Magnetism

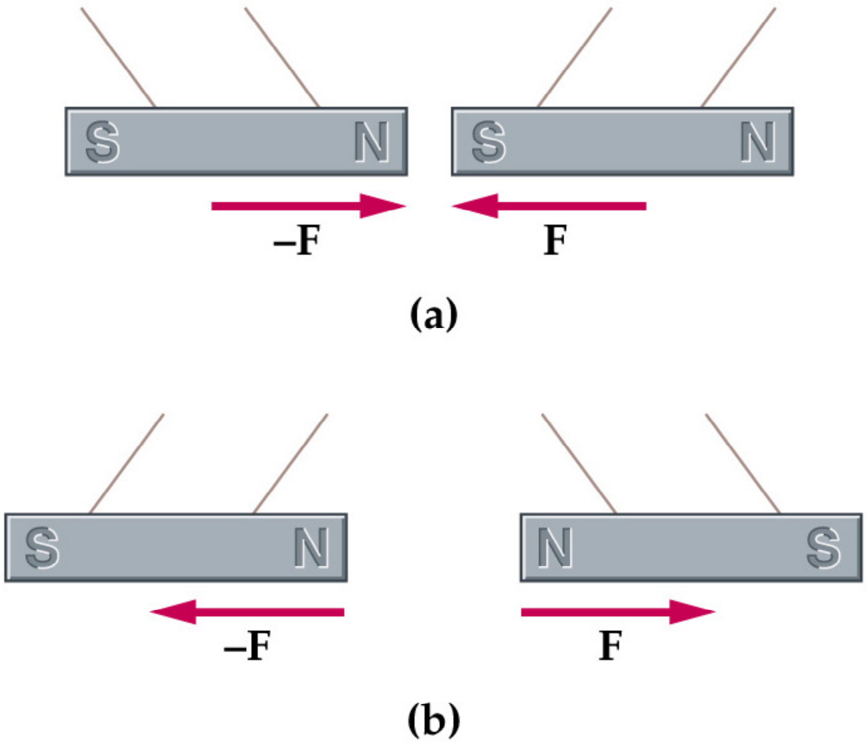
- Known since antiquity
  - Pieces of Magnetite, also called lodestone (Fe_3O_4), were known by Greeks to exert both forces of attraction and repulsion on each other.
- Chinese invented compass for navigation
  - The earth exerts a force on magnetite.

Basic model of Magnetic Materials

- All magnetic materials have two poles
  - Labeled: North and South poles
- Just as in electrostatics:

  Like poles repel each other and opposite poles attract.

  N repels N, S repels S, N attracts S

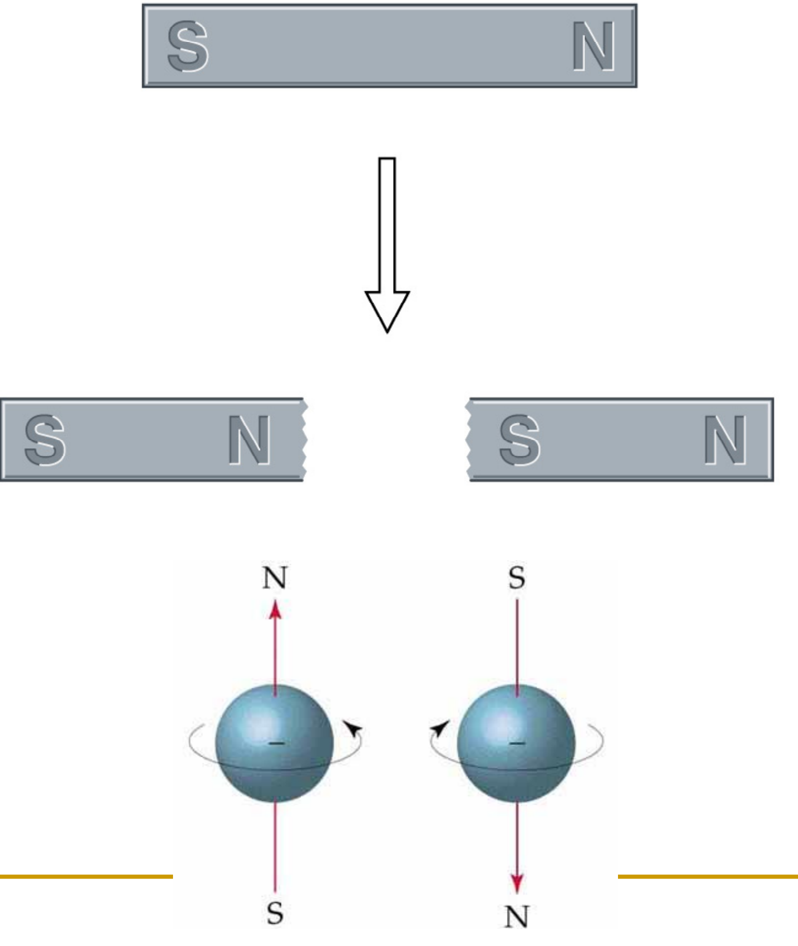


Magnetic Monopoles

Unlike electrostatics:

Magnetic monopoles have never been detected.

But magnetic monopoles would resolve many puzzles in particle physics and cosmology.



Modern View of Magnetism

(Oersted, Faraday, Maxwell, 19th Century
plus Quantum Mechanics – 20th Century)

- Magnetism is associated with *charges in motion* (currents):
  - microscopic currents in the atoms of magnetic materials.
  - macroscopic currents in the windings of an electromagnet.

What is a Magnet?

Every material has these spinning **electrons**.

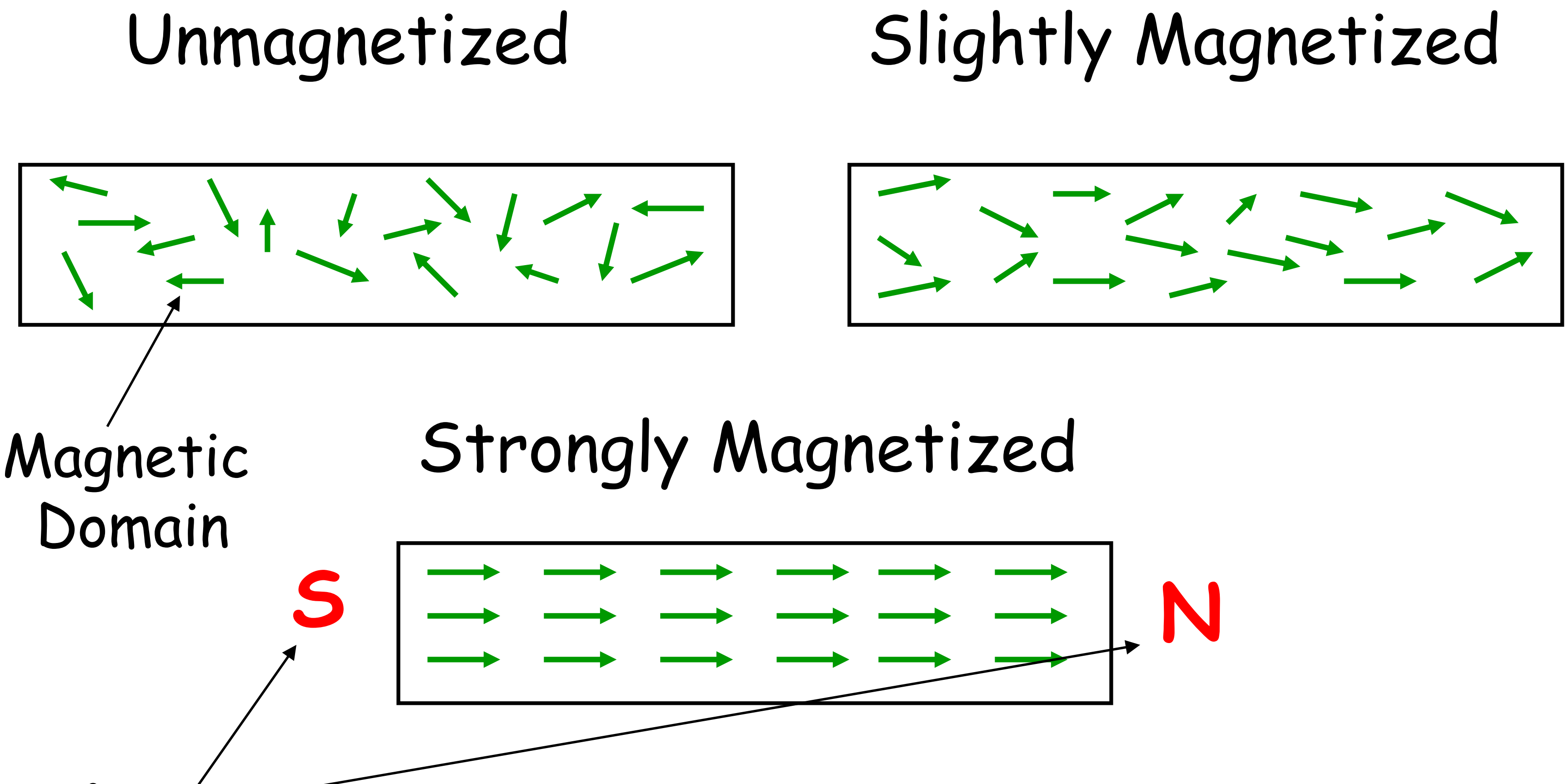
In some objects, atoms that have **electrons** spinning in the same direction group up.

Magnetic Domain

Common materials that have magnetic domains:

Fe Ni Co Nd Fe_3O_4 magnetite

What is a Magnet?

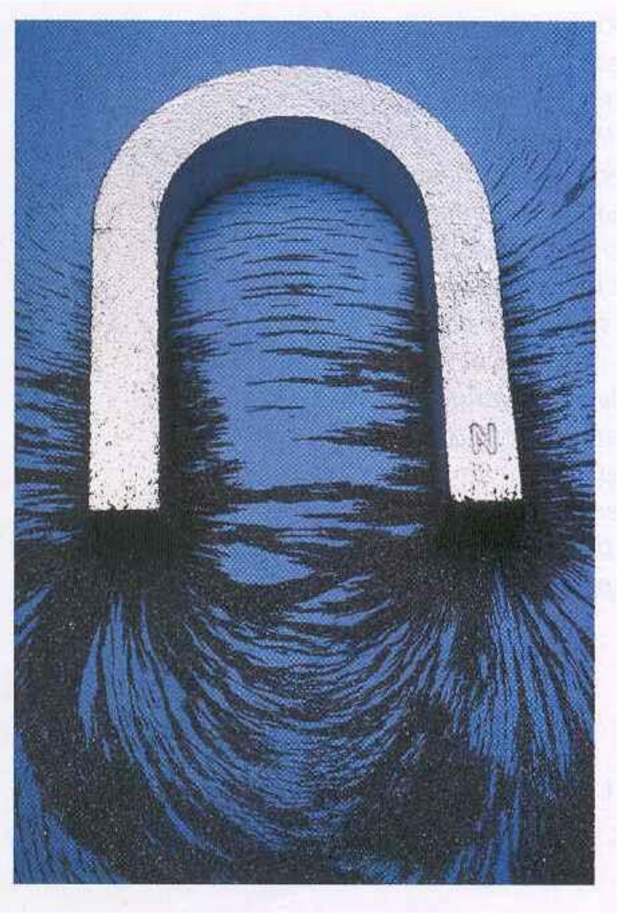


Poles = areas at the ends of a magnetized object that produces magnetic forces.

Magnetic Fields

The region around a moving charge is disturbed by the charge's motion. We call this disturbance a magnetic field B.

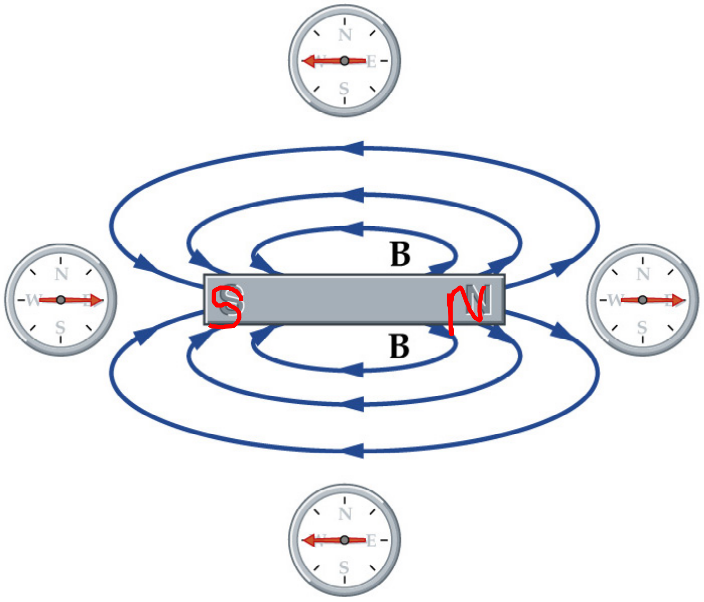
If an isolated charge is moving, the space contains both an electric field AND a magnetic field. If the charge is stationary, only an electric field is present.



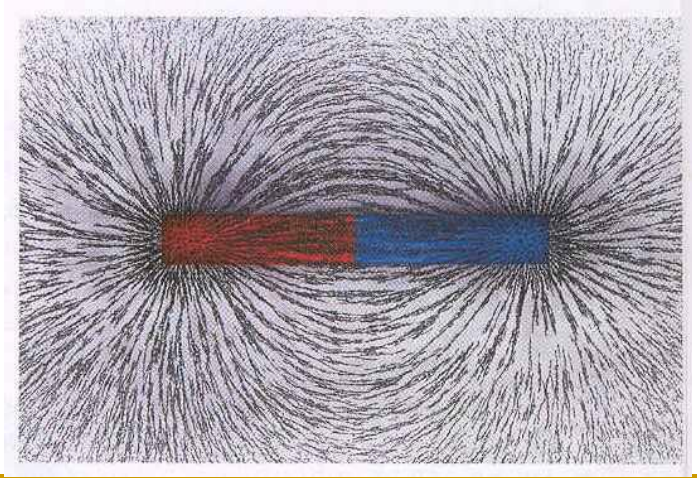
Magnetic field is a vector. It has direction.

Magnetic Field Lines

We can plot the magnetic field lines surrounding a magnetic object.



Magnetic field lines (outside the object) always go from the N pole to the S pole

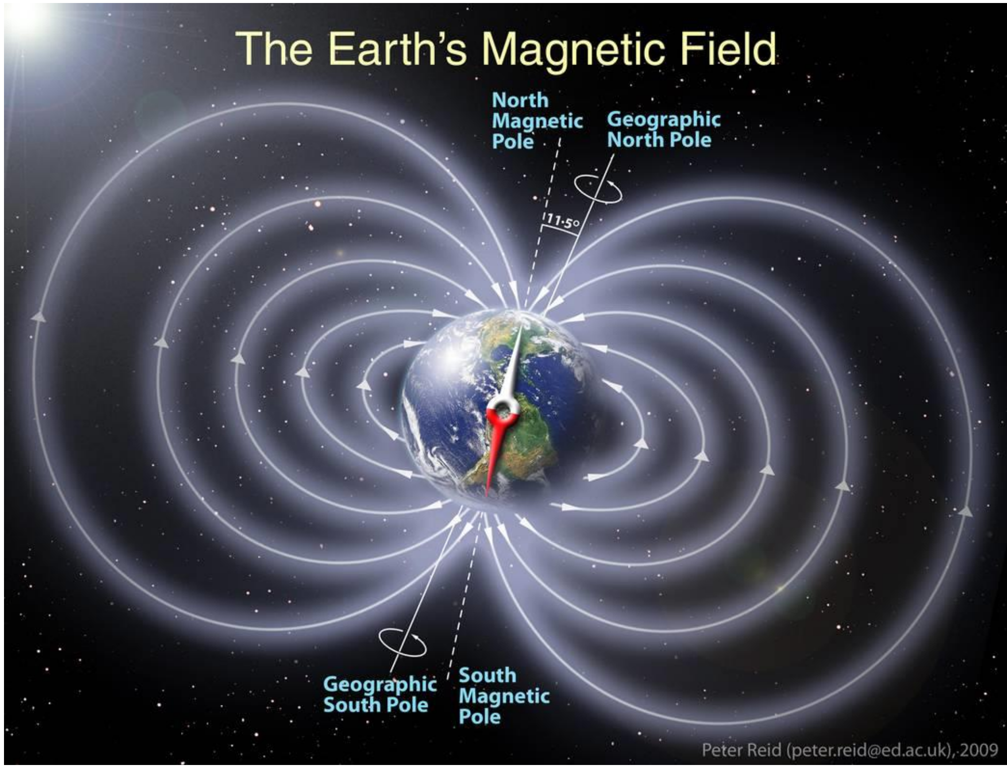


The Earth's Magnetic Field

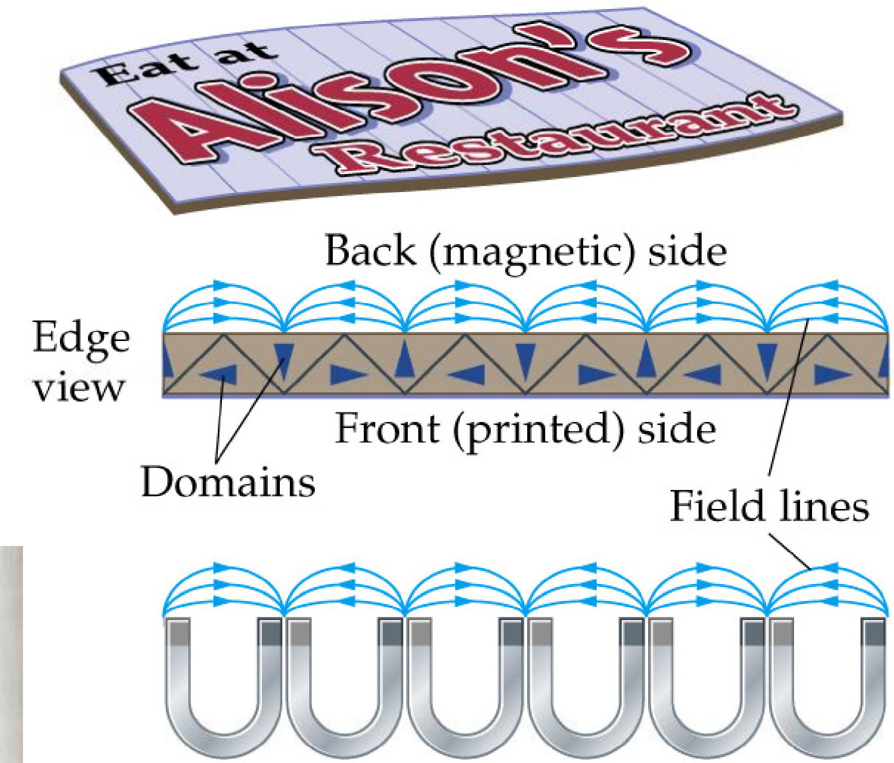
The spinning iron core of the earth produces a magnetic field.

The magnetic north pole corresponds to the geographic south pole.

Intense magnetic fields on the surface of the sun are associated with sun-spots.



Magnetic Fields



Magnetic field lines more intense on one side than the other

TABLE 22–1 Typical Magnetic Fields

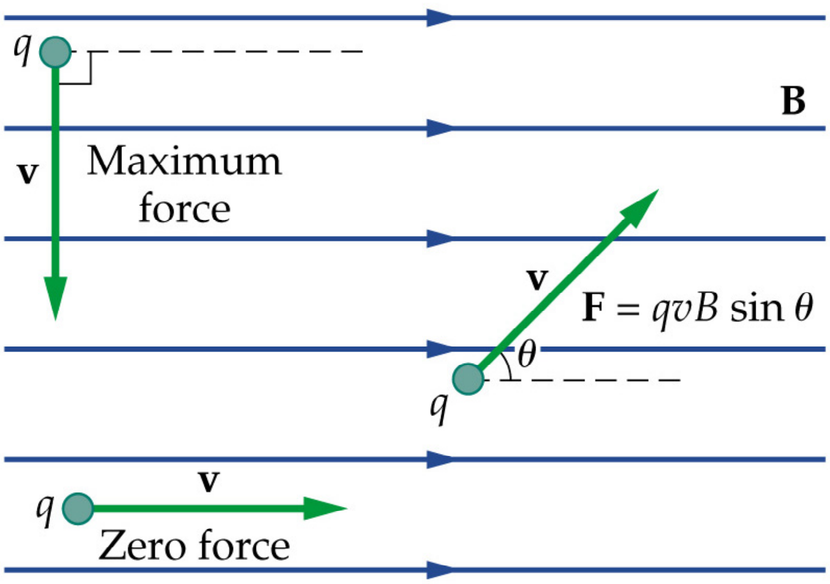
Physical system	Magnetic field (G)
Earth	0.50
Bar magnet	100
Sunspots	1000
Low-field MRI	2000
High-field MRI	15,000
Strongest manmade magnetic field	4×10^5
Magnetar (a magnetic neutron star formed in a supernova explosion)	10^{15}

Magnetic Force on Moving Charges

A charged particle in a static (not changing with time) magnetic field will experience a magnetic force only if the particle is moving.

If a charge q with velocity v moves in a magnetic field B and v makes an angle θ at right angle to B, then the magnitude of the force on the charge is:

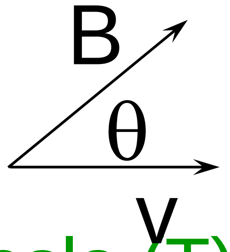
$$F = qv_{\perp}B$$



Magnetic Field Units

We define the magnitude of the magnetic field by measuring the force on a moving charge:

$$B \equiv \frac{F}{qv}$$



The SI unit of magnetic field is the Tesla (T).

Dimensional analysis:

$$1\ \text{T} = 1\ \text{N}\cdot\text{s}/(\text{C}\cdot\text{m}) = 1\ \text{V}\cdot\text{s}/\text{m}^2$$

Sometimes we use a unit called a Gauss (G):

$$1\ \text{T} = 10^4\ \text{G}$$

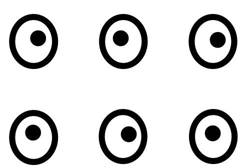
The earth's magnetic field is about 0.5 G.

Notation

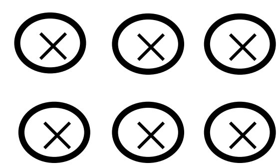
To depict a vector oriented perpendicular to the page we use crosses and dots.

• A cross indicates a vector going into the page (think of the tail feathers of an arrow disappearing into the page).

• A dot indicates a vector coming out of the page (think of the tip of an arrow coming at you, out of the page).



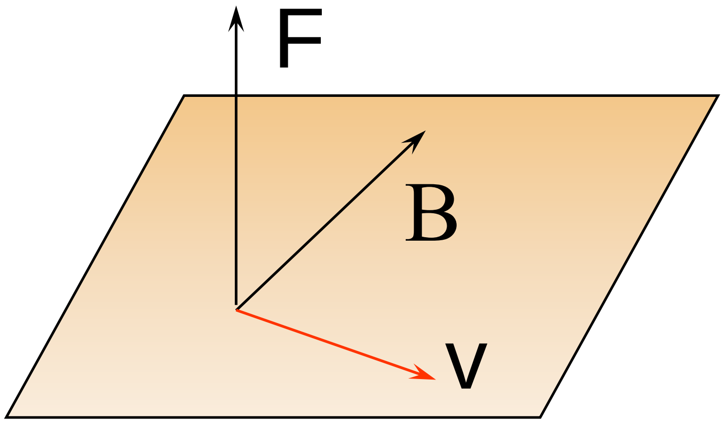
B out of the page

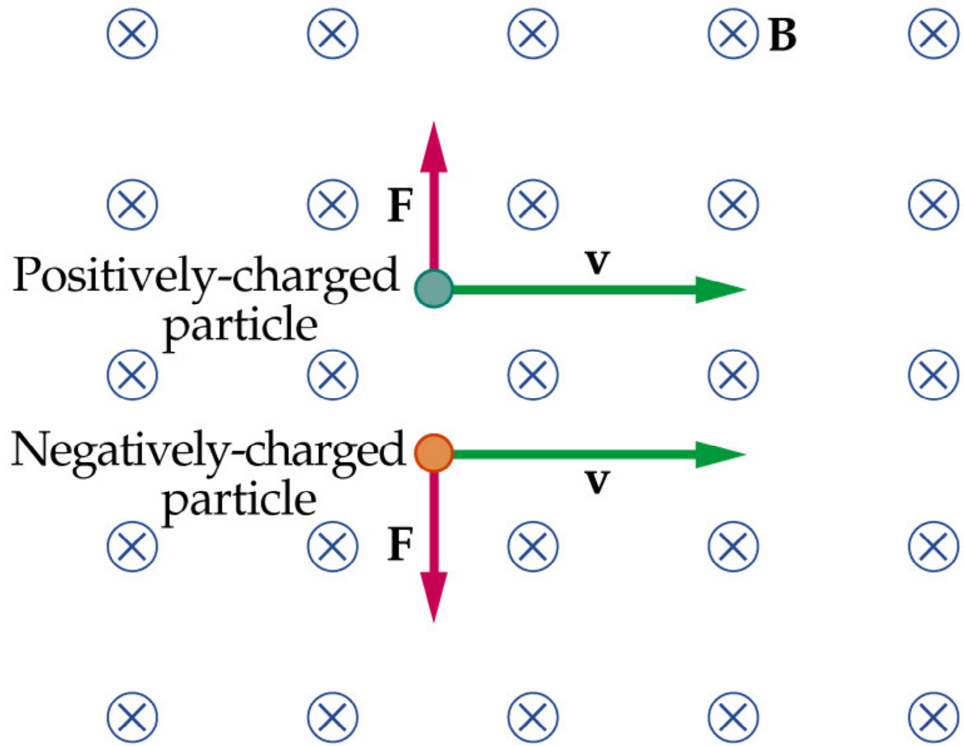


B into the page

Direction of Magnetic Forces

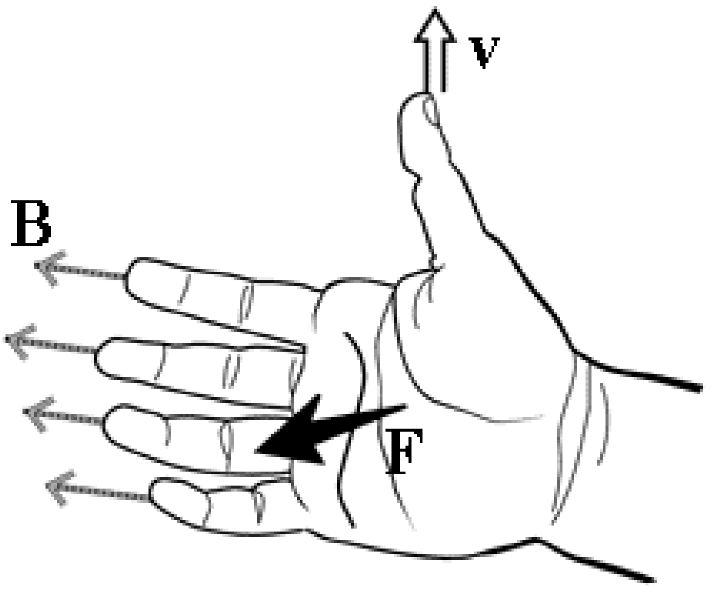
The direction of the magnetic force on a moving charge is perpendicular to the plane formed by B and *v*.



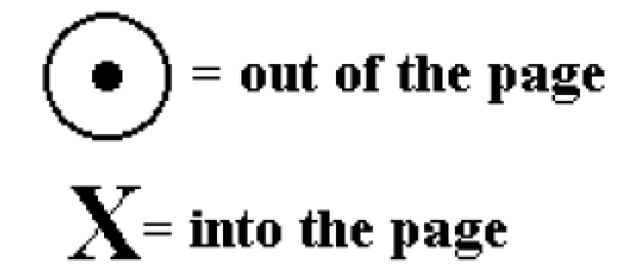


To determine the direction, you must apply the Right Hand Rule (RHR).

Right Hand Rule



To determine the DIRECTION of the force on a **POSITIVE** charge we use a special technique that helps us understand the 3D/perpendicular nature of magnetic fields.

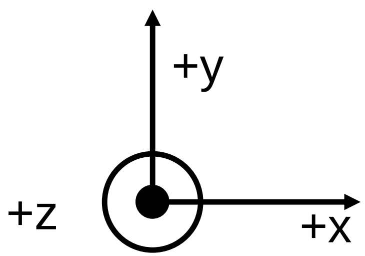


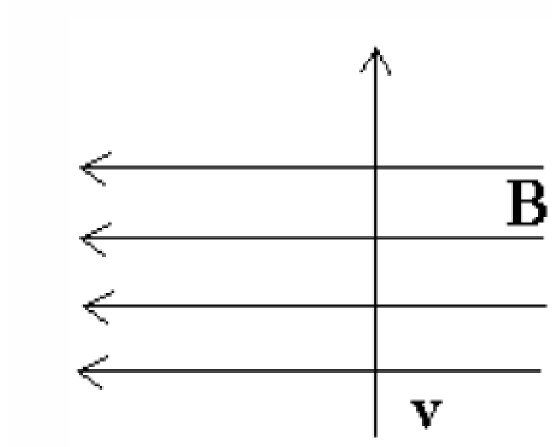
Basically you hold your right hand flat with your thumb perpendicular to the rest of your fingers

- The Fingers = Direction B-Field
- The Thumb = Direction of velocity
- The Palm = Direction of the Force

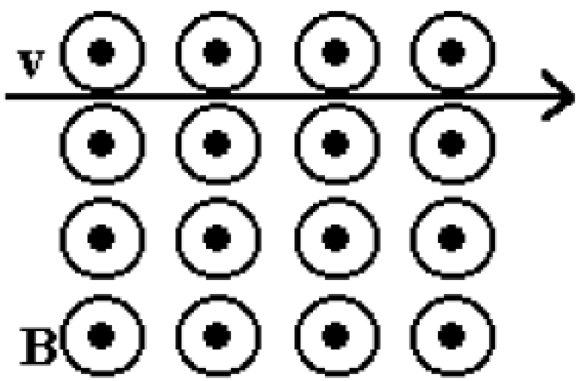
Examples

Determine the direction of the unknown variable for a proton moving in the field using the coordinate axis given

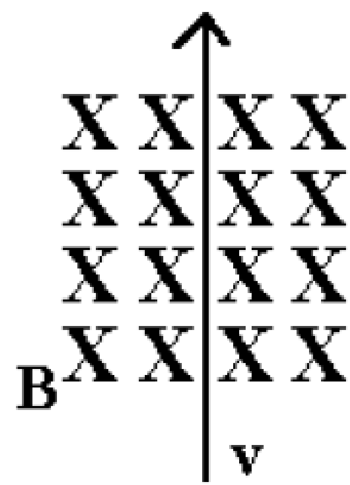




B = -x
v = +y
F = **+z**



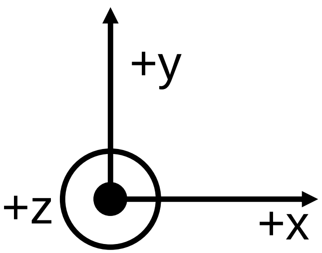
B =+Z
v = +x
F =**-y**

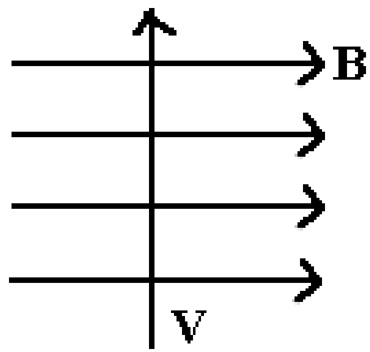


B = -z
v = +y
F = **-x**

Examples

Determine the direction of the unknown variable for an electron using the coordinate axis given.

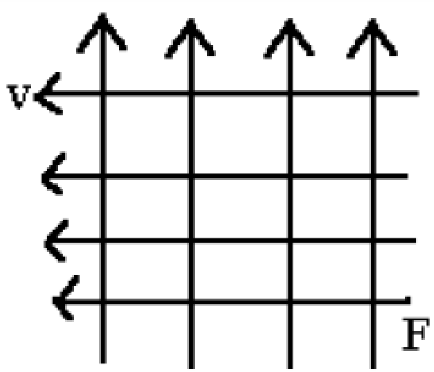




B = +x

v = +y

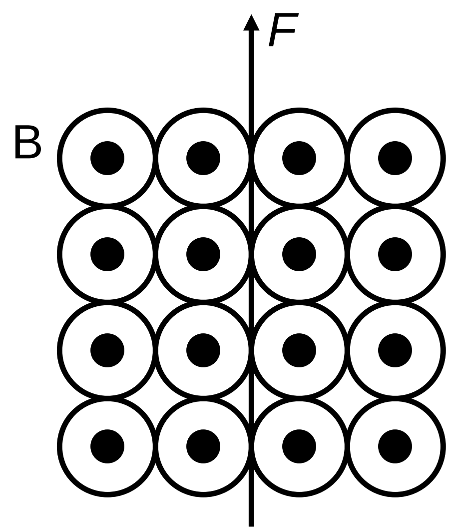
F = **-z**



B = **+z**

v = - x

F = +y

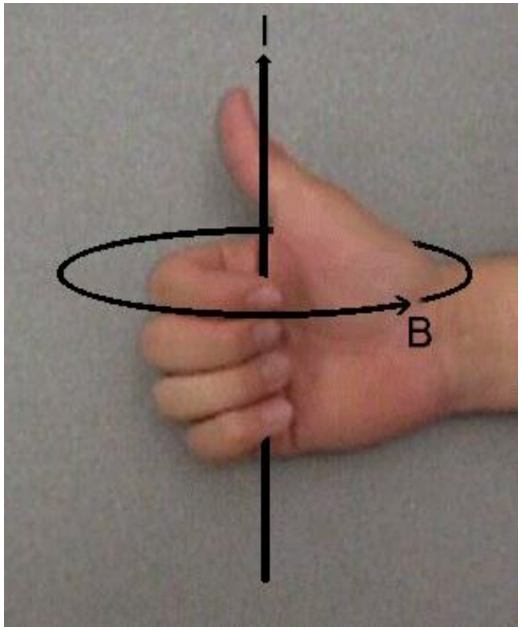


B = +z

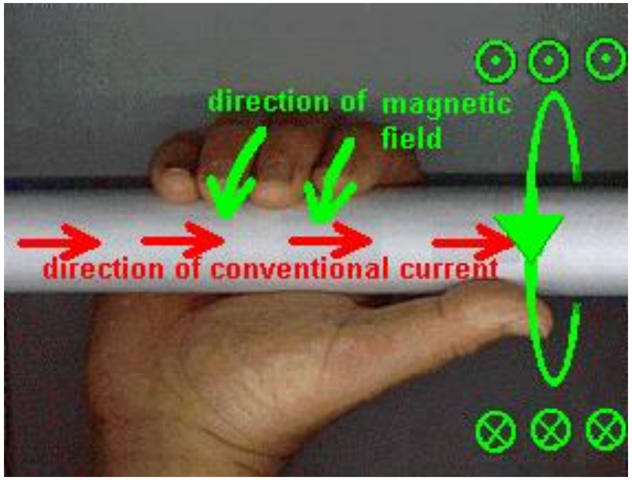
v = **-x**

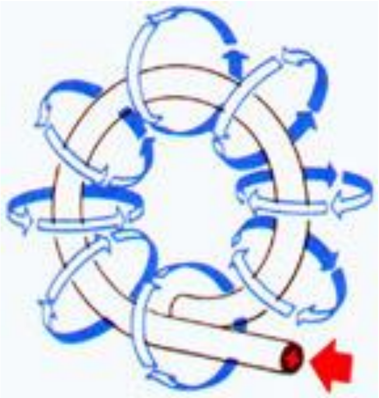
F = +y

A current carrying wire's INTERNAL magnetic field



To figure out the DIRECTION of this INTERNAL field you use the right hand rule. You point your thumb in the direction of the current then CURL your fingers. Your fingers will point in the direction of the magnetic field





Solenoids

A solenoid consists of several current loops stacked together.

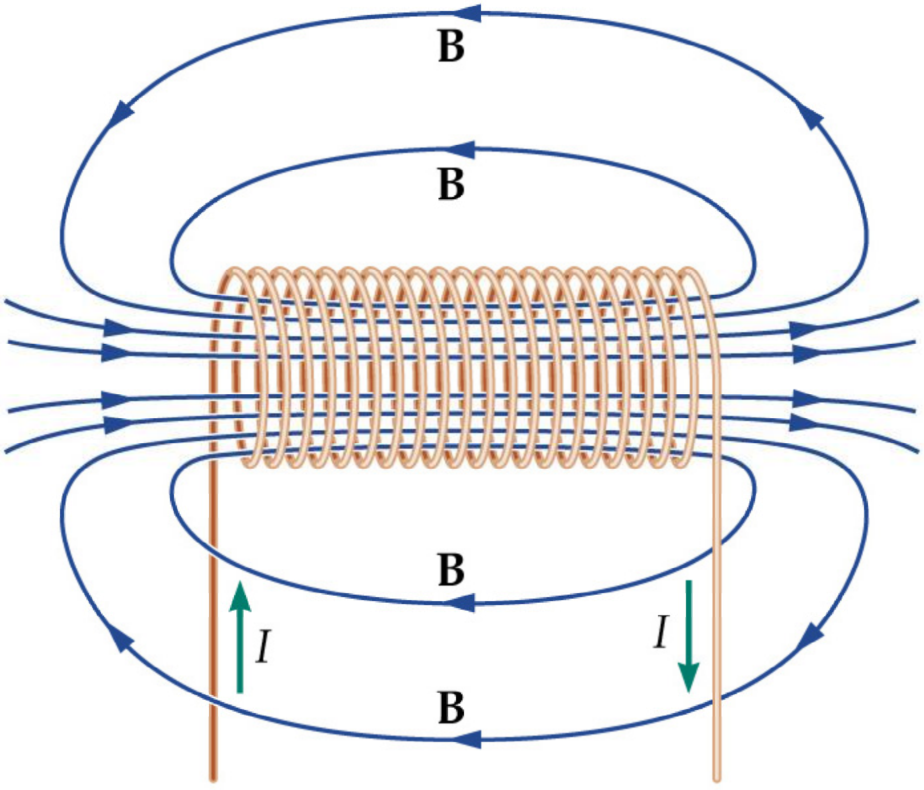
In the limit of a very long solenoid, the magnetic field inside is very uniform:

$$B=\mu_0 n I$$

n = number of windings per unit length,

I = current in windings

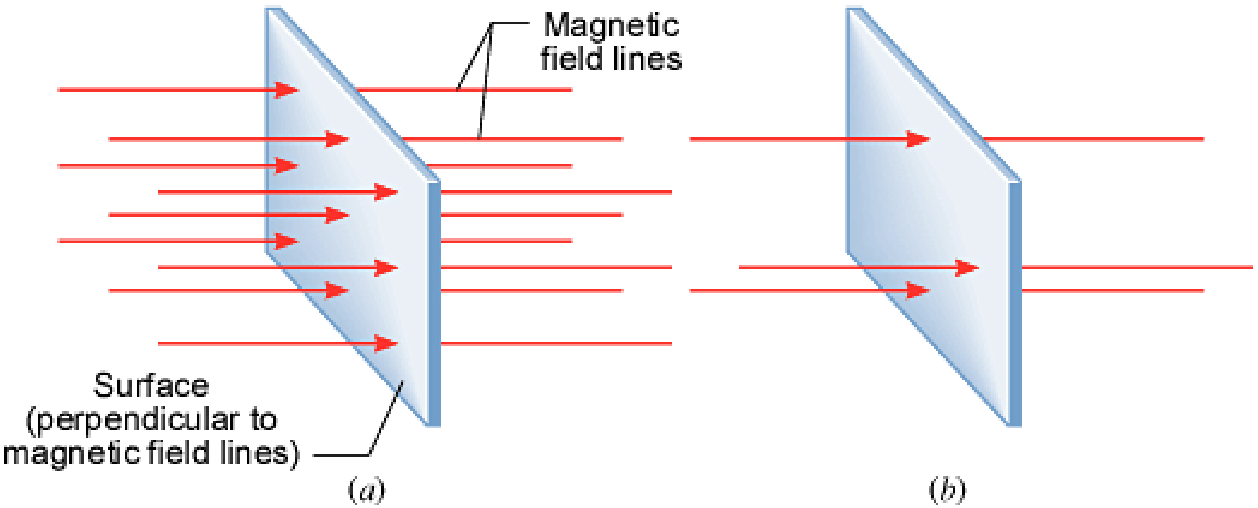
$\mu_0 = 4\pi x10^{-7} T \cdot m / A$



$B \approx 0$ outside windings

Magnetic Flux

The magnetic flux is proportional to the number of magnetic flux lines passing through the area.



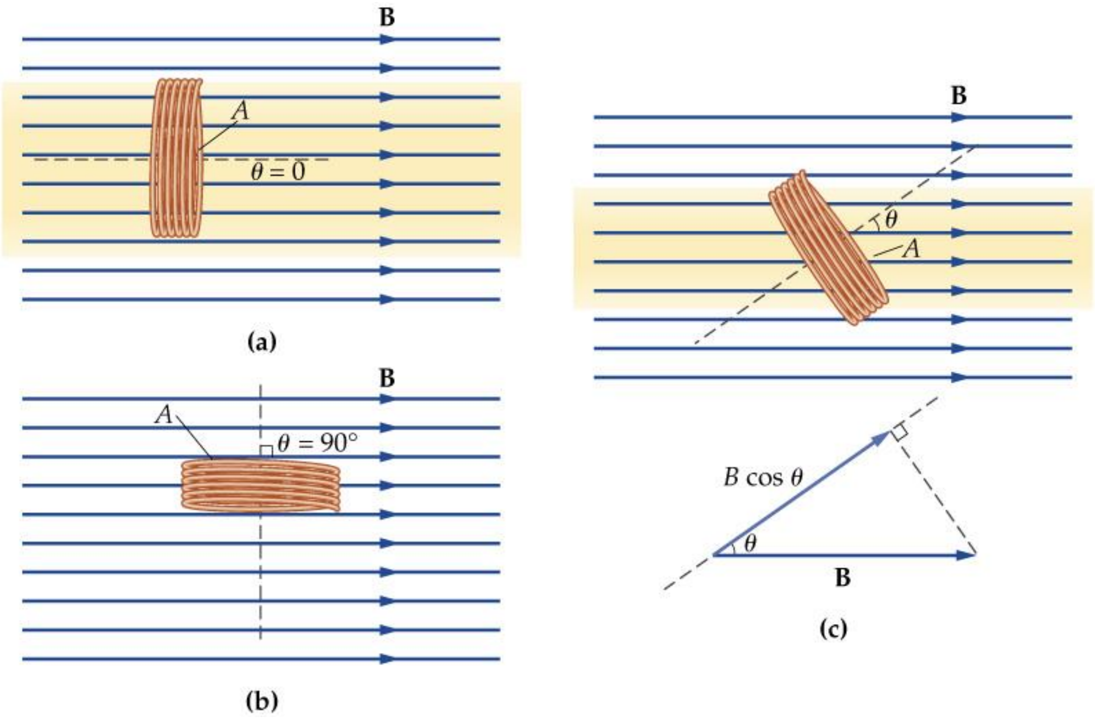
Magnetic Flux

For a "loop" of wire (not necessarily circular) with area *A*, in an external magnetic field *B*, the magnetic flux is: $\Phi = BA\cos\theta$

A = area of loop

θ = angle between *B* and the normal to the loop

SI units of Magnetic Flux: 1 T·m^2 = 1 weber = 1 Wb



Induced Voltage from changing Magnetic Flux

Electric currents produce magnetic fields.

19th century puzzle: Can magnetic fields produce currents?

Imagine placing a small wire coil in the region of a magnetic field:

A static magnet will produce no current in a stationary coil.

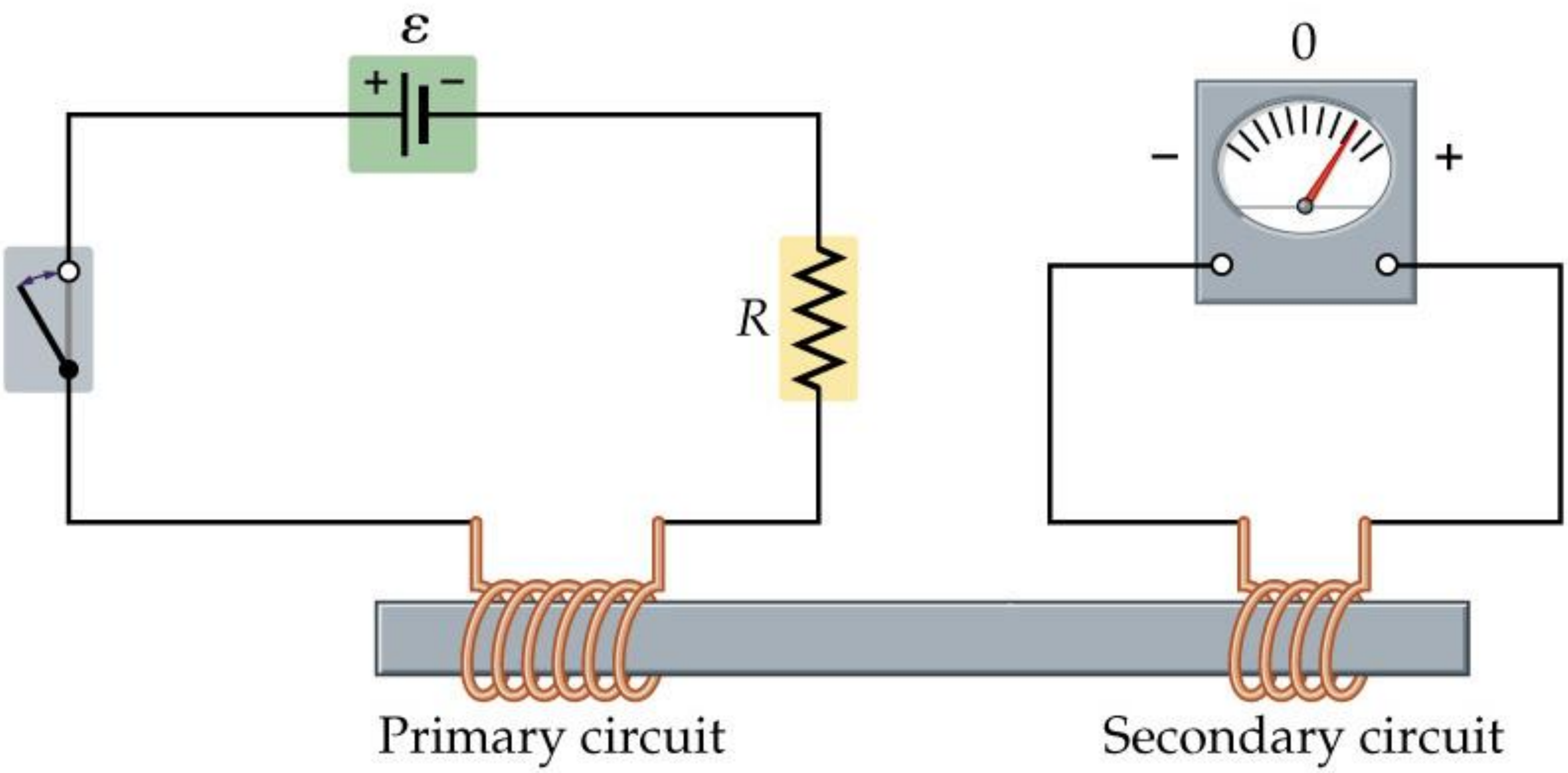
Faraday: If the magnetic field changes, or if the magnet and coil are in relative motion, there will be an induced voltage (and therefore current) in the coil.

Key Concept: The magnetic flux through the coil must change. This will induce a voltage in the coil, which produces a current $I = V/R$ in the coil.

Such a current is said to be induced by the varying B-field.

Examples of Induced Current

Any change of current in primary induces a current in secondary.



Faraday's Law of Induction

Faraday's Law: The instantaneous voltage in a circuit (w/ *N* loops) equals the rate of change of magnetic flux through the circuit:

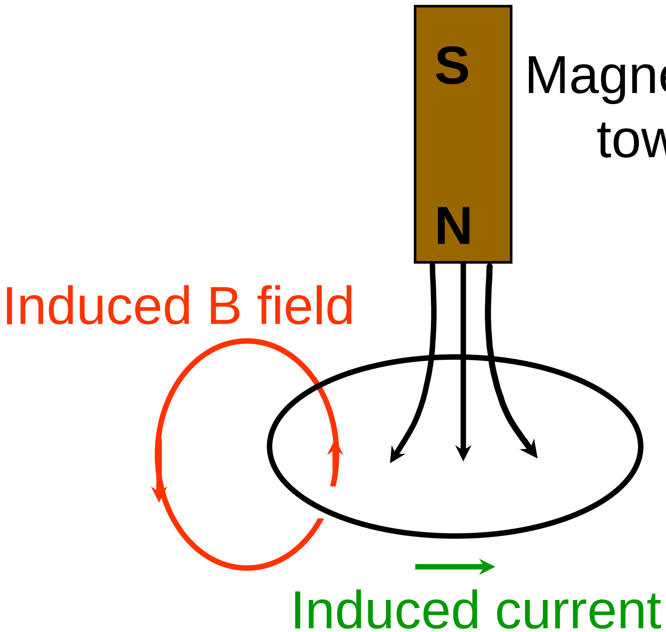
$$V = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Phi_f - \Phi_i}{t_f - t_i}$$

The minus sign indicates the direction of the induced voltage. To calculate the magnitude:

$$|V| = N\left|\frac{\Delta\Phi}{\Delta t}\right| = N\left|\frac{\Phi_f - \Phi_i}{t_f - t_i}\right|$$

Lenz's Law

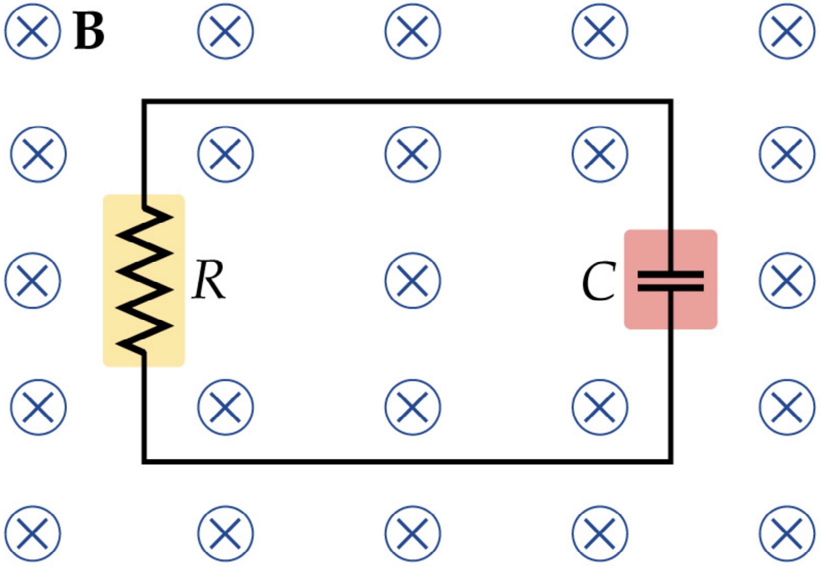
Lenz's Law: An induced current always flows in a direction that opposes the change that caused it.



In this example the magnetic field in the downward direction through the loop is increasing. So a current is generated in the loop which produces an upward magnetic field inside the loop to oppose the change.

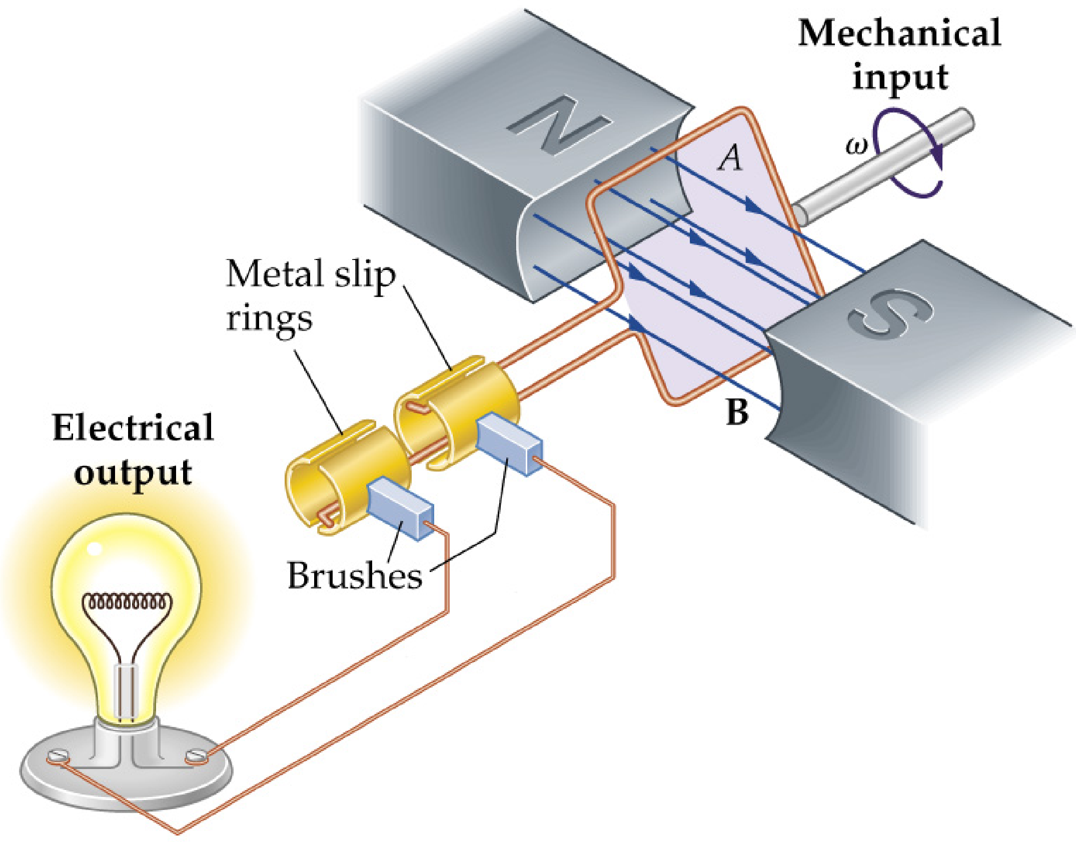
Example Problem 2

The figure shows a circuit containing a resistor and an uncharged capacitor. Pointing into the plane of the circuit is a uniform magnetic field B. If the magnetic field increases in magnitude with time, which plate of the capacitor (top or bottom) becomes positively charged?



Generator

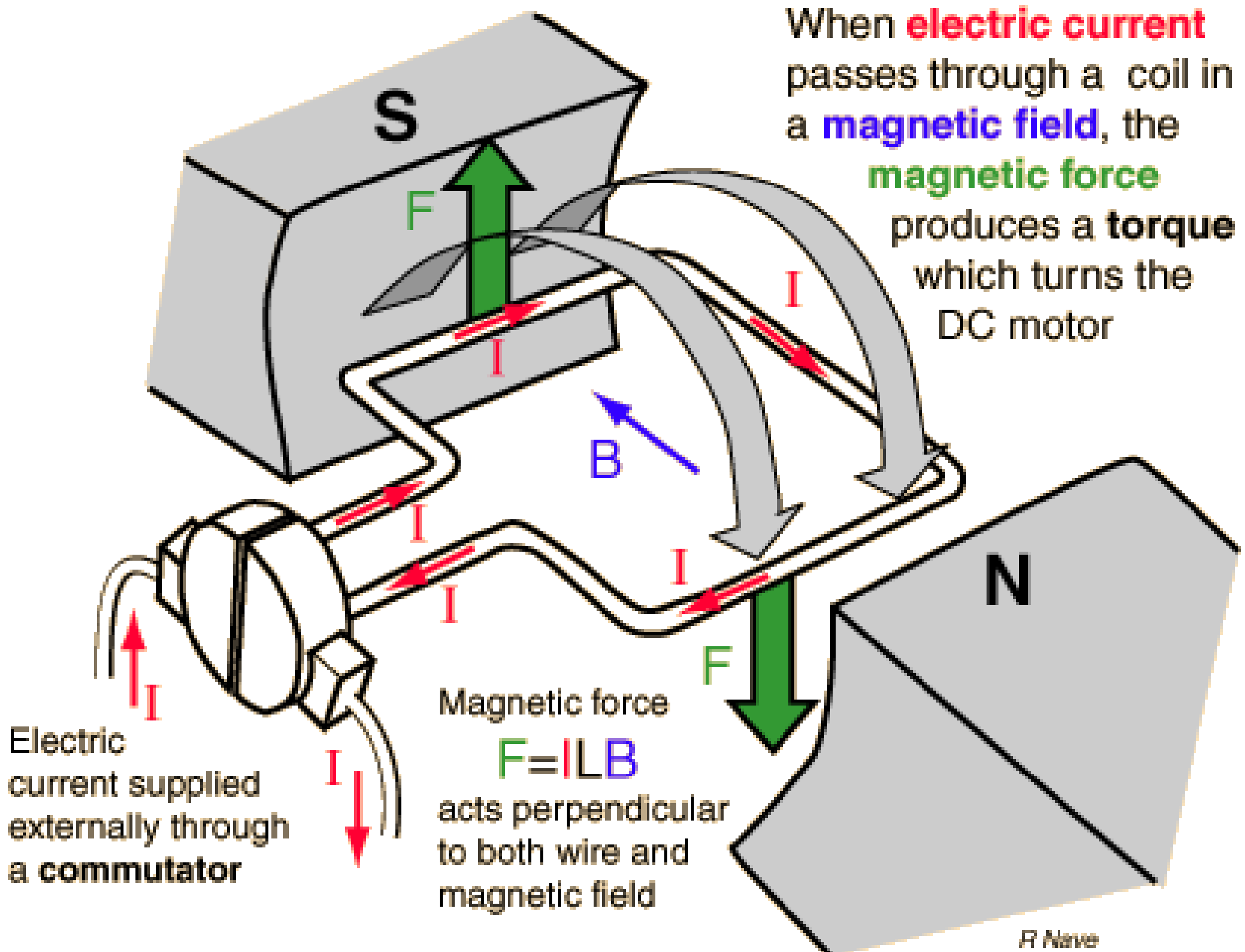
A device that converts mechanical energy into electrical energy.



A coil of wire turns in a magnetic field. The flux in the coil is constantly changing, generating an emf in the coil.

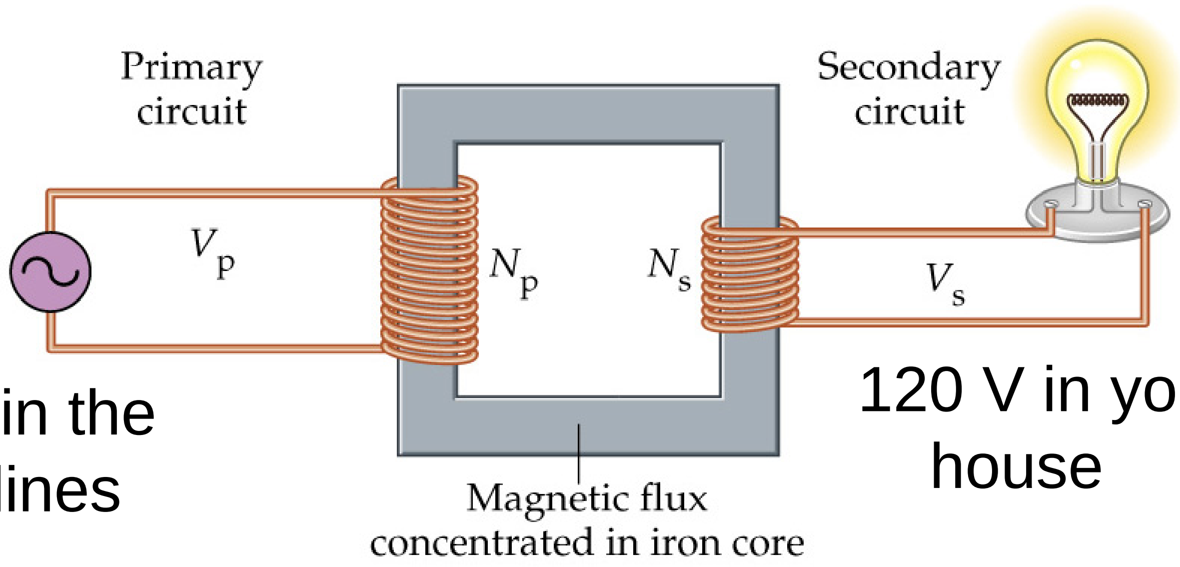
Electric Motor

A device that converts electrical energy into mechanical energy.



Transformers

A transformer is a device used to change the voltage in a circuit. AC currents must be used.



75,000 V in the power lines

120 V in your house

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

p = primary

s = secondary

Example Problem 3

A disk drive plugged into a 120-V outlet operates on a voltage of 9.0 V. The transformer that powers the disk drive has 125 turns on its primary coil. (a) Should the number of turns on the secondary coil be greater than or less than 125? (b) Find the number of turns on the secondary coil.

Electromagnetic Waves

Maxwell's Theory

In 1865, James Clerk Maxwell developed a theory of electricity and magnetism.

His *starting points* were:

- Electric field lines originate on + charges and terminate on - charges
- Magnetic field lines form closed loops
- A varying magnetic field induces an electric field
- A magnetic field is created by a current

Maxwell’s theory is a mathematical formulation that relates electric and magnetic phenomena.

His theory, among other things, predicted that electric and magnetic fields can travel through space as waves.

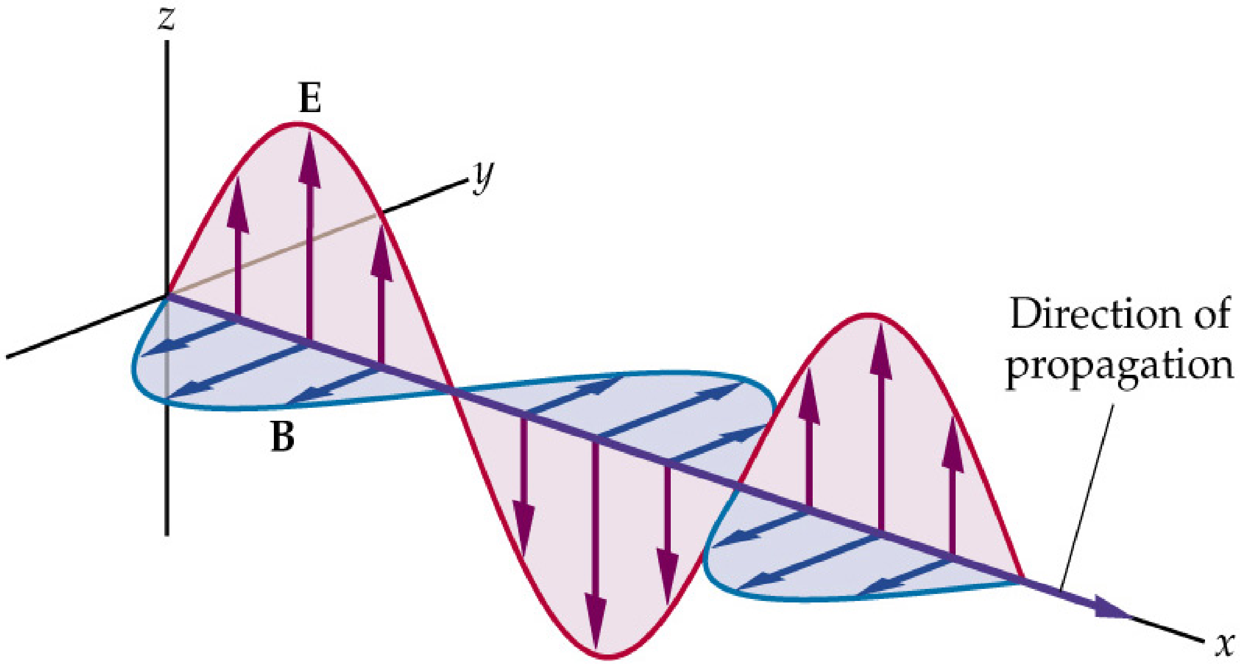
The uniting of electricity and magnetism resulted in the Theory of Electromagnetism.

Properties of EM Waves

The radiated EM waves have certain properties:

- EM waves all travel at the speed of light c.
- The E and B fields are perpendicular to each other.
- The E and B fields are in phase (both reach a maximum and minimum at the same time).
- The E and B fields are perpendicular to the direction of travel (transverse waves).

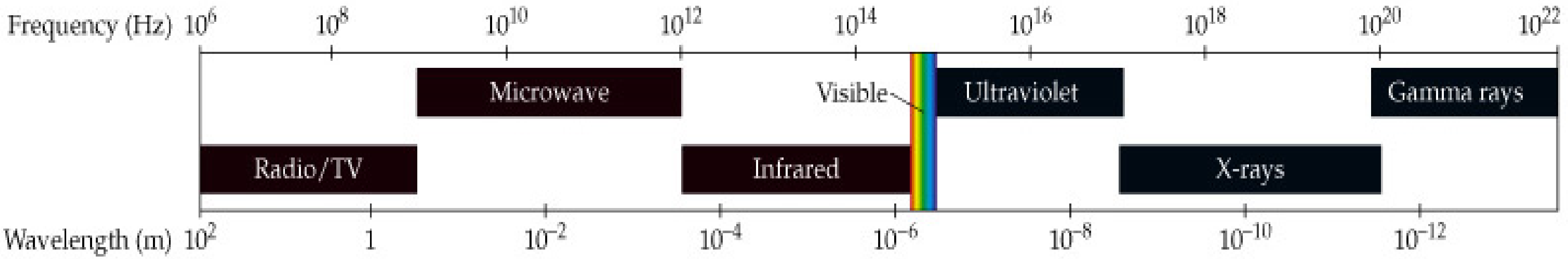
Field directions in an electromagnetic wave



An electromagnetic wave propagating in the positive *x* direction: E and B are perpendicular to each other and in phase. The direction of propagation is given by the thumb of the right hand, after pointing the fingers in the direction of E and curling them toward B (palm towards B).

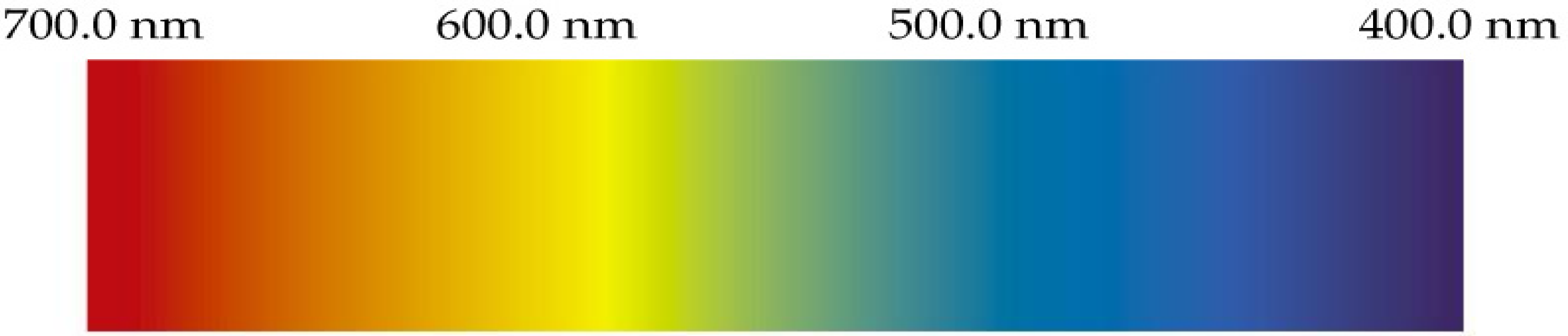
EM waves can be generated in different frequency bands:

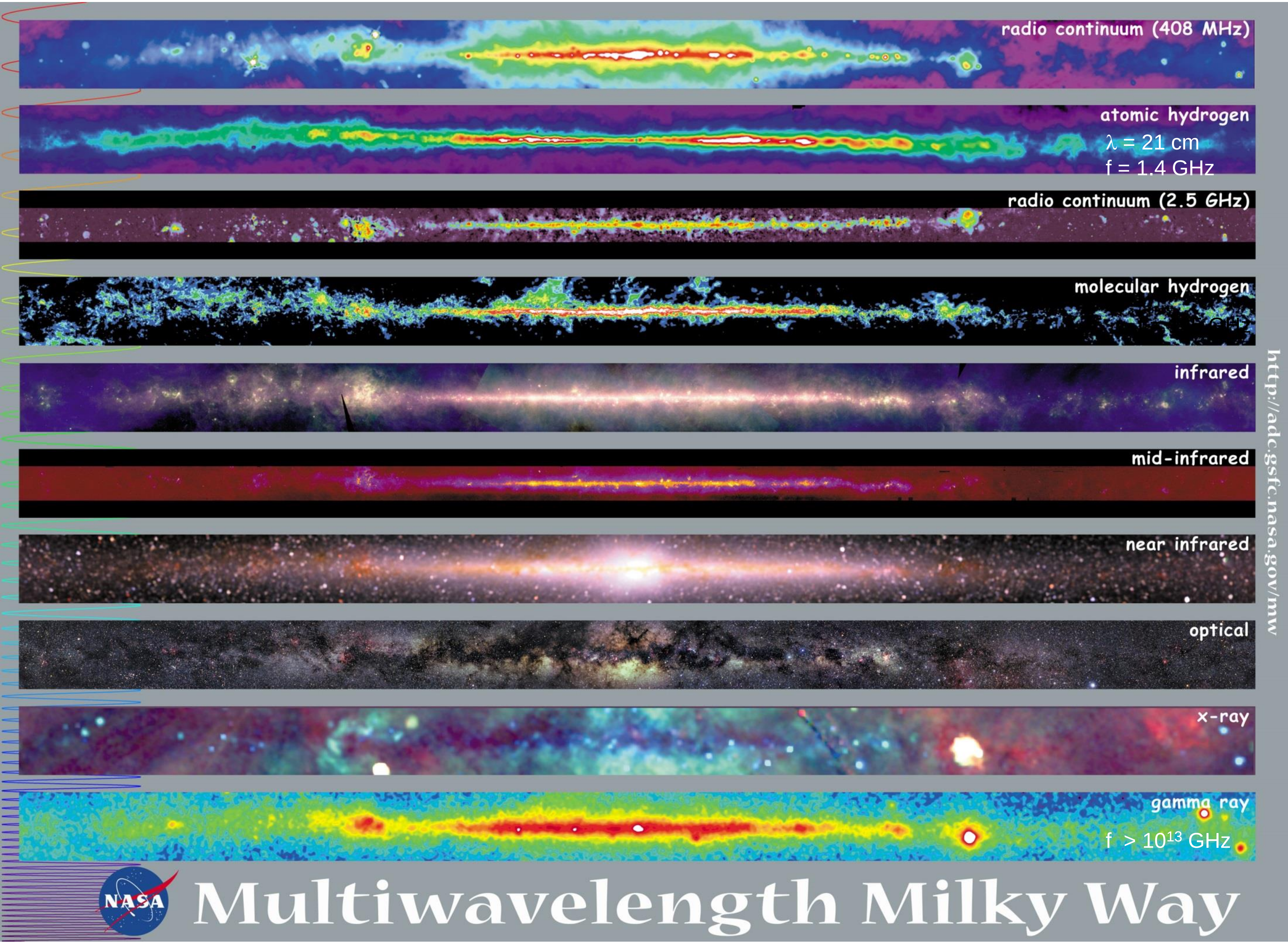
radio, microwave, infrared, visible, ultraviolet, x-rays, gamma rays



Note that the visible portion of the spectrum is relatively narrow.

The boundaries between various bands of the spectrum are not sharp, but instead are somewhat arbitrary.




radio continuum (408 MHz)
atomic hydrogen
λ = 21 cm
f = 1.4 GHz
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
f > 10^13 GHz
NASA
Multiwavelength Milky Way
http://adc.gsfc.nasa.gov/mw