PY1E04: Lecture 5

Introduction to Physics
(Electromagnetism)

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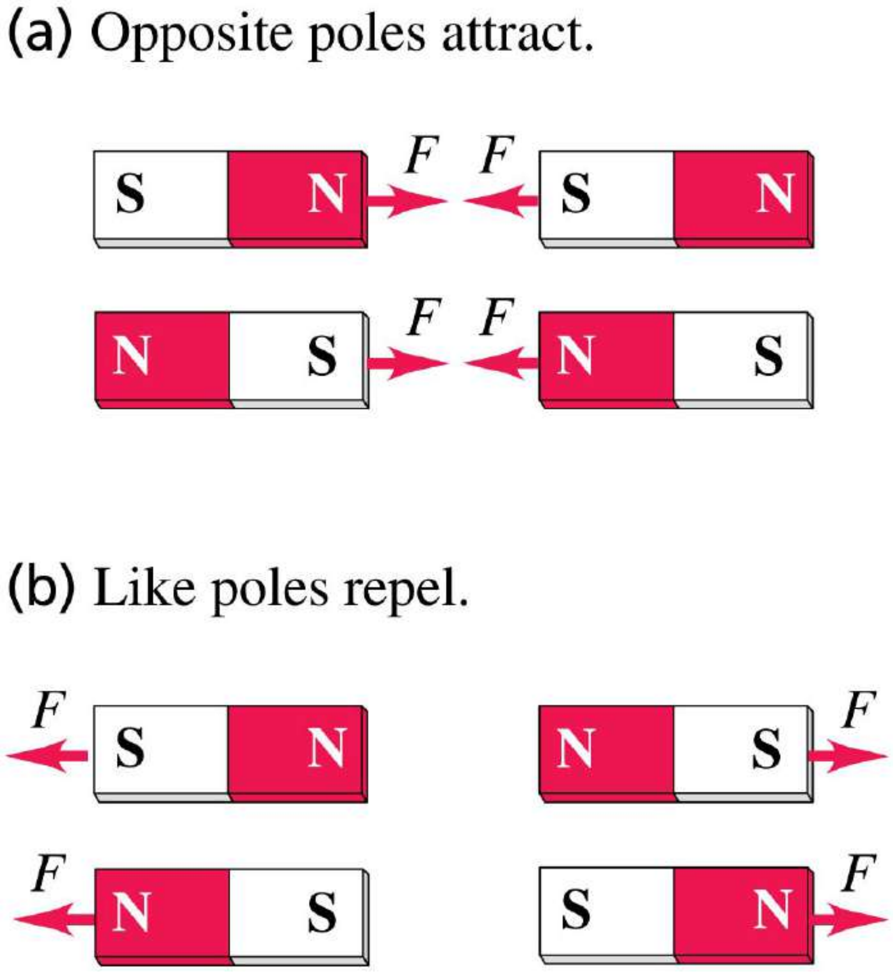
Magnetism

Classic examples include:
- Permanent magnets, which attract unmagnetized iron objects and can also attract or repel other magnets.

- A compass needle aligning itself with the Earth's magnetism is an example of this interaction.

→ But the fundamental nature of magnetism is the interaction of moving electric charges.

Magnetic poles



If a bar-shaped permanent magnet, or bar magnet, is free to rotate, one end points north; this end is called a **north (N) pole**.

The other end is a **south (S) pole**.

Magnetic poles

(a) Opposite poles attract.

(b) Like poles repel.

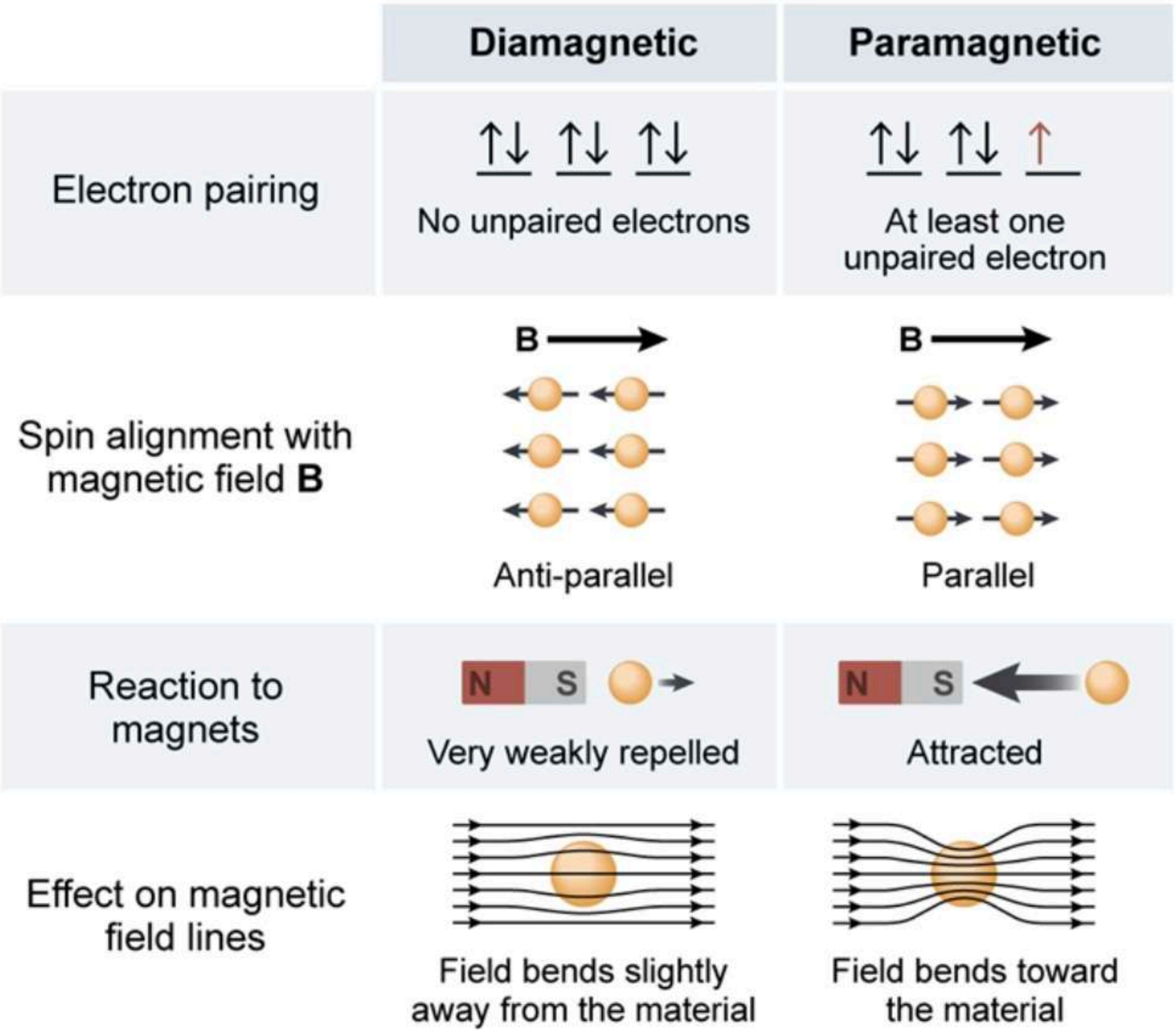
Types of magnetic materials

Paramagnetism: Paramagnetic materials (Aluminum, Tungsten, Oxygen) with unpaired electrons form **weak magnetic dipoles** at the atomic level when exposed to a magnetic field ($B_{induced} \sim B_{applied} \times 10^{-5}$).

Diamagnetism: Diamagnetic materials (Gold, Copper, Water) with all electrons paired respond to magnetic fields by developing a **weakly opposing magnetic field** ($B_{induced} \sim -B_{applied} \times 10^{-5}$).

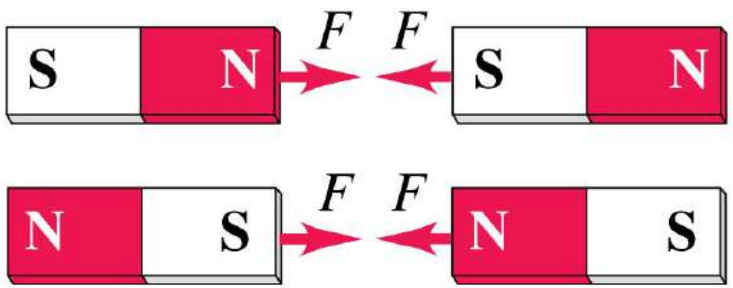
Ferromagnetism: Ferromagnetic materials (Iron, Cobalt, Nickel) exhibit a long-range ordering phenomenon at the atomic level which causes the unpaired electron spins to line up parallel with each other in a region called a domain ($B_{induced} \sim B_{applied} \times 10^{5}$).

Types of magnetism

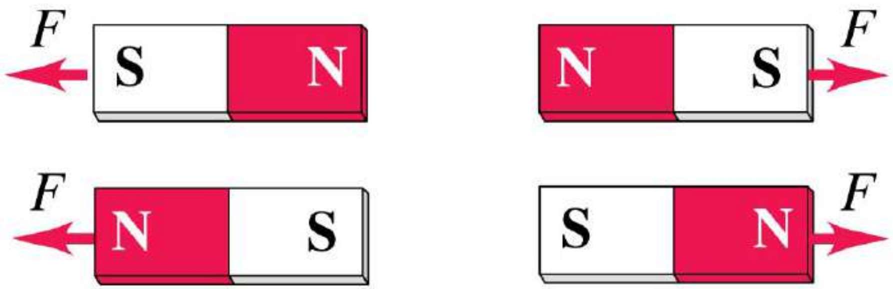


Magnetic poles

(a) Opposite poles attract.

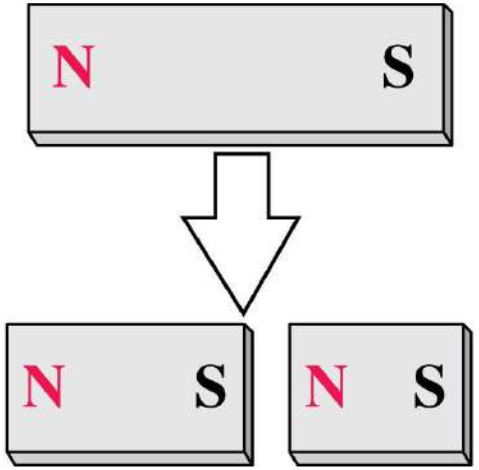


(b) Like poles repel.



In contrast to electric charges, magnetic poles always come in pairs and can't be isolated.

Breaking a magnet in two ...



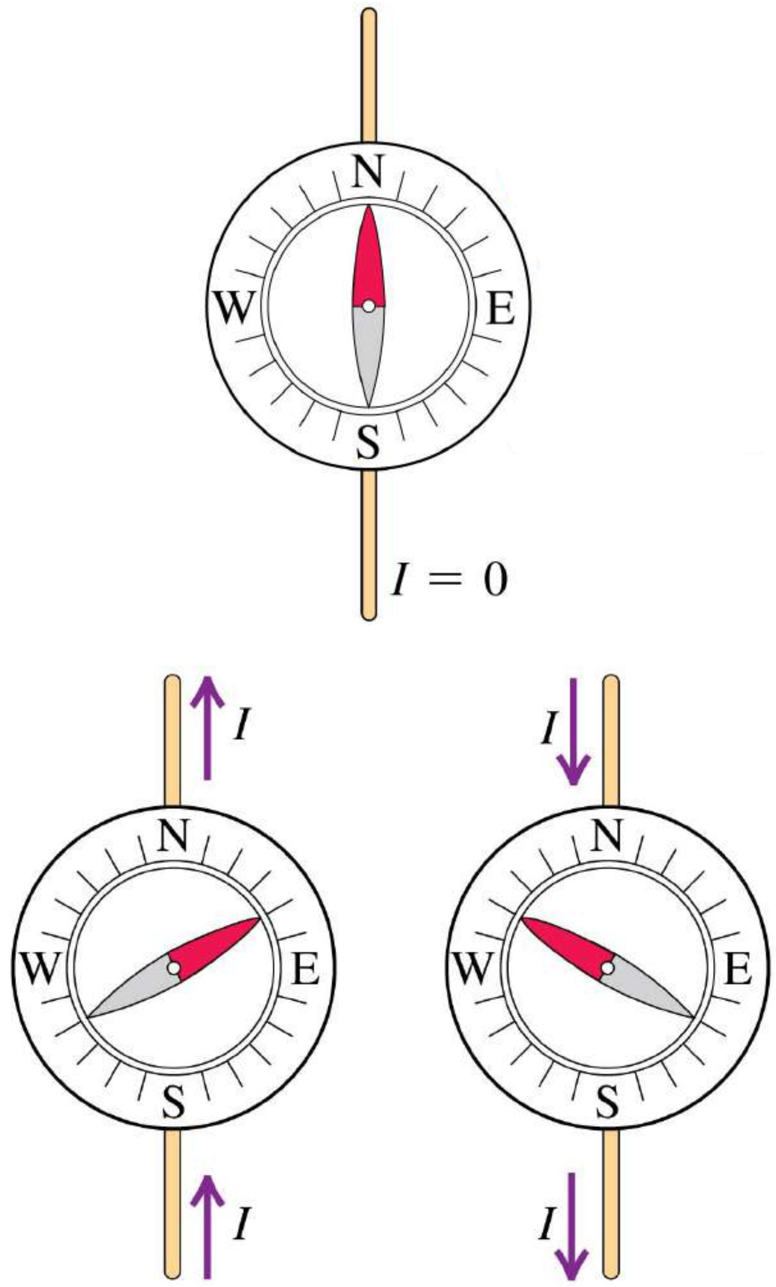
... yields two magnets, not two isolated poles.

Electric current and magnets

A compass near a wire with no current points north, However, if an electric current runs through the wire, the compass needle deflects somewhat.

A moving charge (or current) creates a magnetic field in the surrounding space. The magnetic field, ***B***, exerts a force on any other moving charge (or current) that is present in the field.

The unit of ***B*** is the Tesla (T).

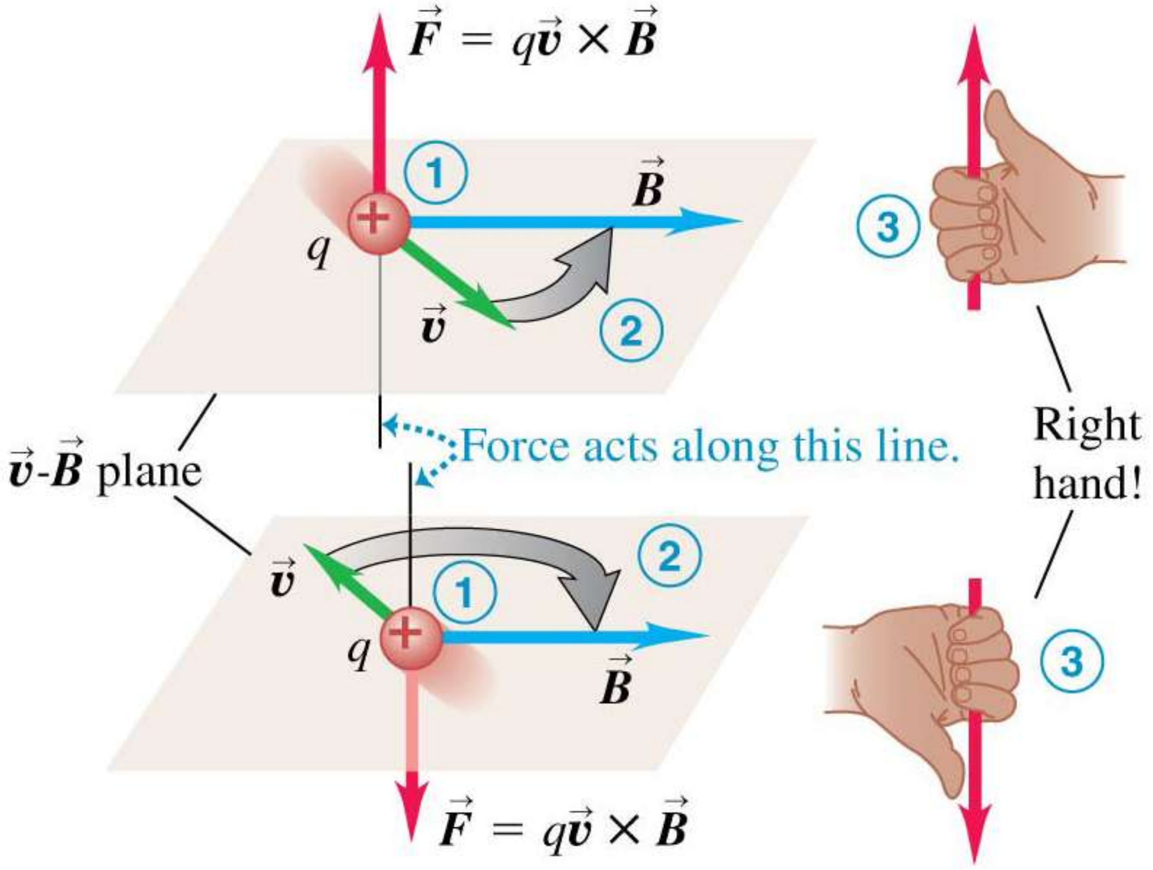


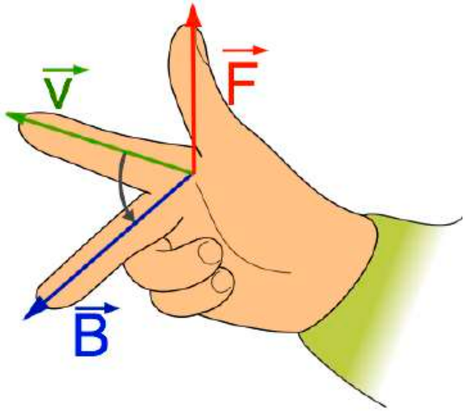
Right hand rule

The right-hand rule gives the direction of the force on a *positive* charge.

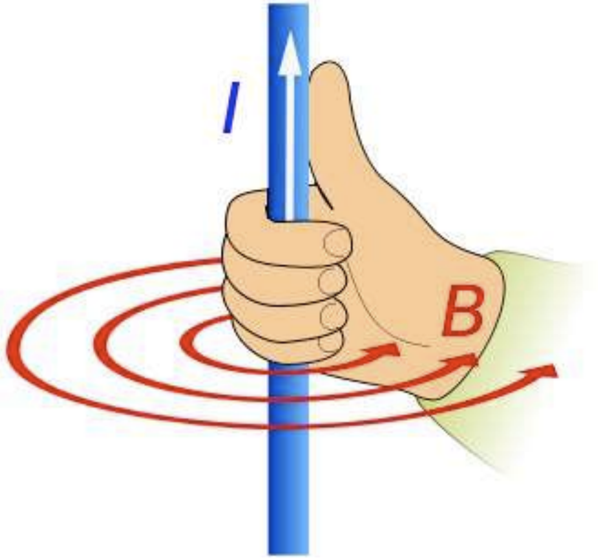
If the charge is negative, the direction of the force is opposite to that given by the right-hand rule.

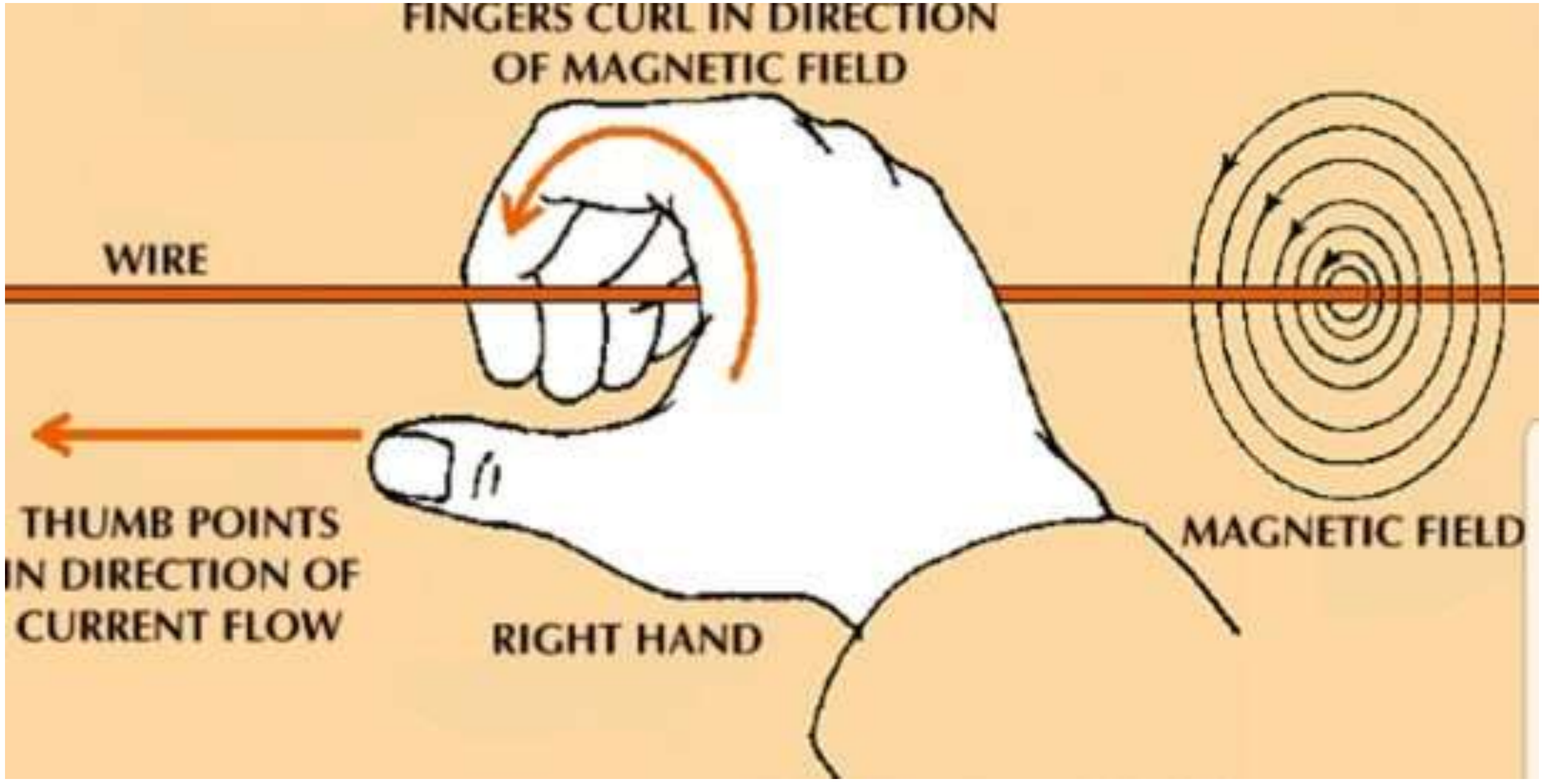
Positive and negative charges moving in same direction through magnetic field experience magnetic forces in opposite directions.





Right hand rule

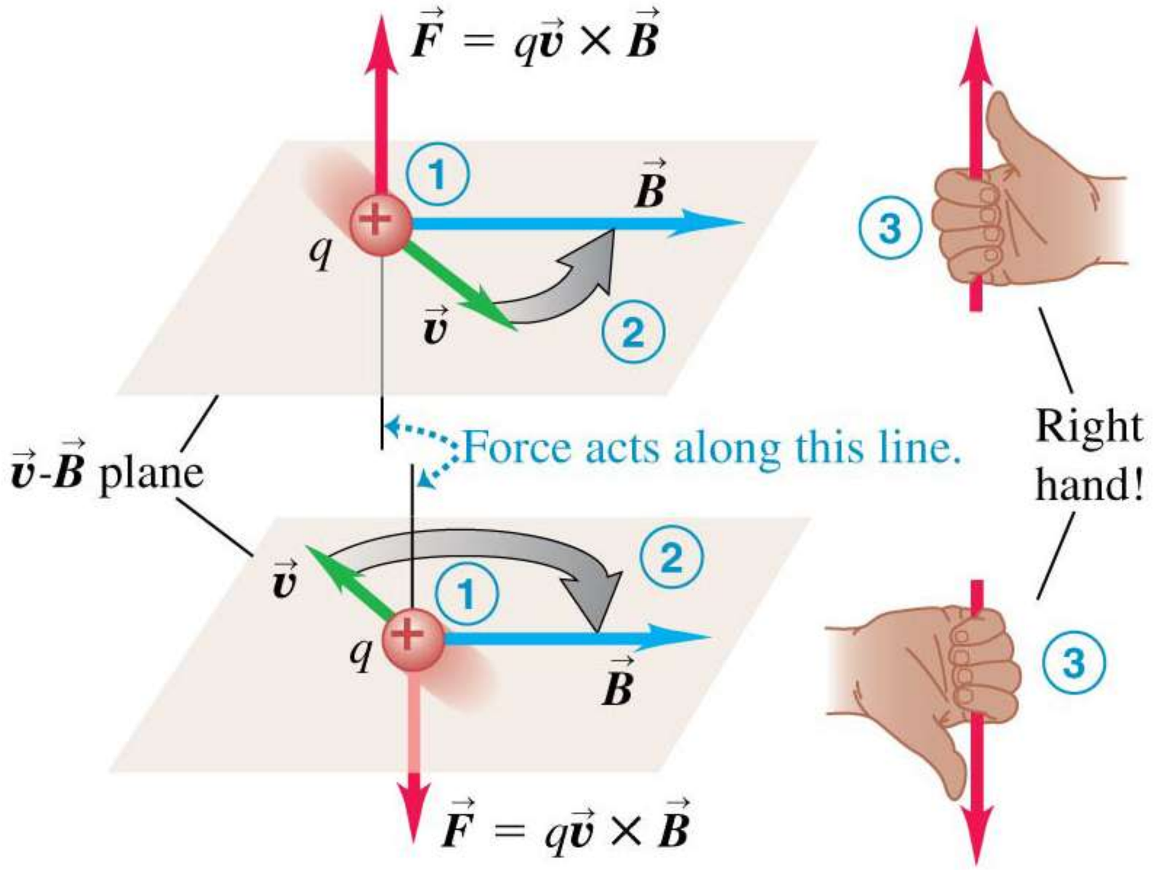




Right hand rule

The direction of the magnetic force is always perpendicular to velocity, ***v****,* and B, so

$$\boldsymbol{F}_{mag} = \boldsymbol{q}\,(\boldsymbol{v} \times \boldsymbol{B})$$



Right hand rule

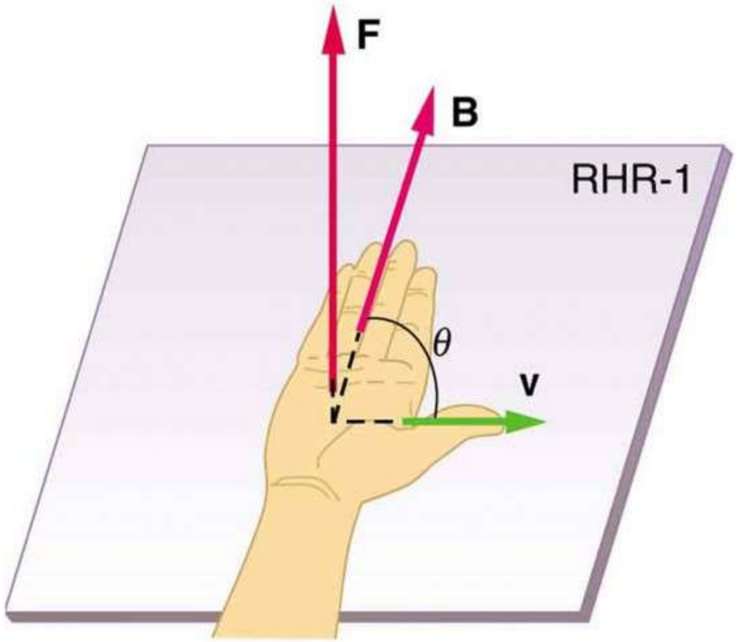
In practice it depends on the angle between the directions of ***v*** and ***B***,

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

F is measured in Newtons.

$1\ \mathrm{T} = 1\ \mathrm{N} / \mathrm{C\ ms^{-1}} = 1\ \mathrm{N} / \mathrm{A\ m}$

Besides Tesla, another unit of B, the Gauss ($1\ \mathrm{G} = 10^{-4}\ \mathrm{T}$), is also in common use.



$F = qvB\sin\theta$

F $\perp$ plane of **v** and **B**

Reminder: Vector product

If the vector product ("cross product") of two vectors is $\boldsymbol{C} = \boldsymbol{A} \times \boldsymbol{B}$ then:

Magnitude of **vector (cross) product** of vectors $\vec{B}$ and $\vec{A}$

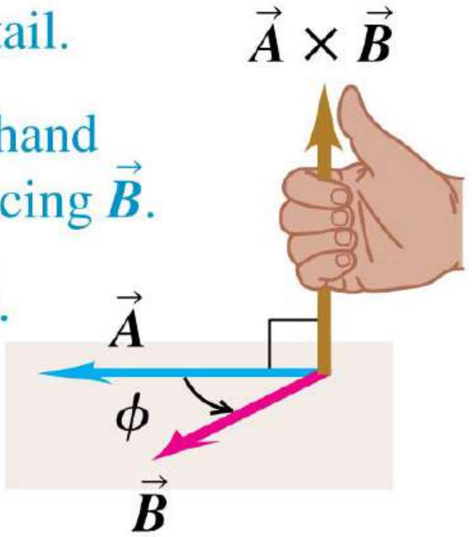
$$C = AB \sin\phi$$

Magnitudes of $\vec{A}$ and $\vec{B}$

Angle between $\vec{A}$ and $\vec{B}$ when placed tail to tail

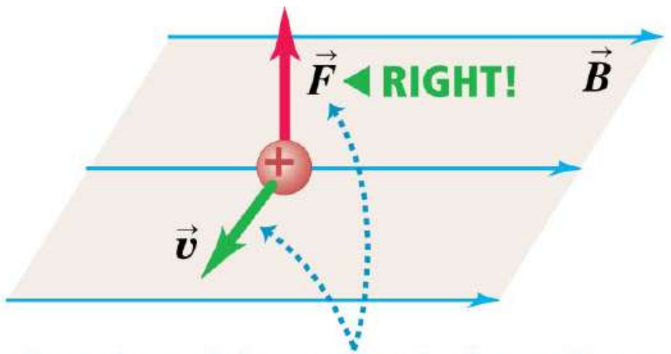
The direction of the vector product can be found using the right-hand rule:

1. Place $\vec{A}$ and $\vec{B}$ tail to tail.
2. Point fingers of right hand along $\vec{A}$, with palm facing $\vec{B}$.
3. Curl fingers toward $\vec{B}$.
4. Thumb points in direction of $\vec{A} \times \vec{B}$.

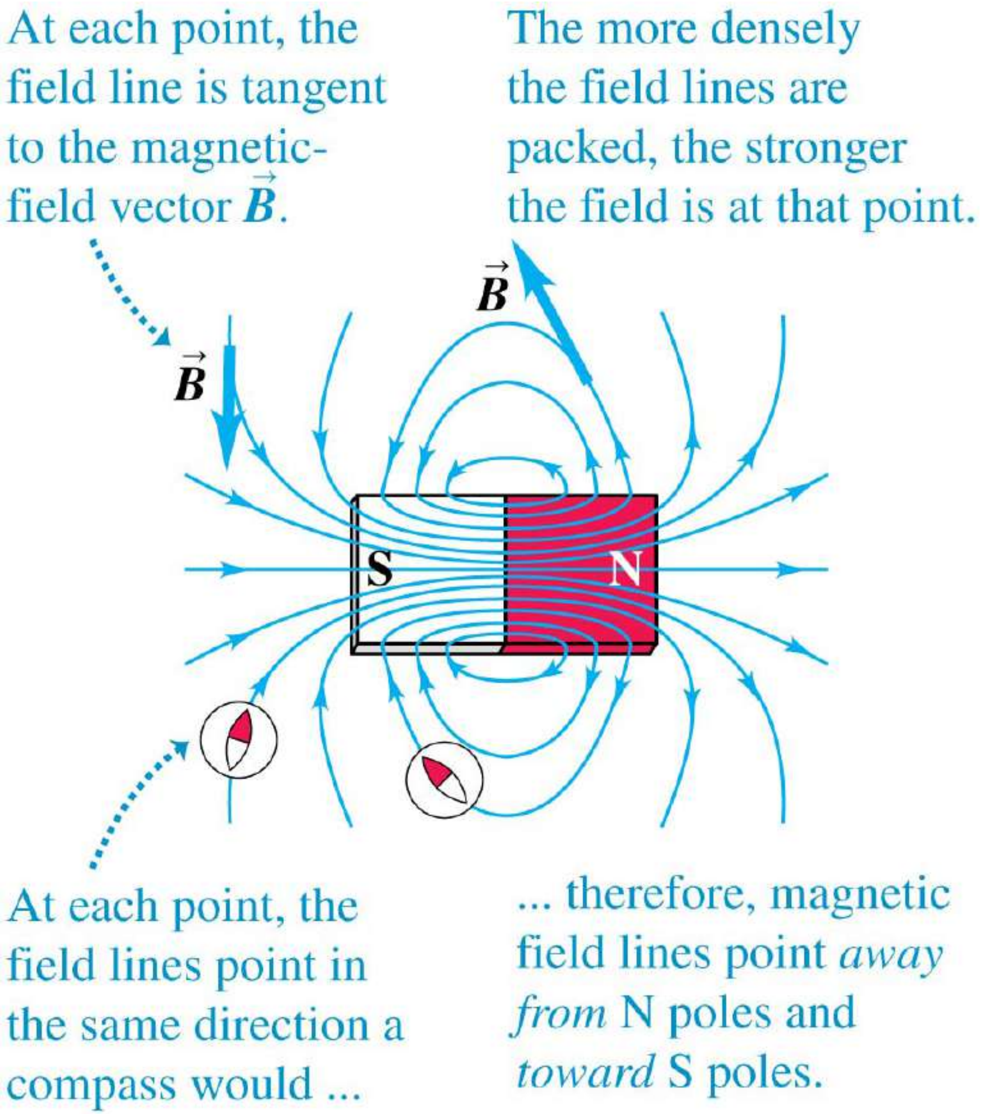


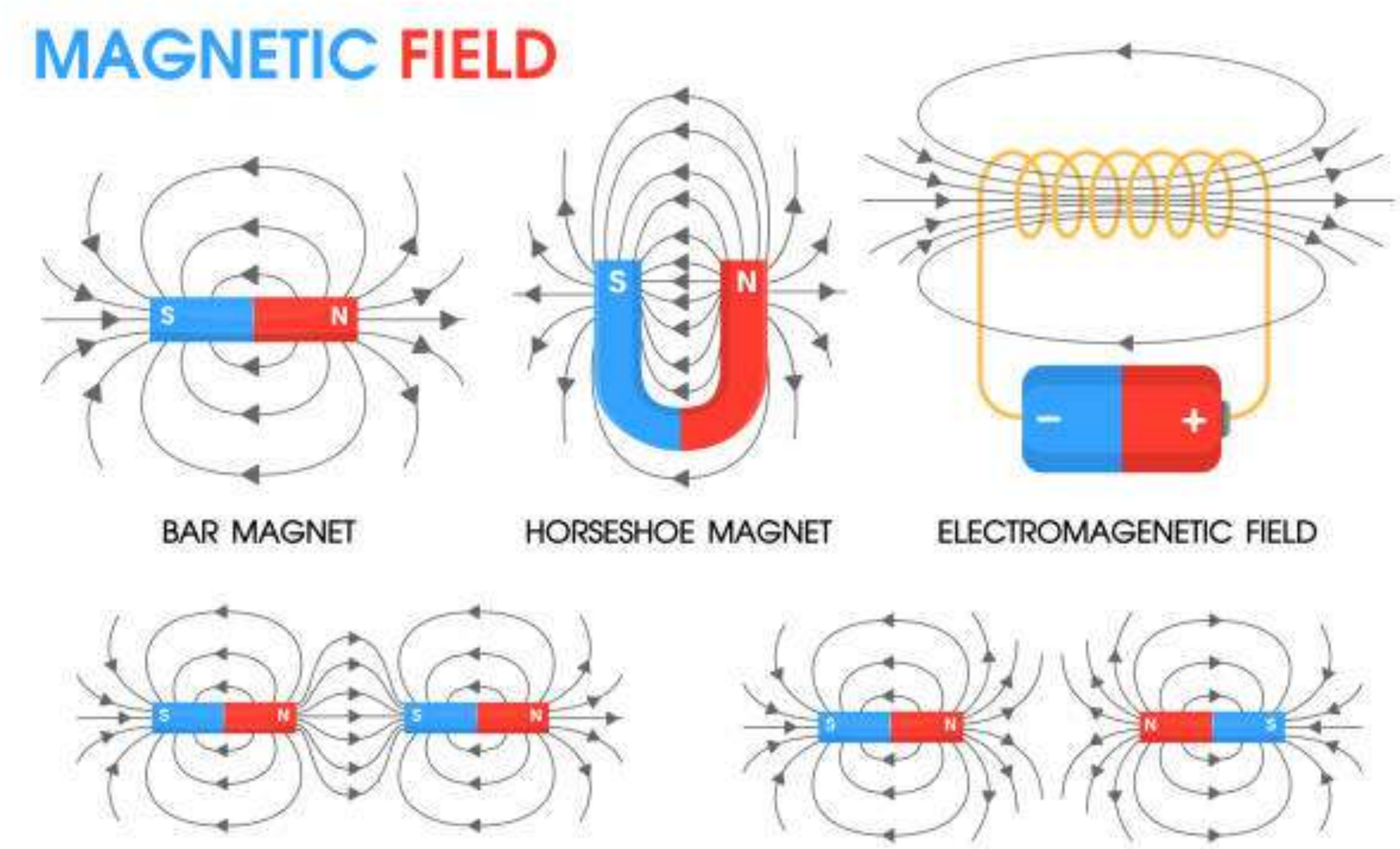
Magnetic field lines

We can represent any magnetic field by magnetic field lines drawn so that the line through any point is tangent to the magnetic field vector at that point.



The direction of the magnetic force depends on the velocity $\vec{v}$, as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

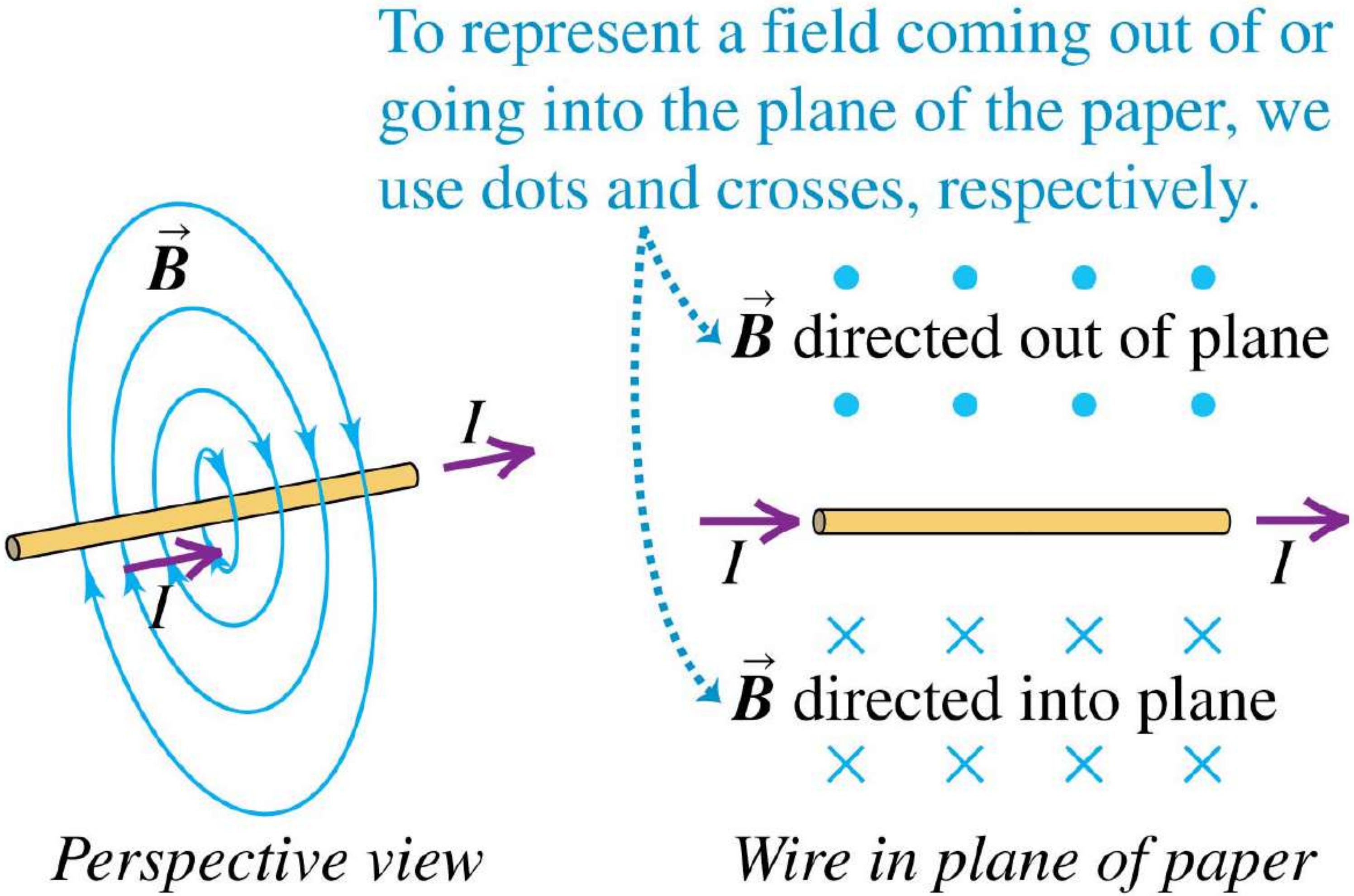




UNLIKE POLES ATTRACT

LIKE POLES REPEL

Magnetic field lines



In what direction is the force on the moving charge?

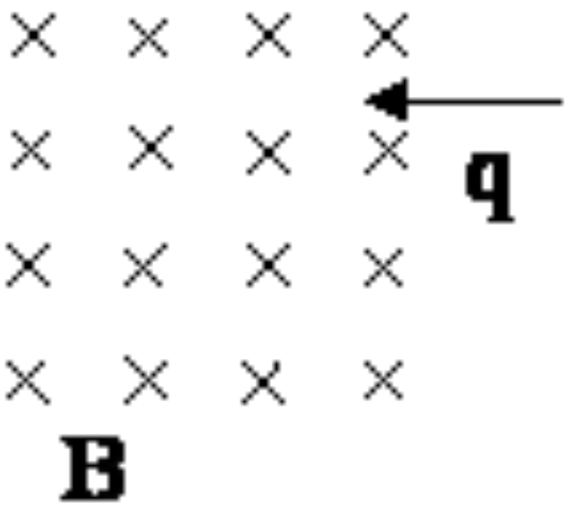
a) Up

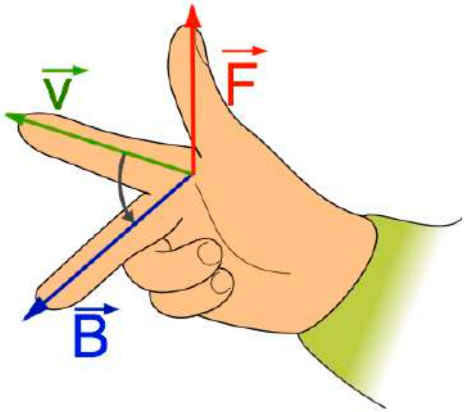
b) Down

c) Left

d) Right

e) Into the page





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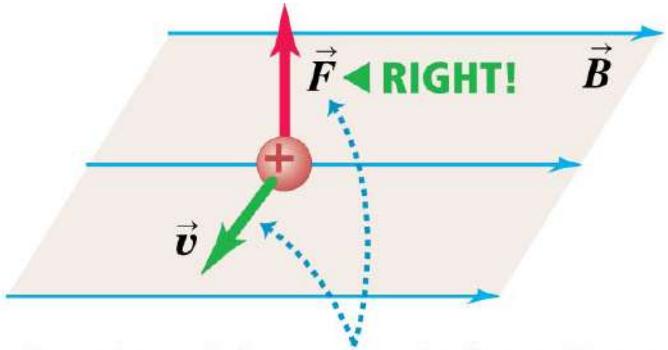
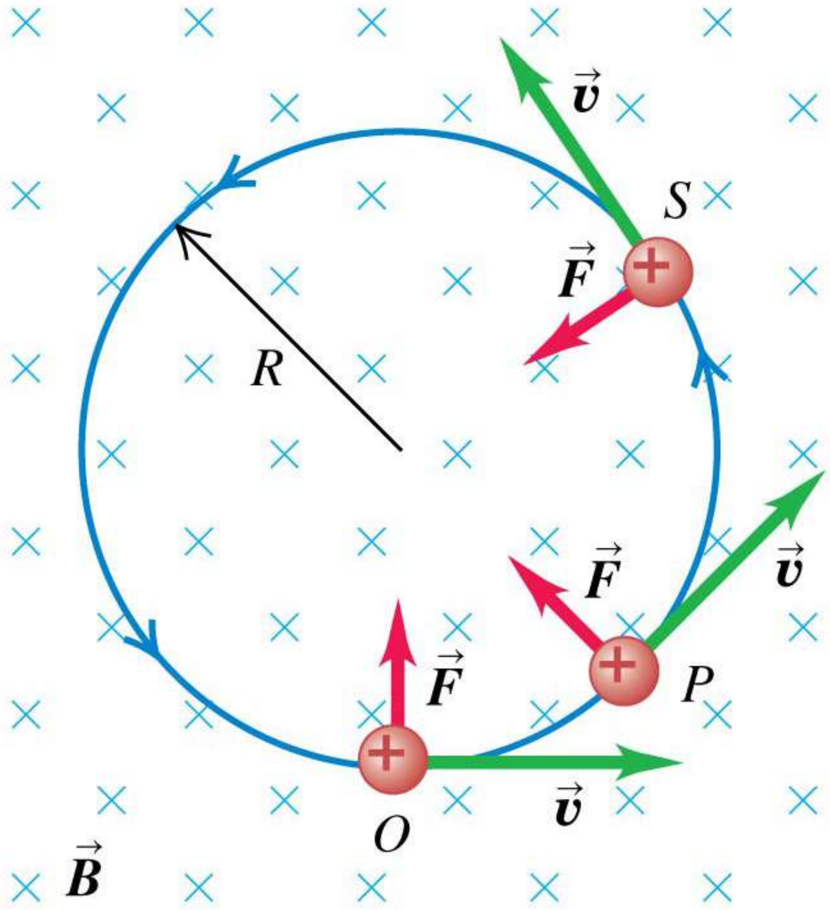
Magnetic field lines

It is important to remember that magnetic field lines are not lines of magnetic force. The force on a charged particle is not along the direction of a field line.



The direction of the magnetic force depends on the velocity $\vec{v}$, as expressed by the magnetic force law $\vec{F} = q\vec{v} \times \vec{B}$.

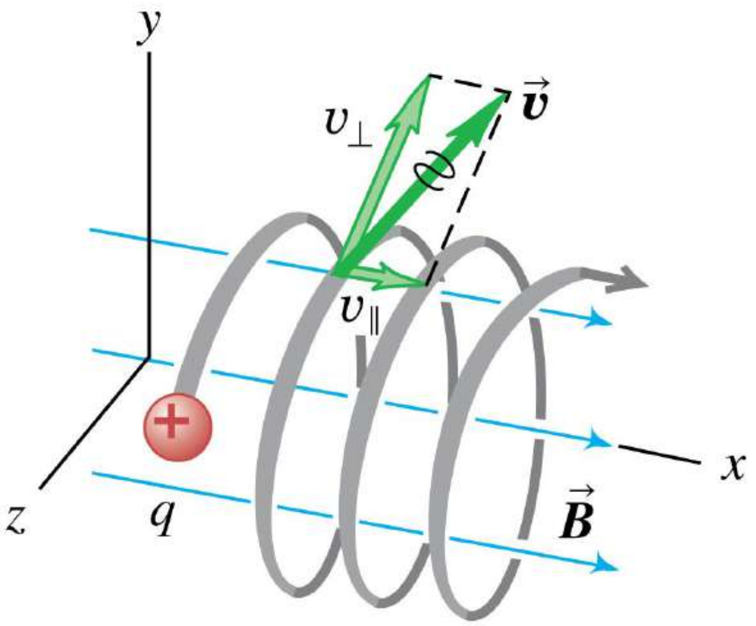
A charge moving at right angles to a uniform $\boldsymbol{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.



Helical motion

If the particle has velocity components parallel to and perpendicular to the field, its path is a **helix**.

This particle's motion has components both parallel ($v_{\parallel}$) and perpendicular ($v_{\perp}$) to the magnetic field, so it moves in a helical path.



Lorentz force

When a charged particle moves through a region of space where both **electric and magnetic fields** are present, both fields exert forces on the particle. The total force is the vector sum of the electric and magnetic forces:

$$\vec{F} = q(\vec{E} + \vec{v} \times \overrightarrow{B})$$

The magnetic force:

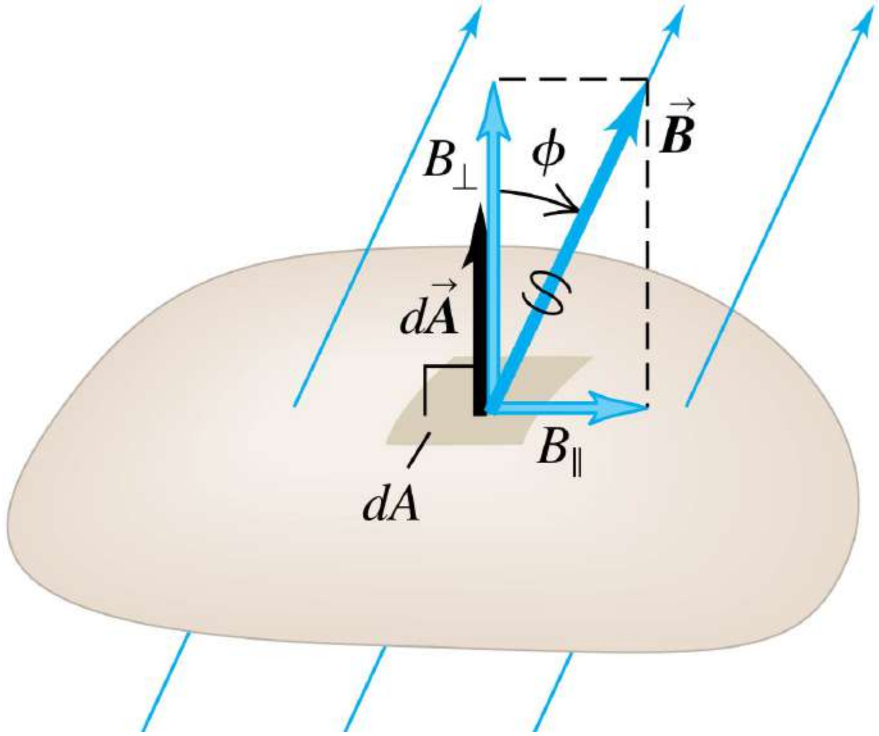
- A moving charge (or current) creates a magnetic field in the surrounding space.
- The magnetic field exerts a force on any other moving charge (or current) that is present in the field.

Magnetic flux

The magnetic flux through the area element is defined to be:

$$d\Phi_B = B_\perp dA$$

The total magnetic flux through the surface is the sum of the contributions from the individual area elements:



Magnitude of magnetic field $\vec{B}$

Component of $\vec{B}$ perpendicular to surface

Magnetic flux through a surface

$$\Phi_B = \int B\cos\phi \, dA = \int B_\perp \, dA = \int \vec{B} \cdot d\vec{A}$$

Angle between $\vec{B}$ and normal to surface

Element of surface area

Vector element of surface area

Gauss's Law for magnetism

The magnetic flux through any closed surface is zero:

Gauss's law for magnetism:

$$\overbrace{\oint \vec{B} \cdot d\vec{A}}^{\text{The total magnetic flux through } any \textbf{ closed surface} \text{ ...}} = 0 \quad \text{... equals zero.}$$

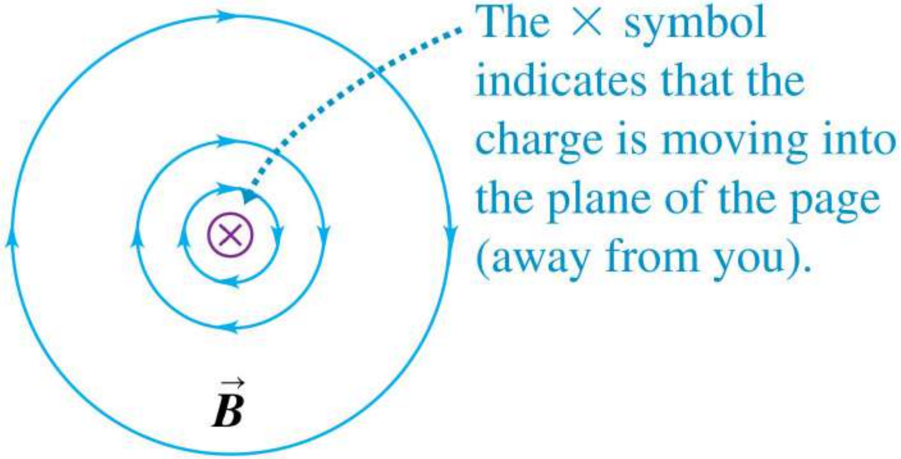
The SI unit of magnetic flux Φ_B is called the weber:

$1\ \mathrm{Wb} = 1\ \mathrm{T} \cdot \mathrm{m}^2$

Gauss's Law for magnetism

Moving charge

View from behind the charge



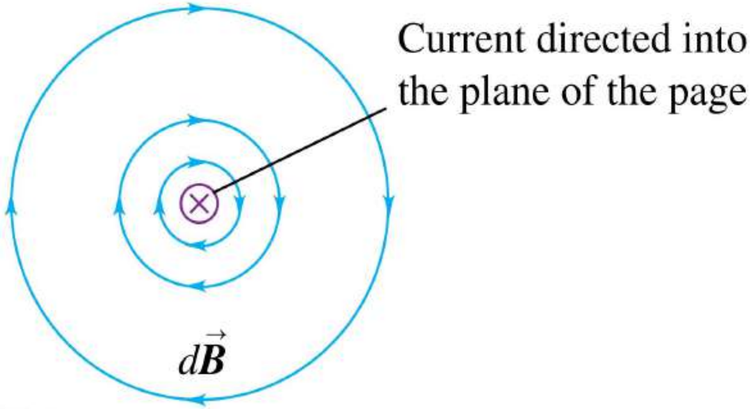
Magnetic field due to a point charge with constant velocity:

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v} \times \hat{r}}{r^2}$$

- μ_0: Magnetic constant
- q: Charge
- $\vec{v}$: Velocity
- $\hat{r}$: Unit vector from point charge toward where field is measured
- r: Distance from point charge to where field is measured

Current element

View along the axis of the current element



Magnetic field due to an infinitesimal current element:

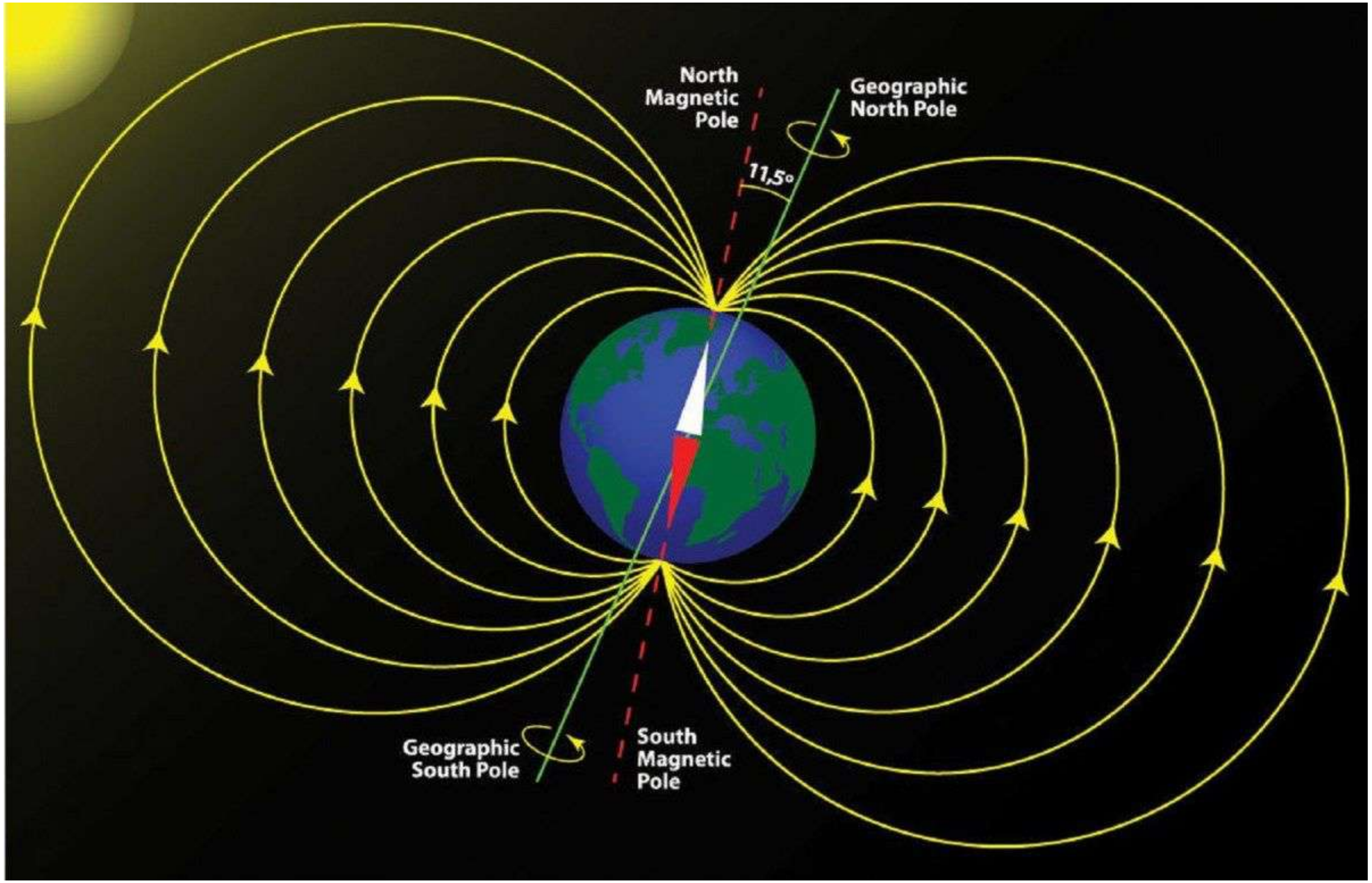
$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{l} \times \hat{r}}{r^2}$$

- μ_0: Magnetic constant
- I: Current
- $d\vec{l}$: Vector length of element (points in current direction)
- $\hat{r}$: Unit vector from element toward where field is measured
- r: Distance from element to where field is measured

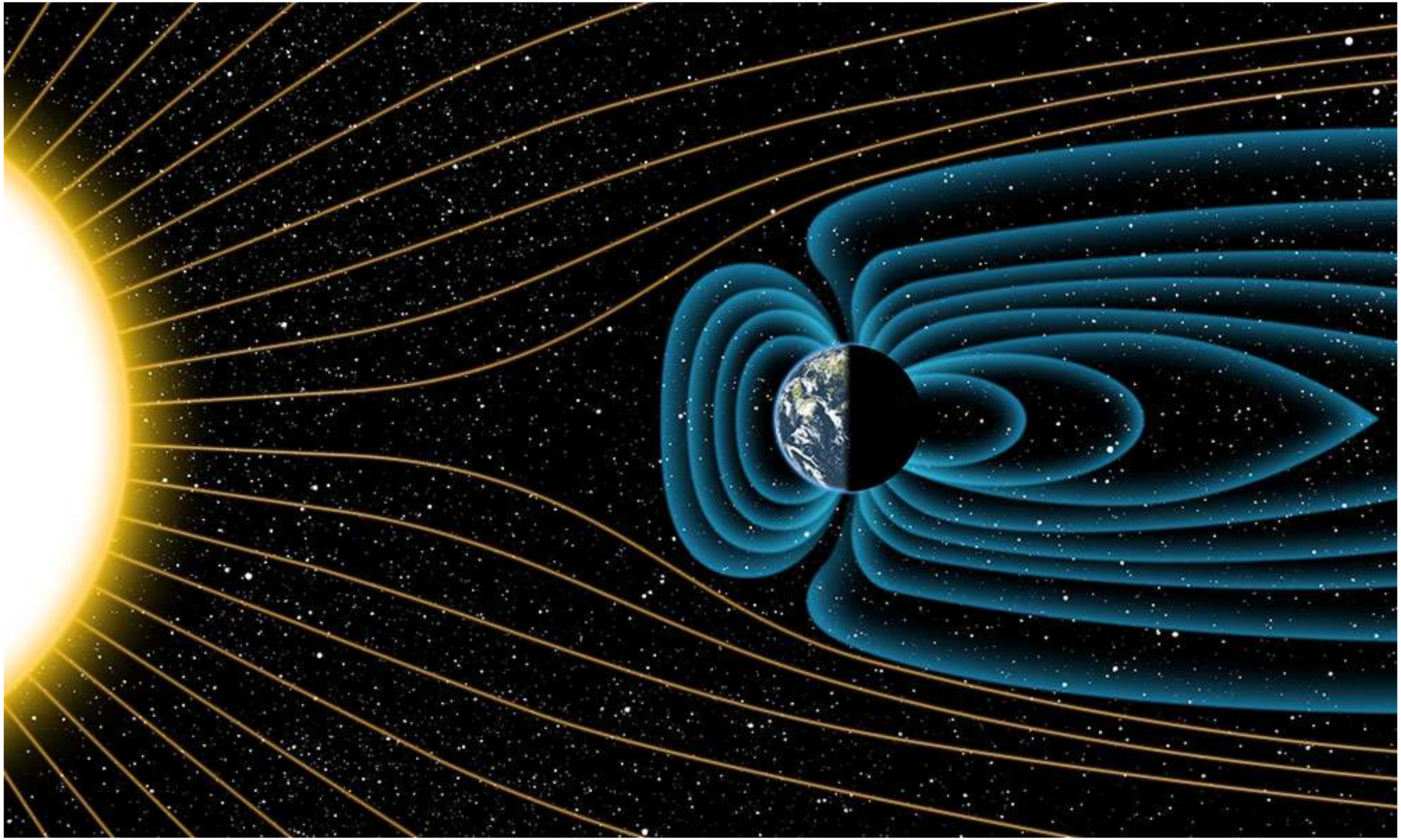
Magnetic poles

The earth’s magnetic axis is not quite parallel to its geographic axis (the axis of rotation), so a compass reading deviates somewhat from geographic north -- magnetic declination.

Also, the magnetic field is not horizontal at most points on the earth’s surface; its angle up or down is called magnetic inclination.

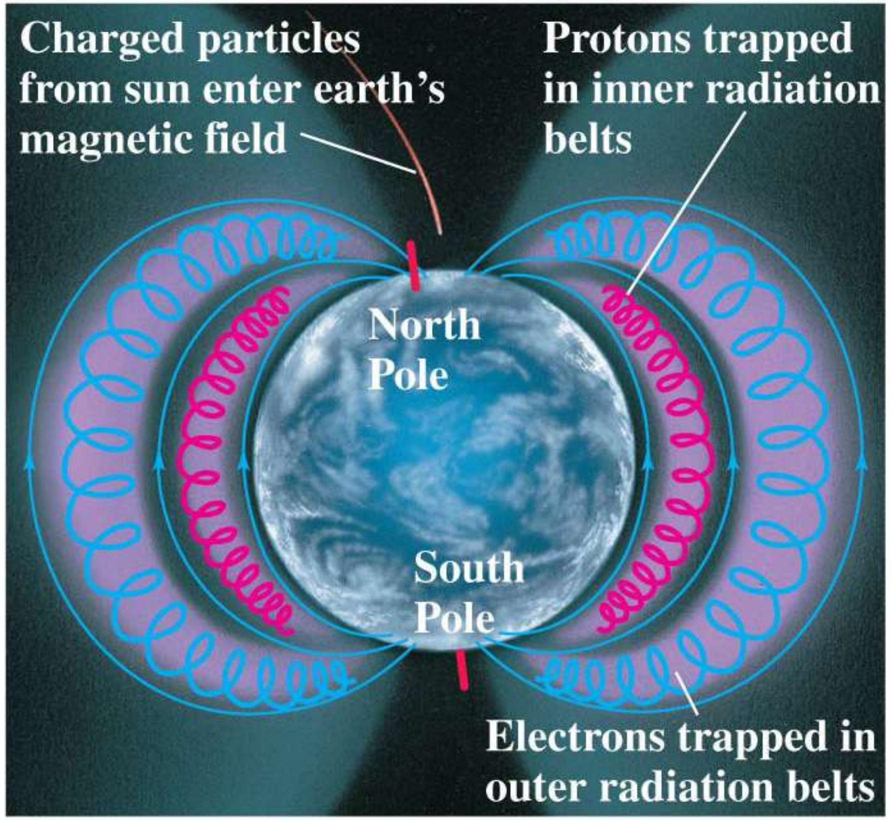


Magnetic poles – Earth's magnetic field

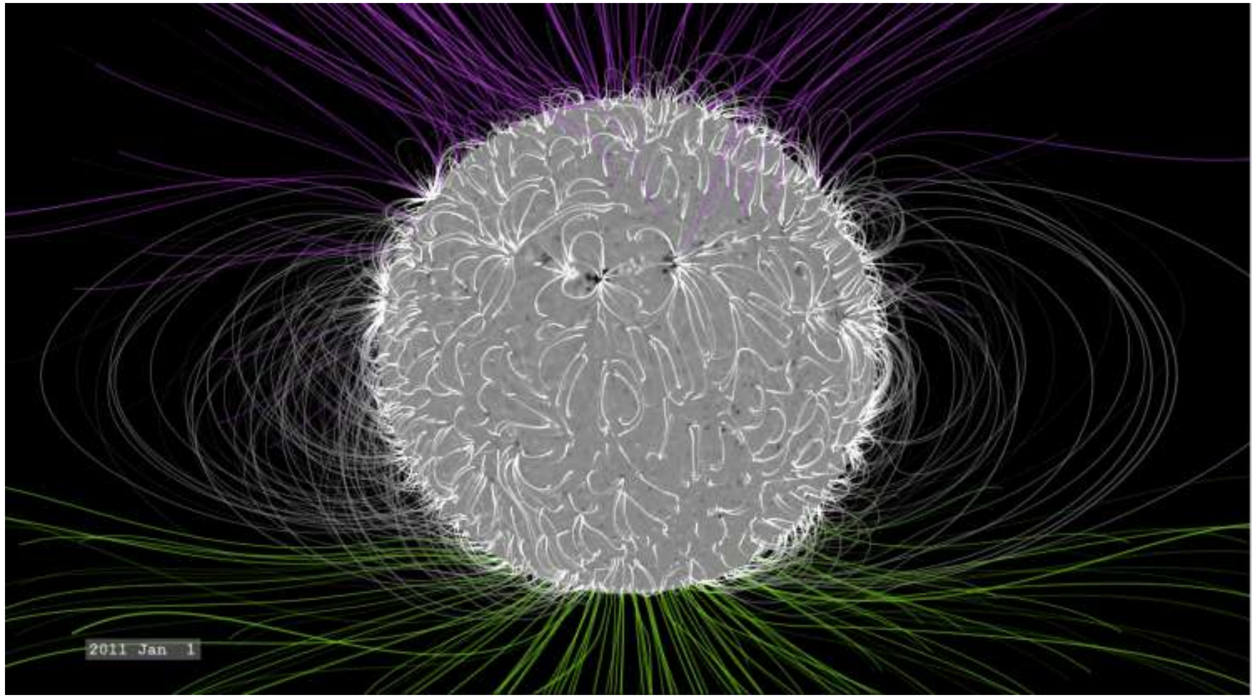


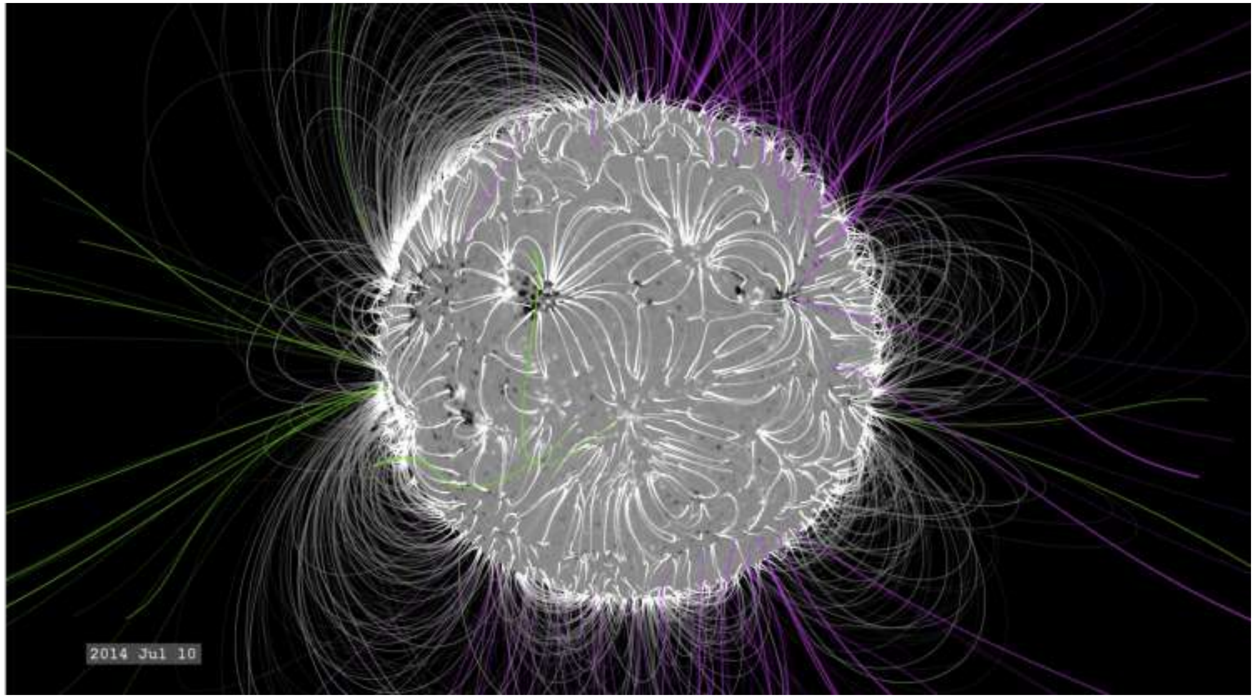
Magnetic poles – Van Allen Belts

Near the poles, charged particles from these belts can enter the atmosphere, producing the aurora borealis (“northern lights”) and aurora australis (“southern lights”).



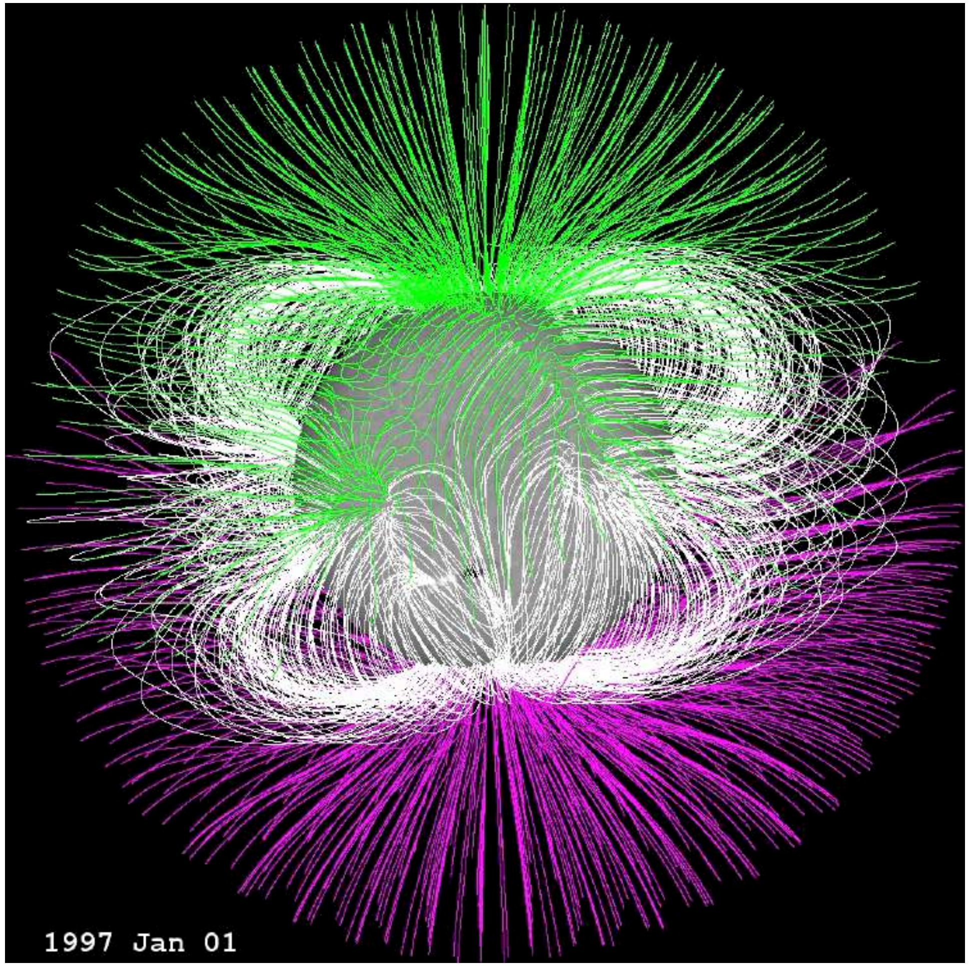
Magnetic poles – solar magnetic fields

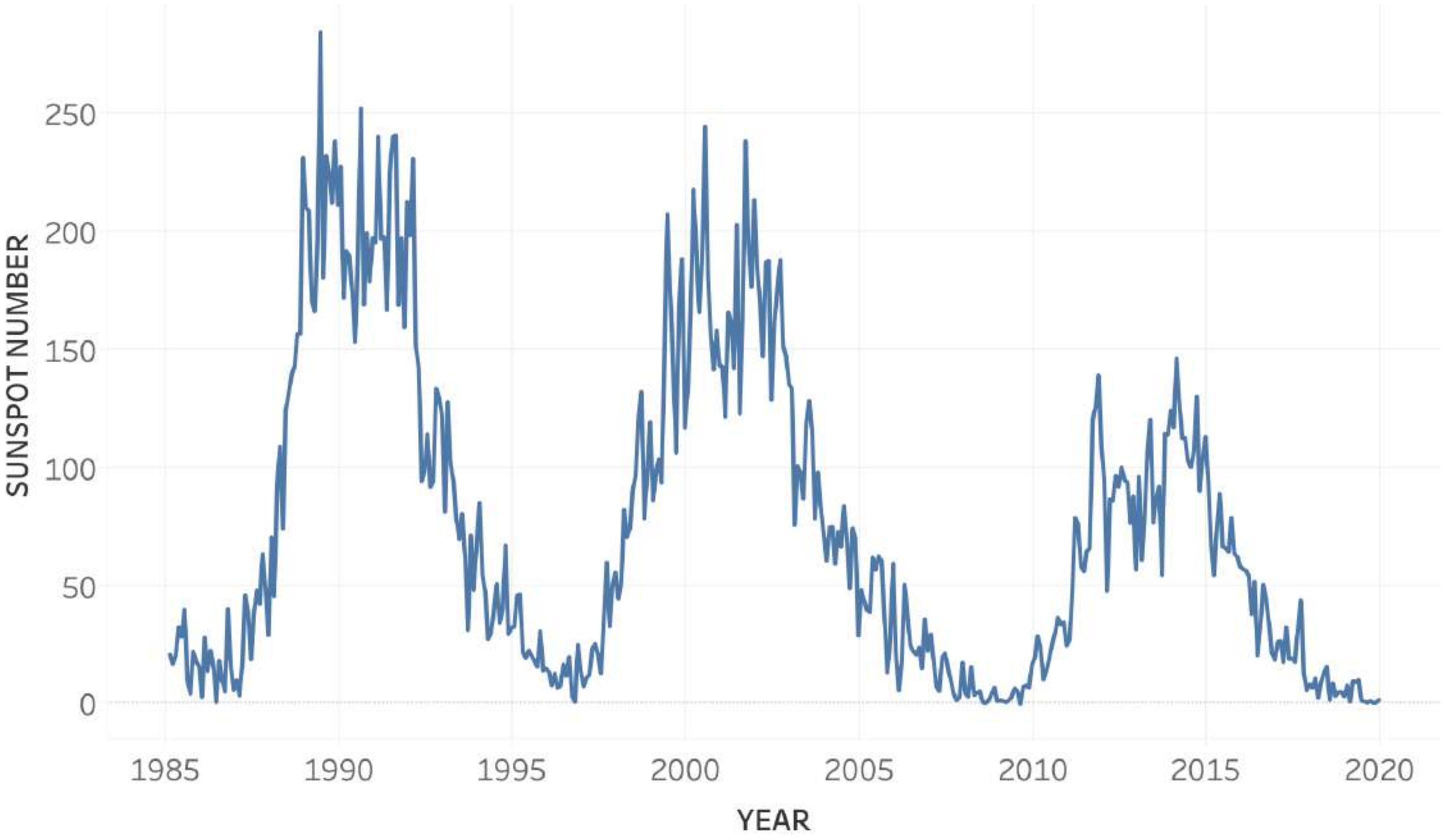




https://www.nasa.gov/feature/goddard/2016/understanding-the-magnetic-sun

Magnetic poles – solar magnetic fields



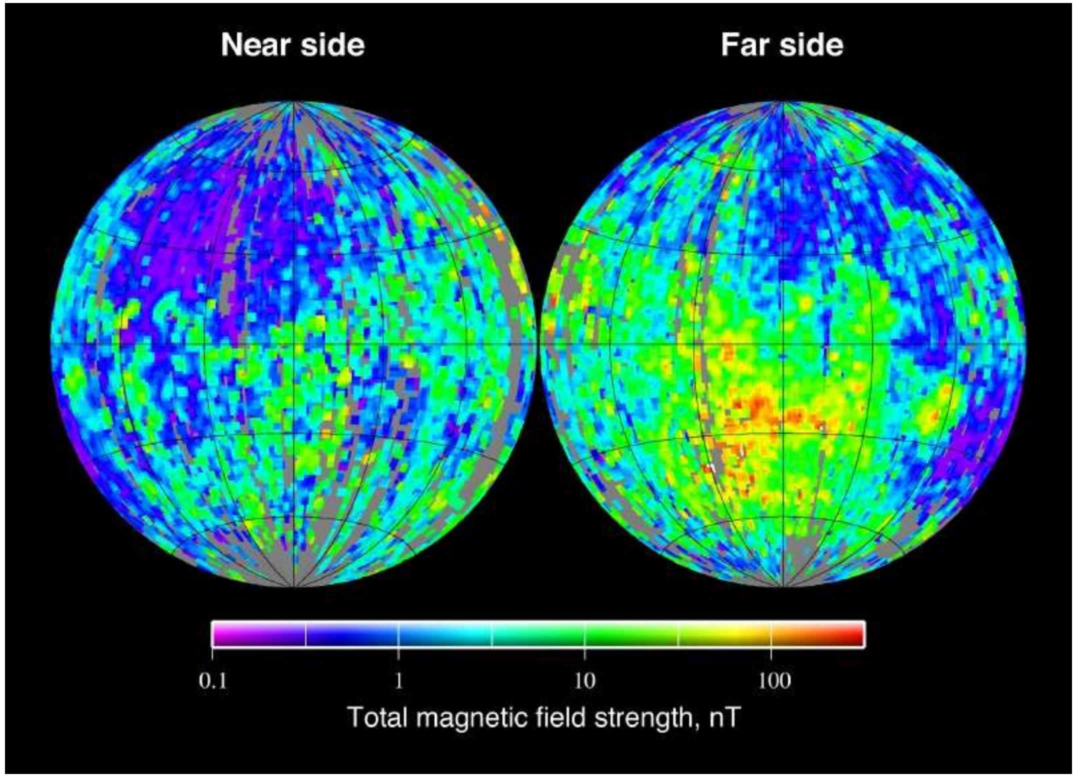


Magnetic poles – the Moon

The Earth's magnetic field is caused by currents circulating within its molten, conducting interior. These currents are stirred by our planet's relatively rapid spin (one rotation per 24 hours).

The moon's internal currents are much weaker; it is much smaller than the earth, has a predominantly solid interior, and spins slowly (one rotation per 27.3 days).

Hence the moon's magnetic field is only about 10^{-4} as strong as that of the Earth.



Magnetic field values

	Tesla	Gauss
Human brain	1 pT	10 nG
Heliosphere	10 nT	100 µG
Earth	10’s of µT	100’s mG
Fridge magnet	5 mT	50 G
Sunspot	200 mT	2 kG
MRI	2 T	20 kG
Strongest lab magnetic	45 T	450 kG
Magnetar	100 GT	1 PG

Summary

- Magnetic fields and the right hand rule CH 27

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

- Magnetic flux CH 27
- Magnetic materials CH 28

Next time: Magnetic fields continued CH 28/29