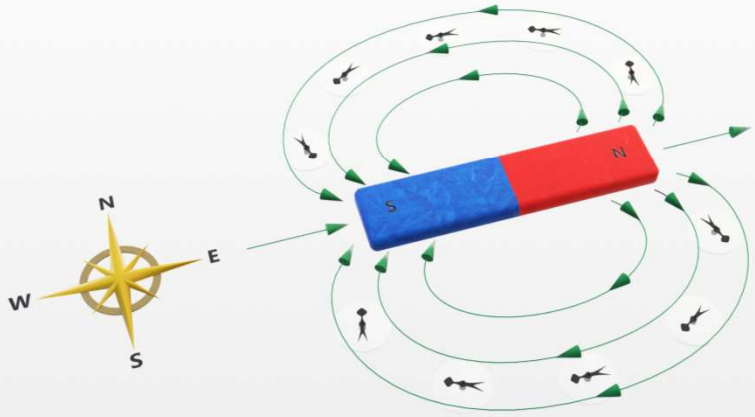
Magnetism: Natural and Artificial

Presenter: Simon Parker



SCOPE / AGENDA

Planning to cover the following:

- Definition, Etymology and Types of Magnetism
- History – key dates and people
- Magnetic materials
- Magnetic fields
- Measuring magnetism
- Geomagnetism – on Earth and in the Solar System
- The impact of the Sun on the Earth
- Electromagnetism – including motors, generators and transformers
- Applications

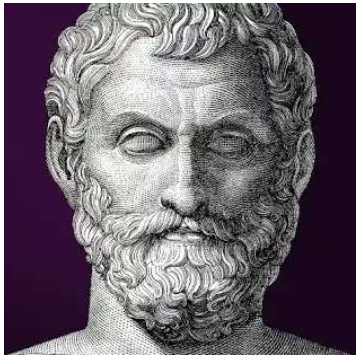
DEFINITION

Very difficult to find a single definition which is clearly related to all sorts of magnetism. Many definitions are circular (e.g. ‘magnetism is a force exerted by magnets…’).

Key features:

- An invisible force / field / phenomenon …
- Produced by the motion of electric charge …
- Resulting in attractive and repulsive forces between objects

ETYMOLOGY



Thales of Miletus (c. 600 BCE) knew that iron ores (‘lodestone’) were found to attract particles of iron, near *Magnesia on the Maeander* in Asia Minor (modern day western Türkiye).

TYPES OF MAGNETISM

	Ferromagnetism	Geomagnetism	Electromagnetism
Source / Cause	Material made of compounds or alloys of Iron (Fe).	Planetary bodies.	The flow of electrical charge / current.
Examples	Lodestones (mostly magnetite – $Fe^{2+}Fe^{3+}{}_2O_4$), Manufactured magnets – bar, horseshoe, ring.	Earth, Sun, **some** of the planets in our Solar System.	Generators, Motors, Televisions (CRTs), Medical (MRI), Transportation (MagLev).
Discovery	From 10^{th} Century BCE.	16^{th} Century CE.	19^{th} Century CE.

HISTORY (BCE)

BCE:

Pre 1000 BCE - The Olmec civilization (Central America). Several finds:

Statues with significant magnetic anomalies. Carving to make use of intrinsic properties:

- Cabezones - heads with strong anomaly over right temple (forward of the ear)
- Barrigones – potbellies with strong anomaly over navel

Polished magnetic bar. May have been part of a magnetic compass.

- Visible groove cut along axis (sighting line?)
- Accurate to within 1^{o} of modern compass

625 to 545 BCE – Thales of Miletus spoke of lodestones (aka loadstones, i.e. leading stones).

200 BCE to 200 CE – Han / Tang Dynasties China - spoon-shaped piece of lodestone sitting on a cast bronze plate. Referred to as a 'south-pointer'. Used for divination, rather than navigation.

94 – 50 BCE – Titus Lucretius Carus – wrote of magnets and lodestones in his *De Rerum Natura* ('On the Nature of Things').

HISTORY (CE)

Application of compass to navigation:

- 1100 – China
- 1187 – Western Europe (possibly via Marco Polo…)
- 1220 – Islamic world
- 1300 – Scandinavia (although some evidence that Leif Erikson and other Norse explorers used them in their Atlantic expeditions)

1391 – Geoffrey Chaucer mentioned the use of lodestone and 32 points on the compass in his "Treatise on the Astrolabe".

William Gilbert (1544-1603) – The creator of the science of magnetism:

- discovered that the Earth is a magnet
- argued that electricity and magnetism were not the same thing
- published "*De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure*" (On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth) in 1600

1632: Ben Jonson wrote his last play – The Magnetic Lady.

Understanding of connection between magnetism and electricity – C19:

- 1820: A magnetic needle is deflected by an electric current - discovery by Oersted, developed as theory by Ampère
- 1821: The first electric motor was demonstrated - Faraday
- 1831: Electromagnetic induction (generating a current in a wire due to a changing magnetic field) - Faraday
- 1861: First mathematic model for connection between electricity and magnetism (electromagnetic waves) - Maxwell and Heaviside

HISTORY (RECENT)

1940s – Walter M. Elsasser proposed the Dynamo theory to explain the Earth's magnetic field.

1940s (late) – Eric Laithwaite developed model of linear induction motor.

1946 – First patent related to a nuclear fusion reactor was registered (by UKAEA).

1958 – Explorer space missions confirmed presence of Van Allen belts.

1959 – 'magnetosphere' coined to describe interaction of solar wind with the Earth's magnetic field.

1967 – First use of 'magnetic mirror' to control plasma in a fusion reactor.

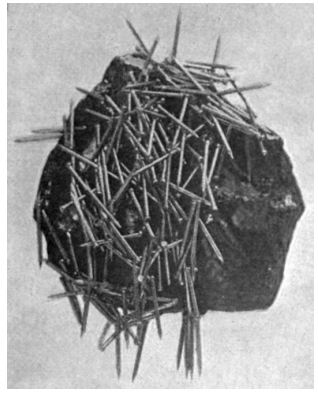
1973 – First MRI images published in *Nature (inventor awarded Nobel prize in 2003).*

1984 – First commercial use of magnetic levitation in Birmingham Airport rail link.

FERROMAGNETIC MATERIALS

Lodestones –

- Naturally magnetized pieces of magnetite (Fe_3O_4), with inclusions of maghemite (Fe_2O_3) and impurities of Ti, Al and Mn
- Believed to have become magnetized due to lightning strikes
- Mostly found near the Earth's surface, rather than at depth



AlNiCo alloys – from 1930s

- Alloys of Iron, with varying proportions of **Al** (8-12%), **Ni** (15-26%), **Co** (5%-24%), **Cu** (<6%), **Ti** (<1%)
- May be Isotropic (magnetized in any direction) or Anisotropic (fixed in the direction of magnetization)
- May be cast (molten alloy poured into a mould) or sintered (compacting using pressure and heat without melting)
- Magnetic field strength may be 3000x that of the Earth's magnetic field

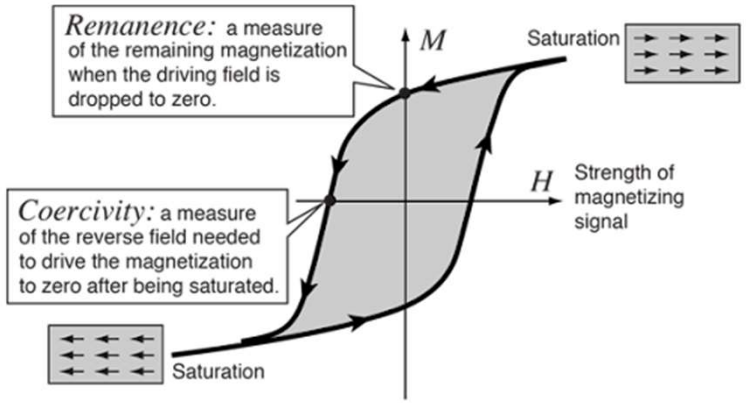
Rare Earth alloys – from 1970s

- **Nd** (Neodymium), **SmCo** (Samarium-Cobalt)
- Brittle and vulnerable to corrosion – so normally plated or coated.
- Raw material production concentrated in China and mined in Myanmar – with China applying export bans
- Classified by many countries as strategically important - with USA pursuing alternatives to REs
- Super-strong – 20% more than the best AlNiCo

MAGNETIC PROPERTIES

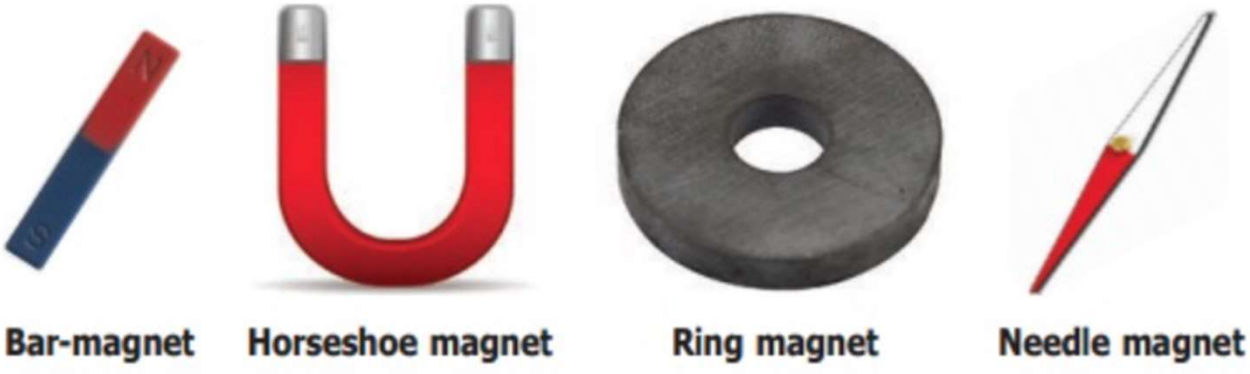
Key properties:

- **Curie temperature** – the temperature above which a material loses its permanent magnetic properties.
  [356 ^{o}C for Ni, 760 ^{o}C for Fe, 1075 ^{o}C for Co]
- **(Relative) Permeability** – a measure of magnetization produced when a material is placed in a magnetic field.
  [1.00 for a vacuum, 40 for Ni, 55 for Co, several 1000s for Fe]
- **Hysteresis** – a non-linear property of magnetic materials which means that magnetism remains after the field has been removed, a negative field needs to be applied to remove the magnetism and despite a field being applied it takes time for the magnetism to return.
- **Coercivity** – the ability of a ferromagnetic material to withstand a magnetic field without becoming demagnetized.
- **Remanence** – the magnetization that remains when an external magnetic field is removed.
- **Flux density** – magnetic field within a material considered as a concentration of magnetic field links per unit cross-sectional area.
  Measured in Tesla (T).

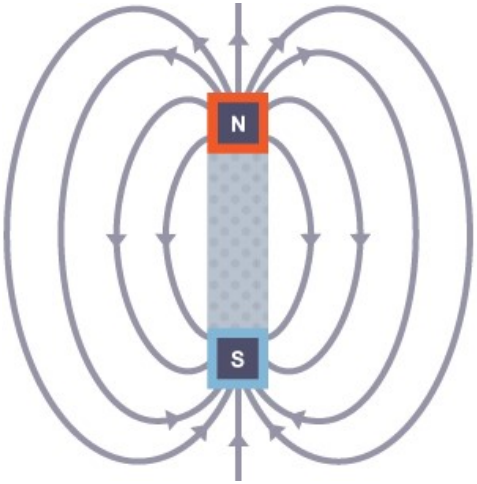


Y-axis: flux density (B)
X-axis: applied magnetic field (H)

MAGNET FORMS

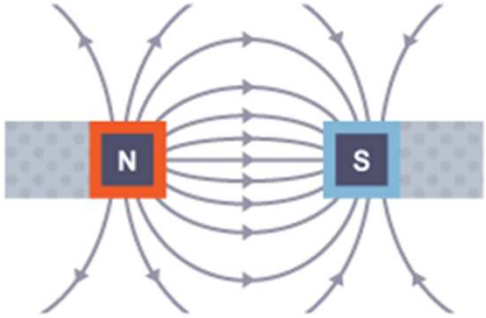


MAGNETIC FIELDS

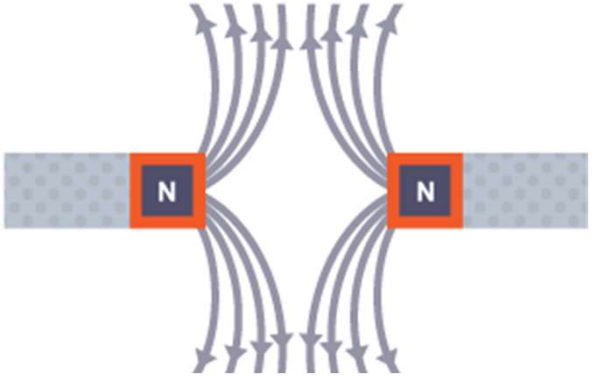


Field lines:
- have arrows on them, going from North to South
- are concentrated at the poles

Forces act in the direction of the tangent to the field line.



N pole of one magnet approaches S pole of another:
- Field lines go from one magnet to the other
- The closer they get, the more lines of force – hence a stronger attractive force

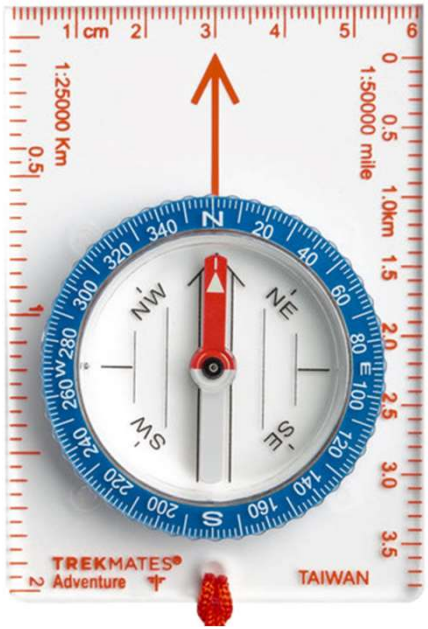


N pole of one magnet approaches N pole of another:
- Lines of force go from North of one to South of other
- The closer they get, the more 'null space' between them – hence a stronger repulsive force

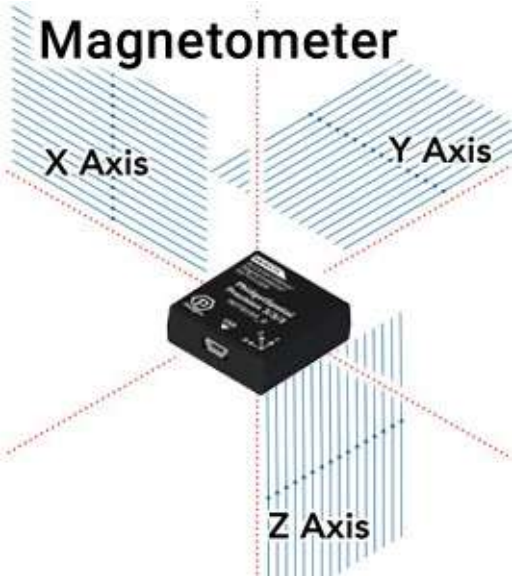
MAGNETIC FIELDS - DEMO

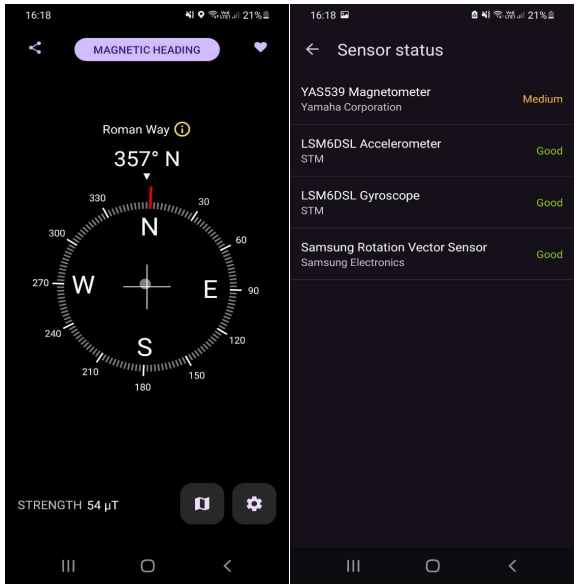
Magnetic Field Around Stack of Magnets With Iron Filings
(https://www.youtube.com/watch?v=snNG481SYJw)

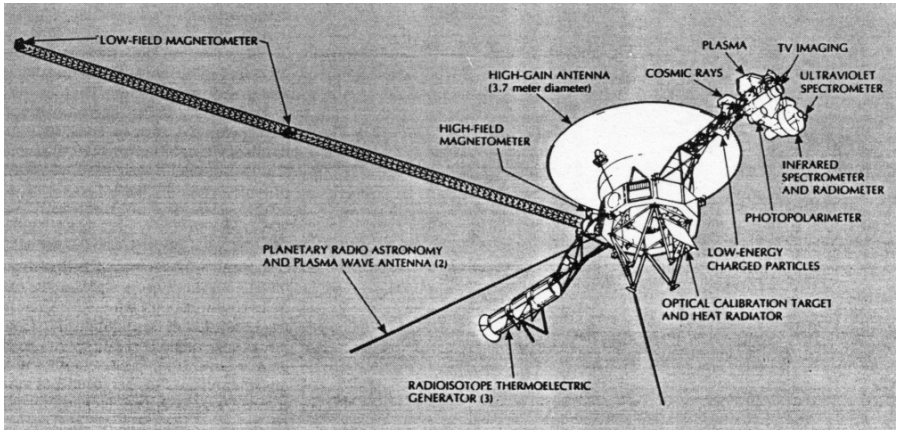
COMPASSES



MAGNETOMETERS







GEOMAGNETISM

The Earth acts *as though* it is a giant bar magnet.

The temperature difference between the inner core (solid) and the outer core (liquid) causes convection which sets up electric currents which generate magnetic fields.

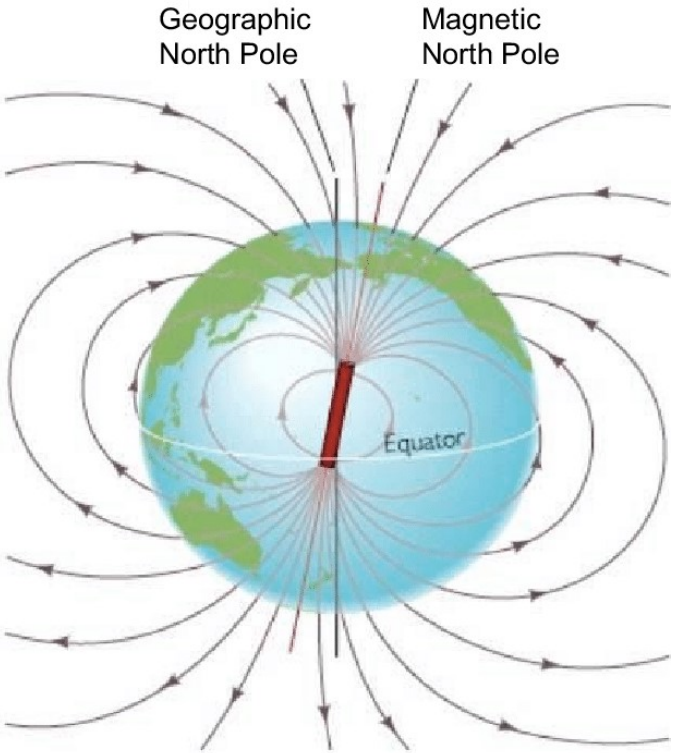
Technically, the northern hemisphere contains the South Magnetic pole, as it is that which attracts our 'north-seeking' compass needle.

The magnetic and geographic poles are in different places and the angle between them varies over the earth's surface - known as magnetic declination (*more in a moment*).

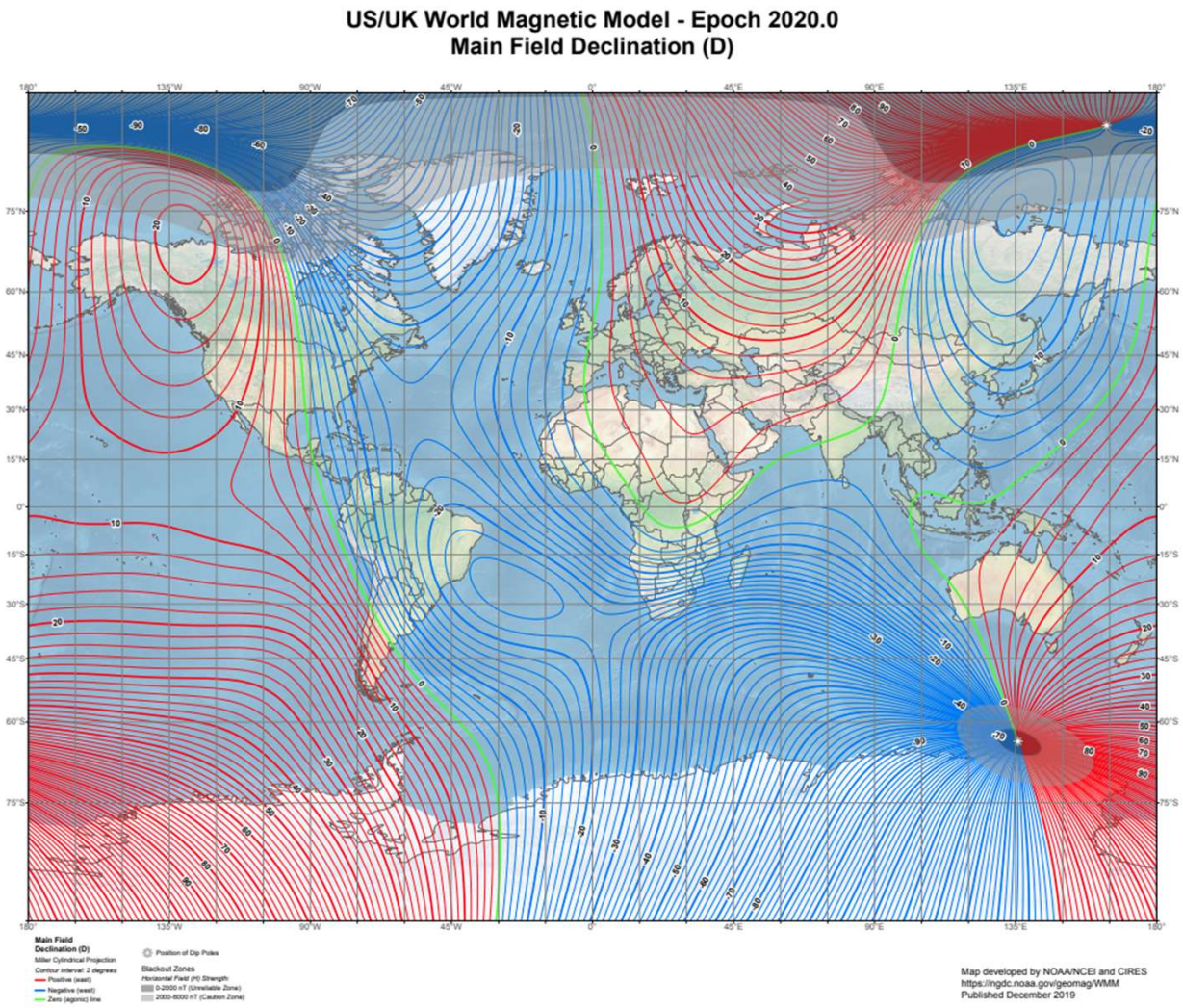
The Magnetic North Pole is currently at 86^{o} N, 142^{o}E (NW of Ellesmere Island, Canada).

The magnetic field lines are parallel to the earth's surface in equatorial regions and perpendicular in polar regions – known as magnetic inclination (*more in a moment*).

The Earth's magnetic field *can* reverse, but infrequently – 183 times in the last 83 million years.



GEOMAGNETISM – DECLINATION



Each line is an isogone – connecting points of equal declination.

The interval between each line is 0.2°.

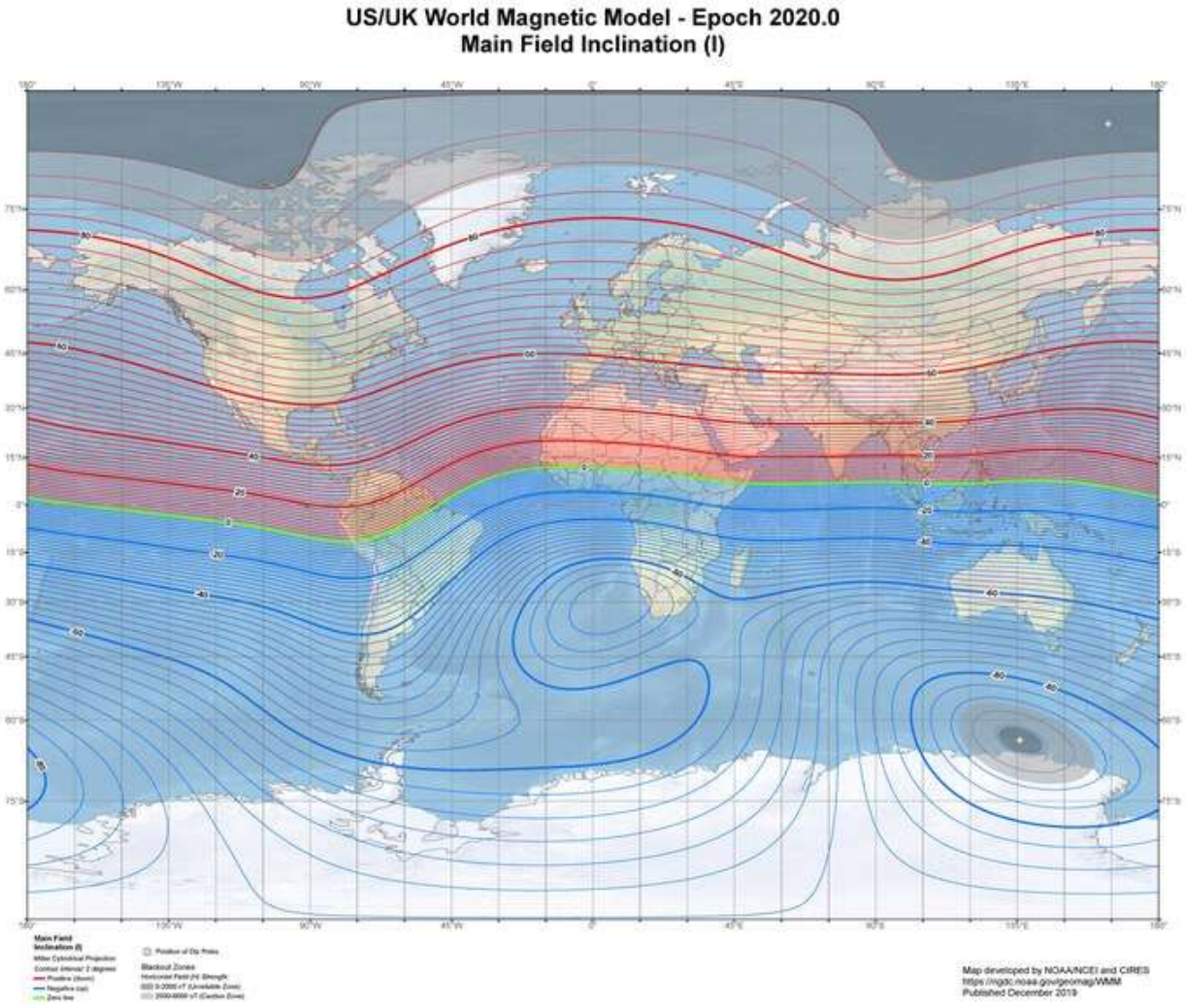
The UK is close to an agonal line with declination between 0° and 4°W.

Declination has changed over time, e.g. London:

- 1580 - 11° E
- 1665 - 1° W
- 1765 - 20° W
- 1800 - 24° W
- 1925 - 13° W
- 1935 - 11° W
- 2020 - 1° E

OS Maps shows relationship between Grid North, True North and Magnetic North and an estimate of the annual change in declination.

GEOMAGNETISM – INCLINATION



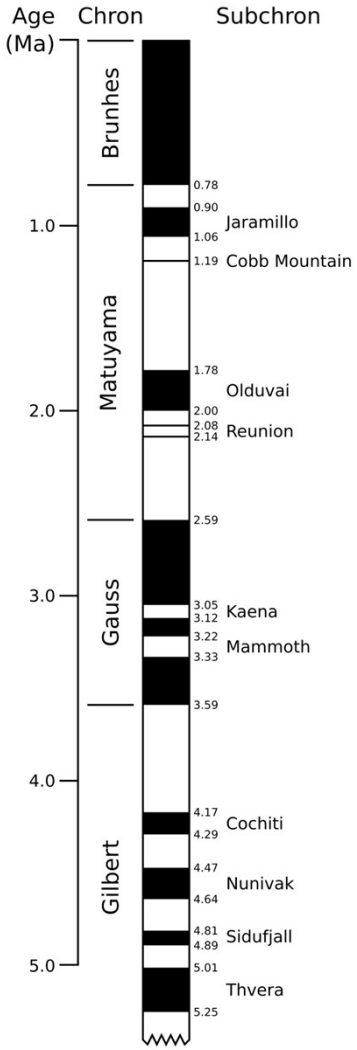
Each line is an isocline – connecting points of equal inclination.

The interval between each line is 2^{o}.

The UK has an inclination between 65^{o} (S) and 72^{o} (N).

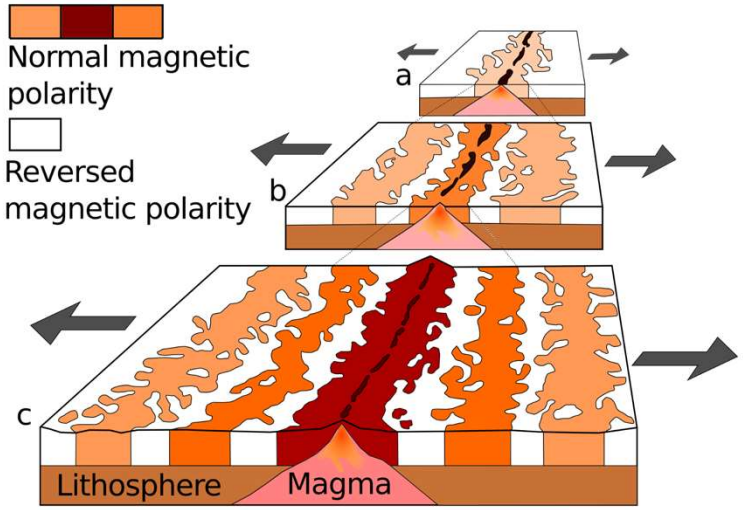
Inclination *not likely* to have changed much over time.

GEOMAGNETISM – REVERSALS



The diagram shows periods when the direction of the Earth's field is as it is now in black, and in the opposite direction in white.

- Scale – 1 Million Years (Ma)
- Chron – The period whilst the direction remains (mostly) the same. *Named after prominent researchers in magnetism.*
- Subchron – sub-division of the chron where there may be some variation or 'failed' reversals.

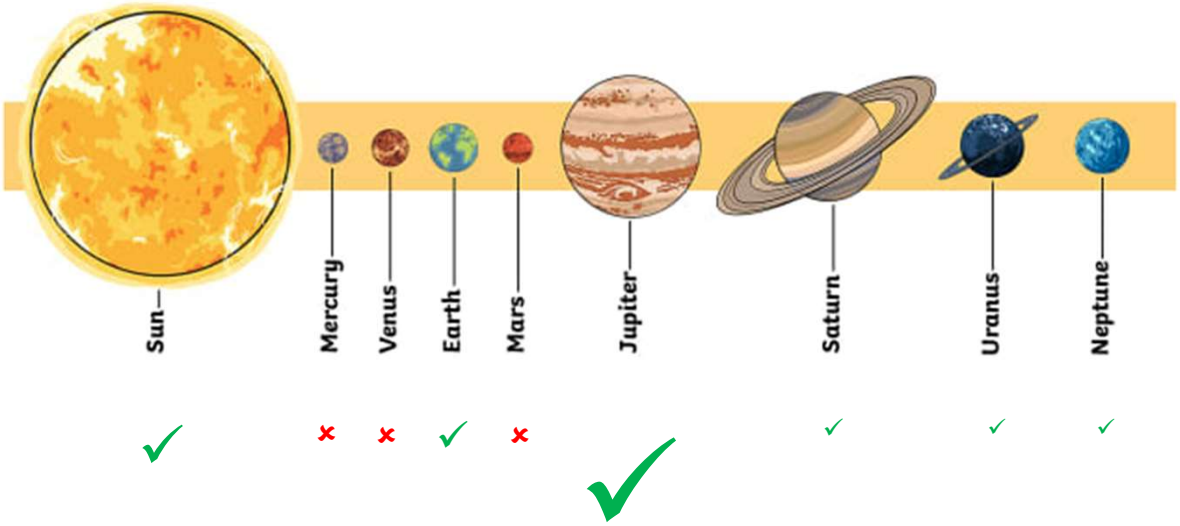


NOTES:

- 183 reversals in 83 Ma yrs ⇒ 0.45 Ma between reversals *on average.*
- 0.78 Ma since the last reversal (the 'Brunhes-Matuyama reversal'), so *we're overdue*…
- **However**, the pattern of reversals is random and highly variable, so not possible to predict.

- Reversals take around 10 ka to take effect (shorter at the equator than at the poles).
- Study / discovery of reversals started in early C20 – Bernhard Brunhes, Motonori Matuyama.
- Magnetic rocks record the prevalent geomagnetic field at the time that they cool.

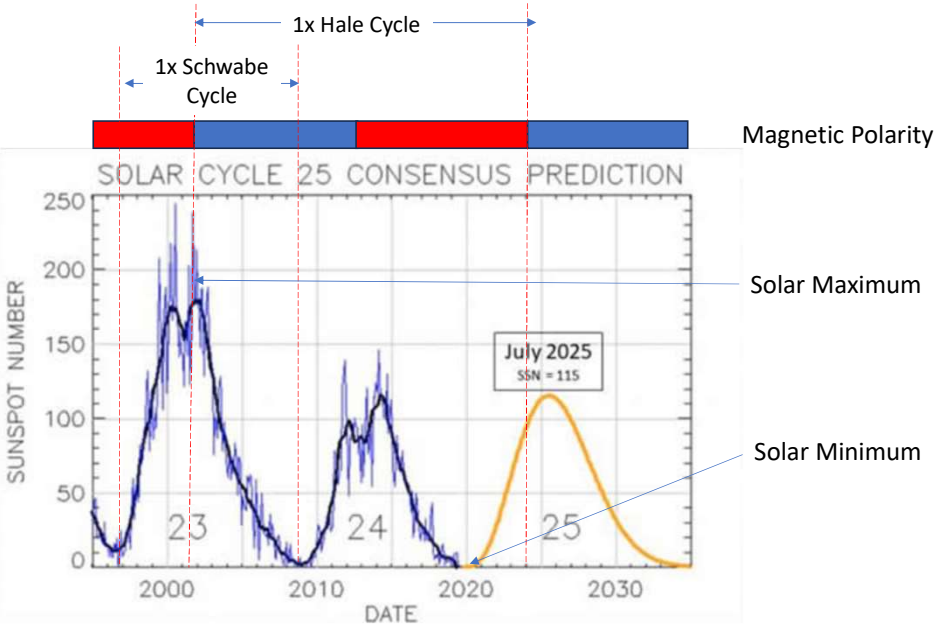
GEOMAGNETISM – SOLAR SYSTEM

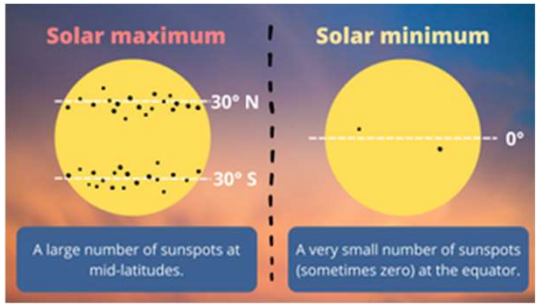


Mercury – field is < 1% that on Earth (0.3 µT).
Earth – Field is around 50 µT.
Jupiter – largest magnetic field in the solar system (20,000x that of earth – 1 T). *[Compare with MRI scanner at 3 T].*
Saturn – magnetic declination close to zero (magnetic and geographic polls coincide). Strength around 50% of Earth (21 µT).
Jupiter and Saturn – field believed to be due to compressed Hydrogen in the core.
Uranus – declination is around 60^{o}. Field is around 10 µT.
Neptune – field is around 10 µT.

Solar activity is cyclical:

- The time between Solar Minima is known as a Solar Cycle (*the 'Schwabe Cycle'*) – *close to 11 years.*
- The Sun's magnetic field reverses as it approaches a maximum – most recently 2013.
- Every 22 years (*the 'Hale cycle'*), the field direction reverses and reverts to it's original.





Point in Cycle	# of sunspots	Locn. of sunspots	Magnetic field
Maximum	Many	Mid-latitudes	Complex, no clear poles, likely to change soon / have changed recently.
Minimum	Few	Equator	Simple, clear N+S, relatively stable.

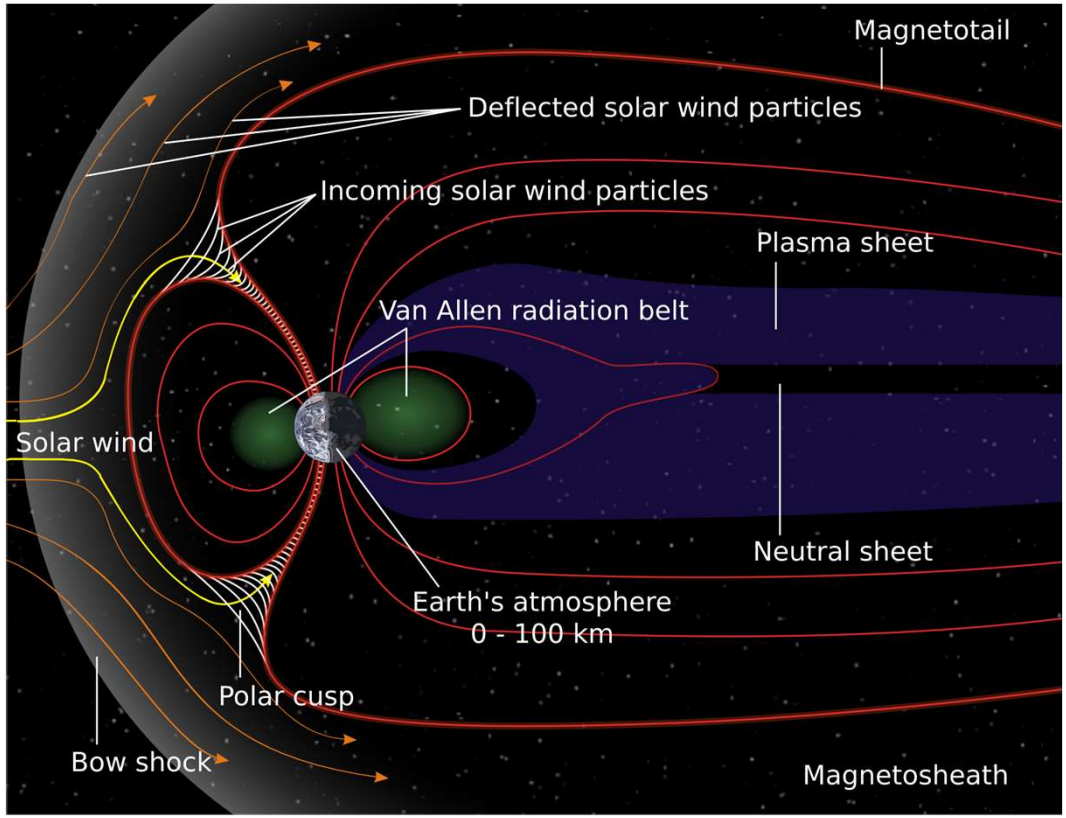
GEOMAGNETISM - MAGNETOSPHERE

Magnetosphere – the area around a planet dominated by the planet's magnetic field.

The shape of Earth's magnetosphere is influenced by the solar wind. It protects us from highly-charged particles from the Sun. Without it, our atmosphere would be eroded. Mars' lack of a magnetic field resulted in disappearance of its atmosphere.

Key areas:

- **Bow shock** – boundary between magnetosphere and the ambient.
- **Polar cusp** – region where the solar wind is channeled to Earth's magnetic poles to form aurorae.
- **Van Allen belts** – zones of energetic charged particles.
- **Magnetosheath** – region where the Earth's field is weakened by the solar wind.
- **Magnetotail** – opposite side of the Earth to the Sun.



GEOMAGNETISM – AURORAE

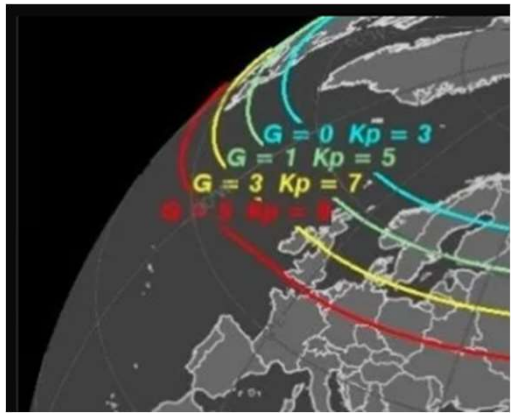
Aurora Borealis (N. hemisphere), Aurora Australis (S. hemisphere).

Caused by charged particles from the sun ('solar wind') hitting gas molecules in ionosphere and 'exciting' them to emit photons of visible light.

Colour depends on the gas that was hit:

- Oxygen – green or orange-red
- Nitrogen – blue, purple or red

'Natural' aurora belt extends from North Pole to Greenland and Norway. It takes severe, extreme solar storms to bring the aurora directly overhead the UK.



Kp-Scale	G-Scale	Frequency	Auroral Activity
0-3	N/A	7 years/cycle	Quiet
4			Active
5	1	900 days/cycle	Minor
6	2	360 days/cycle	Moderate
7	3	130 days/cycle	Strong
8	4	60 days/cycle	Severe
9	5	4 days/cycle	Extreme

[Each cycle lasts approx. 11 years]

ELECTROMAGNETISM

Definition: Electromagnetism is 'an interaction that occurs between particles with electric charge via electromagnetic fields' – another circular definition…

We're going to cover the relationship between:

- Electric currents through conductors.
- Magnetic fields in a medium.
- Forces which result in movement.

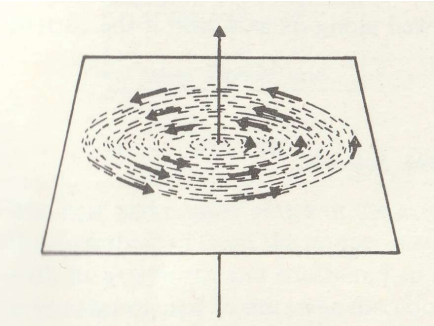
Where we are heading:

1. Current flowing in conductor in a magnetic field generates a force which can move something – the motor effect.
2. Causing the movement of a conductor in a magnetic field can causes a current to flow – the generator effect.

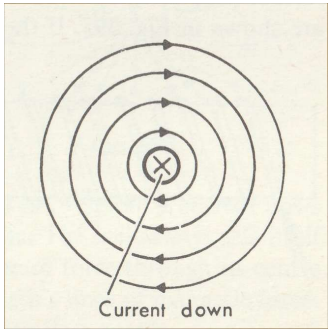
Both are essential to modern life!

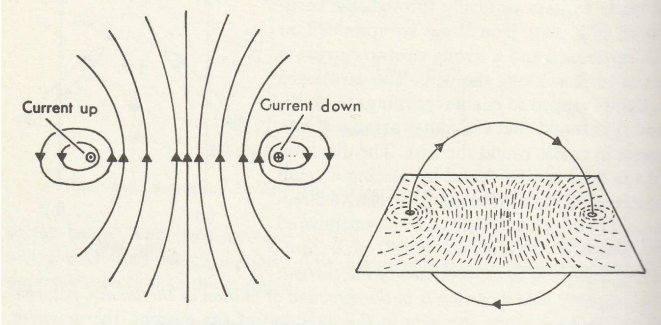
MAGNETIC FIELD DUE TO A CURRENT

Oersted demonstrated (1820) that a current through a wire generated a magnetic field.



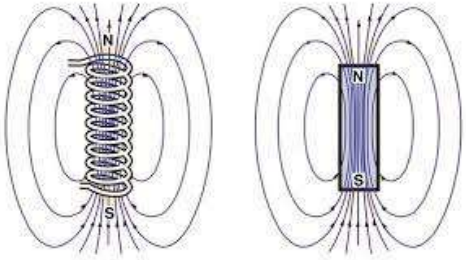
The direction of the magnetic field is at right-angles to the conductor and can be remembered by thinking of a screw being tightened.





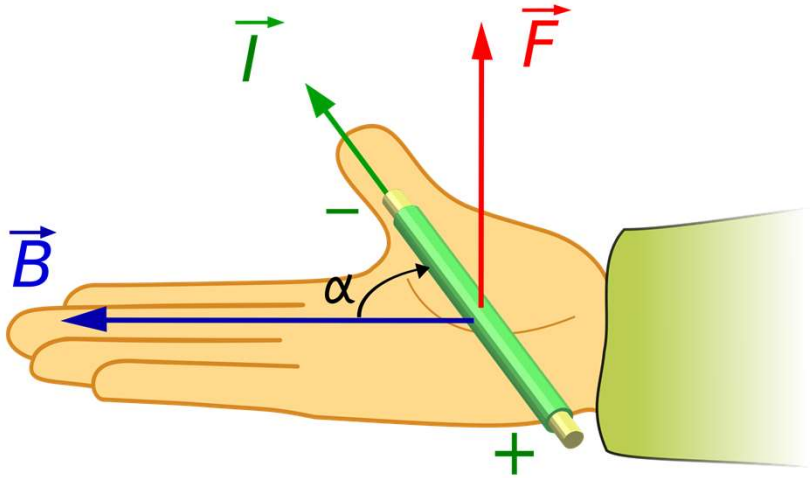
If a loop is formed, the magnetic field from where the current is flowing up is combined with that of the current flowing down.

If multiple loops are used, a coil or solenoid is formed, and the magnetic field becomes indistinguishable from a bar magnet.



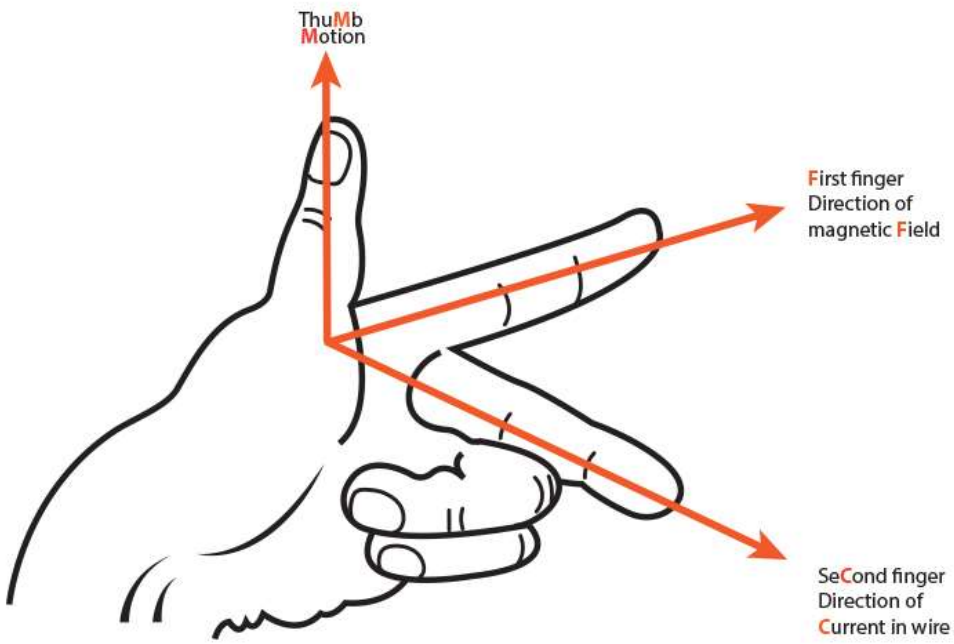
FORCE ON A CONDUCTOR IN A MAGNETIC FIELD

A wire carrying a current within a magnetic field experiences a force which is proportional to the sizes of the current and magnetic field – the Laplace force.

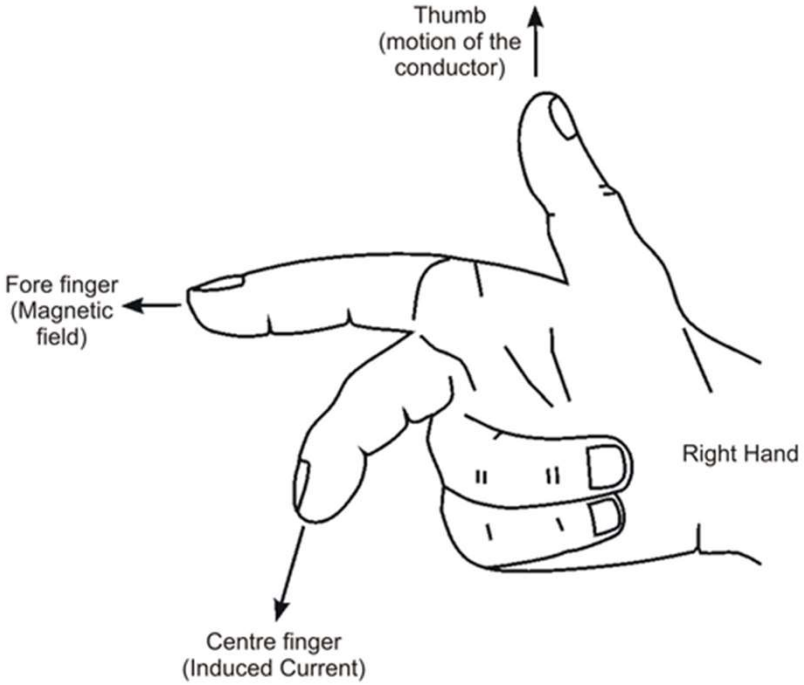


FLEMING'S RULES

After John Ambrose Fleming (1849-1945).



Left-Hand Rule – Motor Effect



Right-Hand Rule – Generator Effect

thuMb -> Motion

First or Fore finger -> magnetic Field

seCond (or Centre) finger -> Current

MAXWELL'S EQUATIONS

A set of (coupled, partial-differential) equations that form the basis for *classical* electromagnetism, relating electric and magnetic fields. After James Clerk Maxwell. Subsequently updated by Oliver Heaviside and more correctly known as Maxwell-Heaviside equations.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

Where:
E – electric field (vector)
B – magnetic field (vector)
J – current density (vector)
ρ - electric charge density
ε_0 – vacuum permittivity
μ_0 – vacuum permeability

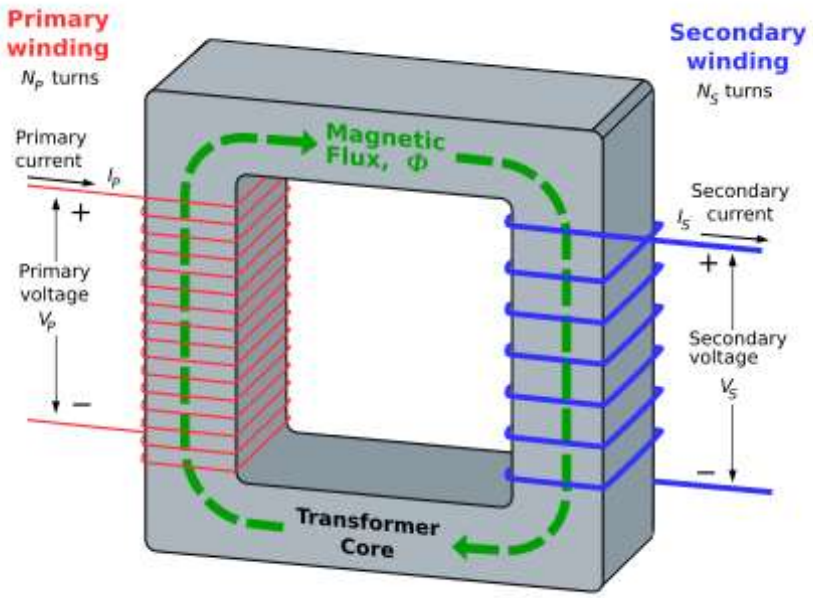
DON'T PANIC – I won't attempt to explain these, but just wanted to show some apparently simple equations that relate fundamental physical entities.

How the Electric Motor Works
(https://www.youtube.com/watch?v=evWpDrRAyCc)

How electricity is generated
(https://www.youtube.com/watch?v=sAO9gYaMZkg&t=168s)

TRANSFORMERS

Uses the principle of *induction* to transfer electrical energy from one electrical circuit into another.



1. Alternating current in the primary circuit (I_P) causes a magnetic flux (Φ) in the transformer core.
2. Varying flux in the transformer core results in a current in the secondary circuit (I_S).

In an **ideal** transformer the ratio of the voltages is the same as the ratio of the turns in the coils, i.e.

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

This can be used to step up or step down the voltage for transmission over distances or use by low power devices.

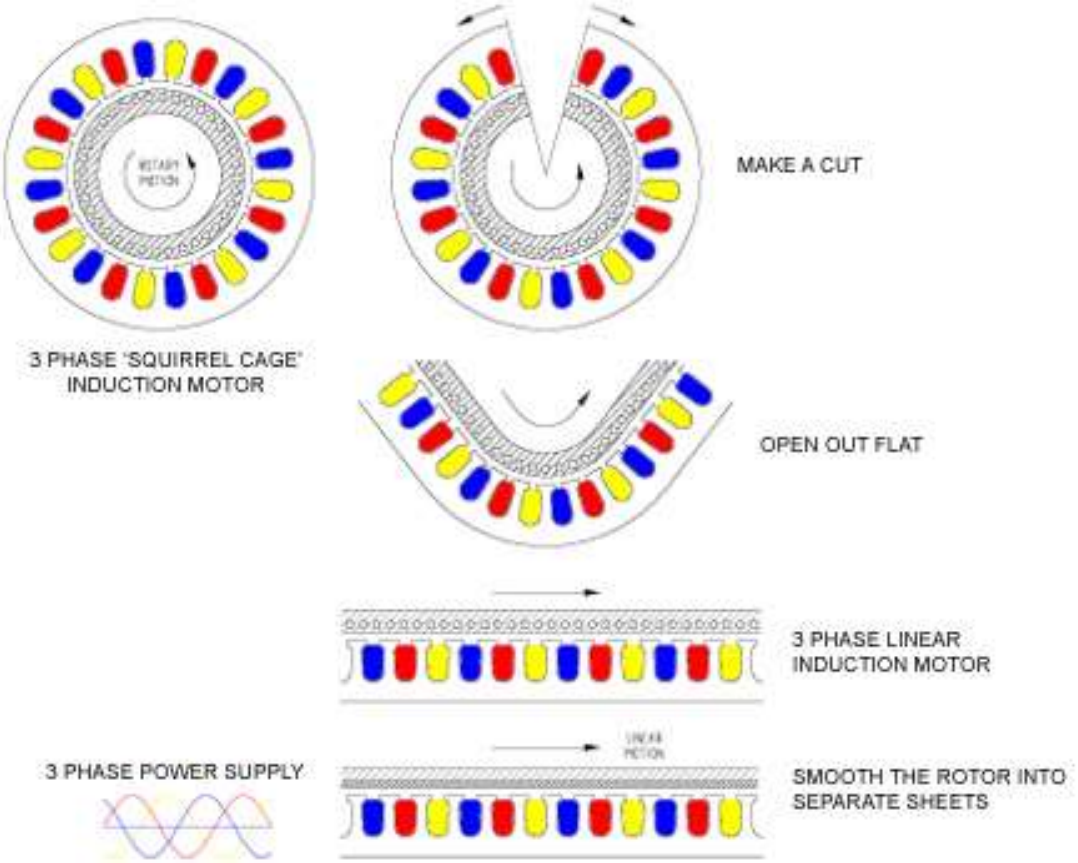
In a **real** transformer there are losses due to:

- Hysteresis and flux leakage in the magnetic circuit.
- Heating in the transformer core and the coil windings.

INDUCTION MOTORS

How to Understand Induction Motors
(https://www.youtube.com/watch?v=nA5T851FAT0)

LINEAR INDUCTION MOTORS



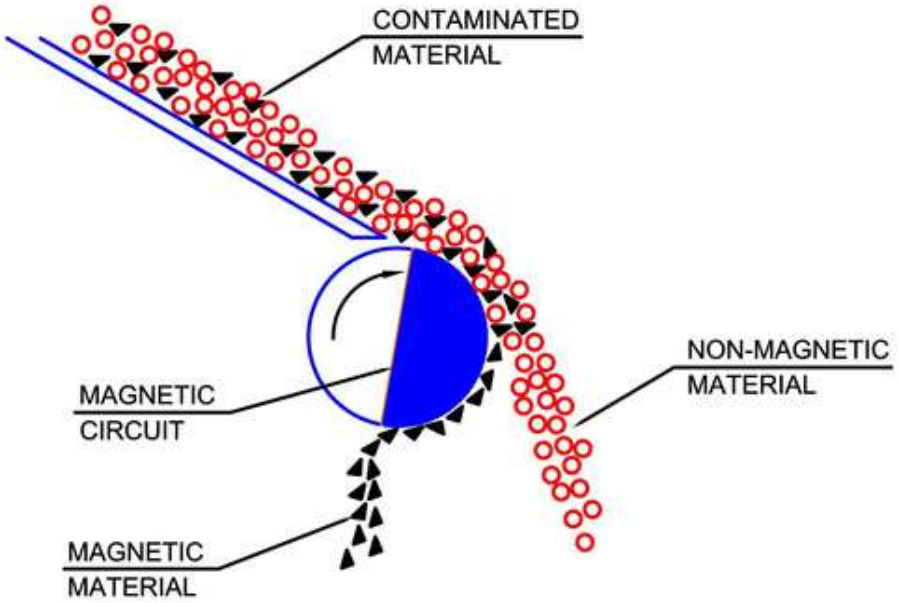
APPLICATIONS - RECYCLING

Scrap Metal Merchants

Used to separate large ferrous items from bulk collection.

Pickup/release controlled by switching on/off electromagnet.

Magnet strength is around 1 T.
[Compare with 3 T for MRI scanner]

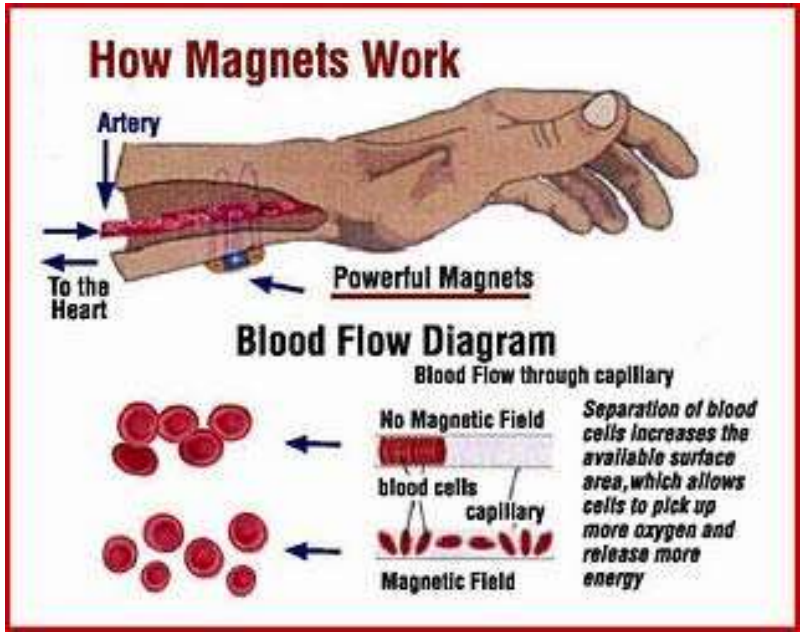


Recycling Centres

Separation of ferrous from non-ferrous material.

Brushes or application of magnetism over part of drum used to release magnetic material.

APPLICATIONS - MEDICAL



MRI (Magnetic Resonance Imaging)

Certain nuclei absorb RF energy when in a magnetic field.

Absorption can be detected and turned into an image.

Normally looking for Hydrogen, so MRI scan is really mapping location and density of water and fat.

Field strength varies from 0.2 – 7 T (commonly 3 T).

Magnetic Healing

Involves placing magnets on the skin for therapeutic benefit.

Magnets may also be electrically charged, or treatment combined with acupuncture.

Theory is based on re-balancing the magnetic fields naturally present in the body.

APPLICATIONS – NON-DESTRUCTIVE TESTING

Magnetic Particle Inspection (MPI)

Used to detect shallow / fine cracks in the surface of ferromagnetic material.

Works by identifying discontinuity in magnetic flux lines due to defects.

First used in 1860s to test cannon barrels.

By 1930s, commonly used in railway industries for flaws in locos and rail.

APPLICATIONS - MILITARY

<u>EMALS – Electro-Magnetic Aircraft Launch System</u>

300ft long A.C. Linear Induction Motor

Accelerates 45,000 kg aircraft to 150 mph

45s to recharge

2017 – installed on one US carrier – USS Gerald R. Ford

Not considered to be reliable enough. Unlikely to be installed into more carriers until 2030's.

<u>Railgun</u>

D.C. Linear Motor

Imparts high kinetic energy to a projectile

High muzzle velocity compared with conventional guns (Mach 8.8 vs Mach 5.9).

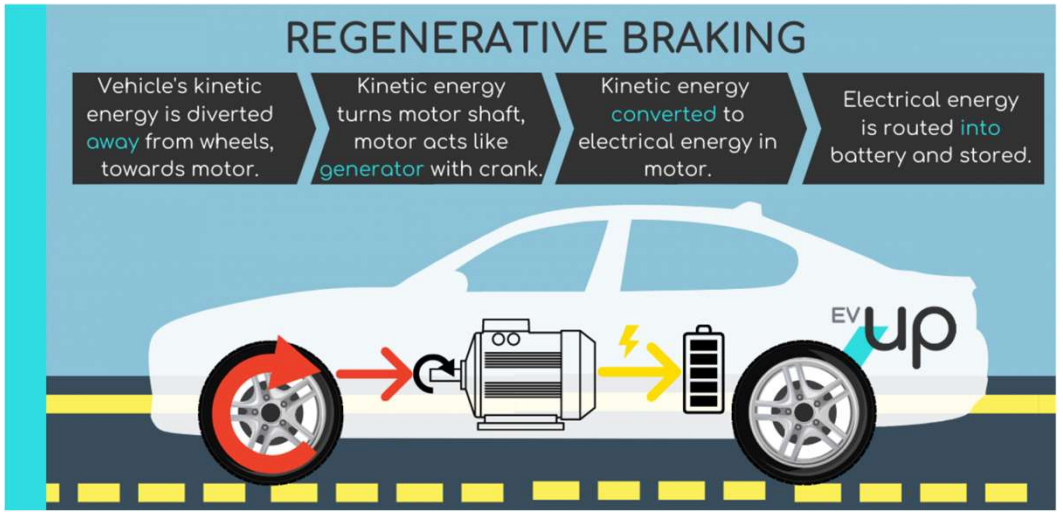
Launch current of several million Amps.

Could be used for satellite launch, as well as warfare.

Concept dates back to early C20.

Still in the research stage.

APPLICATIONS - TRANSPORT



MagLev Trains

Levitation using repulsive magnetic force (e.g. N↔N).

Propulsion using linear induction motor.

Short (600m) track at Birmingham Airport (1984-95).

6x operational services – 3x China, 2x S.Korea, 1x Japan.

Regenerative Braking

Recovering energy whilst braking.

Simplest form: turn motor into generator.

Energy may charge a battery or capacitor or spin a flywheel.

Used on trams, trains and EVs.

Particle Accelerators

Multipole magnets are used to control particle beams:

Dipoles – steering around ring and at ingress and egress.

Quadrupoles – keeping the beam focusses, counteracting spread.

Sextupoles – ensure that particles of different energies stay together.

Octupoles – ensures stability of the beam.

LHC: 1232 dipoles, each 15m long and weighing 35 tonnes.
Field strength is 8.3 T

Magnet Containment Fusion (MCF)

Heating and containment of plasma using magnetic fields to cause fusion and generate power.

Most fusion reactors are toroidal in shape (like a ring).

The fuel (Deuterium / Tritium) is at 10^{8} ^{0}C

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Wikipedia – many and various articles, and articles referenced from them.

YouTube:

- Magnetic Field Around Stack of Magnets With Iron Filings (https://www.youtube.com/watch?v=snNG481SYJw) – Slide 12 (Magnetic Field Demo)
- GCSE Physics - How the Electric Motor Works (https://www.youtube.com/watch?v=evWpDrRAyCc) – Slide 28 (D.C. Motor with Commutator)
- How electricity is generated (https://www.youtube.com/watch?v=sAO9gYaMZkg&t=168s) – Slide 29 (Generator / Dynamo / Alternator)
- How to Understand Induction Motors (https://www.youtube.com/watch?v=nA5T851FAT0) – Slide 31 (Induction Motors)