Static Electricity

IB PHYSICS | UNIT 9 | FORCE FIELDS
PhET Simulation

What happens when you rub the balloon on the sweater?

Electrons transfer from the sweater to the balloon.

*Click Here*
Charge on an Atom

The **protons** and **neutrons** are buried deep in the nucleus and cannot easily be touched.

**Electrons** orbiting the nucleus are easily lost or gained.
How do objects become charged?

- **Friction**
- **Contact**
- **Induction**

What happens when you rub John Travoltage’s foot on the rug?

The foot gains electrons from rubbing on the carpet and the electrons spread out.
How do objects become charged?

**Friction**
- Before: charge = -4
- After: charge = 0

**Contact**
- What is the charge of each object?
- Before: charge = 0
- After: charge = -1

**Induction**
- Draw in the Electrons
- Before: charge = 0
- After: charge = -3
How do objects become charged?

Friction
- Draw in the Electrons

Contact

Induction

Why is their hair standing up?

Each hair is positively charged
How do objects become charged?

Friction

- A foam plate is rubbed with fur and given a charge.

Contact

- An aluminum plate is brought near the foam, inducing e⁻ movement to rim.
  - When touched on the rim, e⁻ move through the hand to the ground.

Induction

- The aluminum plate, having lost e⁻, now has a + charge.
  - Remaining e⁻ move around until the + charge redistributed.
Use your knowledge responsibly

Late at night and without permission, Reuben would often enter the nursery and conduct experiments in static electricity.
### Review of Charges

<table>
<thead>
<tr>
<th>Opposite Charges</th>
<th>Like Charges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite Charges Attract</td>
<td>Like Charges Repel</td>
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</table>

- Opposite Charges:  
  - Attract

- Like Charges:  
  - Repel

<table>
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<tr>
<th>Charge 1</th>
<th>Charge 2</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>Attract</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>Repel</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>Repel</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>Attract</td>
</tr>
</tbody>
</table>
Which one has more force? (circle)

Which charged pair has larger electrostatic forces acting?

smaller distance = greater force
Which one has more force? (circle)

Which charged pair has larger electrostatic forces acting?

- $1 \mu C$ and $1 \mu C$
- $2 \mu C$ and $1 \mu C$

greater charge = greater force
Coulomb’s Law

The force of attraction or repulsion between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

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

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<th>Symbol</th>
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<td>( F ) [N]</td>
</tr>
<tr>
<td>Object 1 Charge</td>
<td>( q_1 ) [C]</td>
</tr>
<tr>
<td>Object 2 Charge</td>
<td>( q_2 ) [C]</td>
</tr>
<tr>
<td>Separation Distance</td>
<td>( r ) [m]</td>
</tr>
</tbody>
</table>
Coulomb’s Constant

Use unit analysis to prove the units of $k$:

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

$$k = \frac{Fr^2}{q_1 q_2} = \frac{Nm^2}{CC} = Nm^2 C^{-2}$$

Solve for $k$  \hspace{1cm} Plug in units  \hspace{1cm} Simplify

$k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$
### IB Physics Data Booklet

#### Sub-topic 5.1 – Electric fields

<table>
<thead>
<tr>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I = \frac{\Delta q}{\Delta t} )</td>
<td>Current</td>
</tr>
<tr>
<td>( F = k \frac{q_1 q_2}{r^2} )</td>
<td>Coulomb’s Law</td>
</tr>
<tr>
<td>( k = \frac{1}{4\pi \varepsilon_0} )</td>
<td>Coulomb constant</td>
</tr>
<tr>
<td>( V = \frac{W}{q} )</td>
<td>Electric potential</td>
</tr>
<tr>
<td>( E = \frac{F}{q} )</td>
<td>Electric field</td>
</tr>
<tr>
<td>( I = nA\nu q )</td>
<td>Current density</td>
</tr>
</tbody>
</table>

#### Sub-topic 5.2 – Heating effect of electric currents

Kirchhoff’s circuit laws:
- \( \Sigma V = 0 \) (loop)
- \( \Sigma I = 0 \) (junction)

#### Sub-topic 5.3 – Electric cells

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<td>( N_A )</td>
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<td>( \sigma )</td>
<td>( 5.67 \times 10^{-8} ) W m(^{-2}) K(^{-4})</td>
</tr>
<tr>
<td>Permittivity of free space</td>
<td>( \varepsilon_0 )</td>
<td>( 8.85 \times 10^{-12} ) C(^2) N(^{-1}) m(^{-2})</td>
</tr>
<tr>
<td>Permeability of free space</td>
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<td>( 4\pi \times 10^{-7} ) T m A(^{-1})</td>
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<td>( c )</td>
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</tbody>
</table>
What is the repulsion force on the positive charge below?

\[ F = k \frac{q_1 q_2}{(2r)^2} \]

\[ F = k \frac{q_1 q_2}{4r^2} \]
What is the repulsion force on the positive charge below?

\[ F = k \frac{2q_1q_2}{r^2} \]
Conceptual Math

Which pair has the greater electrostatic force?

Same!

\[ F = k \frac{2q_1 2q_2}{(2r)^2} = k \frac{4q_1 q_2}{4r^2} = k \frac{q_1 q_2}{r^2} \]
Electrostatic and Gravitational Force
Review of Charges

- Opposite Charges: Attract
- Like Charges: Repel
Coulomb’s Law

The force of attraction or repulsion between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

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

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### IB Physics Data Booklet

#### Sub-topic 5.1 – Electric fields

\[ I = \frac{\Delta q}{\Delta t} \]

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

\[ k = \frac{1}{4\pi\varepsilon_0} \]

\[ V = \frac{W}{q} \]

\[ E = \frac{F}{q} \]

\[ I = nAvq \]

### *Coulomb’s Law*

#### Sub-topic 5.2 – Heating effect of electric currents

Kirchhoff’s circuit laws:

\[ \Sigma V = 0 \text{ (loop)} \]

\[ \Sigma I = 0 \text{ (junction)} \]

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#### Sub-topic 5.3 – Electric cells

\[ \varepsilon = I(R + r) \]
Sign is important!

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

\( k = 8.99 \times 10^9 \, \text{N} \, \text{m}^2 \, \text{C}^{-2} \)

+ \( F \) \rightarrow Repel \ (++) or (-)(-)

- \( F \) \rightarrow Attract \ (++) or (-)(+)
Quantifying Charge

The total charge in Coulombs can be related to the number of electrons.

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<tr>
<td>Planck’s constant</td>
<td>$h$</td>
<td>$6.63 \times 10^{-34}$ Js</td>
</tr>
<tr>
<td>Elementary charge</td>
<td>$e$</td>
<td>$1.60 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>Electron rest mass</td>
<td>$m_e$</td>
<td>$9.110 \times 10^{-31}$ kg $= 0.000549$ u $= 0.511$ MeV c$^{-2}$</td>
</tr>
<tr>
<td>Proton rest mass</td>
<td>$m_p$</td>
<td>$1.673 \times 10^{-27}$ kg $= 1.007276$ u $= 938$ MeV c$^{-2}$</td>
</tr>
<tr>
<td>Neutron rest mass</td>
<td>$m_n$</td>
<td>$1.675 \times 10^{-27}$ kg $= 1.008665$ u $= 940$ MeV c$^{-2}$</td>
</tr>
<tr>
<td>Unified atomic mass unit</td>
<td>$u$</td>
<td>$1.661 \times 10^{-27}$ kg $= 931.5$ MeV c$^{-2}$</td>
</tr>
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</table>
Quantifying Charge

The coulomb was selected to use with electric currents which makes it a very large unit for static electricity. Get your metric prefixes ready.
Try This

Determine the electrical force of attraction between two balloons with separate charges of \(+3.5 \times 10^{-8}\) C and \(-2.9 \times 10^{-8}\) C when separated a distance of 0.65 m.

\[
F = k \frac{q_1 q_2}{r^2} = (8.99 \times 10^9) \frac{(3.5 \times 10^{-8})(3.5 \times 10^{-8})}{(0.65)^2}
\]

\[
F = -2.16 \times 10^{-5} \text{ N}
\]
Gravity

What is Gravity?

Idea #1: A downward force that stops you from flying away

Idea #2: An attraction towards larger objects

Idea #3: All mass attracts all other mass

Circle the answer that you agree with most
The force of attraction between bodies with mass is directly proportional to the product of the two masses and inversely proportional to the square of the distance between them.

\[ F = G \frac{Mm}{r^2} \]

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Universal Law of Gravitation

\[ F = G \frac{Mm}{r^2} \]

\[ G \rightarrow \text{Universal Gravitational Constant} \]

\[ G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \]
Sub-topic 6.2 – Newton’s law of gravitation

*Universal Law of Gravitation

\[ F = G \frac{Mm}{r^2} \]

\[ g = \frac{F}{m} \]

\[ g = G \frac{M}{r^2} \]

**Fundamental constants**

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Gravity – Equal and Opposite

The force on the skydiver is the same as the force on the earth but the earth’s huge mass means that there is hardly any acceleration.
Measuring the proper distance

Technically Newton’s Law of Gravitation defines how to calculate the gravitational force between two point masses

(Not a point mass)

Fortunately, Newton’s shell theorem states that:

“A spherically symmetric shell of mass $M$ acts as if all of its mass is located at its center.”
Try This

Determine the force of gravitational attraction between the earth \((m = 5.98 \times 10^{24} \text{ kg})\) and a 70-kg physics student if the student is in an airplane at 40000 feet above earth's surface. This would place the student a distance of \(6.39 \times 10^6 \text{ m}\) from earth's center.

\[
F = G \frac{Mm}{r^2} = (6.67 \times 10^{-11}) \frac{(5.98 \times 10^{24})(70)}{(6.39 \times 10^6)^2}
\]

\[
F = 684 \text{ N}
\]
Comparison

Electrostatic Force

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

- \( k \rightarrow \text{Coulomb Constant} \)
- \( q_1, q_2 \rightarrow \text{Charges [C]} \)

Gravitational Force

\[ F = G \frac{M m}{r^2} \]

- \( G \rightarrow \text{Gravitational Constant} \)
- \( M, m \rightarrow \text{Masses [kg]} \)
Permittivity

Coulomb’s Constant is sometimes expanded to this form:

\[ k = \frac{1}{4\pi \varepsilon_0} \]

\( \varepsilon_0 \rightarrow \text{Permittivity of Free Space (vacuum)} \)

\( \varepsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2} \)

*Solving for k will get Coulomb’s Constant for a vacuum*
### Sub-topic 5.1 – Electric fields

- \( I = \frac{\Delta q}{\Delta t} \)
- \( F = k \frac{q_1 q_2}{r^2} \)
- \( k = \frac{1}{4\pi \varepsilon_0} \)
- \( V = \frac{W}{q} \)
- \( E = \frac{F}{q} \)
- \( I = n A v q \)

### Sub-topic 5.2 – Heating effect of electric currents

- Kirchhoff’s circuit laws:
  - \( \Sigma V = 0 \) (loop)
  - \( \Sigma I = 0 \) (junction)
- \( R = \frac{V}{I} \)
- \( P = VI = I^2 R = \frac{V^2}{R} \)

### Sub-topic 5.3 – Electric cells

- \( \varepsilon = I(R + r) \)

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*Solving for k*
Permittivity changes relative to the substance

Relative Permittivity

\[ \varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \]

IB might ask you about this: the higher the relative permittivity, the harder it is for electrostatic forces to travel over a distance...

<table>
<thead>
<tr>
<th>Relative Permittivities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space (a vacuum)</td>
<td>1</td>
</tr>
<tr>
<td>Dry Air</td>
<td>1.0005</td>
</tr>
<tr>
<td>Paper</td>
<td>4</td>
</tr>
<tr>
<td>Concrete</td>
<td>4</td>
</tr>
<tr>
<td>Rubber</td>
<td>6</td>
</tr>
</tbody>
</table>
Force Fields

IB PHYSICS | UNIT 9 | FORCE FIELDS
What is the force of gravity between the earth and the moon?

\[ F = G \frac{Mm}{r^2} \]

Given:
- Earth mass \( m = 6 \times 10^{24} \) kg
- Moon mass \( m = 7.4 \times 10^{22} \) kg
- Distance \( r = 3.8 \times 10^8 \) m
- Gravitational constant \( G = 6.67 \times 10^{-11} \) N m^2 kg^{-2}

\[ F = (6.67 \times 10^{-11}) \frac{(6 \times 10^{24})(7.4 \times 10^{22})}{(3.8 \times 10^8)^2} \]

\[ F = 2.05 \times 10^{20} \text{ N} \]
Conversion Check

7 μC $\rightarrow$ C

$7 \times 10^{-6}$ C

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Factor</th>
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<tbody>
<tr>
<td>kilo</td>
<td>k</td>
<td>$10^3$</td>
</tr>
<tr>
<td>hecto</td>
<td>h</td>
<td>$10^2$</td>
</tr>
<tr>
<td>deca</td>
<td>da</td>
<td>$10^1$</td>
</tr>
<tr>
<td>deci</td>
<td>d</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>centi</td>
<td>c</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>milli</td>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>micro</td>
<td>μ</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>nano</td>
<td>n</td>
<td>$10^{-9}$</td>
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</table>
A small cork with an excess charge of +7.0 \(\mu\text{C}\) is placed 14 cm from another cork, which carries a charge of \(-3.2 \mu\text{C}\). What is the magnitude of the electric force between the corks?

\[
F = k \frac{q_1 q_2}{r^2} = (8.99 \times 10^9) \left(\frac{7 \times 10^{-6}}{0.14}\right) \left(-3.2 \times 10^{-6}\right)
\]

\[
F = -10.3 \text{ N}
\]
Force Fields

Vector field that describes the force that would act on a particle at various positions

<table>
<thead>
<tr>
<th></th>
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<th>Gravitational Field</th>
</tr>
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<tbody>
<tr>
<td>Symbol</td>
<td>$E$</td>
<td>$g$</td>
</tr>
<tr>
<td>Unit</td>
<td>$\frac{N}{C} = N , C^{-1}$</td>
<td>$\frac{N}{kg} = N , kg^{-1}$</td>
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Electric Fields point in the direction that a positive charge would travel.
Label these charges as positive (+) or negative (-)
Try This

Predict what the field lines will look like:
Gravity as a field
Gravity as a field
Gravity as a field

- The gravitational field distorts the space around the mass that is causing it so that any other mass placed at any position in the field will “know” how to respond immediately.

- Bigger masses “curve” the rubber sheet more than smaller masses.
Gravity as a field

How do we visually represent the strength of the field?

Vector Density
### Sub-topic 5.1 – Electric fields

\[ I = \frac{\Delta q}{\Delta t} \]

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

\[ k = \frac{1}{4\pi\varepsilon_0} \]

\[ V = \frac{W}{q} \]

\[ E = \frac{F}{q} \]

\[ I = nA\nu q \]

### Sub-topic 6.2 – Newton’s law of gravitation

\[ F = G \frac{Mm}{r^2} \]

\[ g = \frac{F}{m} \]

\[ g = G \frac{M}{r^2} \]

### Sub-topic 5.3 – Electric cells

\[ \varepsilon = I(R + r) \]
Remember $g$?

$g = 9.81 \text{ m s}^{-2}$

$g$ representing acceleration is not the whole story...

$g \rightarrow \text{Gravitational Field Strength}$

$$g = \frac{\text{N}}{\text{kg}} = \frac{\text{kg} \times \text{m s}^{-1}}{\text{kg}} = \text{m s}^{-1}$$
Wait, does that mean $g$ changes?

400 km + 6370 km = 6770 km

$g = G \frac{M}{r^2}$

$F = G \frac{M}{r^2} = (6.67 \times 10^{-11}) \frac{(6 \times 10^{24})}{(6,770,000)^2}$

$F = 8.73 \text{ N kg}^{-1}$
What is the force of gravity for each position?

\[ F = (75 \text{ kg})(5 \text{ N kg}^{-1}) \]
\[ F = 375 \text{ N} \]

\[ F = (75 \text{ kg})(8 \text{ N kg}^{-1}) \]
\[ F = 600 \text{ N} \]

\[ F = (2,000,000 \text{ kg})(5 \text{ N kg}^{-1}) \]
\[ F = 10,000,000 \text{ N} \]

\[ F = (2,000,000 \text{ kg})(8 \text{ N kg}^{-1}) \]
\[ F = 16,000,000 \text{ N} \]
What is the electric field strength if a particle with a charge of +6.3 μC experiences a force of 0.0025 N?

\[
E = \frac{F}{q} = \frac{0.0025 \text{ N}}{6.3 \times 10^{-6} \text{ C}}
\]

\[E = 397 \text{ N C}^{-1}\]
Think about this...

Two isolated point charges, $-7 \, \mu\text{C}$ and $+2 \, \mu\text{C}$, are at a fixed distance apart. At which point is it possible for the electric field strength to be zero?

Forces cancel out
Try this

What is the gravitational field strength halfway between the centers of the earth and the moon?

$m = 6 \times 10^{24} \text{ kg}$

$r = \frac{3.8 \times 10^8 \text{ m}}{2} = 1.9 \times 10^8 \text{ m}$

$m = 7.3 \times 10^{22} \text{ kg}$

$F = (6.67 \times 10^{-11}) \left( \frac{6 \times 10^{24}}{1.9 \times 10^8} \right)^2 = 0.011 \text{ N kg}^{-1}$

$F = (6.67 \times 10^{-11}) \left( \frac{7.3 \times 10^{22}}{1.9 \times 10^8} \right)^2 = 0.00013 \text{ N kg}^{-1}$

$F = 0.011 - 0.00013 = 0.0109 \text{ N kg}^{-1}$

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

$G = 6.67 \times 10^{-11} \frac{\text{N m}^2}{\text{kg}^2}$
Try this

Where would an object experience a gravitational field of 0 N kg\(^{-1}\)?

\[ G \frac{M_e}{r_e^2} = G \frac{M_m}{r_m^2} \]

\[ r = 3.8 \times 10^8 \text{ m} \]

\[ r_m = 3.8 \times 10^8 - r_e \]

\[ m = 6 \times 10^{24} \text{ kg} \]

\[ m = 7.3 \times 10^{22} \text{ kg} \]

\[ g = G \frac{M}{r^2} \]

\[ G = 6.67 \times 10^{-11} \frac{\text{N} \times \text{m}^2}{\text{kg}^2} \]

\[ \sqrt{\frac{6 \times 10^{24}}{r_e}} \]

\[ \sqrt{\frac{7.3 \times 10^{22}}{(7.3 \times 10^{22} - r_e)}} \]

\[ (9.31 \times 10^{20}) - (2.45 \times 10^{12})r_e = (2.70 \times 10^{11})r_e \]

\[ (9.31 \times 10^{20}) = (2.72 \times 10^{12})r_e \]

\[ r_e = 3.42 \times 10^8 \text{ m} \]
Magnetism & Right Hand Rule
Magnets

Magnetic materials have the ability to attract or repel other types of magnetic materials.

But not all materials are magnetic.
Rules of Interaction

N  S  →  N  S
S  N  ←  S  N
S  N  ←  N  S
N  S  →  N  S
Cutting Magnets in Half

Poles cannot be isolated – a magnet cannot be broken to get a separate north and south pole. Instead, it creates two magnets, each with a north and south pole.
MagneticDomains

In order for a material with domains to become magnetic, the domains have to be aligned by an external magnetic field.

If enough of a materials domains become aligned, the material forms a magnetic dipole and becomes a permanent magnet.
Magnetic Fields

Magnetic field lines point from _________ to _________

North                South

A compass would align with these field lines
B → Magnetic Field Strength

Units: Tesla [T]
A horseshoe magnet is just a bent bar magnet. The rules for magnetic fields still apply.
The Earth is a Magnet
Right Hand Rule #1

If you make a “thumbs up” sign and point your thumb down a wire in the direction of the current, your other four fingers will point in the direction of the magnetic field.

**Thumb** points in direction of the **current**

**Fingers** point in direction of the **field lines**
Drawing in 3D

It can be hard to translate a 3rd dimension into a 2-dimensional diagram so there some conventions to help us out.

How do you represent a direction that’s perpendicular to the paper?

- Into the paper ✗
- Out of the paper ✓
**Drawing in 3D**

**Where is Magnetic Flux Density the highest?**

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Right Hand Rule #1

Draw in the magnetic field lines around these current carrying wires
A wire in a loop has a stronger magnetic field inside the loop than outside...
Creating an electromagnet
Right Hand Rule #2

If you make curl your fingers in the direction of the current around a metal core, you will make a “thumbs up” sign where your thumb is pointing toward the north pole of the electromagnet.

**Fingers** point in direction of the **current**

**Thumb** points in toward the **North Pole** of the magnet
Right Hand Rule #2

Label the north and south poles of these electromagnets
Magnetic Field
Electromagnet Applications
Draw in the Field Lines
Build and Study Electromagnets

Explore what factors can be changed to increase the strength of an electromagnet
Electromagnetic Force

IB PHYSICS | UNIT 9 | FORCE FIELDS
Remember the Right Hand Rule?

1. **Thumb** points in direction of the **current**  
   **Fingers** point in direction of the **field lines**

2. **Fingers** point in direction of the **current**  
   **Thumb** points in toward the **North Pole** of the magnet
**Right Hand Rule #3**

- **Thumb** points in direction of the **current**
- **Fingers** point in direction of the **field lines**
- **Palm** points in direction of the **force**

How do you represent a direction that’s perpendicular to the paper?

- Into the paper ✗
- Out of the paper ◆
Right Hand Rule #3

A current-carrying wire is placed in a magnetic field and the magnetic field exerts a force on the wire.
Right Hand Rule

When electric current is passed through a magnetic field, you get **motion**
Motors vs Generators

Electric Motors convert
Electricity -> Motion

Electric Generators convert
Motion -> Electricity
Speakers
**One ampere is defined as the current that would cause a force of $2 \times 10^{-7}$ N per meter between two long parallel conductors separated by 1 m in a vacuum.**

Consider two parallel wires, with current in the same direction. Do they attract or repel??
Gravitational Field

\[ g = \frac{F}{m} = \frac{[N]}{[kg]} \]

Electric Field

\[ E = \frac{F}{q} = \frac{[N]}{[C]} \]

Magnetic Field

\[ B = \frac{F}{I} = \frac{[N]}{[A]} = [T] \]
The magnetic field strength is sometimes referred to as magnetic flux and depends on how perpendicular the current is in relation to the field direction.

Max flux

Less flux

No flux given.
Magnetic field Strength

The force on the wire is proportional to the charge moving perpendicular to the field. Because of these the perpendicular component must be used in the calculation.

\[ B = \frac{F}{IL\sin\theta} \]
Fields

\[ B = \frac{F}{IL \sin \theta} \quad F = BIL \sin \theta \]

<table>
<thead>
<tr>
<th>F</th>
<th>Magnetic force</th>
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<tr>
<td></td>
<td><em>Newtons</em> [N]</td>
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<table>
<thead>
<tr>
<th>B</th>
<th>Magnetic field strength</th>
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<td><em>Tesla</em> [T]</td>
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<table>
<thead>
<tr>
<th>I</th>
<th>Current</th>
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<tr>
<td></td>
<td><em>Amperes</em> [A]</td>
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<table>
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<tr>
<th>L</th>
<th>Length of conductor in uniform magnetic field</th>
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<th>θ</th>
<th>Angle between magnetic field and current</th>
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### Sub-topic 5.1 – Electric fields

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<th>Formula</th>
<th>Description</th>
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<tbody>
<tr>
<td>( I = \frac{\Delta q}{\Delta t} )</td>
<td>Electric current</td>
</tr>
<tr>
<td>( F = k \frac{q_1 q_2}{r^2} )</td>
<td>Force due to electric charge interaction</td>
</tr>
<tr>
<td>( k = \frac{1}{4\pi\varepsilon_0} )</td>
<td>Electric constant</td>
</tr>
<tr>
<td>( V = \frac{W}{q} )</td>
<td>Voltage</td>
</tr>
<tr>
<td>( E = \frac{F}{q} )</td>
<td>Electric field</td>
</tr>
<tr>
<td>( I = nAvq )</td>
<td>Current density</td>
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### Sub-topic 5.2 – Heating effect of electric currents

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<tr>
<th>Formula</th>
<th>Description</th>
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<tbody>
<tr>
<td>Kirchhoff’s circuit laws: ( \Sigma V = 0 ) (loop) ( \Sigma I = 0 ) (junction)</td>
<td>Kirchhoff’s laws for electric circuits</td>
</tr>
<tr>
<td>( R = \frac{V}{I} )</td>
<td>Resistance</td>
</tr>
<tr>
<td>( P = VI = I^2 R = \frac{V^2}{R} )</td>
<td>Power</td>
</tr>
<tr>
<td>( R_{\text{total}} = R_1 + R_2 + \cdots )</td>
<td>Total resistance</td>
</tr>
<tr>
<td>( \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots )</td>
<td>Reciprocal of total resistance</td>
</tr>
<tr>
<td>( \rho = \frac{RA}{l} )</td>
<td>Resistivity</td>
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### Sub-topic 5.3 – Electric cells

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<tbody>
<tr>
<td>( \varepsilon = I(R + r) )</td>
<td>Emf of an electric cell</td>
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### Sub-topic 5.4 – Magnetic effects of electric currents

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<tbody>
<tr>
<td>( F = qvB \sin \theta )</td>
<td>Lorentz force on a charged particle</td>
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<tr>
<td>( F = BIL \sin \theta )</td>
<td>Lorentz force on a current-carrying conductor</td>
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A current of 3.8 A in a long wire experiences a force of $5.7 \times 10^{-3}$ N when it flows through a magnetic field of strength 25 mT. If the length of wire in the field is 10 cm, what is the angle between the field and current?

$$F = BIL \sin \theta$$

$$\theta = \sin^{-1} \left( \frac{F}{BIL} \right) = \sin^{-1} \left( \frac{(5.7 \times 10^{-3})}{(25 \times 10^{-3})(3.8)(0.1)} \right)$$

$F = 5.7 \times 10^{-3}$ N
$B = 25$ mT = $25 \times 10^{-3}$ T
$I = 3.8$ A
$L = 10$ cm = $0.1$ m

$\theta = 36.87^\circ$
When there is an magnetic force on a current carrying wire, the force is really on the moving charges inside of the conductor.

Single charged particles can also experience a magnetic force when moving through a magnetic field...

\[ F = BIL \sin \theta \]
\[ F = B \left( \frac{q}{t} \right) (vt) \sin \theta \]
\[ F = Bq\nu \sin \theta \]
### Sub-topic 5.1 – Electric fields

- \( I = \frac{\Delta q}{\Delta t} \)
- \( F = k \frac{q_1 q_2}{r^2} \)
- \( k = \frac{1}{4\pi \varepsilon_0} \)
- \( V = \frac{W}{q} \)
- \( E = \frac{F}{q} \)
- \( I = nA v q \)

### Sub-topic 5.2 – Heating effect of electric currents

- Kirchhoff’s circuit laws:
  - \( \Sigma V = 0 \) (loop)
  - \( \Sigma I = 0 \) (junction)
- \( R = \frac{V}{I} \)
- \( P = VI = I^2R = \frac{V^2}{R} \)
- \( R_{total} = R_1 + R_2 + \ldots \)
  - \( \frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \)
- \( \rho = \frac{RA}{l} \)

### Sub-topic 5.3 – Electric cells

- \( \varepsilon = I(R + r) \)

### Sub-topic 5.4 – Magnetic effects of electric currents

- \( F = qvB \sin \theta \)
- \( F = BIL \sin \theta \)
Try This...

What is the magnetic force acting on a proton \((+1.6 \times 10^{-19} \text{ C})\) moving at an angle of 32° across a magnetic field of \(5.3 \times 10^{-3} \text{ T}\) at a speed of \(3.4 \times 10^{5} \text{ m s}^{-1}\)?

\[
F = qvB \sin\theta
\]

\[
F = (1.6 \times 10^{-19})(3.4 \times 10^{5})(5.3 \times 10^{-3})\sin32°
\]

\[
q = 1.6 \times 10^{-19} \text{ C}
\]

\[
v = 3.4 \times 10^{5} \text{ m s}^{-1}
\]

\[
B = 5.3 \times 10^{-3} \text{ T}
\]

\[
\theta = 32°
\]

\[
F = 1.5 \times 10^{-16} \text{ N}
\]
Particles Moving Across Fields

- Magnetic field out of screen
  - Fast
  - Slow
- Magnetic field into screen