PHYS 1P22/92

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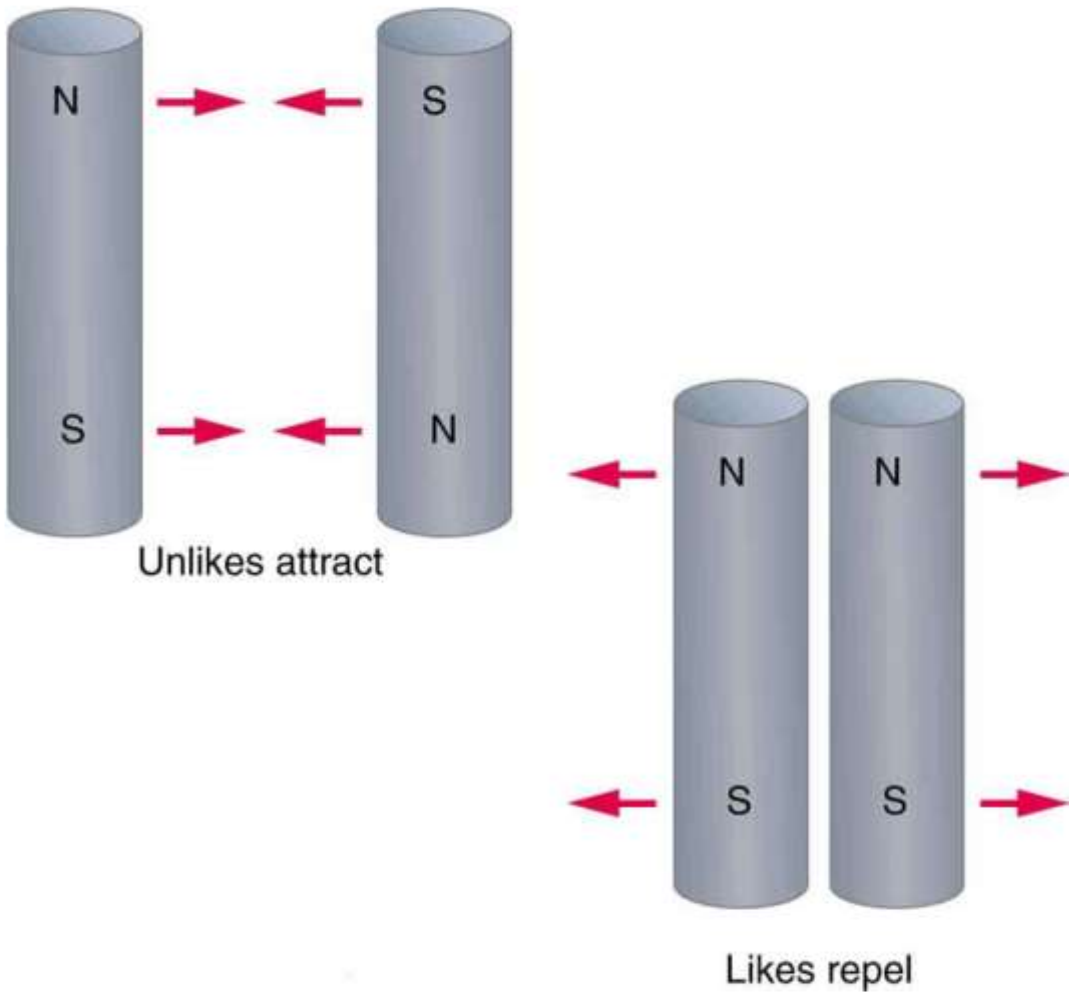
Spring 2024

22. Magnetism

22.1 Magnets

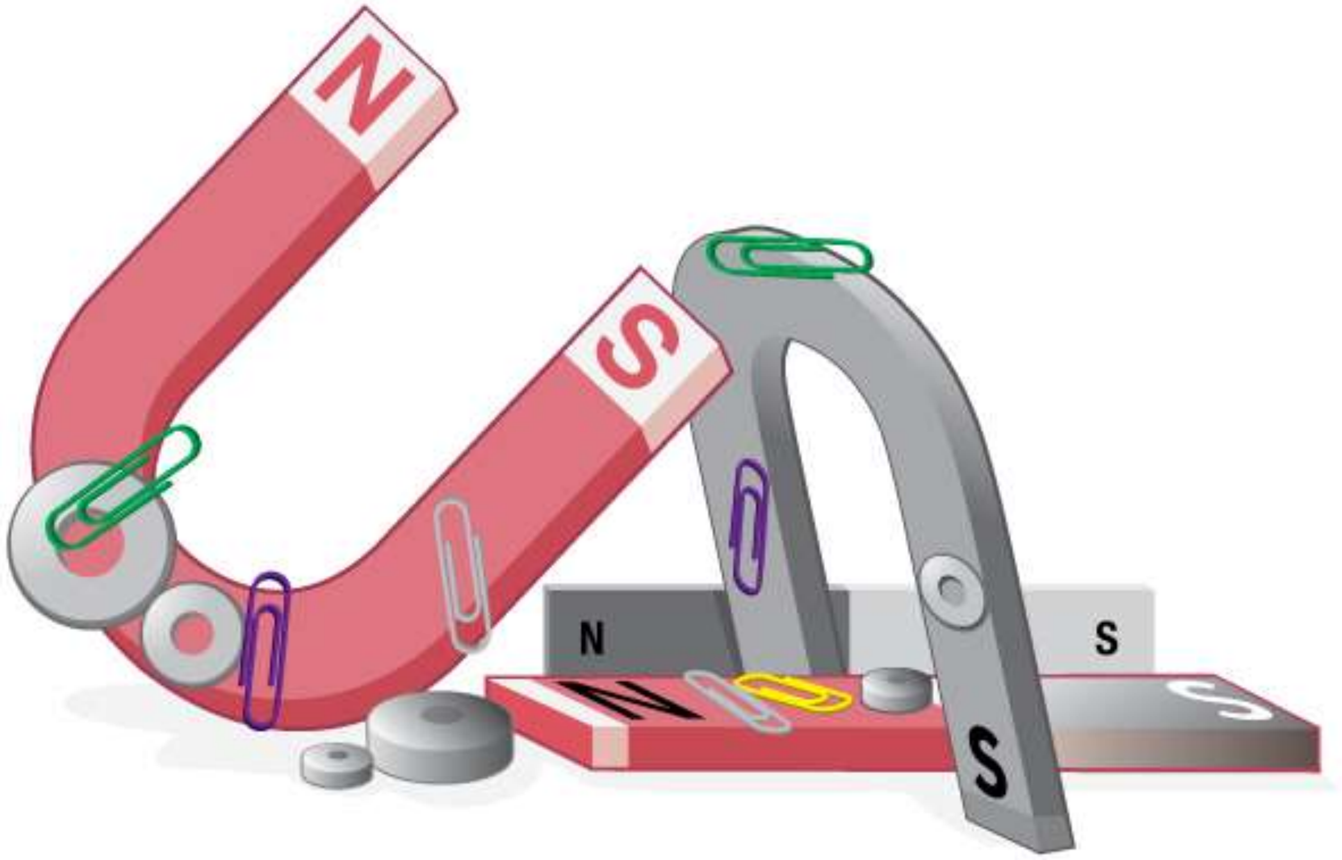
North and south poles

- Interaction between magnets: like poles repel and unlike poles attract.
- Similar to the sign of electric charge, but not the same.



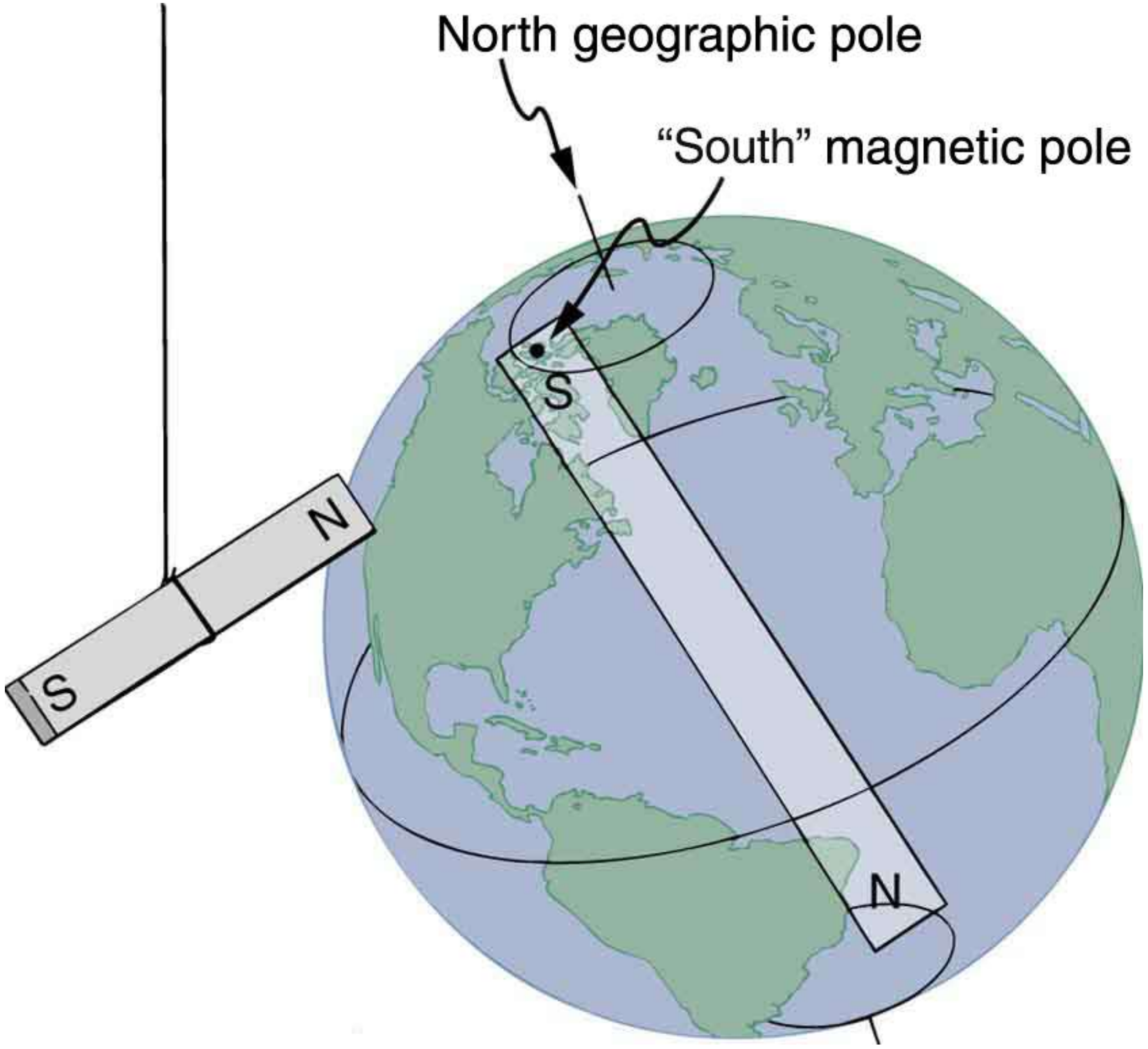
Magnetic materials

- Magnets also attract iron and other magnetic materials which are not themselves magnets.



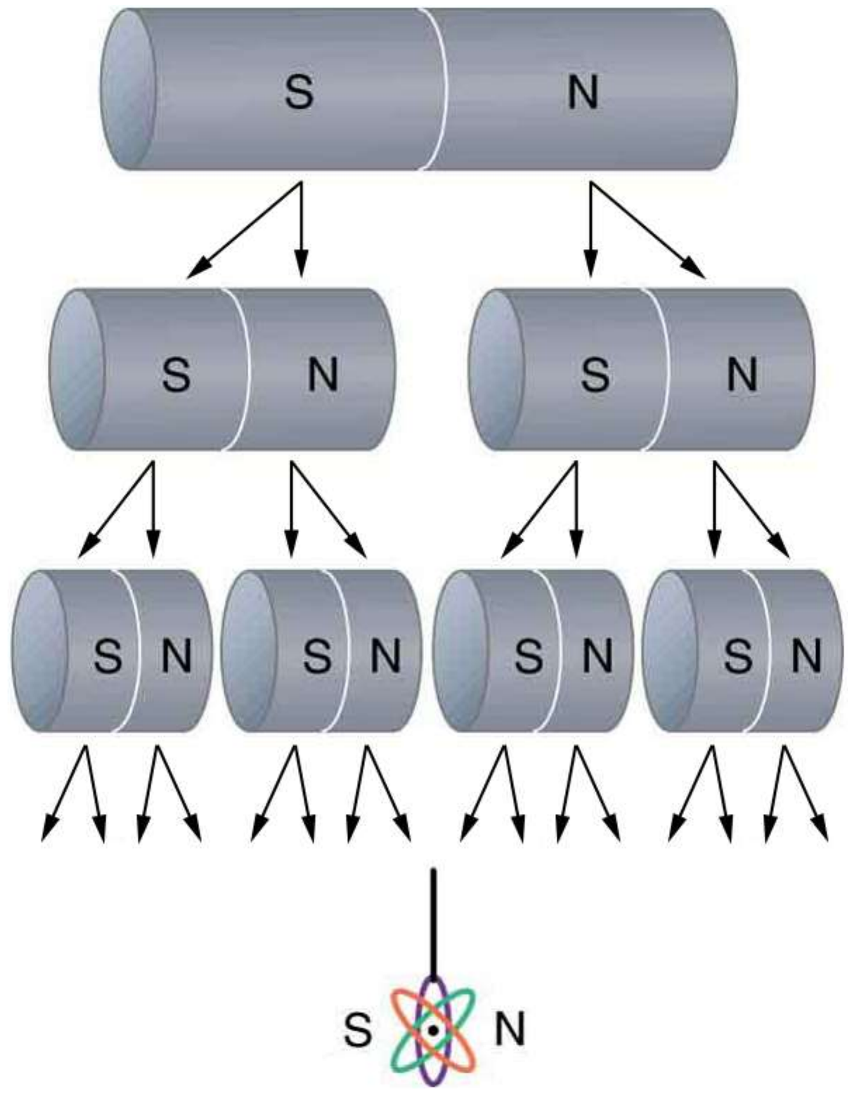
Earth's magnetic field

- Compass: north pole of a magnet points towards the north **geographic** pole.
- The Earth is like a huge magnet, with the south **magnetic** pole at the north **geographic** pole.



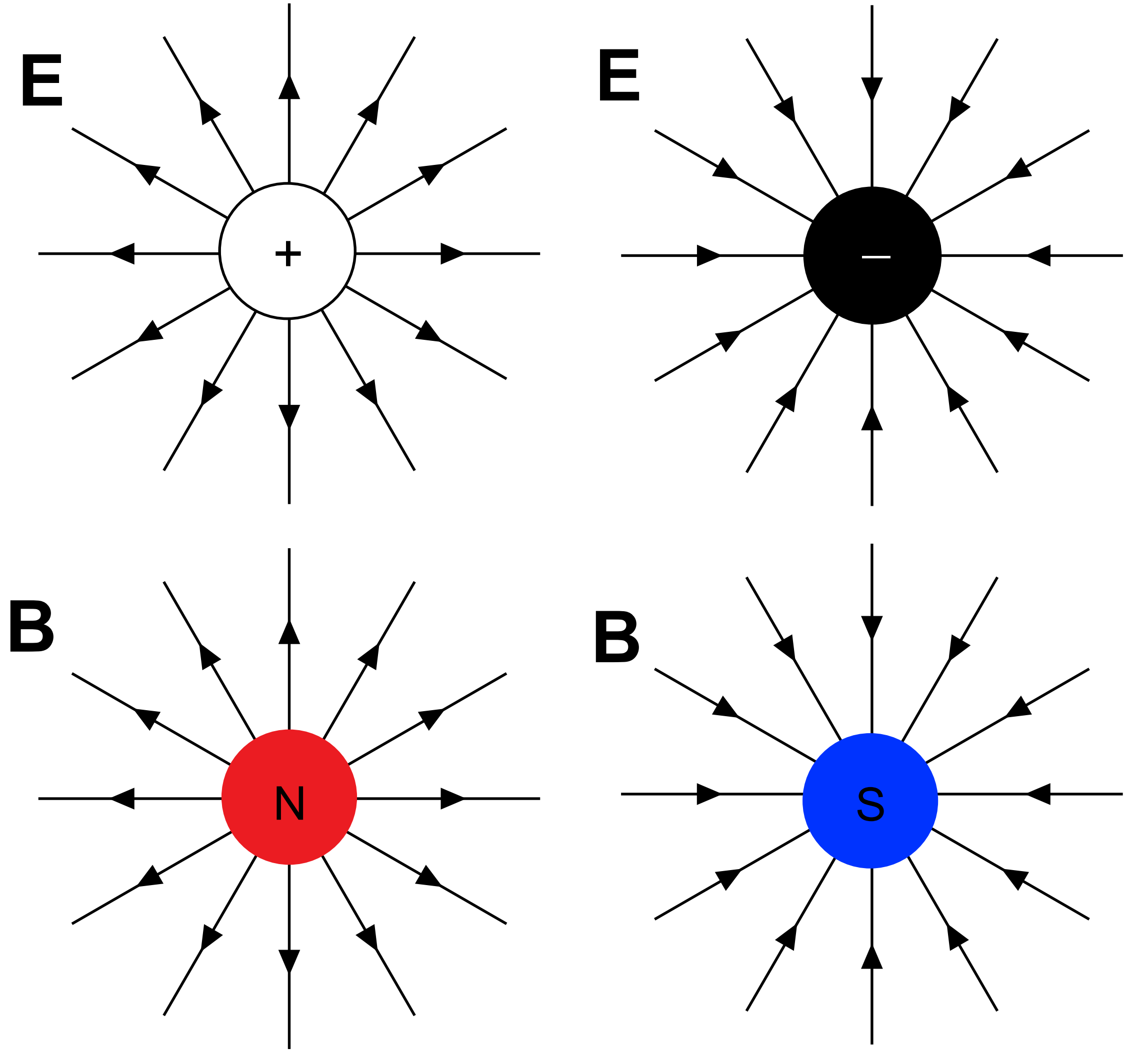
Magnetic dipoles

- Dipole = two poles.
- Poles cannot be separated. Splitting a dipole always results in two smaller dipoles.
- At the lowest scales, the individual atoms are dipoles.
- In fact, even subatomic particles (electrons, protons, neutrons) are also dipoles.



Magnetic monopoles

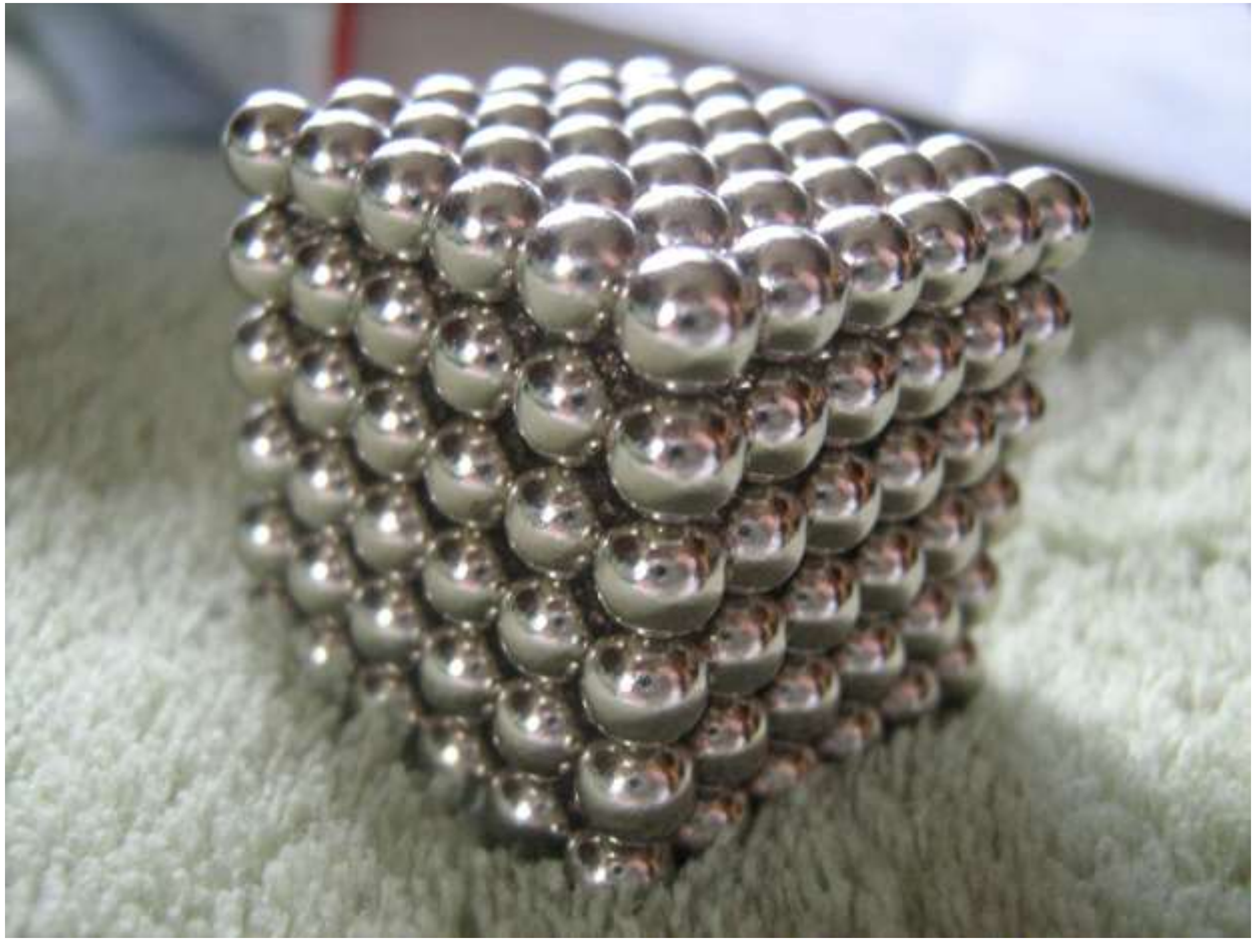
- Monopole = one pole.
- Isolated north or south poles would behave like electric charges.
- Predicted by some very speculative theories, but never observed (those theories are probably incorrect).
- It's currently unknown whether magnetic monopoles exist.



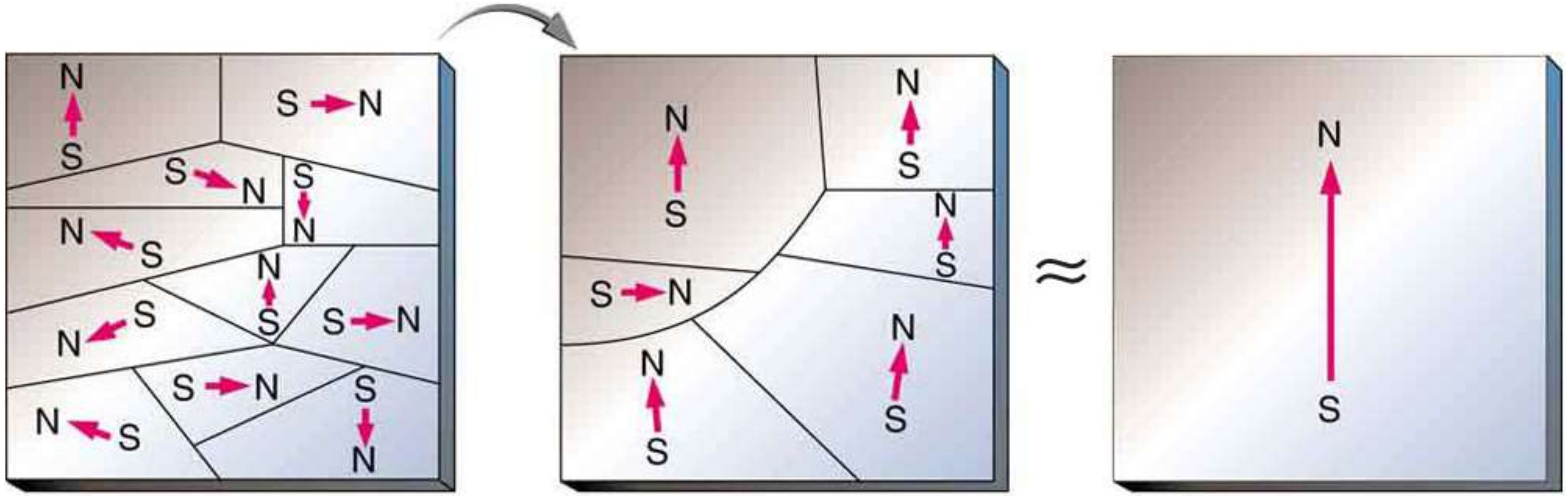
22.2 Ferromagnets and Electromagnets

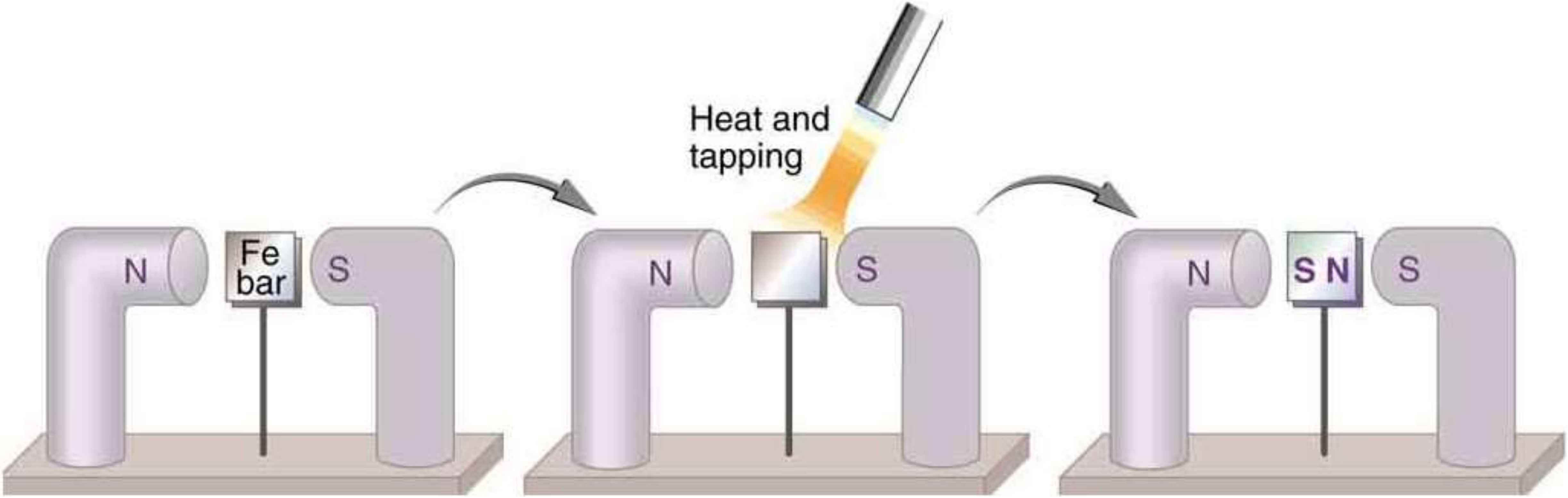
Ferromagnetic materials

- Respond strongly to magnets.
- Can be made into magnets (temporarily or permanently).
- Examples: iron, cobalt, nickel, gadolinium, neodymium.



Magnetization & domains



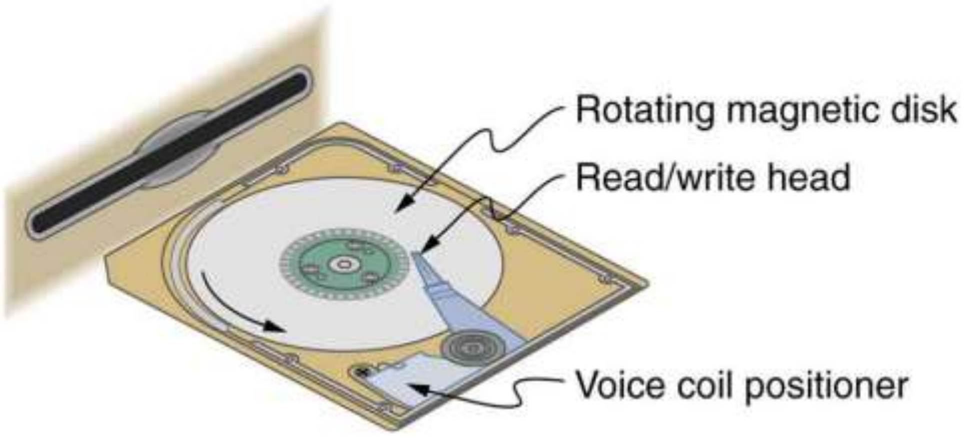


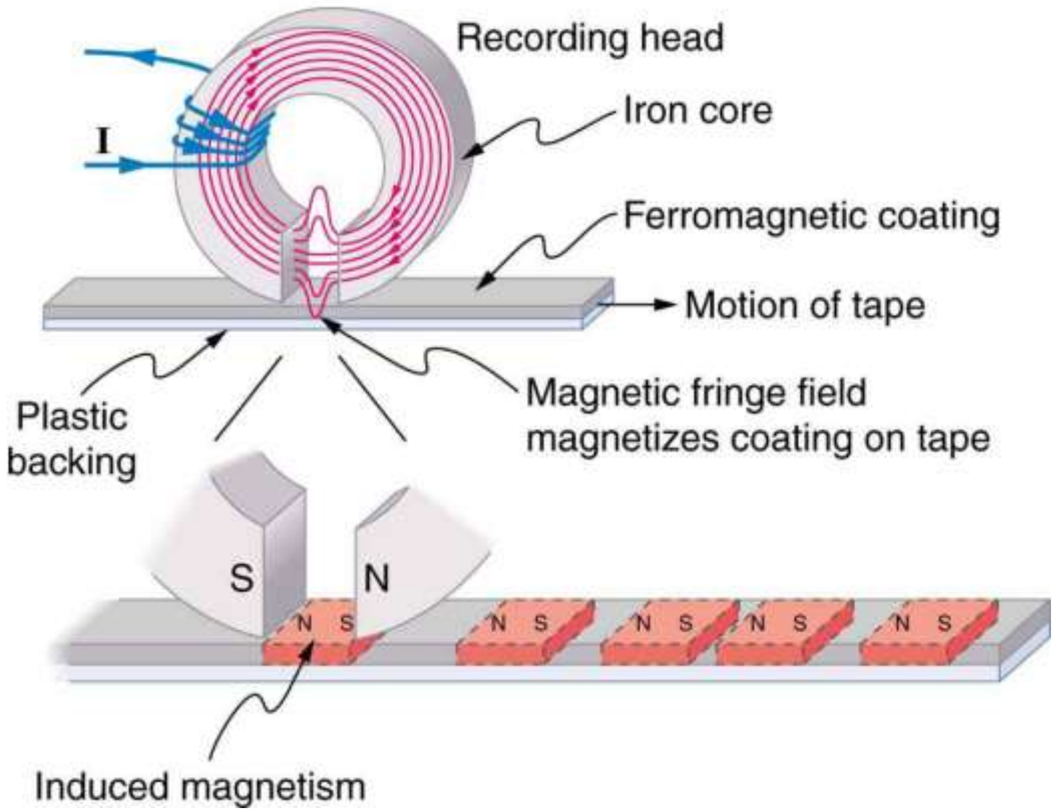
Demagnetization

- A permanent magnet can be demagnetized by hard blows or heat.
- Ferromagnetic materials cannot be magnetized above the Curie temperature.
  - For example: 1043 K (770 °C) for iron.

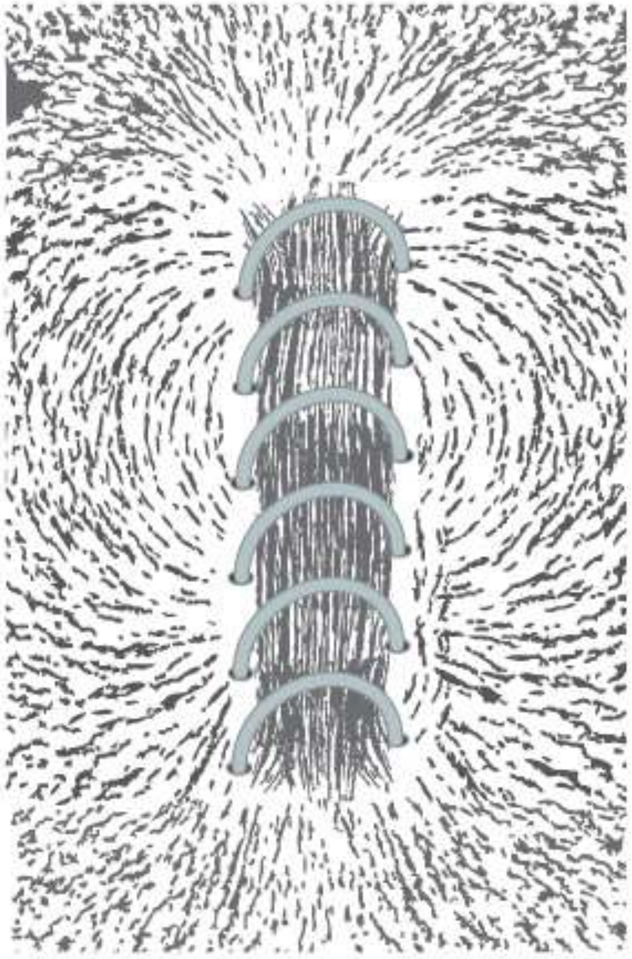
Electromagnets

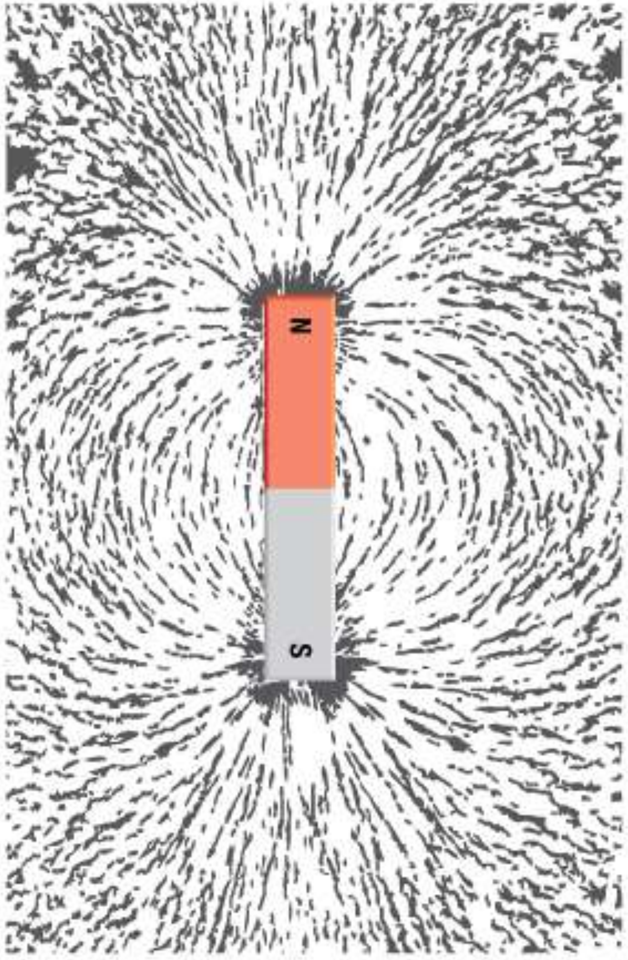
- Electrical current can create temporary magnets.
- Applications:
    - MRI
    - Data storage (but not so much today)



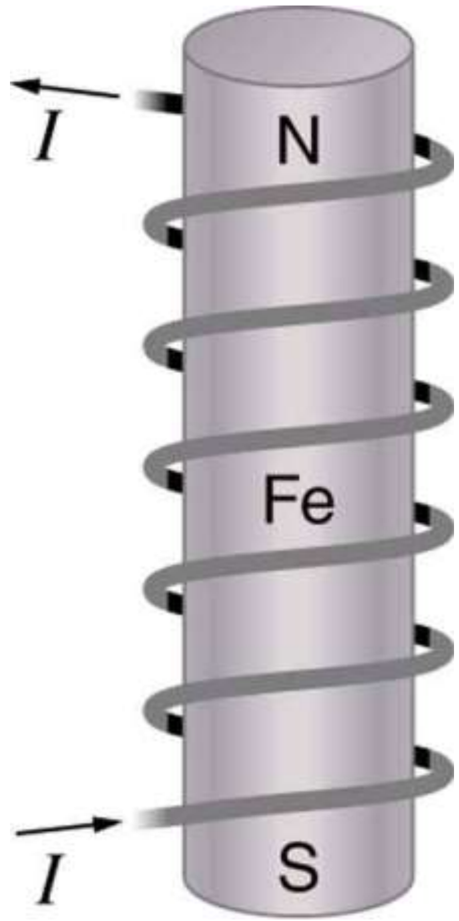


Electromagnet vs. permanent magnet

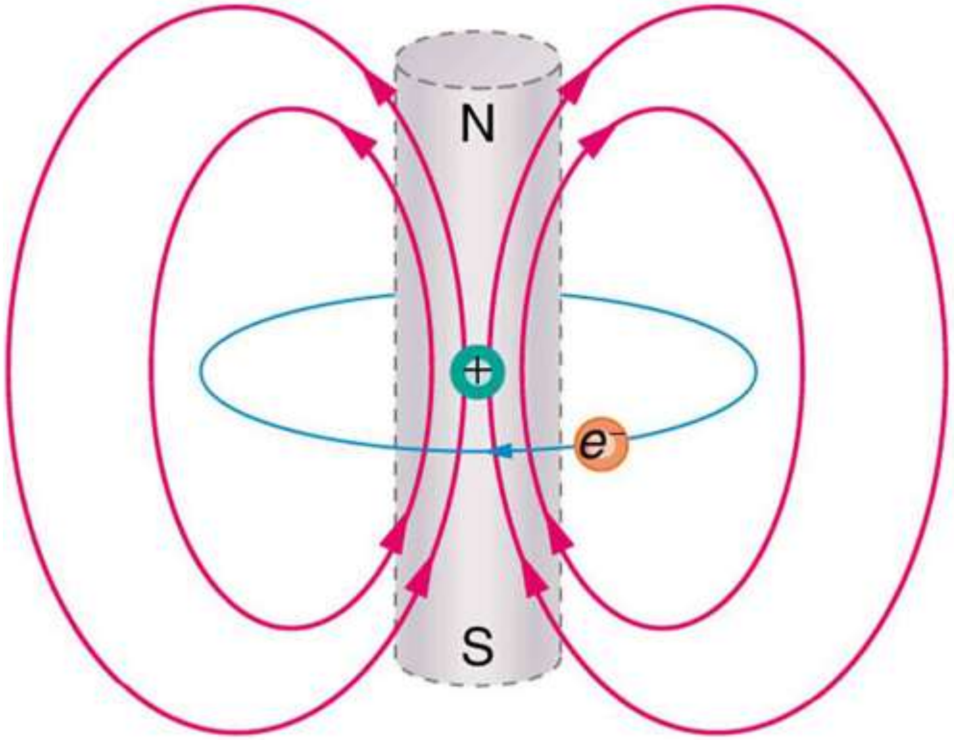




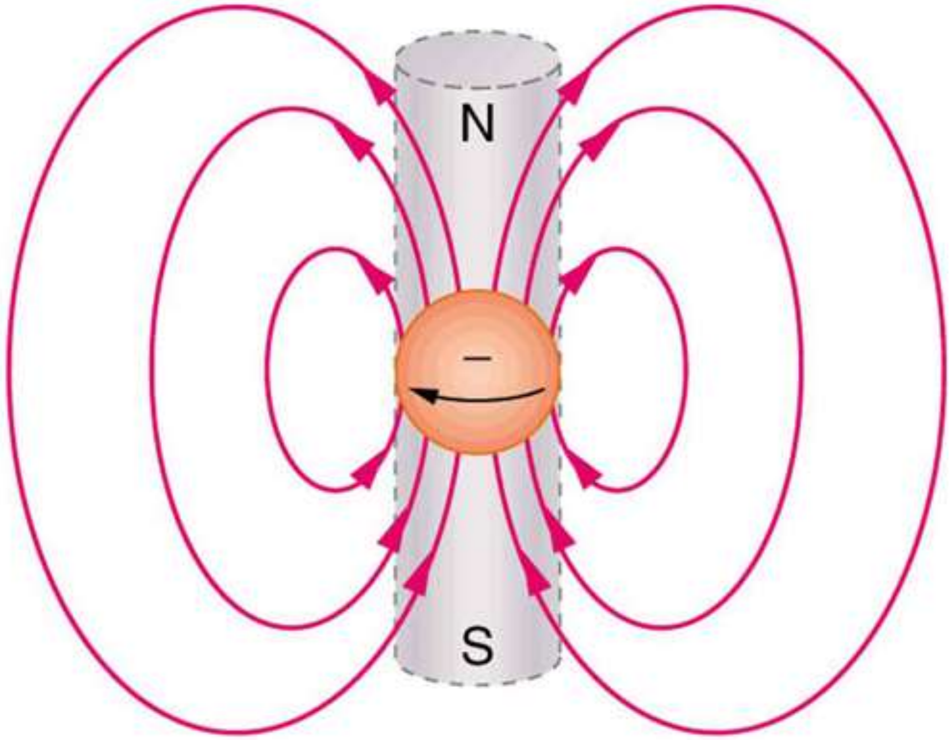
Combining electromagnet and ferromagnet



All magnets are due to electric currents!



Atom



Electron

Simulation

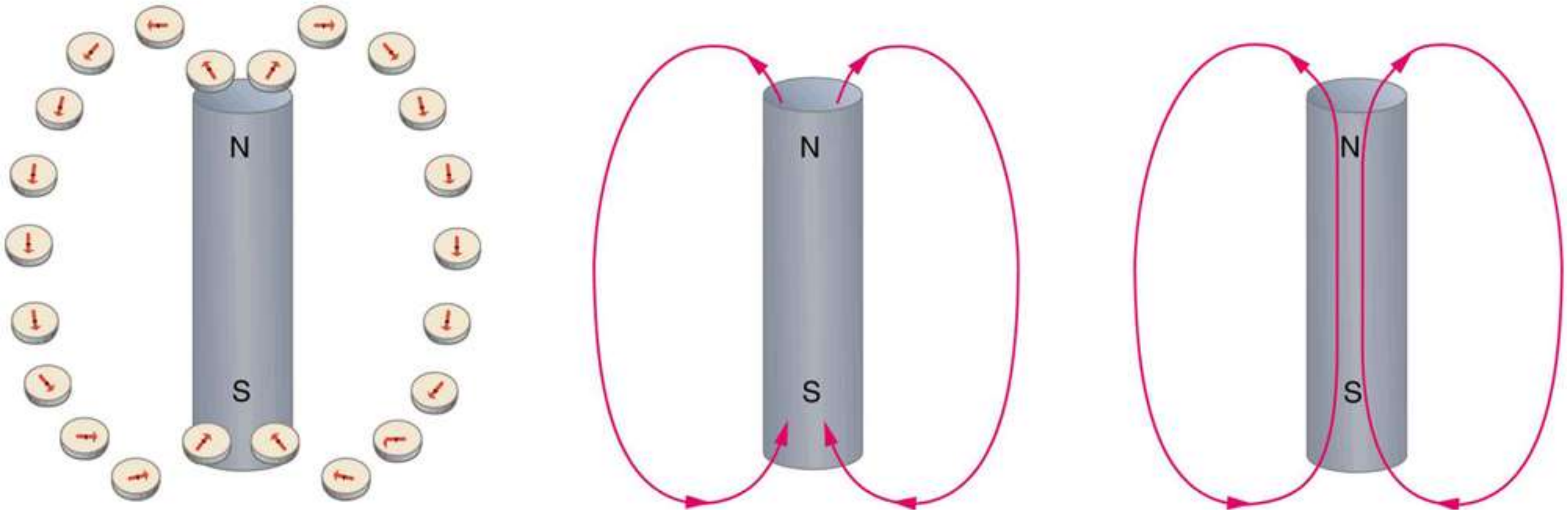
- Simulation of magnets and electromagnets:

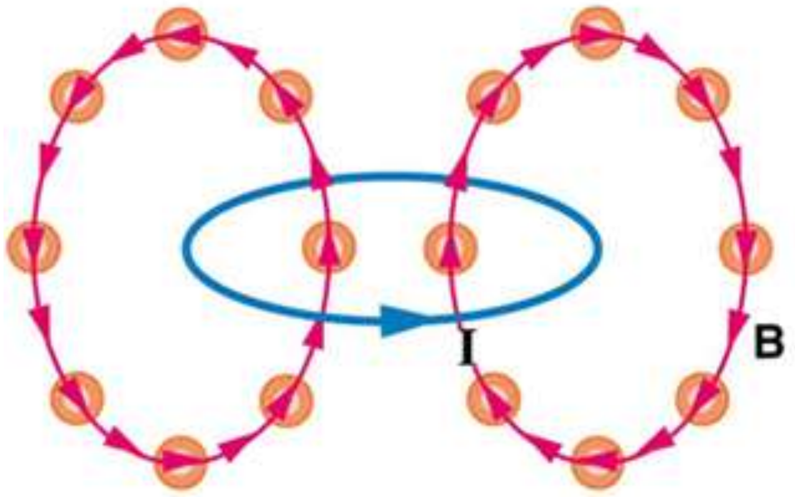
https://phet.colorado.edu/sims/cheerpj/faraday/latest/faraday.html?simulation=magnets-and-electromagnets

22.3 Magnetic Fields and Magnetic Field Lines

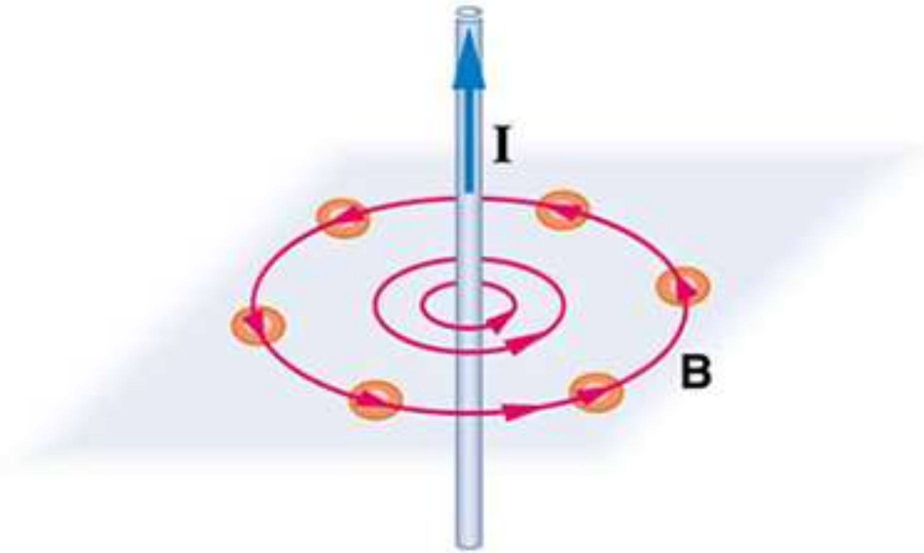
Magnetic field

- Vector **B** at each point.
- Has the same direction as a small compass at each point.
- Field lines: connecting all the arrows (like electric field lines).

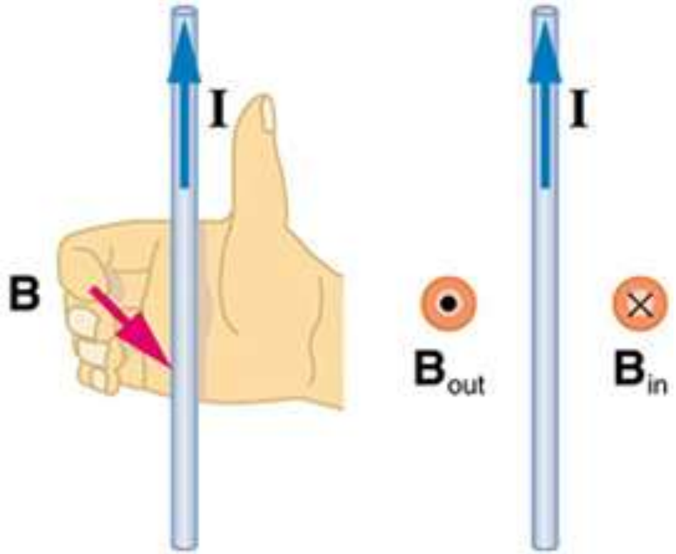




Circular current loop
(similar to bar magnet)



Long straight wire
(field lines circle the wire)



Field goes into the screen
(use right-hand rule)

Rules for magnetic field lines:

1. Tangent to the magnetic field at each point.
2. Density of lines is proportional to magnitude of the magnetic field.
3. Can never cross each other (why?)
4. **Always form closed loops from north to south pole.**

(if magnetic monopoles existed, lines would start and end on them.)

Demonstration

See the magnetic field in 3D! (Live demonstration)

22.4 Magnetic Field Strength: Force on a Moving Charge in a Magnetic Field

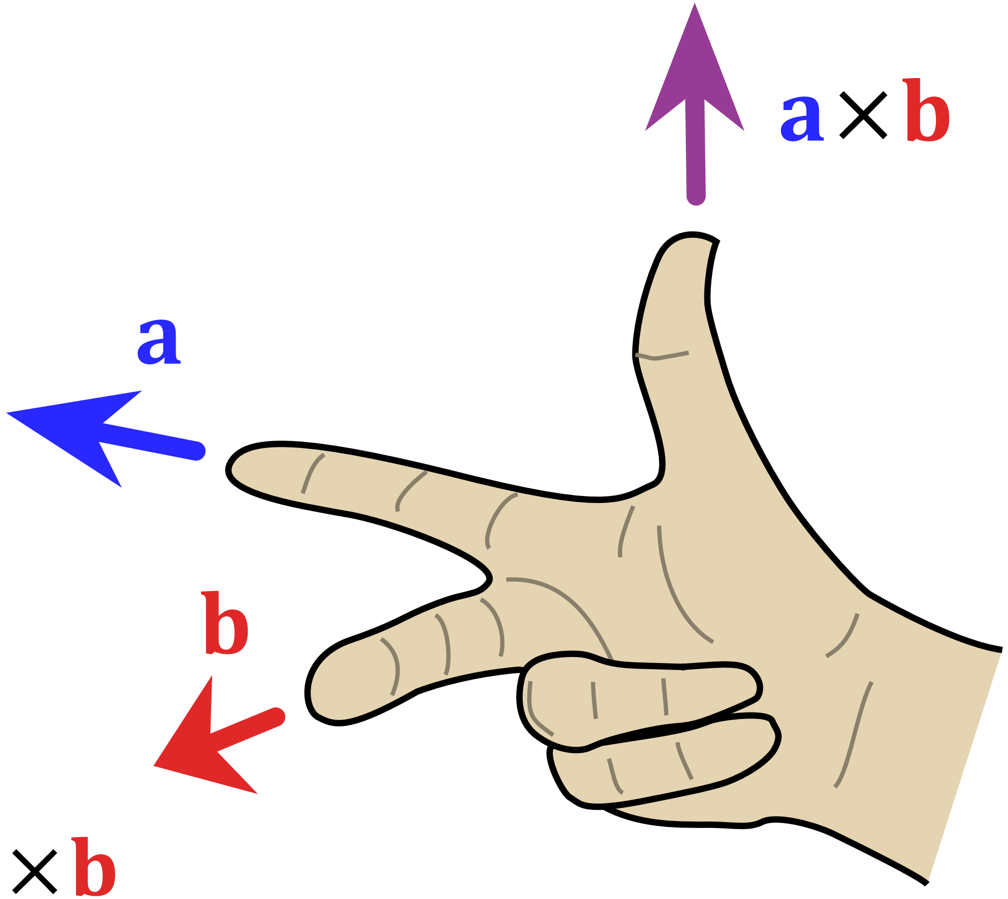
Cross product:

$$\mathbf{a} \times \mathbf{b}$$

- Direction given by right-hand rule.
- Magnitude given by area of a parallelogram:

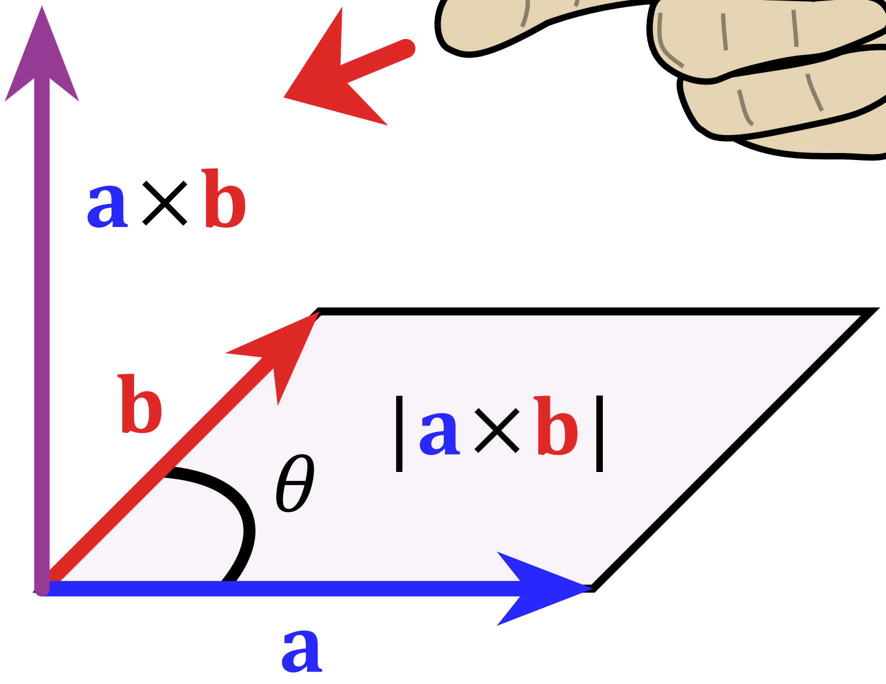
$$|\mathbf{a} \times \mathbf{b}| = |\mathbf{a}||\mathbf{b}| \sin\theta$$

θ is the angle between **a** and **b**.



Properties (prove!):

- $\mathbf{a} \times \mathbf{a} = \mathbf{0}$
- $\mathbf{a} \times \mathbf{b} = \mathbf{0}$ if **a** parallel to **b**
- $|\mathbf{a} \times \mathbf{b}| = |\mathbf{a}||\mathbf{b}|$ if **a** perpendicular to **b**
- $\mathbf{a} \times \mathbf{b} = -\mathbf{b} \times \mathbf{a}$

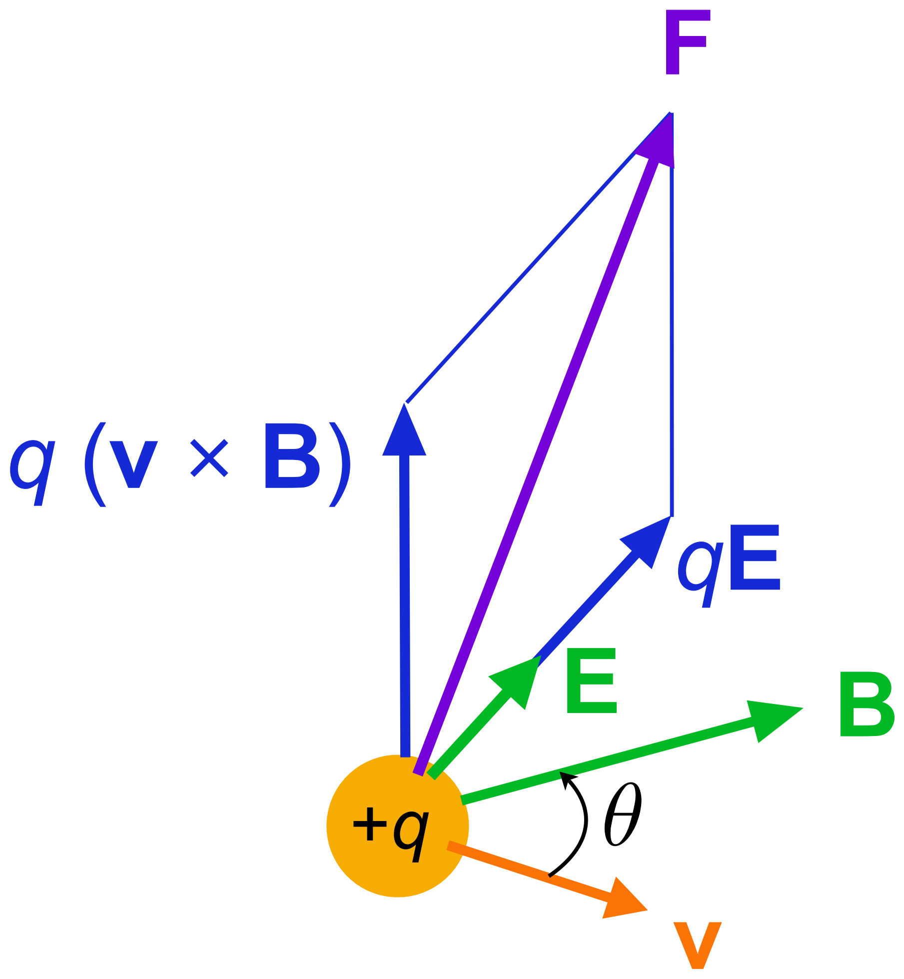


Force on a point charge (electric + magnetic)

- Lorentz force:

  $$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

- $\mathbf{F}$ = force
- q = charge
- $\mathbf{E}$ = electric field
- $\mathbf{v}$ = velocity of charge
- $\mathbf{B}$ = magnetic field
- $\times$ = cross product



Force on a point charge (magnetic only)

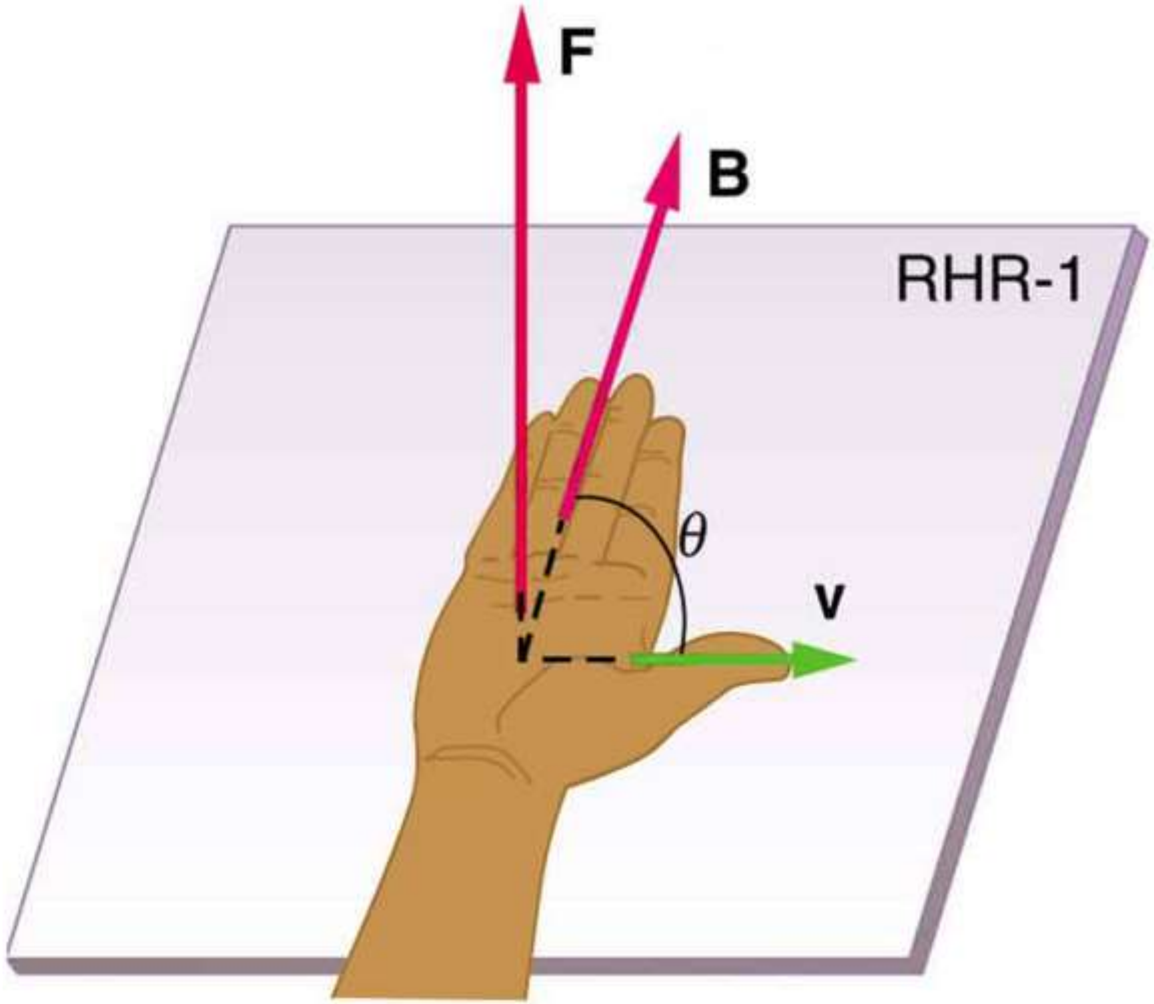
- Lorentz force:

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

- Direction: right-hand rule (there are two, either one works)
- Magnitude:

$$F = qvB \sin\theta$$

- Properties (prove!):
  - No force on neutral particle.
  - No force on charge at rest.
  - No force on charge moving parallel to magnetic field.
  - Strongest force on charge moving perpendicular to magnetic field.



$$F = qvB\sin\theta \quad \Longrightarrow \quad B = \frac{F}{qv\sin\theta}$$

- SI units: **tesla (T)**

$$1\ \mathrm{T} = \frac{1\ \mathrm{N}}{\mathrm{C}\cdot\mathrm{m/s}} = \frac{\mathrm{kg}}{\mathrm{A}\cdot\mathrm{s}^2}\ \text{(in base SI)}$$

- Examples:
  - Earth's magnetic field: $\sim 32\ \mu\mathrm{T} = 32 \times 10^{-6}\ \mathrm{T}$
  - Refrigerator magnet: $\sim 5\ \mathrm{mT} = 5 \times 10^{-3}\ \mathrm{T}$
  - MRI machine: ~ 1.5 to $3\ \mathrm{T}$
  - Large Hadron Collider: $\sim 8\ \mathrm{T}$
  - White dwarf, a very dense stellar remnant (dead star): $\sim 100\ \mathrm{T}$
  - Neutron star, an even denser stellar remnant: $\sim 10^4$ to $10^{11}\ \mathrm{T}$ (magnetar)
- Old units: gauss (G), $1\ \mathrm{G} = 10^{-4}\ \mathrm{T}$.

22.5 Force on a Moving Charge in a Magnetic Field: Examples and Applications

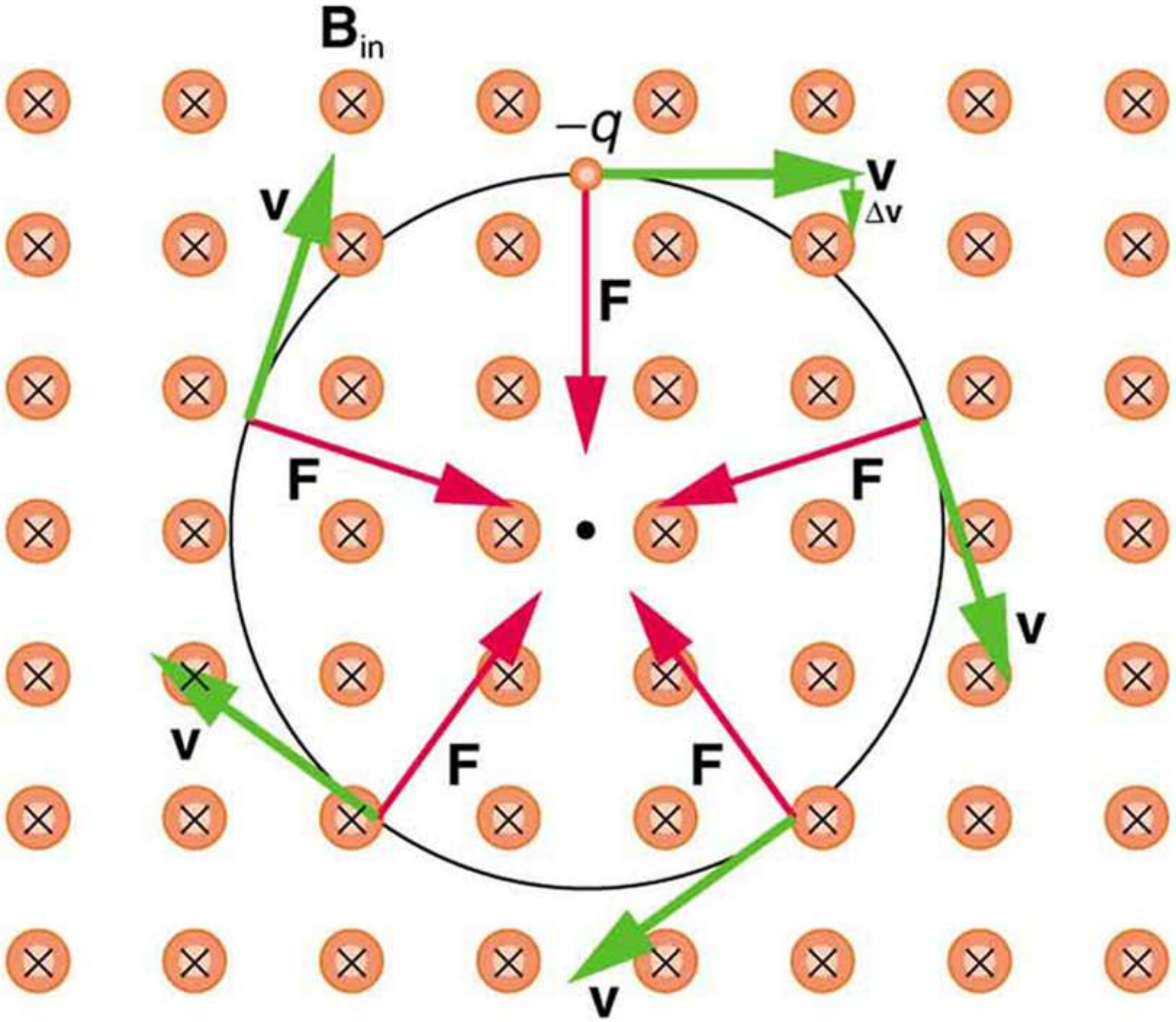
Circular motion

- Magnetic force is always perpendicular to velocity (cross product).
- So it does **no work** on the charged particle:

$$\theta = \frac{\pi}{2} \quad \Rightarrow$$

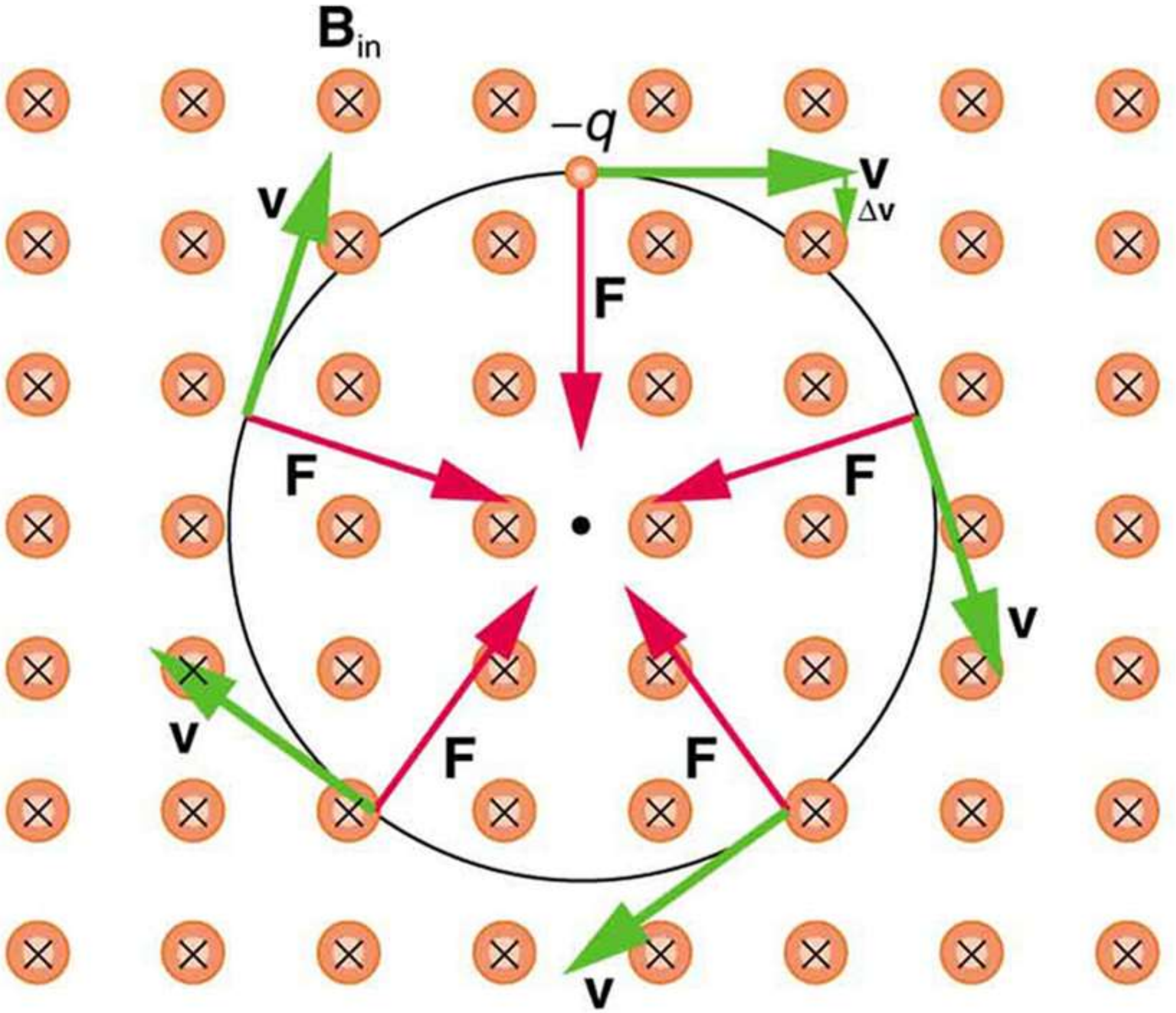
$$W = \mathbf{F} \cdot \mathbf{d} = Fd\cos\theta = 0$$

- Direction of motion changes, but not speed (kinetic energy is constant).



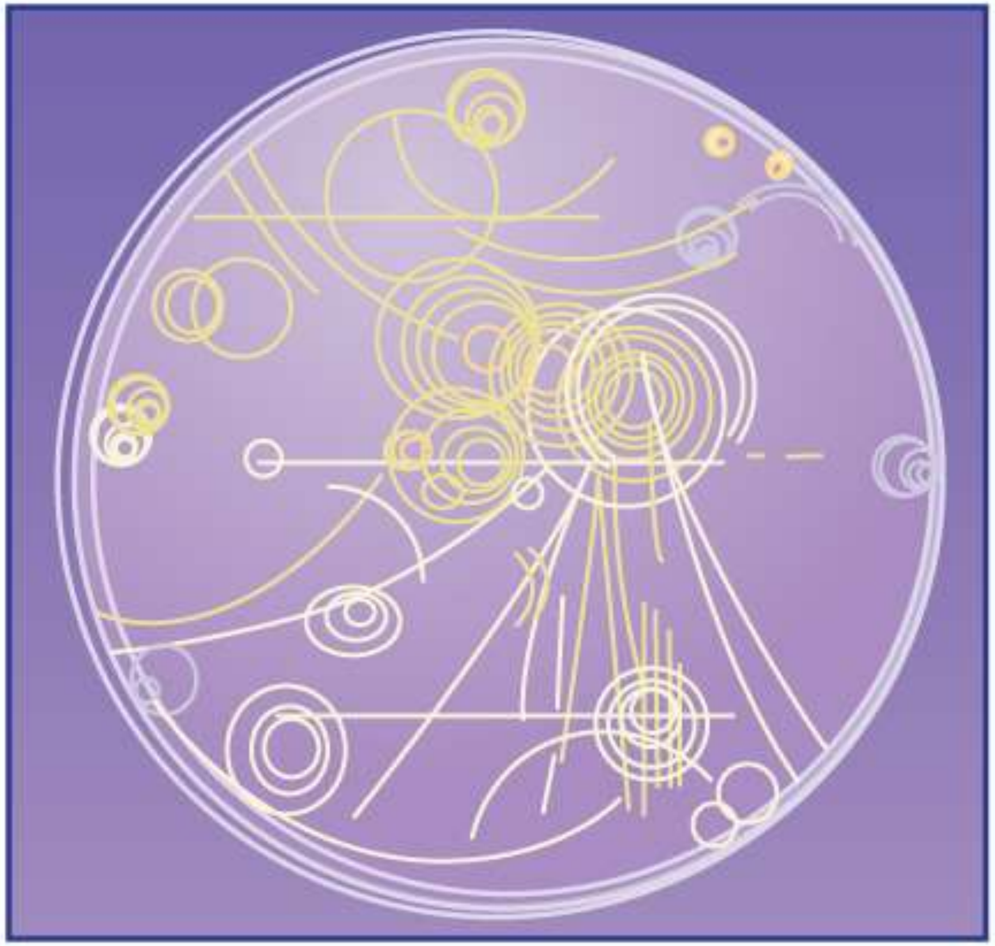
Circular motion

- If **v** is perpendicular to **B** then
$$F = qvB \sin\theta = qvB$$
($\theta = \pi/2$, not the same θ!)
- This supplies the centripetal force:
$$F = \frac{mv^2}{r} = qvB$$
- Thus:
$$r = \frac{mv}{qB}$$



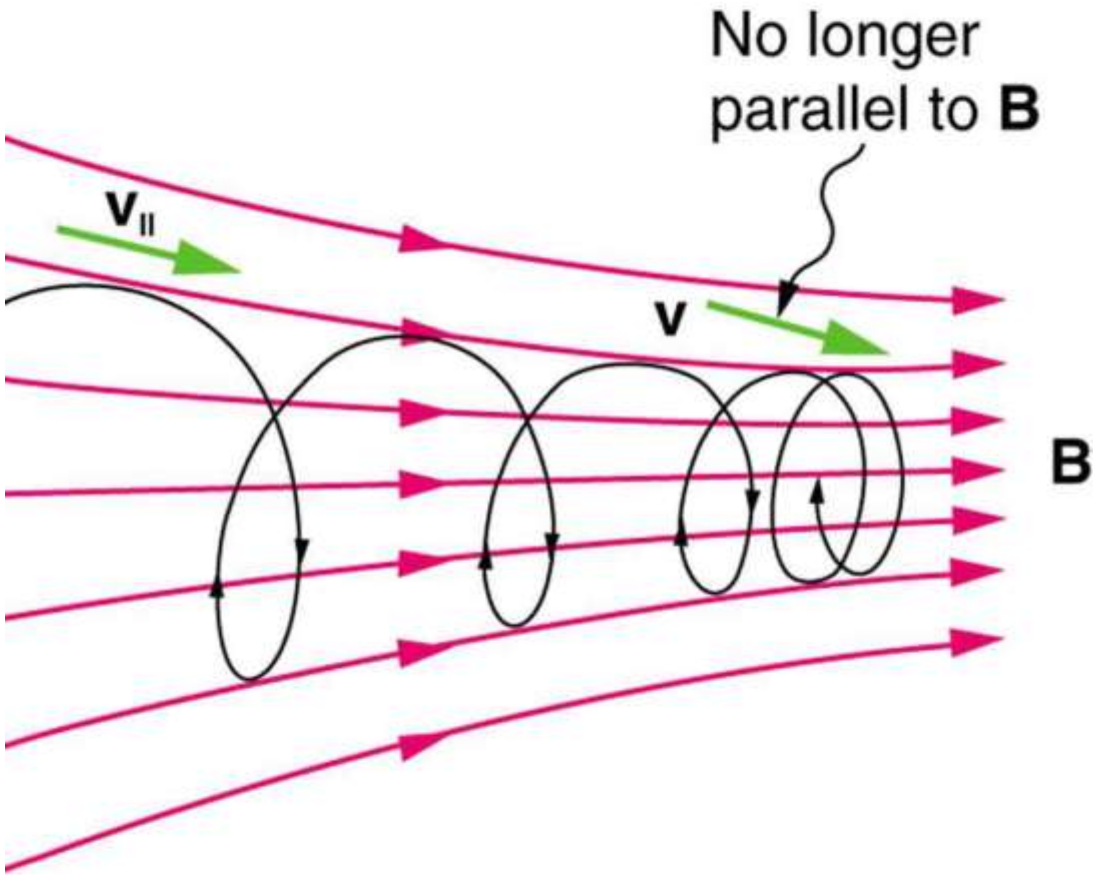
Spiral motion

- If $\mathbf{v}$ is **not** perpendicular to $\mathbf{B}$ then we consider its component $\mathbf{v}_{\perp}$ perpendicular to the field.
- The component $\mathbf{v}_{\parallel}$ parallel to the field is unaffected.
- This causes spiral motion instead of circular.
- Application: bubble chamber. Can detect particles and measure their mass and charge by observing their path in a magnetic field.



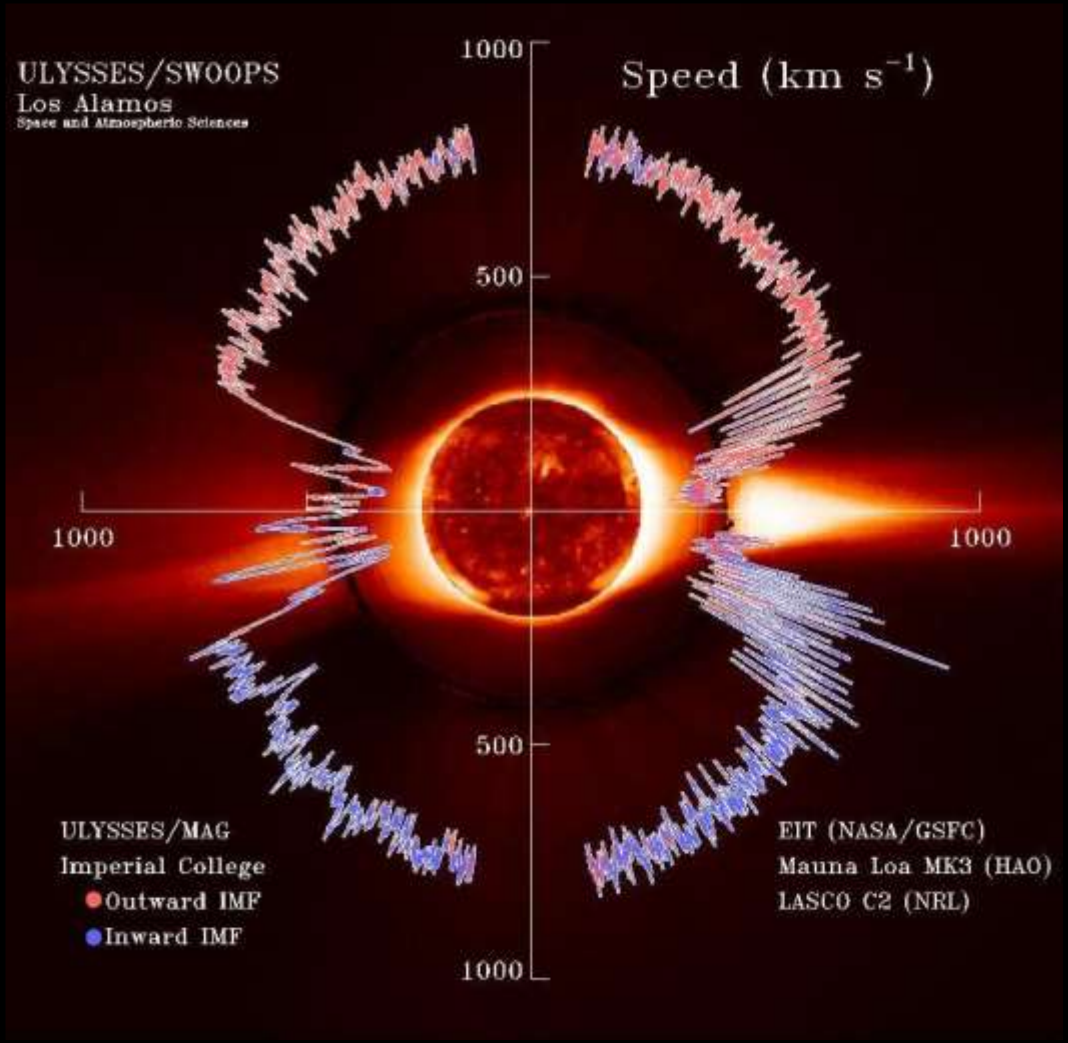
Magnetic mirror

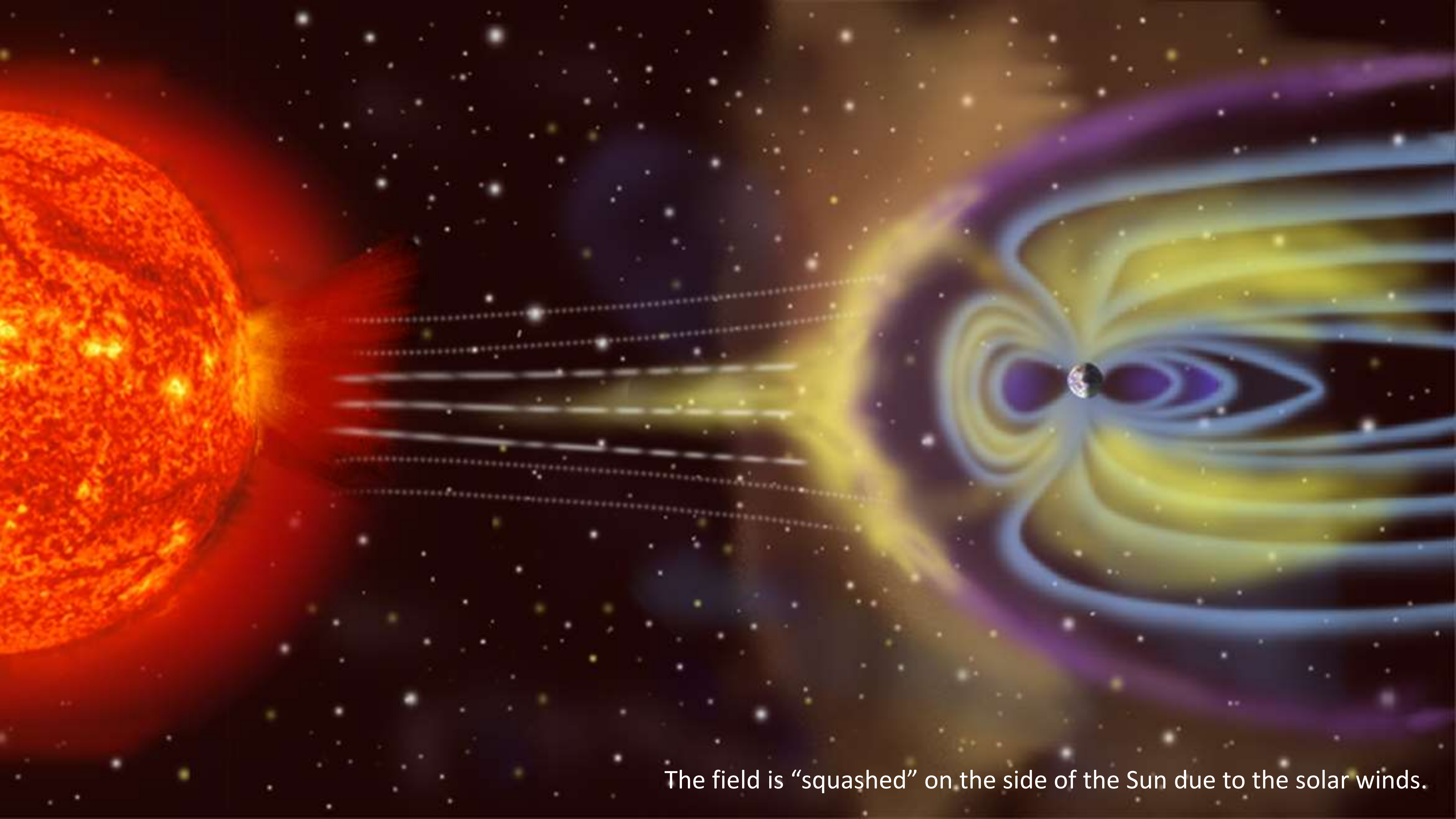
- Field strength increases in direction of motion.
- Charges slow and eventually reverse their motion.



Auroras (northern/southern lights)

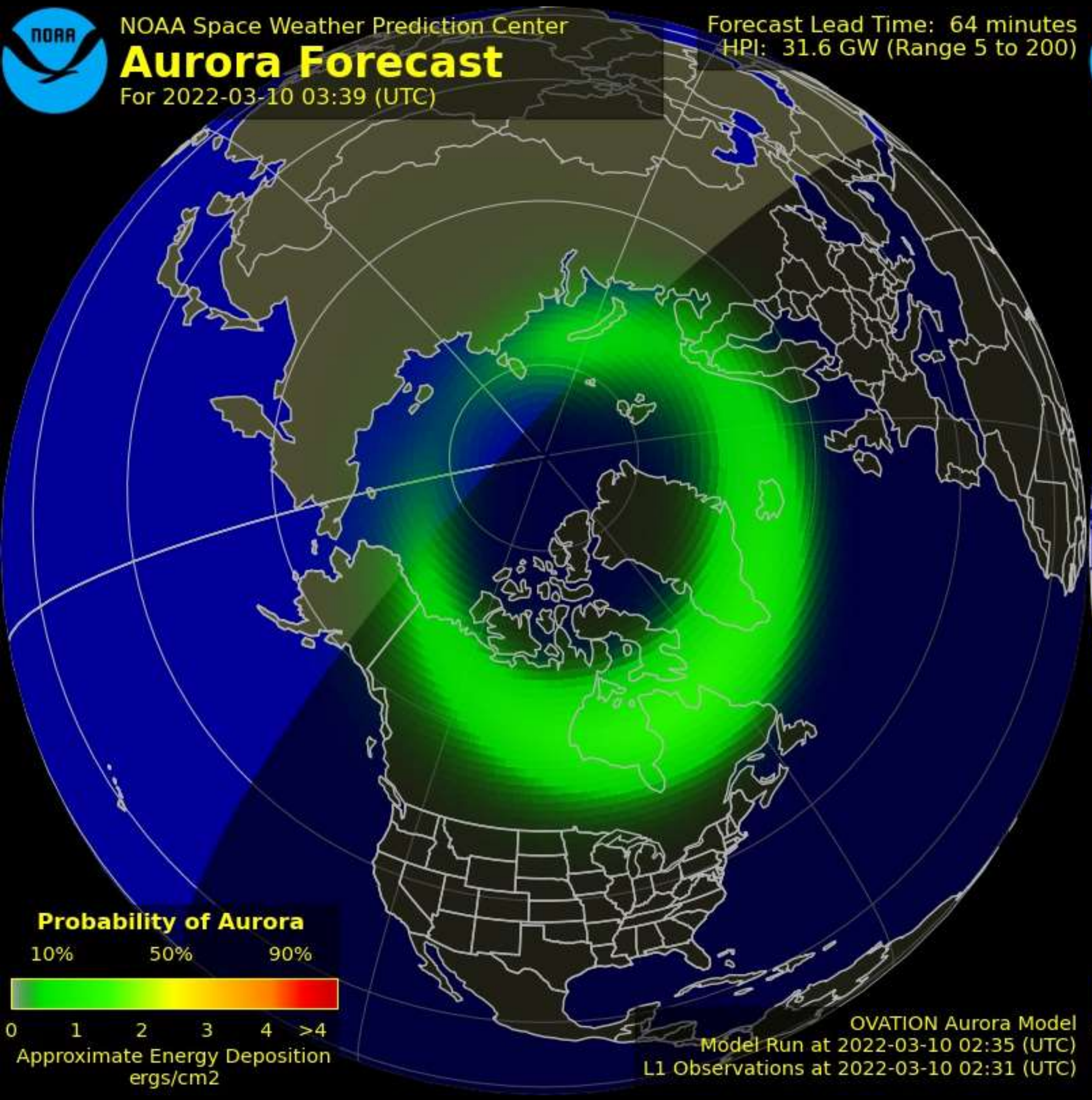
- Solar winds are very fast and very hot charged particles that emanate from the Sun.
  - Protons
  - Electrons
  - Alpha particles (2 protons + 2 neutrons, like a ^{4}He nucleus)
- The Earth is shielded from them by its magnetic field at the magnetosphere.
- Otherwise the atmosphere would be stripped off the planet!

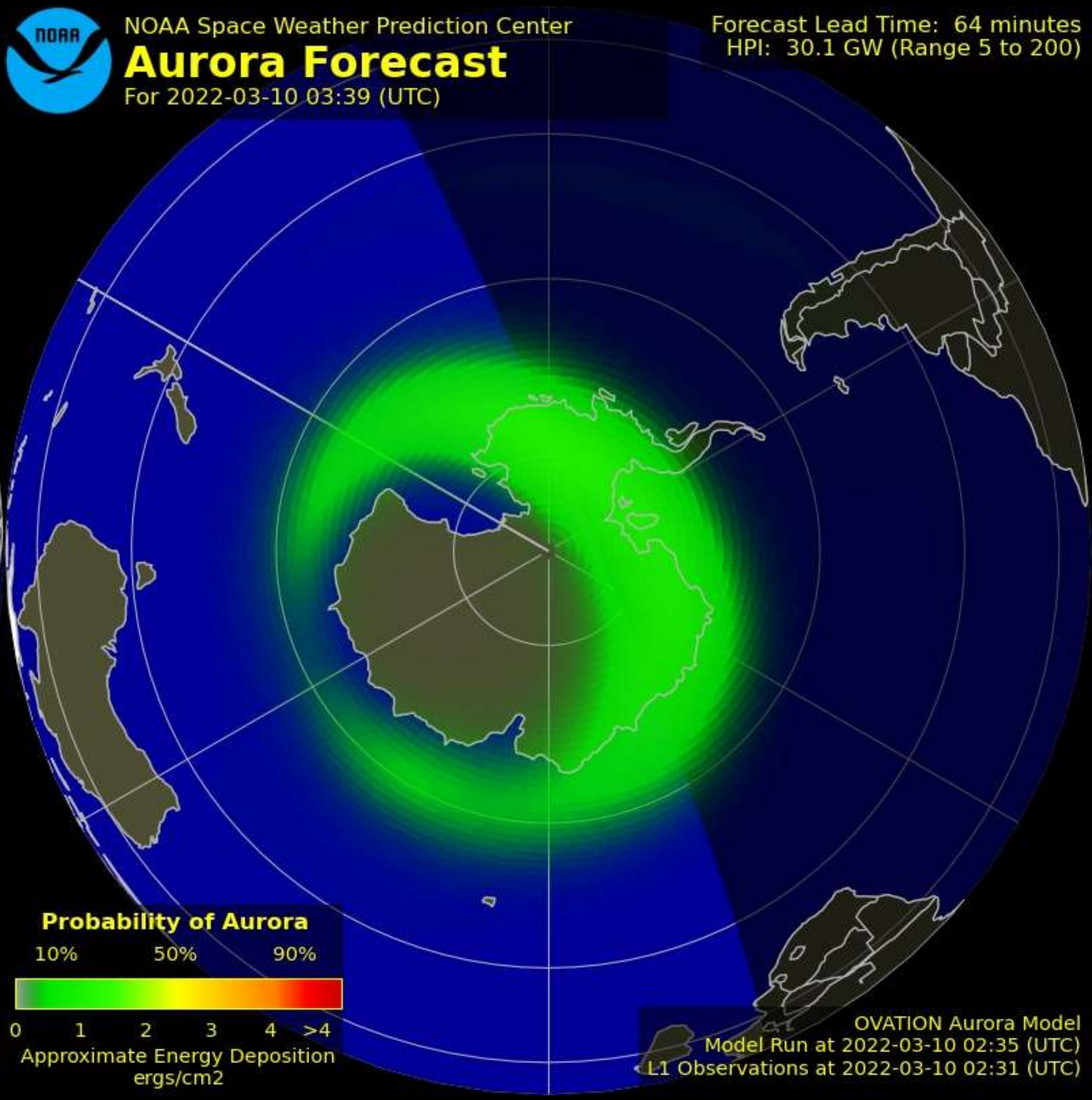




The field is “squashed” on the side of the Sun due to the solar winds.

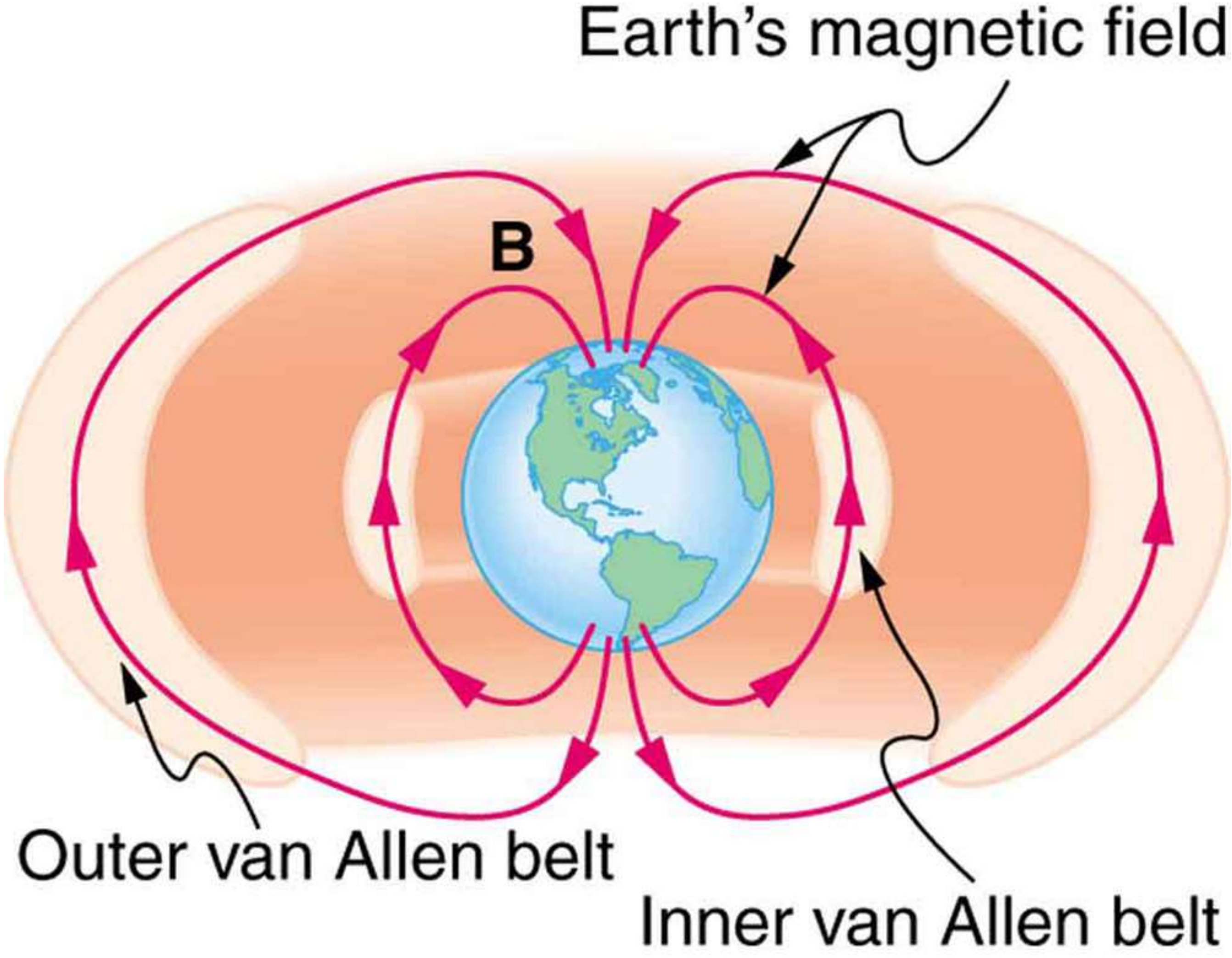
- The particles flow along the magnetic field lines towards the poles.
- When they collide with nitrogen and oxygen atoms in the atmosphere, causing them to emit photons.
    - Oxygen = green/yellow/red light
    - Nitrogen = blue light
- This is called an aurora and can be seen at the “auroral oval”, around 10-20° from the poles.


NOAA Space Weather Prediction Center
Aurora Forecast
For 2022-03-10 03:39 (UTC)
Forecast Lead Time: 64 minutes
HPI: 31.6 GW (Range 5 to 200)
Probability of Aurora
10% 50% 90%
0 1 2 3 4 >4
Approximate Energy Deposition
ergs/cm2
OVATION Aurora Model
Model Run at 2022-03-10 02:35 (UTC)
L1 Observations at 2022-03-10 02:31 (UTC)


NOAA Space Weather Prediction Center
Aurora Forecast
For 2022-03-10 03:39 (UTC)
Forecast Lead Time: 64 minutes
HPI: 30.1 GW (Range 5 to 200)
Probability of Aurora
10% 50% 90%
0 1 2 3 4 >4
Approximate Energy Deposition
ergs/cm2
OVATION Aurora Model
Model Run at 2022-03-10 02:35 (UTC)
L1 Observations at 2022-03-10 02:31 (UTC)

The Van Allen radiation belts

- Regions where energetic charged particles from the solar wind are trapped.
- Inner belt: 1,000-12,000 km from Earth
- Outer belt: 13,000 to 60,000 km from Earth



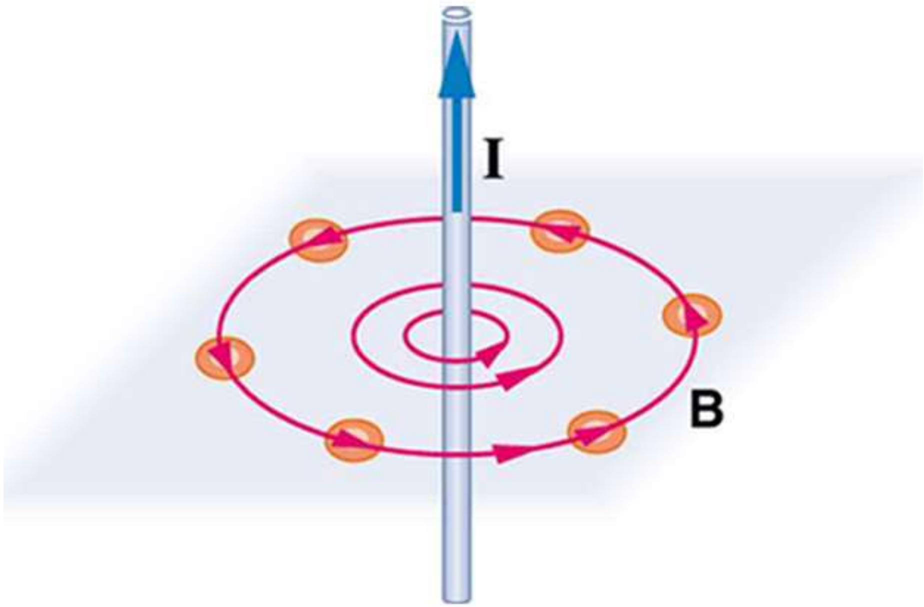
(Skipping sections 22.6-22.8)

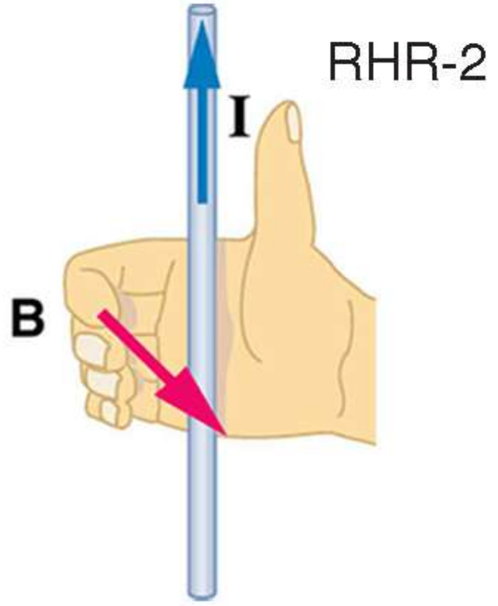
22.9 Magnetic Fields Produced by Currents: Ampere's Law

Long straight wire

$$B = \frac{\mu_0 I}{2\pi r}$$

- B = magnitude of magnetic field.
- $\mu_0 \approx 1.26 \times 10^{-6}\ \mathrm{N/A^2}$ = vacuum permeability.
- I = current.
- r = radius (shortest distance).
- Direction determined by the right-hand rule.

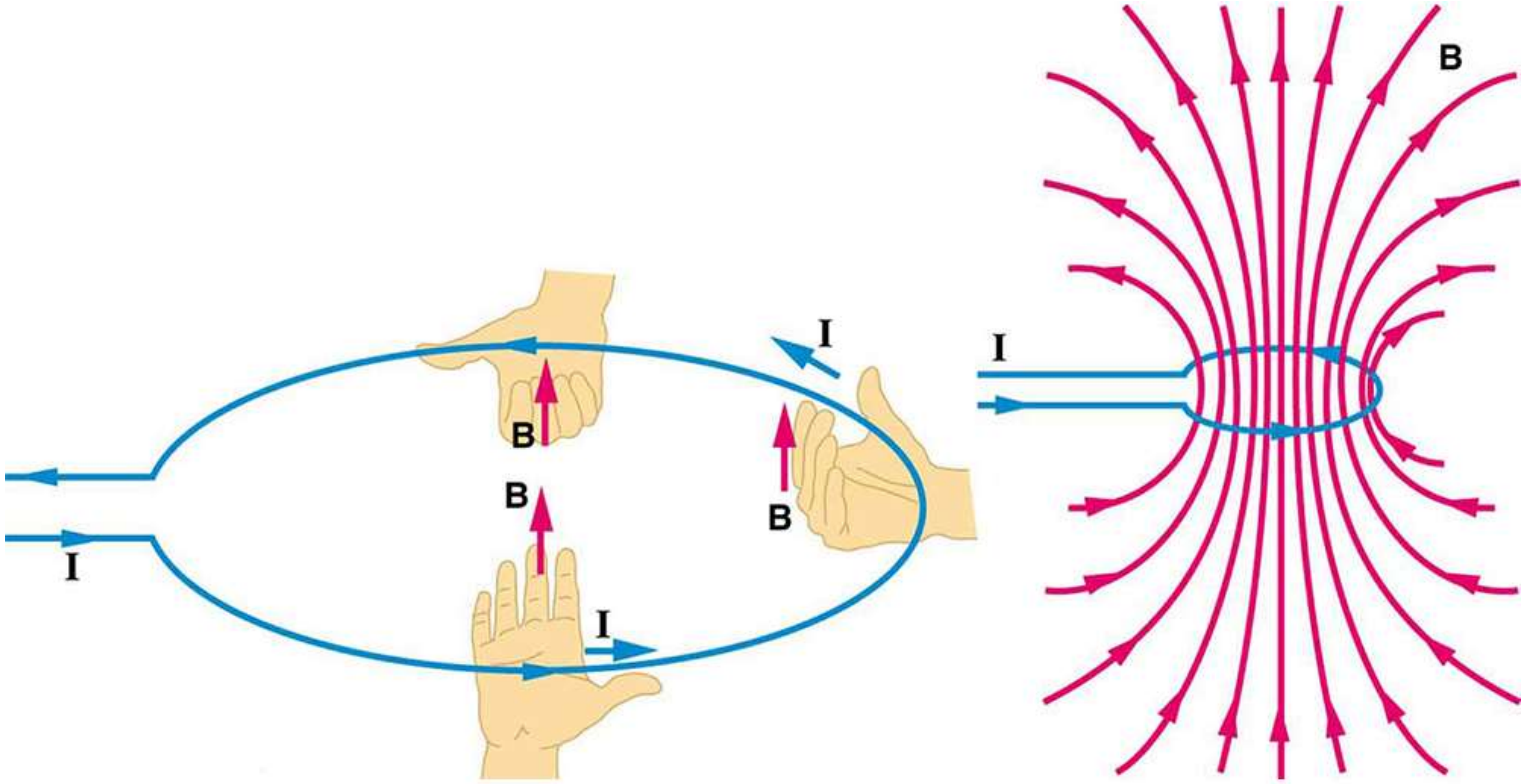




Circular loop

$$B = \frac{\mu_0 I}{2r}$$

Only valid at the center of the loop.



Solenoid (long coil of wire)

Approximately uniform field: $B = \mu_0 n I$

n is the number of loops per unit length. If $N =$ number of loops and $L =$ length, then $n \equiv N/L$.