Electricity and Magnetism

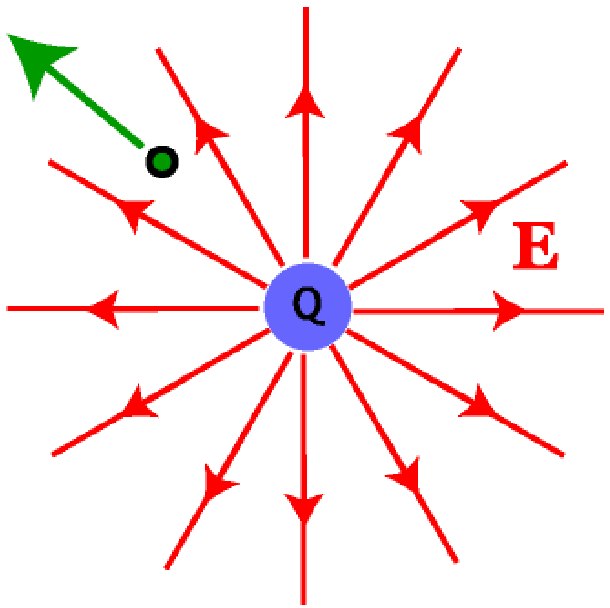
Magnetism

Quick review of electricity

- Electric charge is a property of the subatomic particles

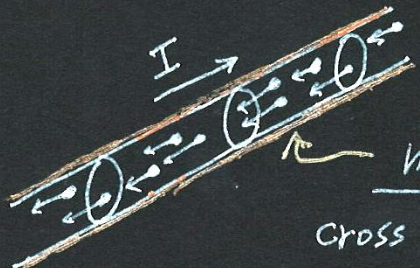
electron	-e
proton	e
neutron	0

- The electric force is *not action at a distance*. The force on q is exerted by the field: $\mathbf{F} = q\,\mathbf{E}(\mathbf{x})$.



Electric Current

↳ a coherent flow of charged particles



Cross sectional area = A $[m^2]$

density of conduction electrons = n $[m^{-3}]$

average velocity " " = v $[m/s]$

Cross sectional area = A $[m^2]$

de

ave

Current $I = \dfrac{\Delta Q}{\Delta t}$ $[C/s]^{\dagger}$

$$I = \frac{e\, n\, (A\, v \Delta t)}{\Delta t} = e n A v$$

†: units 1 ampere = $\dfrac{1 \text{ Coulomb}}{\text{second}}$

"amps"

Part 1 - Magnets

Magnets

Everyone has played with magnets and observed their interesting forces.

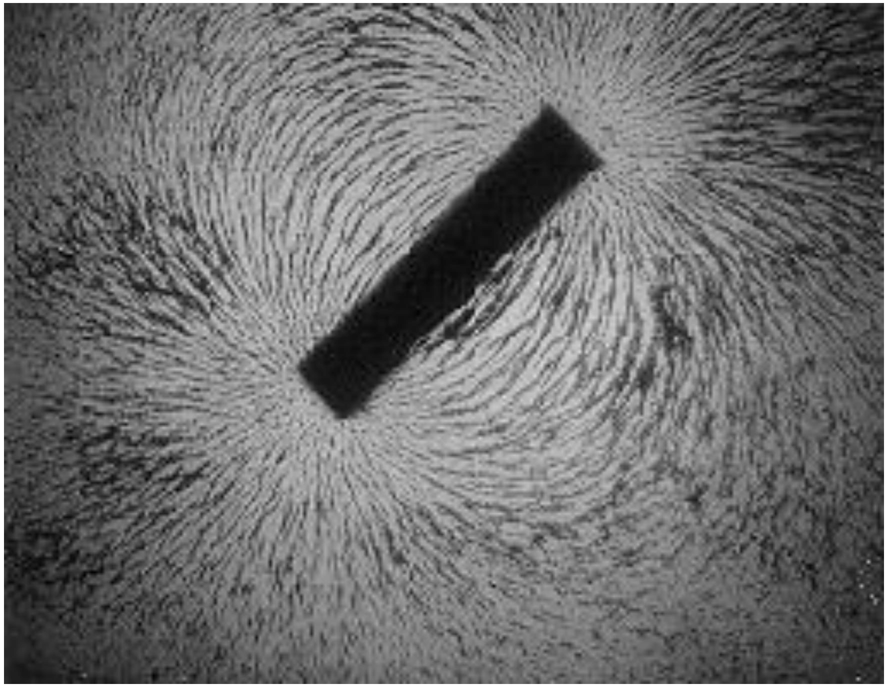
attraction

repulsion

What causes these forces?

What is a magnet?

Magnets



Iron filings trace out the magnetic field lines around a bar magnet.

(Michael Faraday)

What is a magnet?

What is the magnetic field?

Historical

Thales of Miletus (624 – 547 BCE) observed natural ferromagnets: they attract iron.

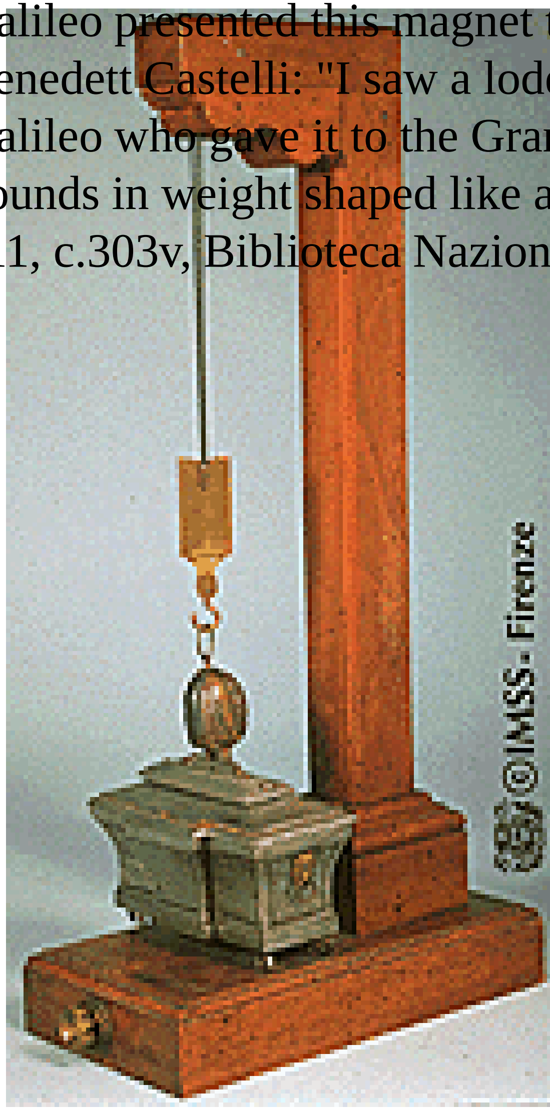
- lodestone
- magnetite

► William Gilbert (1544-1603) coined the word "magnet" from the name of a province in Greece—Magnesia—where magnetic iron ore is found.

(magnetite)

Seventeenth century. Galileo Galilei. Magnetite, iron, wood. Magnet, 40 x 50 mm; Support 175 x 320 x 670 mm

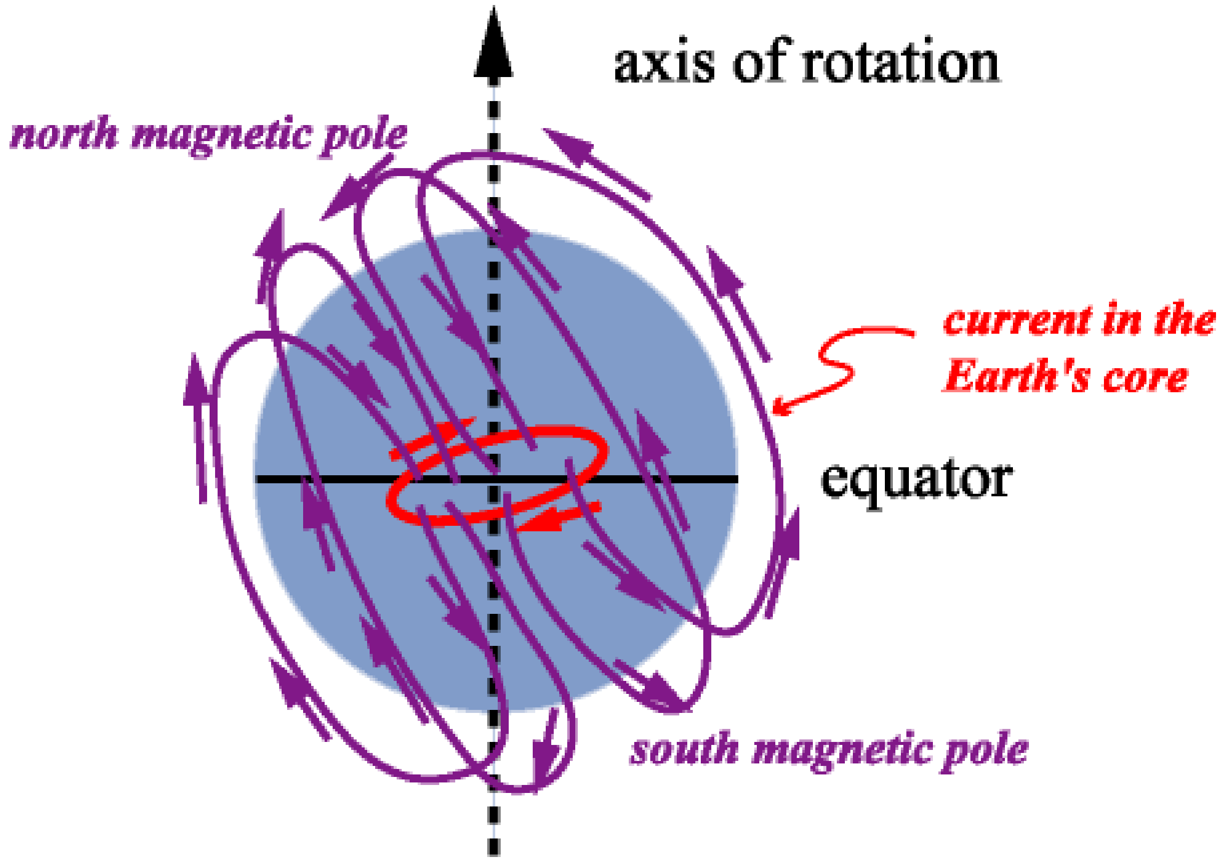
Galileo presented this magnet to Ferdinand II de Medici as is attested by Benedett Castelli: "I saw a lodestone of six ounces, very well armed with iron by Galileo who gave it to the Grand Duke Ferdinand. It holds a piece of iron fifteen pounds in weight shaped like a casket." (*Discorso sopra la calamita*, Ms. Galil. 111, c.303v, Biblioteca Nazionale Centrale, Florence).



A lodestone of 9.2 kg from the British Maritime Museum

Until the mid-18th century, when an improved compass was invented, mariners on long voyages had to carry with them a piece of magnetite, or lodestone, to restore the magnetism of the compass needle. The soft iron then used for the needle could carry only a weak magnetism, which faded quite quickly. Lodestones were often mounted in brass, bronze or silver cases, and sometimes had an iron or steel 'keeper', a bar to help preserve their magnetic power. The lodestone was stroked in one direction along the compass needle to re-magnetize it. The lodestone shown is unusually large and weighs 20.25 lb (9.2 kg). It was probably for scholarly study rather than use at sea, where a smaller lodestone was more convenient.

Magnetic field of the Earth



William Gilbert (1600) :
Magnus magnes ipse est globus terrestris.

Modern science of magnetism

Magnetic forces come from "motion" of charged particles.

either true translation in space or motion within an atom

Electric forces come from charge—a property of subatomic particles (electrons and protons).

$-e$ **$+e$**

So…

Static charge $\rightarrow$ an electric field

Electric current $\rightarrow$ a magnetic field

(but that's not the end of the story!)

Ferromagnetic materials …

… materials that can make permanent magnets

A ferromagnet has …

… no moving parts

… no source of energy

Still, it exerts forces.

There is something special about ferromagnetic materials — not all elements have these properties.

Only a few elements can make a permanent magnet.

Fe Z = 26
Co Z = 27
Ni Z = 28

also some rare earths (Gd, Dy)
also some alloys (Al Ni Co , Nd Fe B)
ceramic refrigerator magnets

gadolinium
dysprosium

Part 2 –
magnetic field and electric current

Electric current and magnetic field

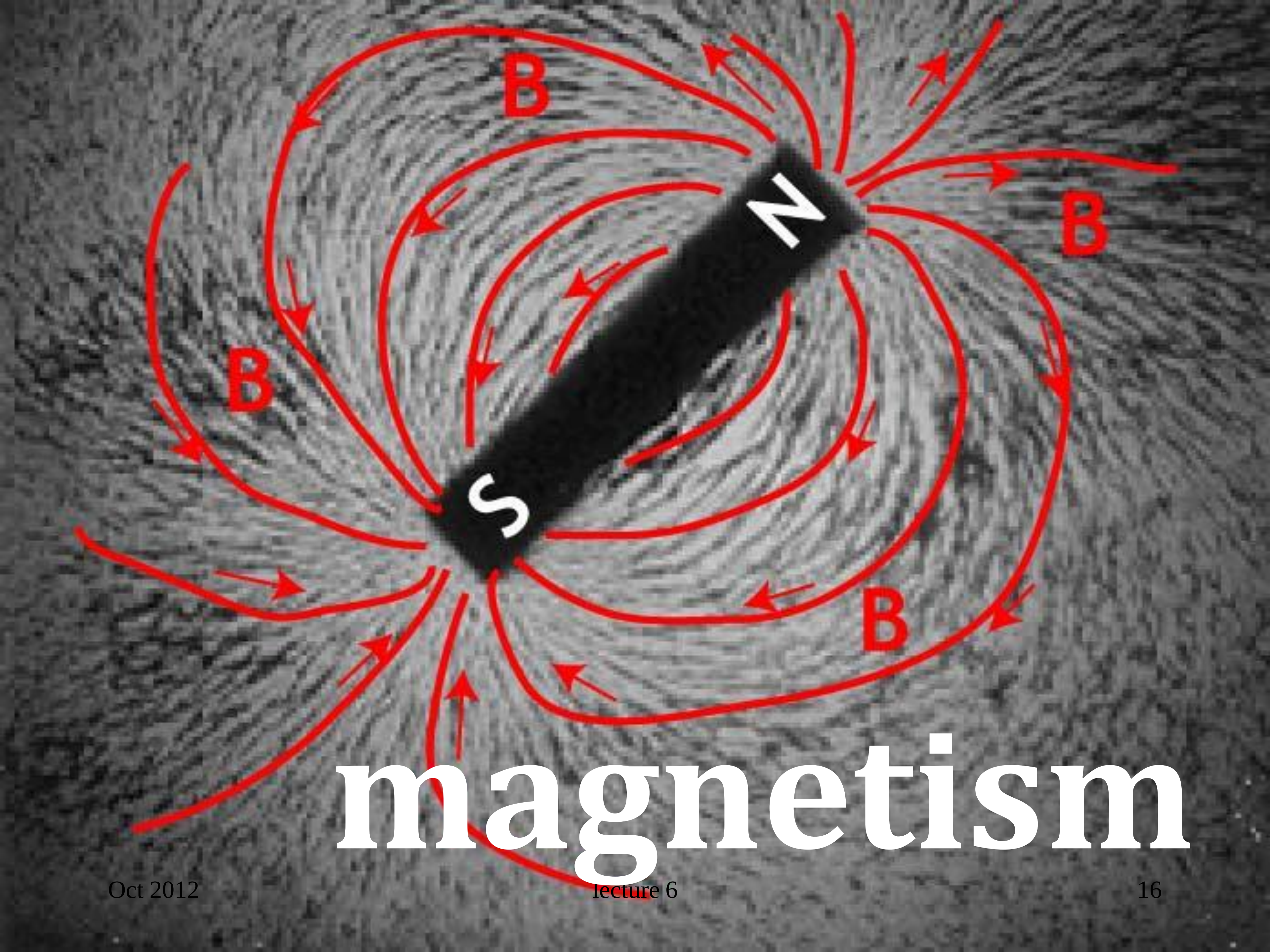
Current (moving charge) = I

Magnetic field = B

The two aspects of the interaction…

(1) B exerts a force on I.

(2) I creates B.



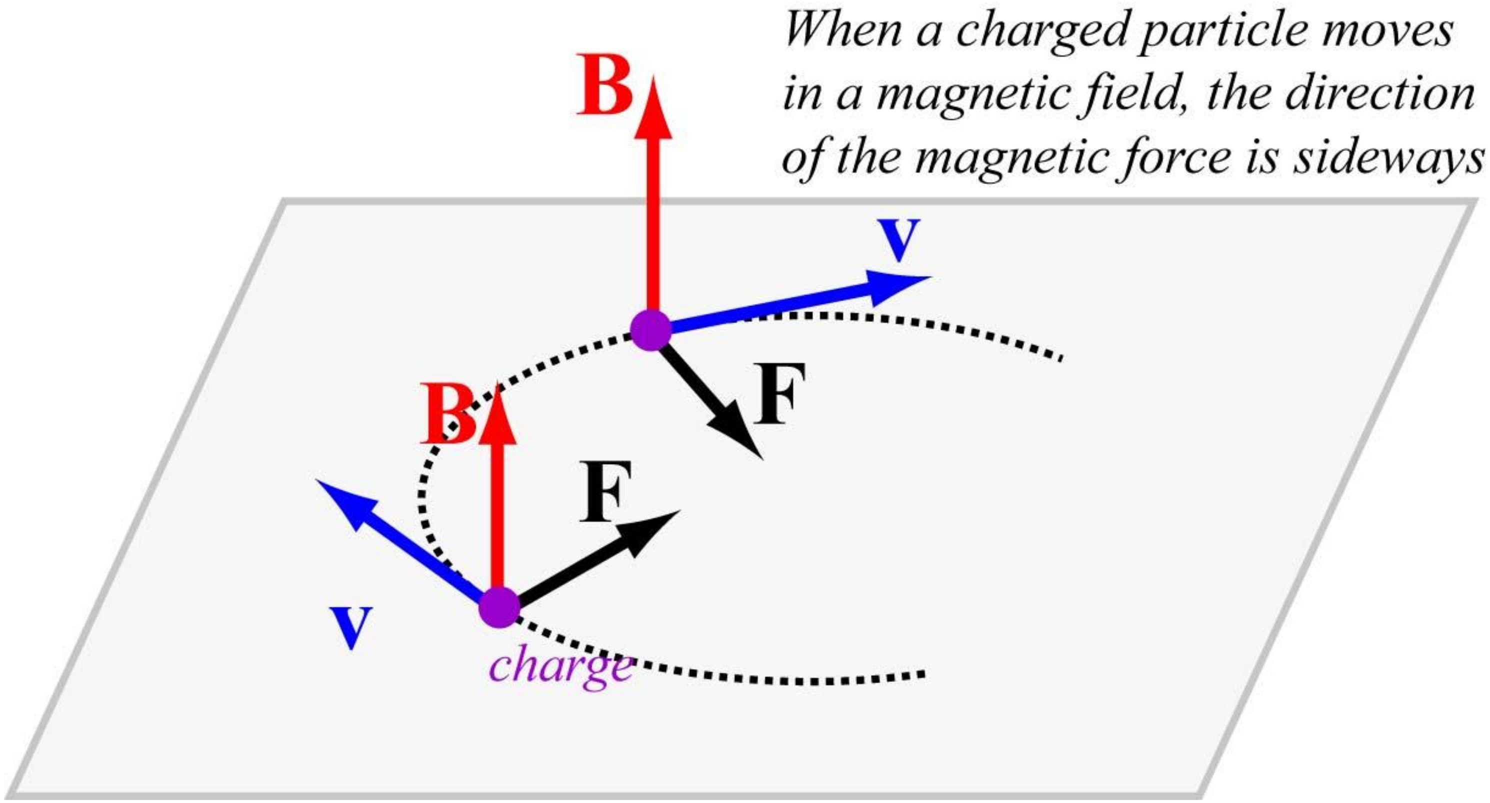
magnetism

The Lorentz force

If a charged particle moves across a magnetic field, the force on the particle is $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$.
(q = charge of the particle, **v** = velocity, **B** = magnetic field)

We use this force to define the magnetic field.

The magnetic force on a moving charge



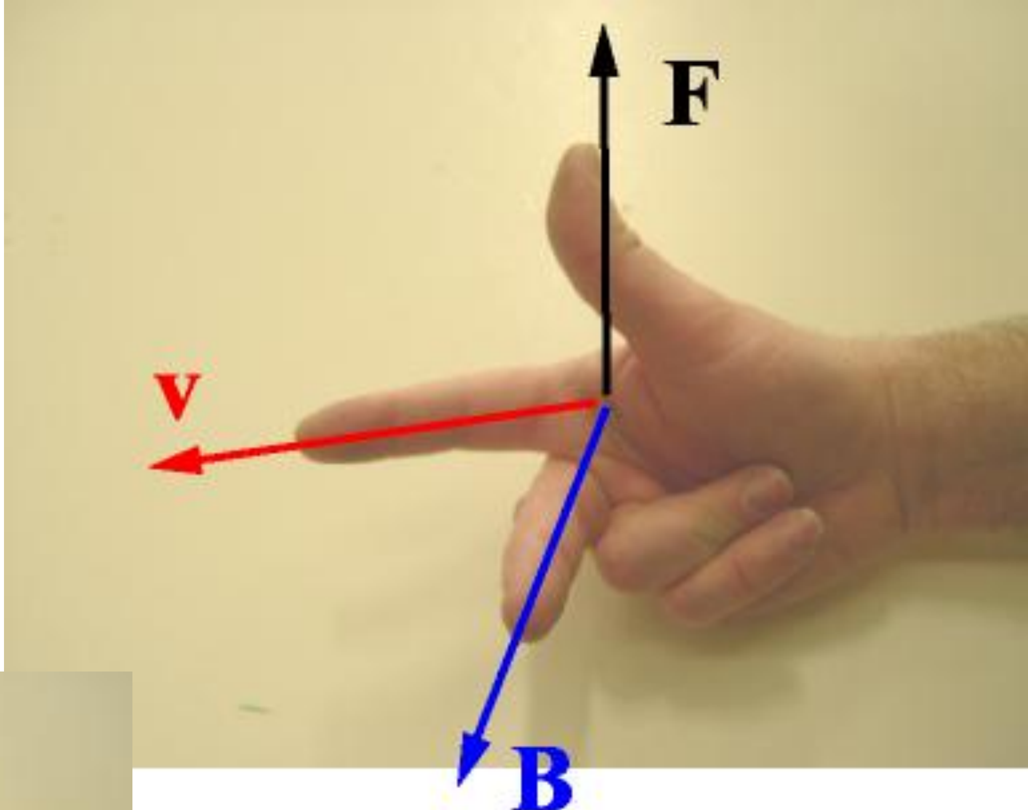
The magnetic force is sideways, perpendicular to the velocity vector.

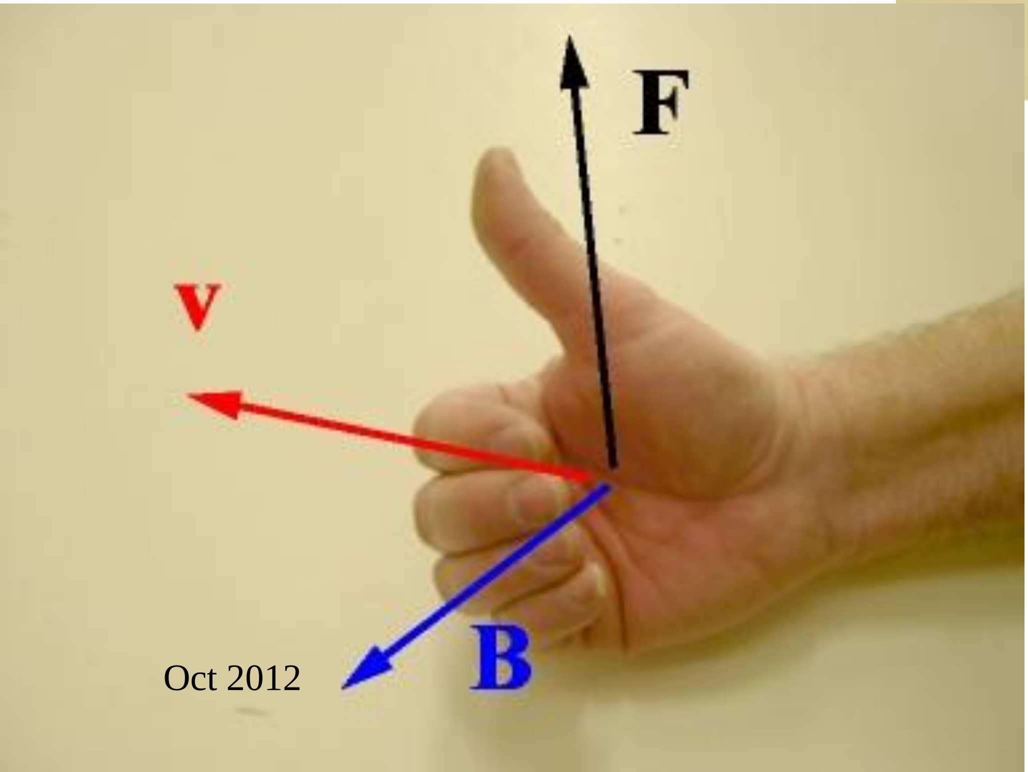
The right-hand rule

… applied to the magnetic force on a moving charge,

F = q**v** x **B.**

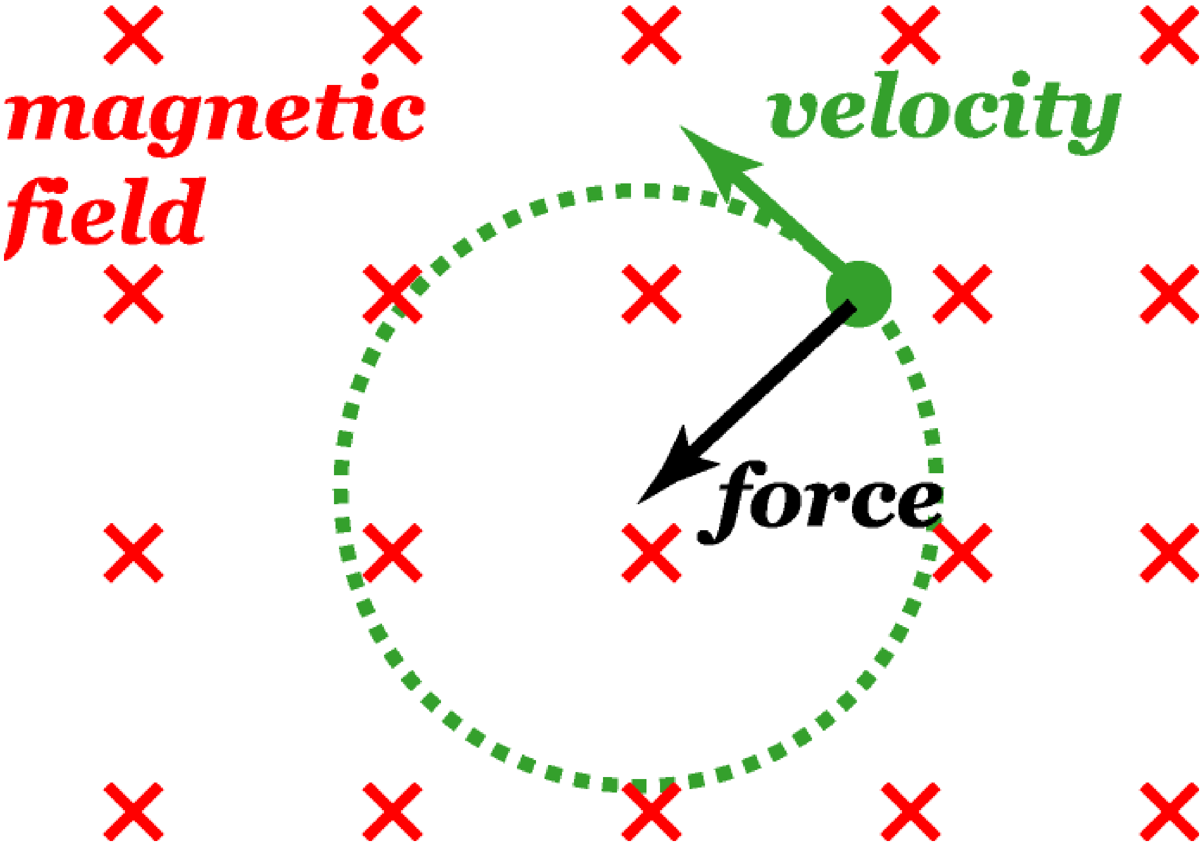
(“v cross B”)





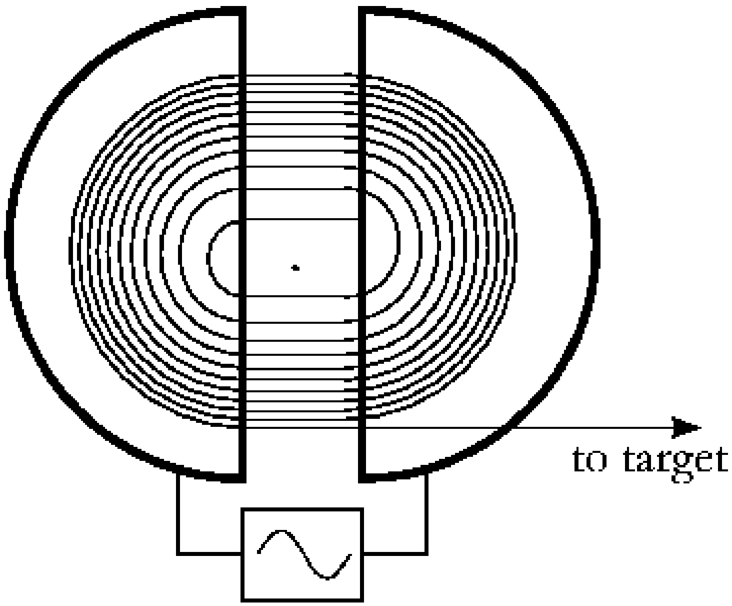
- **v** cross **B** is perpendicular to both **v** and **B.**
- The thumb points in the direction of **v x B.**
- If q is positive (assumed in the pictures) **F** is in the direction of **v x B**. If q is negative, **F** is in the opposite direction.

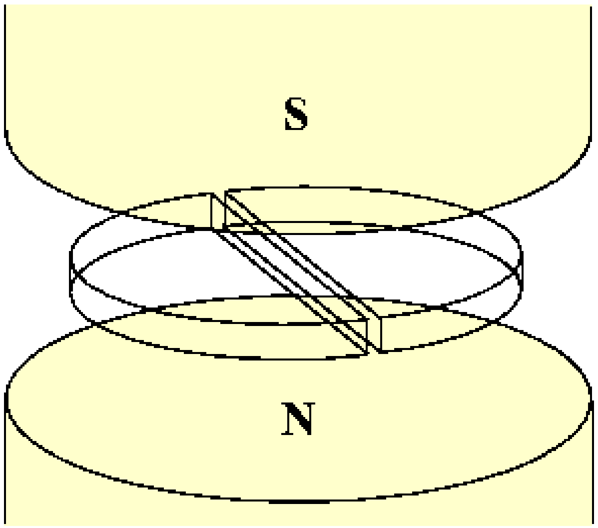
The magnetic force on a moving charge is
F = *q* **v** × **B**, perpendicular to the velocity.
Therefore a charged particle in a magnetic field moves on a circular path.



Equation of motion

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





PRINCIPLE OF THE CYCLOTRON

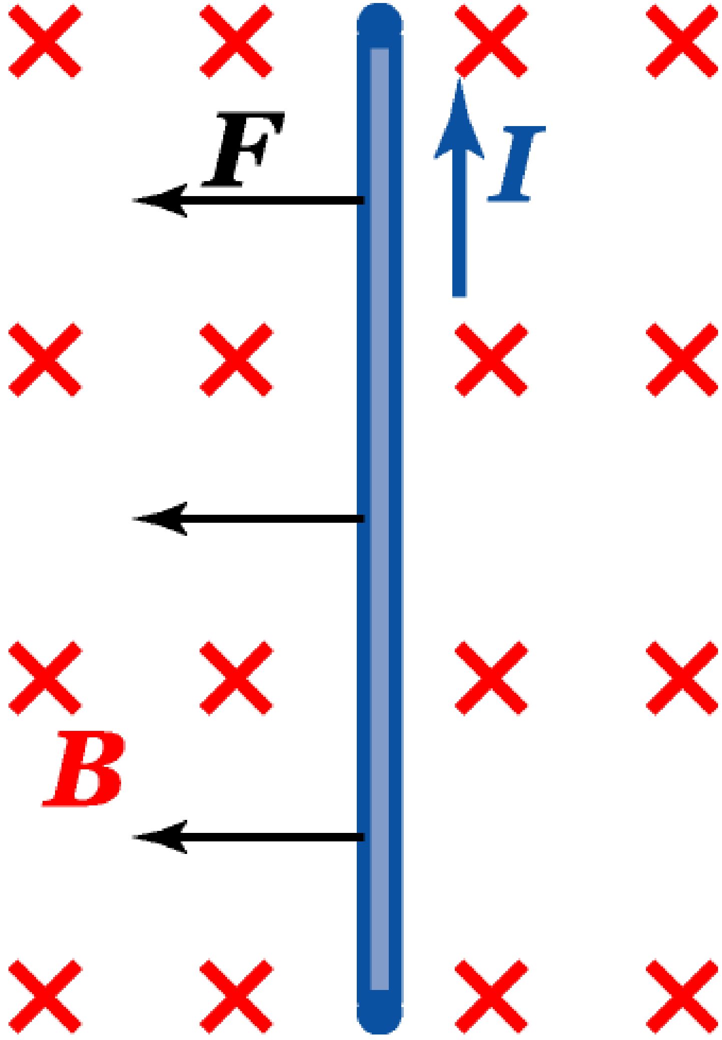
The alternating electric field increases the particle energy. The constant magnetic field causes the particles to circle.

MSU is the site of the National Superconducting Cyclotron Laboratory.

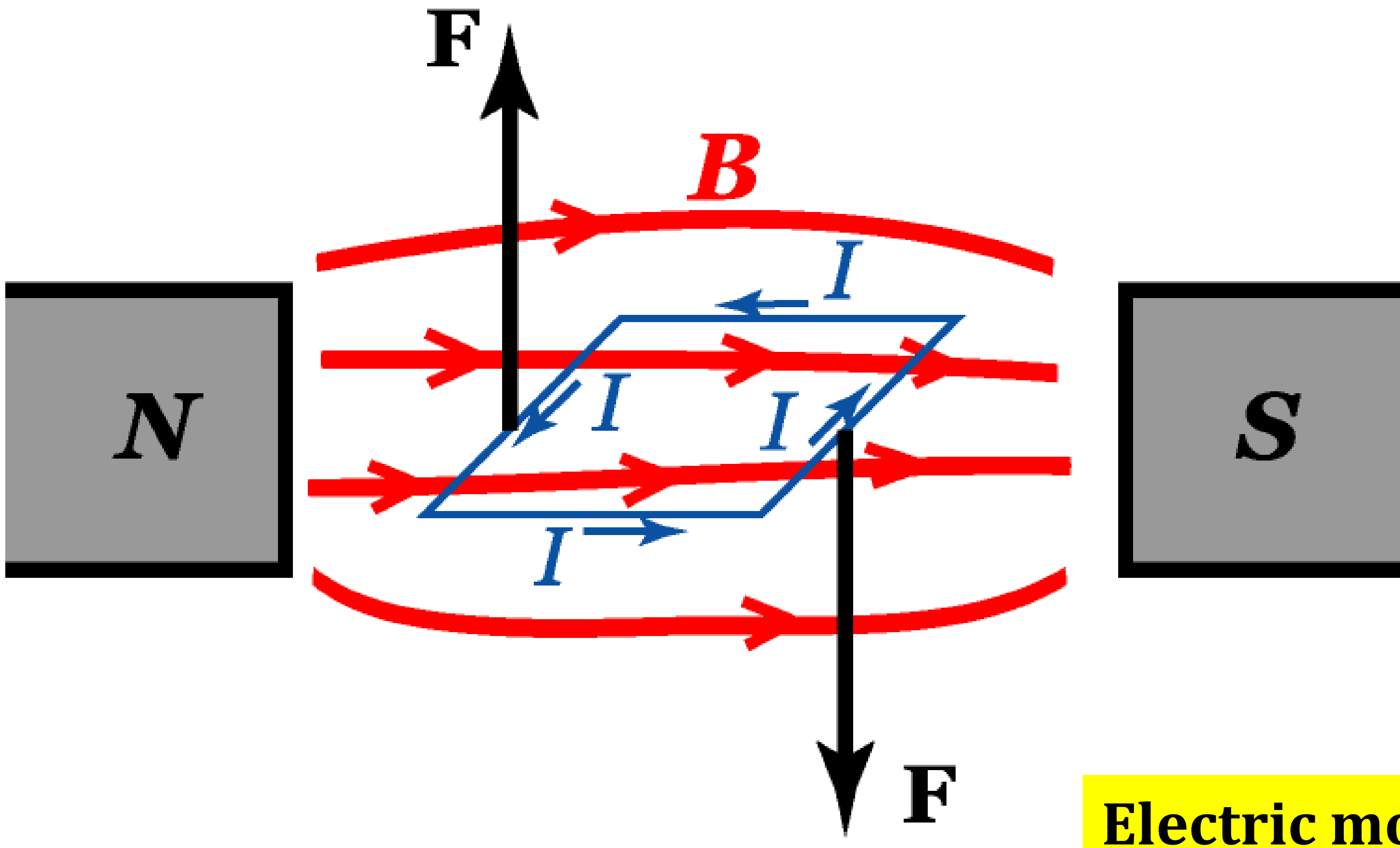
Theorem. The magnetic force on a current carrying wire is **F** = *L* **I** x **B** .

Proof.

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \quad N$$
$$= Nq\frac{\Delta \mathbf{x}}{\Delta t} \times \mathbf{B}$$
$$= (\frac{Nq}{\Delta t})\Delta \mathbf{x} \times \mathbf{B}$$
$$= L\,\mathbf{I} \times \mathbf{B}$$



The magnetic forces around a loop of electric current create a net *torque*



Electric motors

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