delta V_g}{\Delta r}$

Escape velocity

The speed an object needs in order to completely escape the gravitational field it is in

$V_g = 0$

$U = m\,\Delta V_g = \dfrac{GMm}{R}$

$V_g = -\dfrac{GM}{r}$

$$\frac{GMm}{r} = \frac{mv^2}{2}$$

Gravitational potential practice

1. What is the gravitational potential 42 000km from the centre of the Earth ($M_E = 6.0x10^{24}$kg)?

2. Using your answer to q1, calculate the potential energy gain of a 70kg satellite lifted from the Earth's surface (6400km from Earth's centre) to a 42 000km orbit.

3. Calculate the escape velocity from the Moon (M_M = $7.3x10^{22}$kg, r_M=1700km)

Radial electric field

Electric field E (N/C)

$$E = \frac{kQ}{r^2} = \frac{Q}{4\pi\epsilon_0 \, r^2}$$

k=8.99x10^{+9} Nm^{2}C^{-2}; ε_0=8.854x10^{-12}Fm^{-1};
Q is charge (C); r is distance from centre (m)

E is directed away from positive charges (outwards)

E is directed towards negative charges (inwards)

Force on a charge q at the location is given by

$$F = qE = \frac{kQq}{r^2} = \frac{Qq}{4\pi\epsilon_0 r^2}$$

This is known as Coulomb's law

Radial electric field practice

1. Calculate the electric field strength near the surface of a 7.5cm radius sphere holding 50nC.

2. Calculate the force of attraction between a 200nC and 25nC charge if their centres are 10cm apart.

3. Calculate the electric field strength half way between two oppositely charged 15nC small spheres separated by 3.0cm.

Radial electric potential

Potential = Energy per unit of charge: $V = \frac{U}{q}$

As with gravitational fields,

- we take our U=0 reference at infinity
- electric potentials and energies are given by

$$V = \frac{kQ}{r} = \frac{Q}{4\pi\epsilon_0 r} \text{ so } U = \frac{kQq}{r} = \frac{Qq}{4\pi\epsilon_0 r}$$

- potential near a positive charge is positive
- potential near a negative charge is negative
- potentials are scalars, and can be added if there is more than one charge nearby

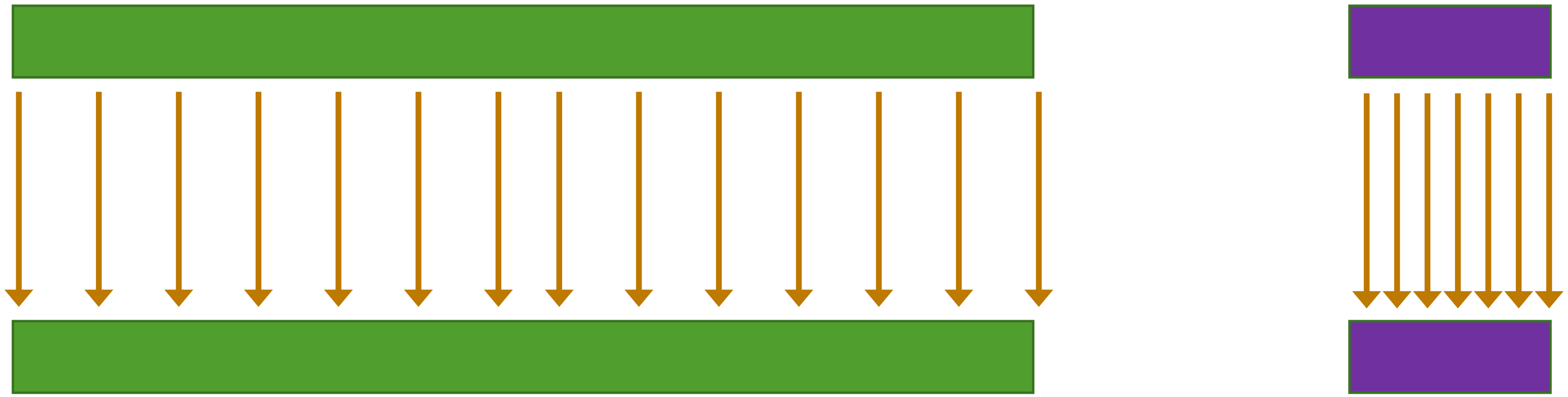
Radial electric potential practice

1. Calculate the electric potential at the surface of a metal sphere of radius 7.5cm carrying 50nC.

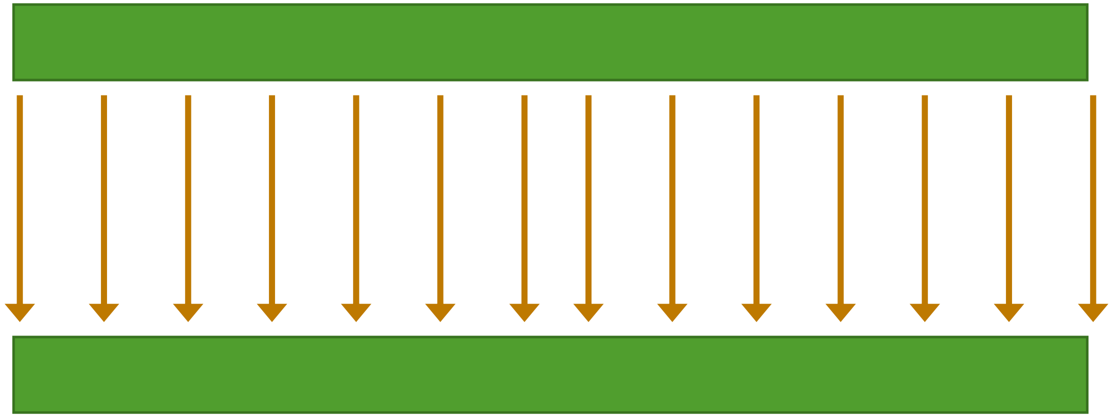
2. A sphere of radius 5.0cm is connected to a +5kV supply. What will the potential be 2cm away from the sphere?

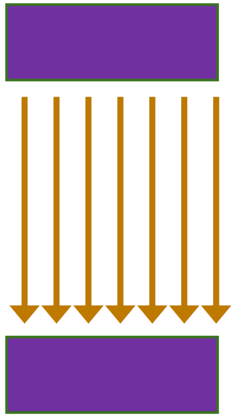
3. Calculate the energy needed to force two protons so that their centres are 3.0×10^{-15}m apart.

Which is the stronger magnet?



Which is the stronger magnet?





more magnetic flux Φ

more magnetic flux density B

Magnetic field overview

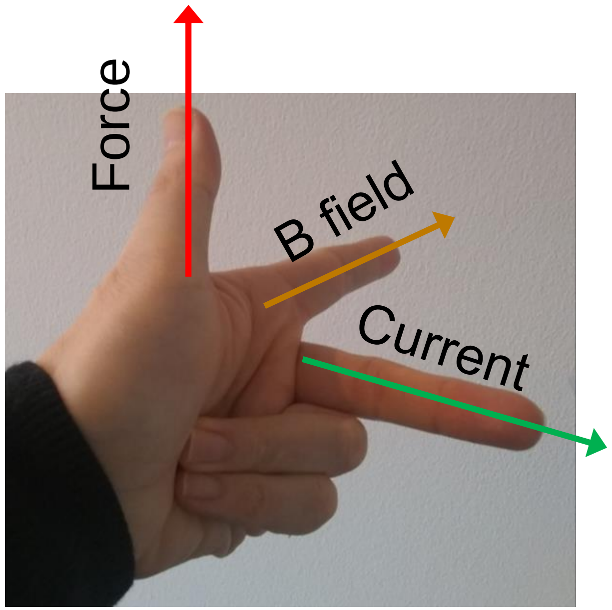
Magnetic flux density B	Magnetic flux Φ	Magnetic flux linkage $N\Phi$
Strength of the field at a point in space	Total field produced, or affecting a region	Field as it affects a coil of wire
Closeness of field lines (lines passing per unit area)	Number of field lines	Number of field lines passing through the coil x number of turns on the coil
Unit: tesla (T) 1T = 1Wb/m^2	Unit: weber (Wb) 1Wb = 1Vs	Unit: weber-turn (Wb)
Defining equation: $F = BIL \sin\theta$	Defining equation: $\Phi = BA\cos\theta$	Defining equation: $N\Phi = BAN\cos\theta$
F is force on wire of length *L* in magnetic field, carrying current *I* at angle θ to field	*A* is area of region, θ is angle between field and area's normal	*A* is area of region, θ is angle between field and coil's normal, *N* is number of turns on coil
		Faraday's Law $V = \frac{\Delta(N\Phi)}{\Delta t}$

Magnetic force on a current

When a current flows in a wire at right angles to a magnetic field, it experiences a force

$$F = B\,I\,L$$

where B is the magnetic flux density in tesla (T). 1T=1NA^{-1}m^{-1}

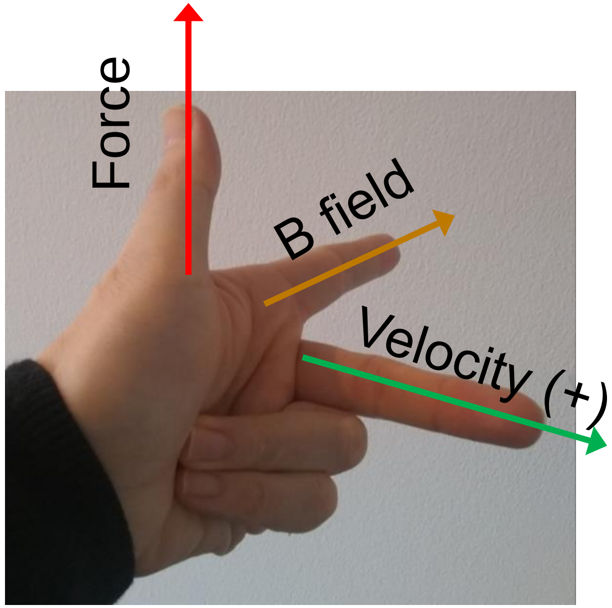


The direction of the force is given by Fleming's Left Hand Rule.

If the wire is not at right angles, then $F = B\,I\,L \sin\theta$ where θ is the angle between current and field.

Magnetic force on a charge

When a charged particle moves at right angles to a magnetic field, it experiences a force



$$F = B\,q\,v$$

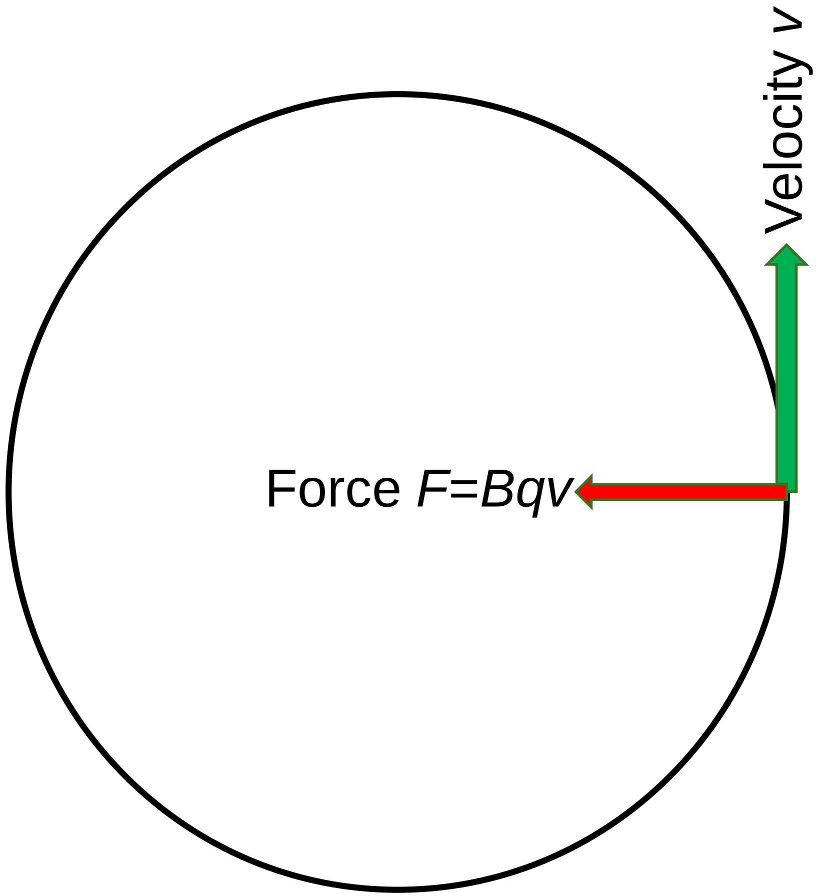
The direction of the force is given by Fleming's Left Hand Rule.

Middle finger should point opposite to velocity if q is negative

If the velocity is not at right angles, then $F = B\,q\,v\sin\theta$ where θ is the angle between velocity and field.

$$F = BIL = B\frac{q}{t}L = Bq\frac{L}{t} = Bqv$$

Circular Paths in Magnetic Fields



$$T = \frac{2\pi r}{v} = \frac{2\pi}{v} r = \frac{2\pi}{v} \times \frac{mv}{Bq} = \frac{2\pi m}{Bq}$$

Force Bqv is always perpendicular to velocity, does no work and provides centripetal acceleration $a = \frac{v^2}{r}$

$$F = ma$$

$$Bqv = \frac{mv^2}{r}$$

$$r = \frac{mv}{Bq}$$

If velocity is not perpendicular to magnetic field, use this formula replacing v with $v \sin\theta$ where θ is angle between field and velocity

Circles and voltage

For particle in magnetic field

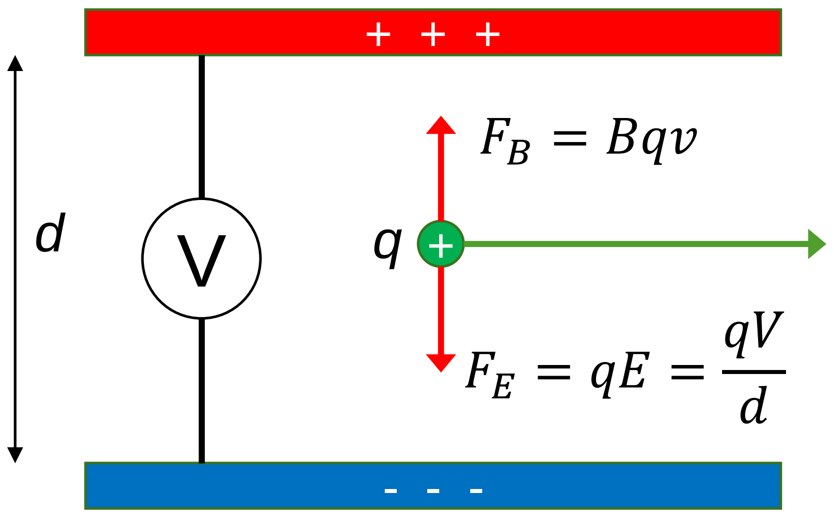
$$r = \frac{mv}{Bq}$$

For particle accelerated by electric field

$$qV = \frac{1}{2}mv^2$$

Eliminating v gives

Velocity selectors



Magnetic field is into the page

For one speed, electric and magnetic forces are equal and opposite, so particle travels in straight line:

$$F_E = F_B$$
$$\frac{qV}{d} = Bqv$$
$$v = \frac{V}{Bd}$$

A particle going slower than *v*...

A particle going faster than *v*...

Magnetic flux density practice

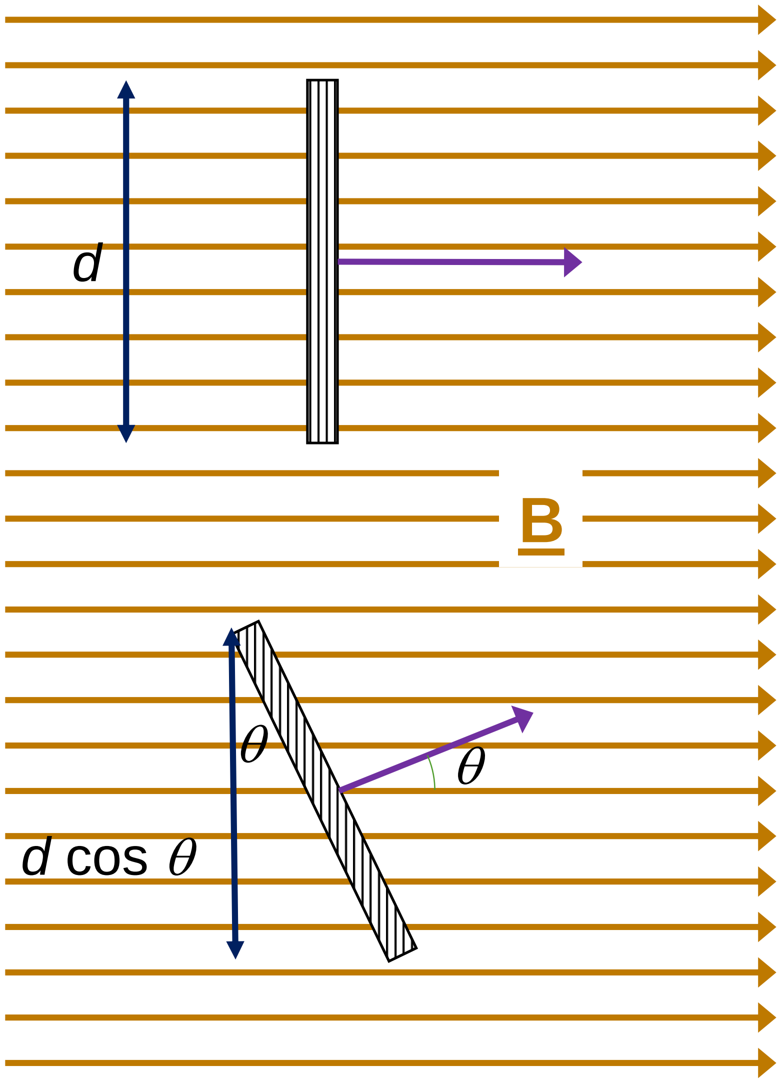
In these questions, you may assume that the current or velocity is perpendicular to the magnetic field.

1. Calculate the force on a 15cm wire carrying 72A if 5cm of the wire is in a 2.4×10^{-2}T magnetic field.

2. Calculate the acceleration of an electron moving at 30km/s in a 0.25T field.

3. Calculate the radius of the path of a proton accelerated through a potential difference of 20MV in a 2.5T field.

Magnetic flux and flux linkage



For coil of area $A = wd$ in magnetic field B

Magnetic flux $\Phi = BA = Bwd$

Flux measured in $Tm^2 = Wb$

If coil is at a diagonal angle, the area is that 'seen by' the field $= wd\cos\theta = A\cos\theta$

$$\Phi = BA\cos\theta$$

Flux linkage = Flux x number of turns

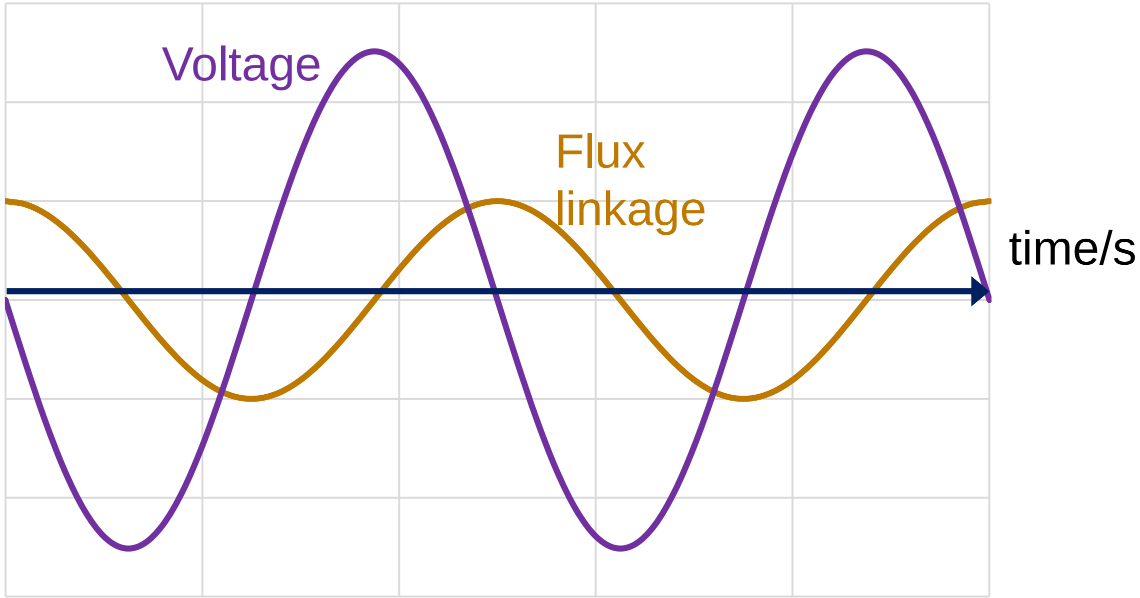
$= NBA\cos\theta$

Electromagnetic induction

If the flux linking a coil changes, a voltage is induced.

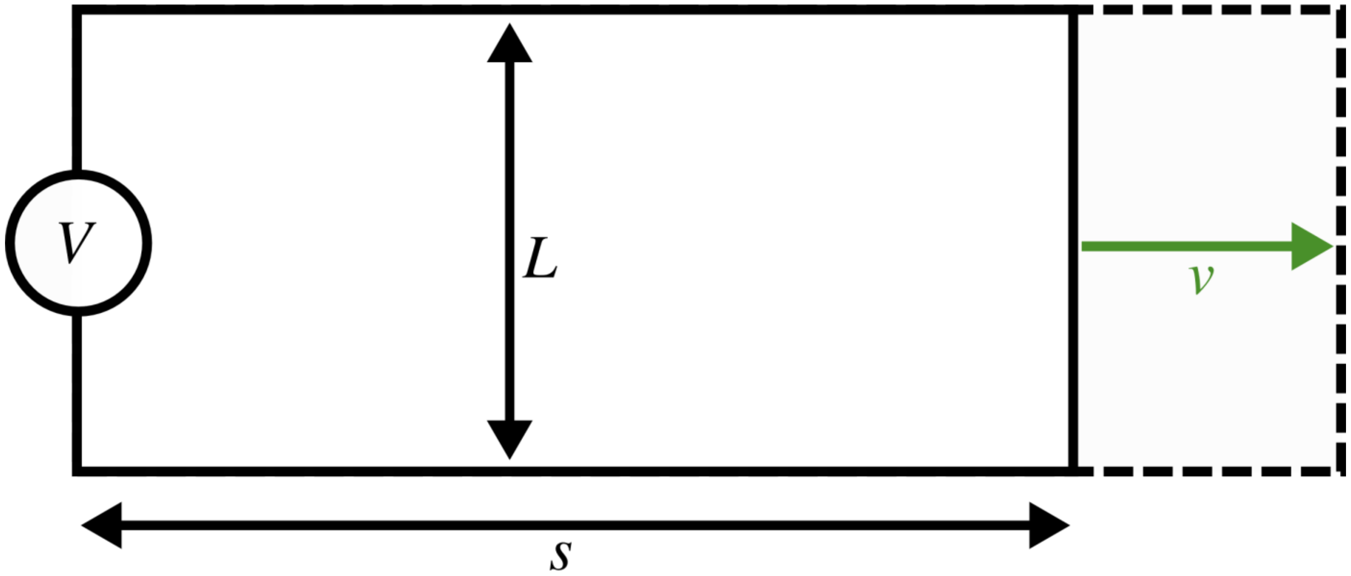
Faraday's law: **Voltage = rate of change of flux linkage**

$$V = \frac{\text{final flux linkage} - \text{initial flux linkage}}{\text{time taken for change}}$$



Units: $\frac{\mathrm{Wb}}{\mathrm{s}} = \frac{\mathrm{Tm}^2}{\mathrm{s}} = \frac{\mathrm{N}}{\mathrm{Am}} \times \frac{\mathrm{m}^2}{\mathrm{s}} = \frac{\mathrm{Nm}}{\mathrm{As}} = \frac{\mathrm{J}}{\mathrm{C}} = \mathrm{V}$

Wire moving in a field



Initial area

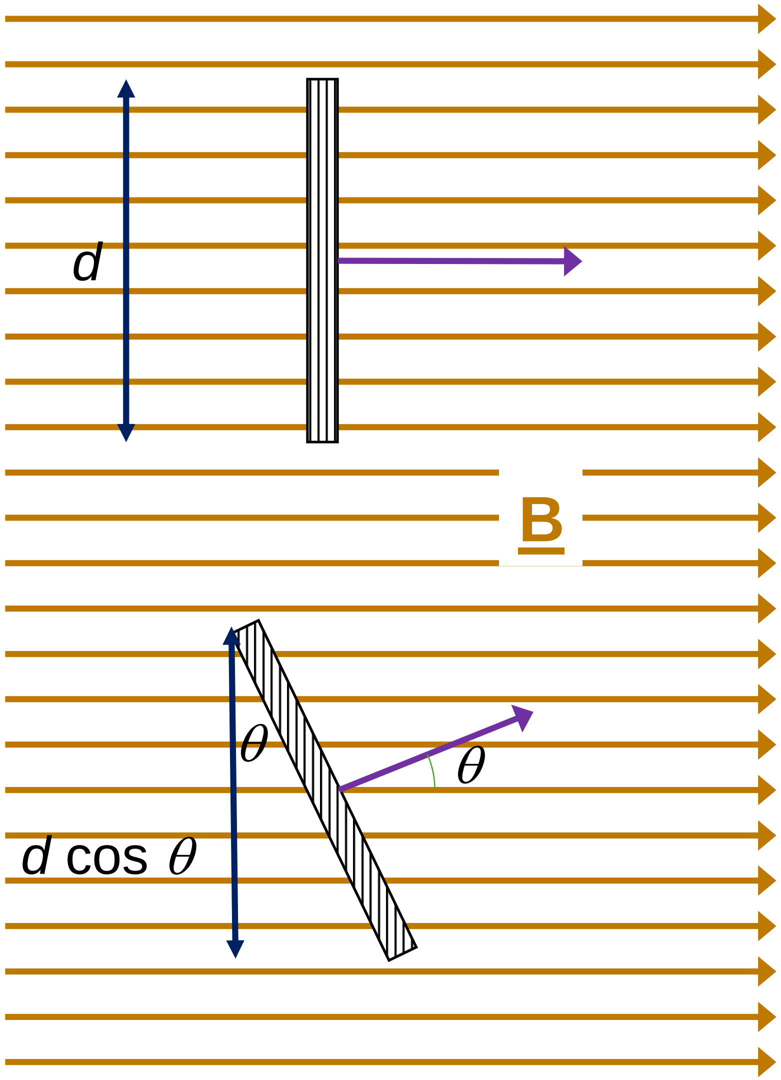
$$A = Ls$$

New area

$$A' = L(s + vt)$$

$$V = \frac{NBA' - NBA}{t} = B\frac{L(s+vt) - Ls}{t} = BLv$$

Rotating coil



Area 'seen by' the field $= A\cos\theta$

$$\Phi = BA\cos\theta$$

Flux linkage $\mathrm{N}\Phi = BAN\cos\theta$

When $\theta = 0, N\Phi = BAN$

When $\theta = 90°,\ N\Phi = 0$

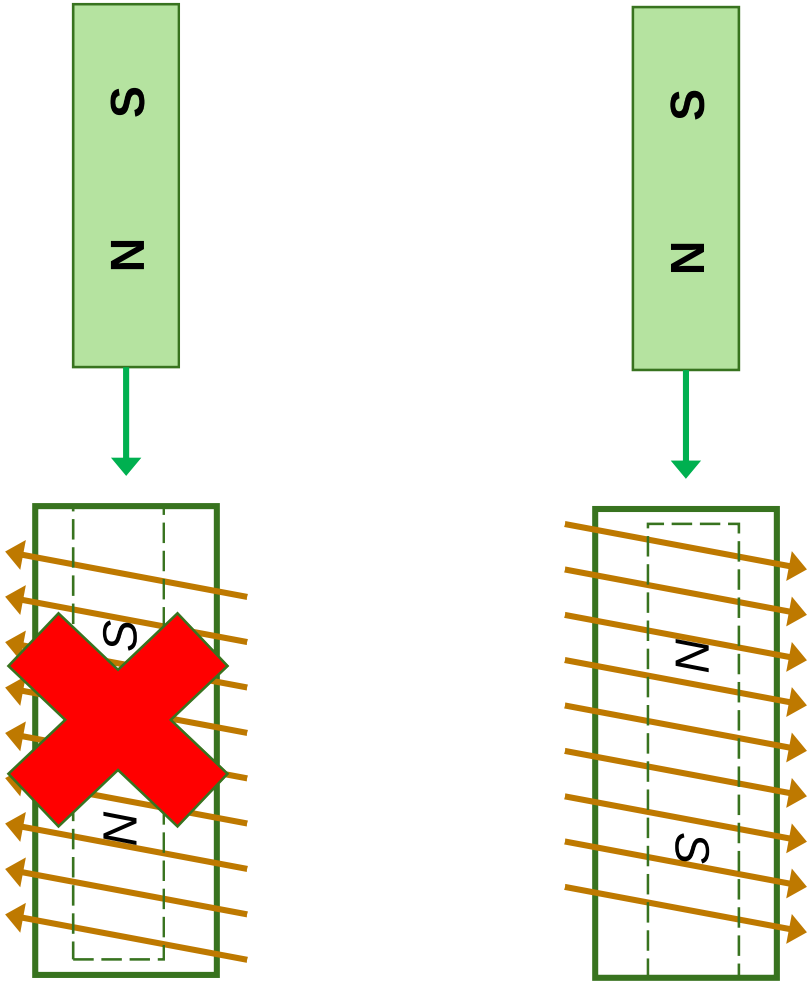
Change in flux $= -BAN$

Average voltage $= \dfrac{BAN}{t}$

For steady rotation, $\theta = \omega t$**, so** $N\Phi = BAN\cos(\omega t)$

and $V = \dfrac{d(N\Phi)}{dt} = -BAN\omega\sin(\omega t)$

Lenz's law



Conservation of energy requires

- magnet's motion resisted

Current flows in direction

- to make a magnetic field
- which opposes
- the ongoing magnetic change

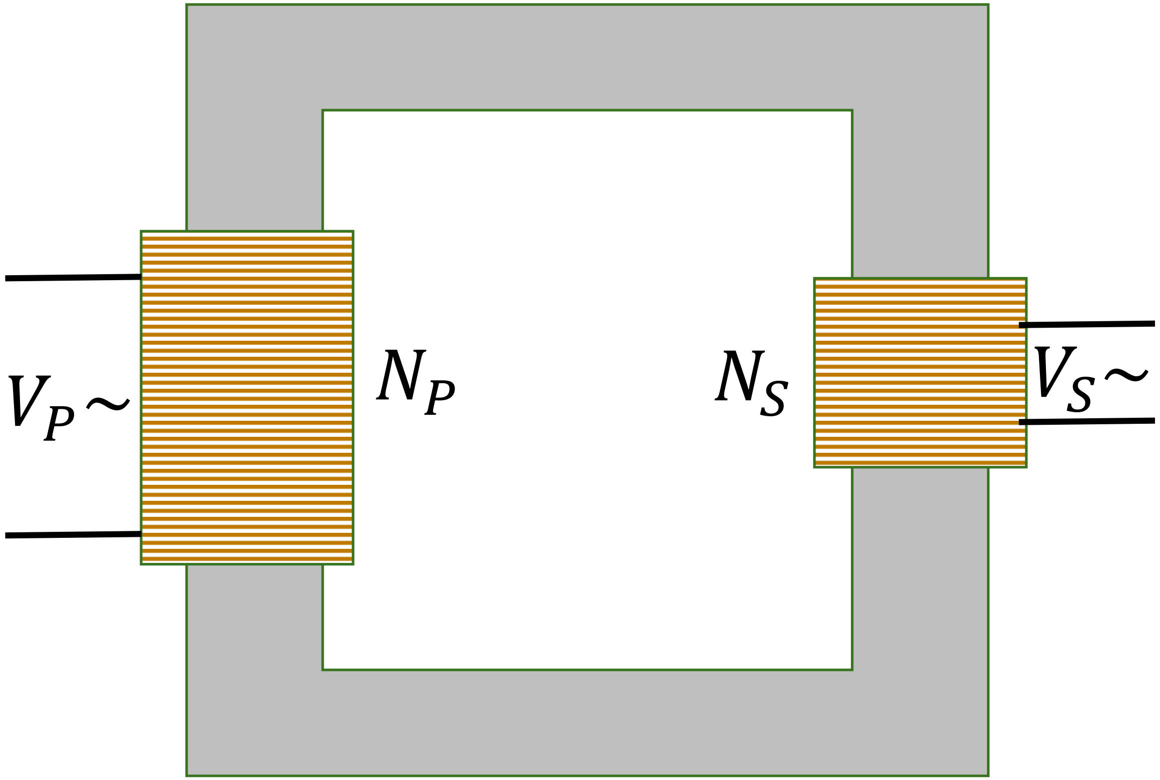
Flux and induction practice

1. Calculate the greatest magnetic flux which can be linked by a 200 turn, 20cm x 5cm coil in a 0.25T.

2. A 20cm x 5cm coil moves out of a 0.25T field in 0.025s. If the coil has 200 turns, calculate the induced voltage.

3. What is the maximum voltage output if the coil above is rotated in the field at 50Hz?

Transformer concepts



Same alternating flux in coils

Primary voltage $V_p = N_P \frac{\Delta\Phi}{\Delta t}$

Secondary voltage $V_s = N_S \frac{\Delta\Phi}{\Delta t}$

So, $\frac{V_P}{N_P} = \frac{V_S}{N_S}$ **and** $\frac{V_S}{V_P} = \frac{N_S}{N_P}$

With currents:

$$V_S I_S = \eta\, V_P I_P$$

Transformer use and limitations

Electrical distribution

- Power loss in cables $P = I^2R$
- To save energy, use lower current
- To transmit same power $P = IV$ use higher voltage
- Use transformers to ‘step-down’ the voltage for safe domestic/industrial use.

Inefficiencies

- Power loss in coils (due to resistance of wire)
- Energy taken to keep remagnetizing the core in alternate directions
- Unwanted currents generated in the core (eddy currents)

Transformer practice

1. The 300 turn primary of a transformer is connected to a 12V car battery. What voltage do we expect from the 1200 turn secondary?

2. How many turns are required on the secondary of a 230V – 5V step down transformer if the primary has 9000 turns?

3. What is primary current when a 230V – 12V step down transformer with 84% efficiency is used to power a 48W motor?

Fields

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