Electricity and Magnetism
Magnetic Fields

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Overview

- magnets
- magnetic field
- Earth's magnetic field
- magnetic force on a charge

Magnets

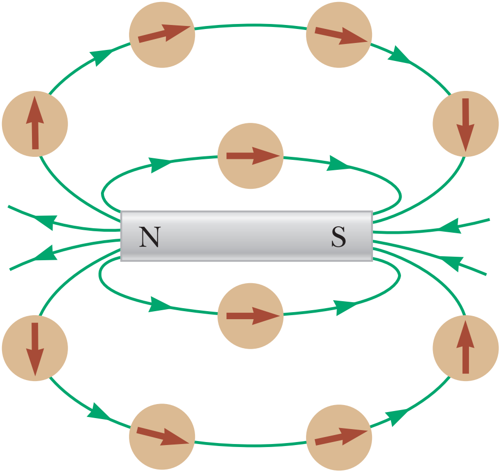
Like charges, magnets also interact at a distance.

They can either attract or repel.

Similarly to charges, they can also attract certain kinds of nearby material (*eg.* iron) by *magnetizing* it. (*cf.* polarization)

Magnets and Magnetic fields

Compass needles point along the direction of a magnetic field.

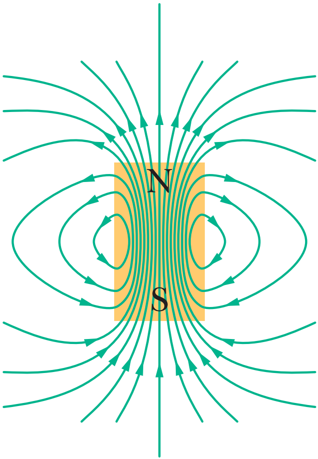


[1] Figure from Serway and Jewett, 9th ed.

Magnetic Field Lines

Draw magnetic field lines similarly to E-field line: lines emerge from North pole, enter South pole, denser lines means a stronger field.

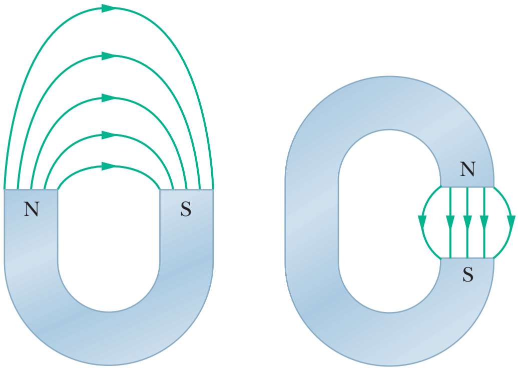
A bar magnet:



[1]Figure from Halliday, Resnick, Walker, 9th ed.

Magnetic Field Lines

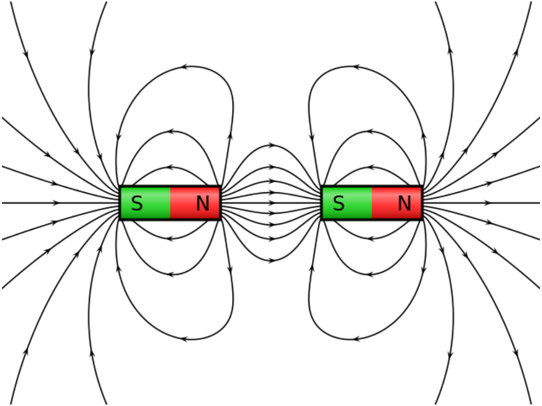
Magnetic fields for a horseshoe magnet and a C-shape magnet:



[1]Figure from Halliday, Resnick, Walker, 9th ed.

Magnetic Field Lines

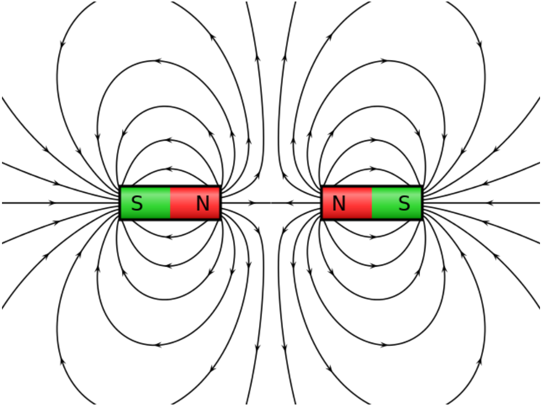
Opposite poles attract each other:



[1]Figure from Wikipedia.

Magnetic Field Lines

Like poles repel each other:



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Magnets vs. electrostatics

Magnets are different from charges, but there are some similarities.

For two magnetic poles in free space small enough to be modeled as points, the magnitude of the force between them is:

$$F = \frac{\mu_0}{4\pi} \frac{q_{m1} q_{m2}}{r^2}$$

where μ_0 is the magnetic permeability of free space, q_{m1} is a magnetic charge.

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This looks a lot like the Coulomb force:

$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$$

However, the equation for magnetic force is not in the textbook. Why?

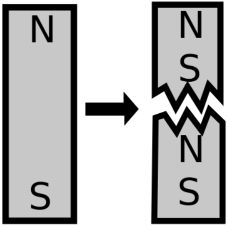
Magnets vs. electrostatics

Magnets also have an important difference from electric charges.

It is possible for a positive or negative electric charge to be found on its own: *eg.* electrons, protons.

Magnetic charges (q_m) are **never** found on their own.

Magnets have a North pole and a South pole. If you break a magnet in two, new North and South poles form:



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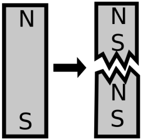
Lack of Magnetic Monopoles

Breaking a magnet in two:



It is impossible to separate a North pole from a South pole.

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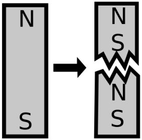

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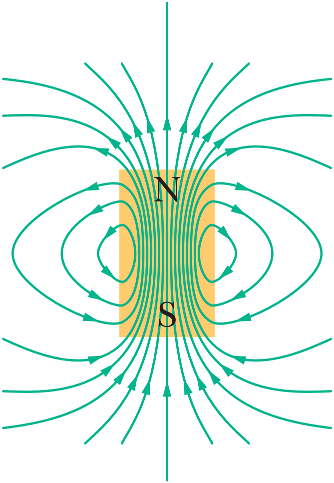
It is unclear at this time why magnetic monopoles do not exist, but they have **never been conclusively observed**.

Some (unconfirmed) theories predict them, and they may have existed in the early universe. Other theories attempt to explain why they do not exist. **EM theory assumes they do not exist.**

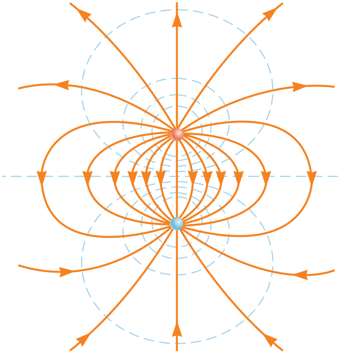
We can think of magnets as behaving similarly to electric dipoles.

Electric dipoles vs. bar magnets

Magnetic field around bar magnet:



Electric field around a dipole:



[1] Figures from Halliday, Resnick, Walker, and Serway and Jewett, 9th ed.

Magnetic Fields

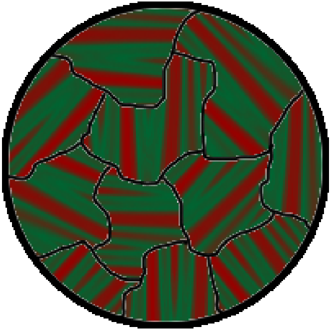
There are two (main) types of sources of magnetic fields:

- **permanent magnets** - some materials have their constituent particles aligned in such a way as to create an overall electric field; typical bar magnets
- **electromagnets** - currents (moving charges) also create magnetic fields

(Materials that interact with magnetic fields do also produce a magnetic field of their own during the interaction.)

Why do some objects have magnetic fields?

Microscopic view of ferrous metal:



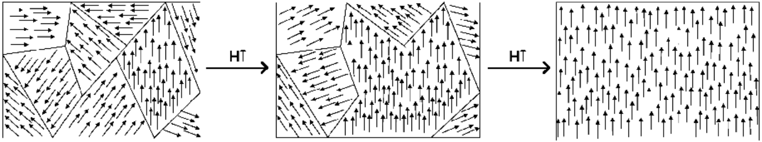
The different red and green regions are magnetic domains.

Within each domain are atoms with their outermost electrons aligned (green) or oppositely aligned (red).

[1]Figure from Wikipedia, by Ra'ike.

Why do some objects have magnetic fields?

Diagram of atomic magnetic moments in ferrous metal:



In a strong external magnetic field regions that align in the field dominate and can remain after the field is removed.

The material then creates its own field!

[1]Figure from Wikipedia, by Jose Lloret and Alicia Forment.

Compasses and the Earth's Magnetic field

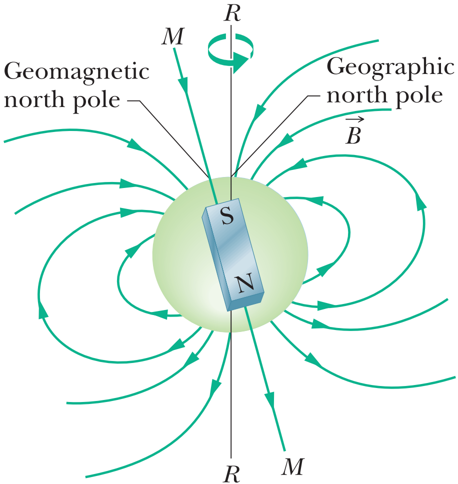
The Earth has a magnetic field.

This is how compasses detect which way North is.

Compasses have a small needle magnet inside, that rotates to align with the Earth's B-field.

The strength of the Earth's field at Earth's surface is ~ 1 Gauss.

Compasses and the Earth's Magnetic field



[1]Figure from Halliday, Resnick, Walker, 9th ed, pg 870.

Compasses and the Earth's Magnetic field

North poles of magnets point northward, so the magnetic pole that points (roughly) North is a south pole

The poles of magnets are perhaps more accurately called:

- north-*seeking* pole
- south-*seeking* pole

but almost always they are just called “north” and “south” poles.

Magnetic Fields and Force

If there were magnetic monopoles, deriving a relation between the force on one and the magnetic field it experiences would be easy: just the same as the case for electric fields.

Deriving the force on a magnetic dipole from another dipole is more difficult.

The easiest place to start: the force on a moving electric charge in a magnetic field.

Electric charges can also be affected by magnetic fields.

Force on a Moving Charge

The force on a moving electric charge in a magnetic field:

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

where **B is the magnetic field**, $\mathbf{v}$ is the velocity of the charge, and q is the electric charge.

Notice this is similar to the relation between electrostatic force and electric field.

$$\mathbf{F}_E = q\,\mathbf{E} \quad \longrightarrow \quad \mathbf{F}_B = q\,\mathbf{v} \times \mathbf{B}$$

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The magnitude of the force is given by:

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if θ is the angle between the **v** and **B** vectors.

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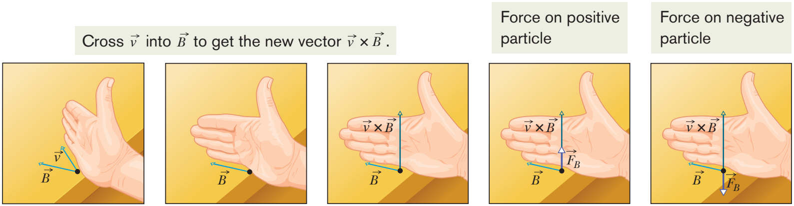
For the direction, right hand rule:



[1] Figure from Halliday, Resnick, Walker, 9th ed.

Force on a Moving Charge

Because this expression involves 3-dimensions, it can be difficult to draw all the vectors involved.

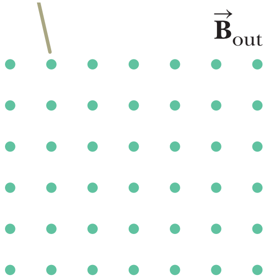
To make diagrams simpler, the magnetic field is often drawn going directly down in to the page or straight up out of it. ($\perp$ to the plane of the diagram).

Dots ($\cdot \quad \cdot \quad \cdot$) or circle-dots ($\odot \quad \odot \quad \odot$) represent field coming up **out** of the page.

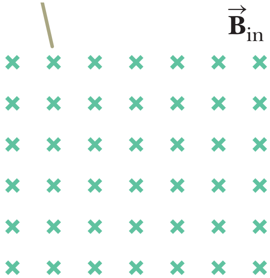
Crosses ($\times \quad \times \quad \times$) or circle-crosses ($\otimes \quad \otimes \quad \otimes$) represent field going down **into** the page.

Magnetic field direction

B points **out of** the page.

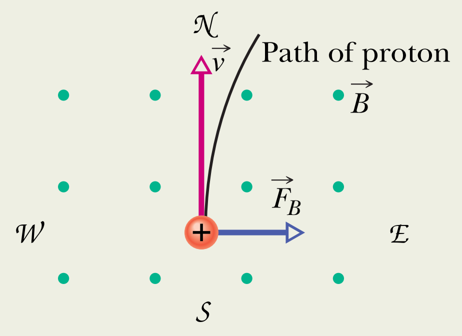


B points **into** the page.



Force on a Moving Charge

For example: here the dots indicate the field is directed upward out of the slide.



The force on the particle is $\perp$ to its velocity and the field.

Force and Field

The force on a moving charge is always perpendicular to the velocity of the particle and the magnetic field.

We could determine the magnetic field strength at a particular point by firing many test particles through that point.

F_B will always be perpendicular to the velocities of the test particles (or $F_B = 0$).

If F_B is the max force on any of the test particles, $\mathbf{B}$ will be $\perp$ $\mathbf{v}$:

$$B = \frac{F_B}{|q|v}$$

The Magnetic Field

The magnetic field is written **B**.

Since we have:

$$B = \frac{F_B}{|q|v}$$

the units are:

$$1 \text{ Tesla} = \frac{1 \text{ Newton}}{(1 \text{ Coulomb})\ (1 \text{ m/s})} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$

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The Tesla is abbreviated to T. It is a really big unit: 1 T is already a stronger field than you encounter except in extreme circumstances.

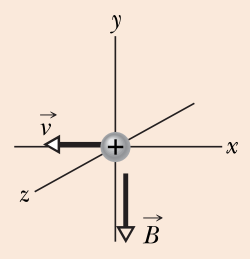
A more convenient unit (but not an SI unit) is the Gauss:

$1 \text{ Gauss} = 10^{-4} \text{ Tesla}$

Questions: Applying the Force equation

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

A **positively** charged particle with velocity $\mathbf{v}$ travels through a uniform magnetic field $\mathbf{B}$. What is the direction of the magnetic force $\mathbf{F}_B$ on the particle?



(A) $+z$

(B) $-z$

(C) $-x$

(D) none

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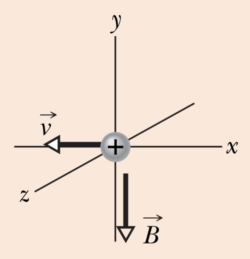

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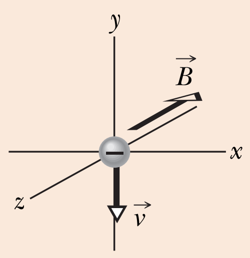

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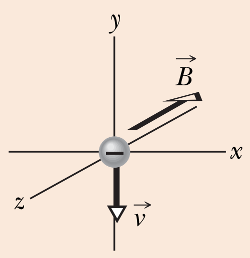

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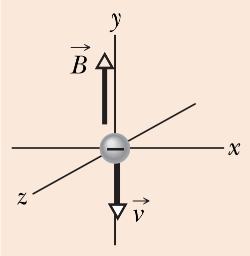

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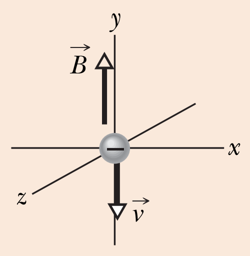

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(D) none $\leftarrow$

Summary

- magnetism
- magnetic field
- magnetic force on a charged particle

Homework Serway & Jewett:

- Ch 29, Obj Qs: 1, 3, 5; Conc. Qs: 1, 7; Problems: 1, 8, 9