Ch. 19
Magnetism

Magnetism

How is magnetism linked to electricity?

Magnetic fields affect moving charges.
(They exert forces on moving charges.)

Moving charges produce magnetic fields.
- Currents produce magnetic fields
  - Linear motion of charges — ex. straight wire
  - Circular motion of charges — ex. coil
- Spinning charges — ex. electron spin

Useful applications for magnets

Picking up heavy loads

Hold objects together

Computer data storage

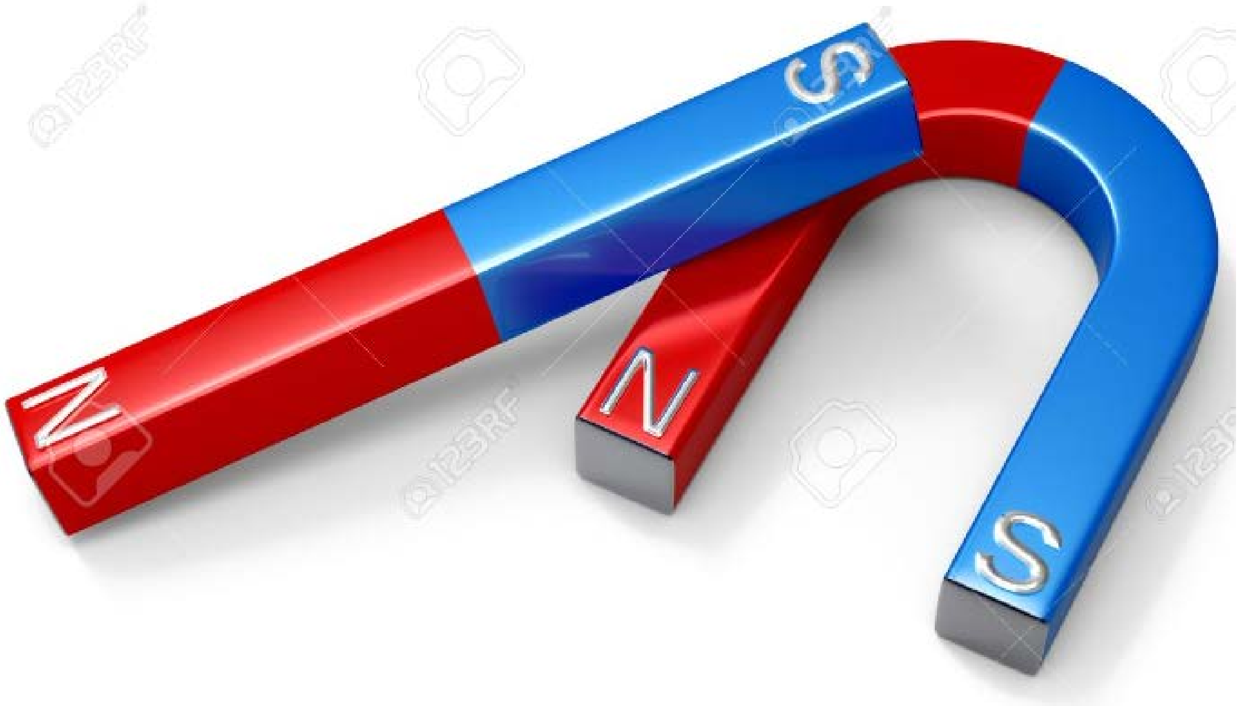
Medical imaging

Guide/steer moving charged particles

Magnets

Two common types of magnets are the iron horseshoe magnet and a simple bar magnet.

These will attract materials containing iron or any other magnetized objects.



Magnets consist of two poles (north and south).

The poles are named after their behavior in presence of the Earth’s magnetic field.

Hang a magnet from a thin string.

- The north pole will point to the Earth’s north pole.
- South pole of magnet points to south pole of Earth.

This is how to make a compass.

Magnetic poles exert attractive or repulsive forces on each other similar to those of the forces of charged particles.

Like poles repel each other and **opposite poles attract** each other.

Then why does the north pole of a compass point north?

The geographic north pole is near (relatively) the magnetic south pole. The geographic south pole corresponds to the magnetic north pole.

See figures 19.4, 19.5

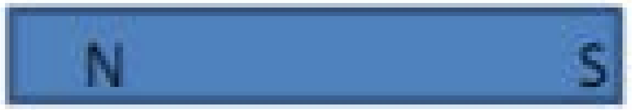
One big difference between positive and negative charges and north and south poles.

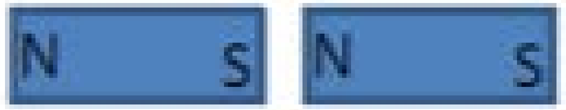
Positive and negative charges can exist in isolation of each other.

Ex. You can have a single positive point charge.

<u>North and south poles cannot exist by themselves. You cannot have a north pole without a south pole!</u>

Take a bar magnet and break it into two pieces. Each piece now has a north and a south pole. You now have two small bar magnets. You can repeat this indefinitely.





Many magnets are made of iron.

An un-magnetized piece of iron can become magnetized by scraping it with a magnet.

A screwdriver can become magnetized this way.

An un-magnetized piece of iron can also become magnetized by placing it near a strong permanent magnet.

Over time the iron will become magnetized.

(This process can be sped up by heating and cooling the iron.)

Soft magnets – (such as iron) are easily magnetized, but also tend to lose their magnetism easily

Hard magnets – (cobalt, nickel) are harder to magnetized, but retain their magnetism longer

Magnetic Fields

Electric fields surround a stationary charge.

Magnetic fields surround a moving charge.

Moving charges still have electric fields but we won’t worry about that for now.

The math is complicated.

Magnetic fields will also surround any magnetized material. (ex. bar magnet).

Magnetic fields are **vector fields**.

Just like electric fields, they have **magnitude and direction**.

Magnetic fields, **B**, at any location points along the direction of a magnetic field line.

Figure 19.2 shows some field lines from a bar magnet.

When you use a compass, the needle will point along the directions of the field line passing through the location of the compass.

You can determine the shape of a magnetic field by either moving around the compass or placing a bunch of compasses at different locations.

Figure 19.3 Iron filings near magnets

The filings line up with the field lines

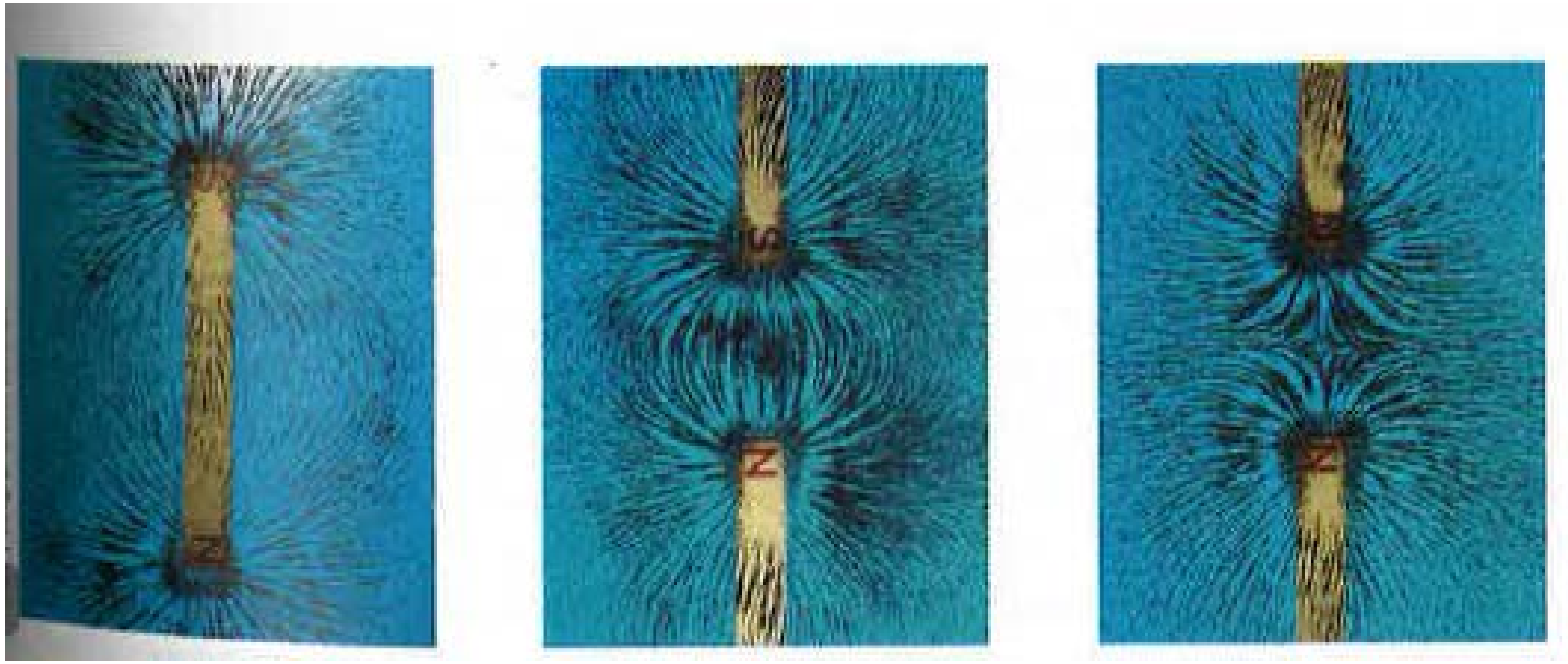


Figure 19.3 (a) The magnetic field pattern of a bar magnet, as displayed with iron filings on a sheet of paper. (b) The magnetic field pattern between *unlike* poles of two bar magnets, as displayed with iron filings. (c) The magnetic field pattern between two *like* poles.

Magnetic fields

Magnetic field lines form closed loops.

This is different from electric field lines.

The direction of the field, outside the magnet, points tangent to field lines, going from north pole to south pole.

Inside the magnet, they return from the south pole to the north pole. **The closed loop is completed**.

Where the field lines are closely bunched, the field is stronger.

Where the field lines are far apart, the field is weaker.

Magnetic Fields

When a charged particle **moves** through a magnetic field, the magnetic field exerts a force on the **moving** particle.

The magnetic force is **maximized** when the charged particle moves in a direction that is **perpendicular** to the magnetic field line.

It is **minimized, becomes zero**, when the charged particle moves **along (parallel or anti-parallel)** the magnetic field line.

Magnetic Fields

To calculate the force from a magnetic field on a moving charge:

$$F_B = q\ v\ B\ \sin\theta$$

q = magnitude of charge

v = velocity of charge

B = magnitude of magnetic field

θ = angle between the charge's velocity and the magnetic field.

Units

B = F/(q v sin θ)

SI unit of magnetic field is the tesla (T)

also called the weber per square meter

$$T = \frac{wb}{m^2} = \frac{N}{C \cdot m/s} = \frac{N}{A \cdot m}$$

the A stands for amps (coulombs per second)

also use the gauss (G) $1\ T = 10^4 G$

Some magnetic field approximate values:

Typical refrigerator magnet:	50 G or 5mT
Rare Earth magnet:	10000 G or 1 T
Superconducting magnets:	$3\text{x}10^5$G or 30 T
Strongest magnetic fields produced:	100T
Magnetic field of Earth:	0.5 G or $0.5\text{x}10^{-4}$T

Magnetic force

$F_B = q\,v\,B \sin\theta$ $F_{max} = q\,v\,B$

What about the direction?

For a ***positively*** charged particle, use the “***right hand rule***”.

1) Point fingers of right hand in direction of the velocity.
2) Curl fingers towards direction of magnetic field, passing through the smaller angle.
3) Thumb points in direction of the force exerted on a positive charge.

If the charge was negative, the thumb points in direction opposite of the force on the positive charge.

Another version of the right hand rule:

If charge is ***positive***:

1) Point index finger in direction of velocity.
2) Point middle finger in direction of magnetic field.
3) Your thumb will point in the direction of the force.

Again if the charge is negative, you need to flip around the direction of the force.

See figures 19.6, 19.7 Work out example 19.2

Magnetic force on a current carrying conductor
(Magnetic force on a wire)

We just saw how a magnetic field interacts with a single moving charge.

Since a current carrying conductor (such as a wire) contains multiple moving charges, a magnetic field will exert a force on the conductor.

Magnetic fields exerts forces on steady streams of charges (currents).

Side note of how to show direction of the B-field, when drawing on paper/chalkboard

Dots for out of the page/board.

Crosses (X) for into the page/board.

Current

Current is charge moved per unit time.

Units Amps (A)   A = C/s

Current through a wire is a number of charges that moves through a wire per unit time.

Magnetic force on a current

Assume a wire of length (L) and cross-section area (A) carries a current perpendicular to the magnetic field.

If we look at each individual charge: $F = q\, v_D\, B$

v_D is the drift (average representative) velocity of the charge.

The total force on the current will be the force on a single charge multiplied by the number of charges in a segment of wire.

v_D is a representative velocity of all the charges.
(some are faster, some are slower)

The total number of charges in the wire segment is: nAL
A = cross section area, L = length,
n = number of charge carriers per unit volume

$F = (qv_D B)(nAL)$ Current, $I = nqv_D A$ (Play with units to clarify this.)

Substituting in the current, we get…

$F = I\ L\ B$ (If the current is perpendicular to the magnetic field.)

When the current is not perpendicular to the magnetic field, we use the more general form of:

$$F = I\ L\ B \sin \theta$$

θ is the angle between the current's direction and the magnetic field.

See figure 19.10 for direction. Right Hand Rule is used.

Now look at what happens to a current loop when placed in a magnetic field.

Take example of a rectangular loop carrying a current (I) in a magnetic field in the same plane as the loop.

Page 670

We want the total force on the rectangular current loop.

Solution:

Find the force on each side and **add them up as vectors**.

The top and bottom sides are parallel/anti-parallel to the B-field so no forces are exerted on them.

Remember the force on a wire perpendicular to the magnetic field is: $F = I L B$

Both sides have the same length and same current so the magnitudes of the forces will be the same.

Using the right hand rule we can find the direction of the forces on the sides of the rectangle.

Force on left side is out of page.

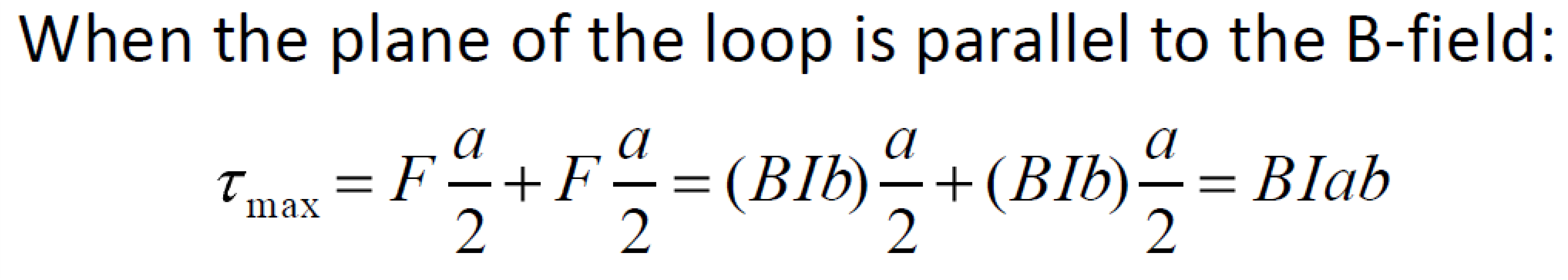
Force on the right side is into the page.

The rectangular loop will spin in the B-field.

The rectangular current loop in page 670 will spin.

In this case, the B-field produces a **torque** on the rectangle current loop.

This is how electric motors work.



When the plane of the loop is parallel to the B-field:

$$\tau_{\max} = F\frac{a}{2} + F\frac{a}{2} = (BIb)\frac{a}{2} + (BIb)\frac{a}{2} = BIab$$

$\tau_{\max}$ = B I A   A is the area of the loop

The torque is **maximized** when the B-field has a direction in the plane of the current loop.

When the B-field is not in the loop's plane, the torque is reduced.

torque in current loop: $\boxed{\tau = B\, I\, A \sin\theta}$

θ is the angle between the B-field and a line perpendicular to the loop.

torque is maximized when $\theta = 90^0$

Torque is **minimized**, equals zero, when the B-field is parallel to the line that is perpendicular to the plane of the loop.

No torque when $\theta = 0$.

Torque on 1 loop $\boxed{\tau = B\,I\,A \sin\theta}$

If you have more than 1 loop (N amount of loops)

total torque = (N) x (torque on 1 loop)

torque on multiple loops: $\tau = N\,B\,I\,A \sin\theta$

Define $\mu = I\,A\,N$ as the magnetic moment.

μ points perpendicular to the plane of the loop.

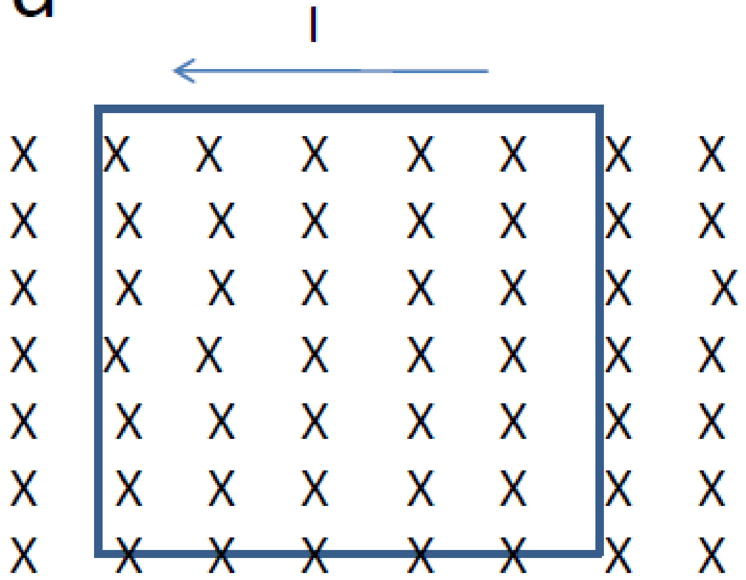
$\boxed{\tau = \mu\,B \sin\theta}$

See example 19.4

Example

rectangular loop in plane of board

B-field going into the board



no torque

The loop will have forces acting on it that 'squeeze' the loop.

If the current flowed clockwise or the B-field is out of the board, the loop would be stretched.

Motion of a charged particle in a magnetic field

Look at figure 19.19 and apply the right hand rule.

The force on the charge is always perpendicular to the motion of the charge.

Because the force is perpendicular to the motion, the magnetic force changes the charge's direction, but does not speed it up or slow it down.

Magnetic forces produce a centripetal acceleration and cause the particle to move in a circular path.

Magnetic forces change direction of the particle's velocity, but not the magnitude.

Magnetic forces don't change the particle's kinetic energy.

Magnetic fields do not do work. (Think back to physics 1, chapter 5.)

Setting magnetic force equal to centripetal force:

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

r is the radius of the circular path.

Can solve for radius: $r = \frac{mv}{qB}$

Using $r = \frac{mv}{qB}$ is how to produce a mass spectrometer.

Particles of different mass to charge ratios will follow paths with different radii.

See example problem 19.6.

So far we have seen how a magnetic field affects a charge.

Now we want to see how a **moving** charge produces a magnetic field.

If you have a single moving charge, a magnetic field is created.

> This can be done by linear motion, circular motion, or by spinning the charge.

If you have a steady flow of charges, a magnetic field will be created.

> We are going to stick to this case.
>
> A steady flow of charge, such as a current through a wire.

B-field of a long straight wire

Running current through a wire produces a magnetic field.

See figure 19.23

Using a rule called Ampere’s Law, it can be found that the magnetic field of a long straight wire is:

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

Where I is the current and r is the radial distance from the wire.

New Constant (permeability)

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

μ_0 is called the permeability of free space.

This constant has to do with the material’s response to a magnetic field. μ varies, depending on the material. In this class we won’t worry about any other values of μ.

We will stick to B-fields in open space (air/vacuum) μ_0

B-field of a wire

Get magnitude from Ampere’s Law

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

Get direction from right hand rule.

- Point thumb in direction of current.
- Your fingers will curl in the direction of the B-field.
- The B-field circles around the current.

See figure 19.24

Ampere's Law

Kind of like the Gauss's Law of magnetism.

If you circle a current with a loop, the B-field at points along the loop times the length of the loop is equal to $\mu_0 I_{enc}$.

Pick a circular loop that is equidistant to the current, you get: $B\,(2\pi r) = \mu_0 I$

solve for B: $B = (\mu_0 I)/(2\pi r)$

Magnetic Force between two parallel wires.

Field from wire 1 $B = \mu_0 I_1/(2\pi r)$

Force on a wire is $F = I\,L\,B$

Force on wire 2 from wire 1

$$F = \frac{\mu_0 I_1 I_2 L}{2\pi d}$$

L is the length of the wires, d is the separation

Magnetic force between wires

By using the right hand rules we see:

Parallel wires carrying **currents in the same direction will attract**.

Parallel wires carrying **currents in opposite directions will repel**.

see figure 19.28

B-field of current loops and solenoids

When you form a current loop, you produce a magnetic field.

Circular current loops produce fields that resemble those of bar magnets.

see figure 19.29, 19.30

B-field from current loop is $B = \frac{\mu_0 I}{2R}$ where R is the radius of the loop.

Current loop

If you have multiple current loops, N of them

$$B = N\frac{\mu_0 I}{2R}$$

get direction from right hand rule

- curl finger in direction of current, thumb points in direction of B-field

or

- point thumb in direction of current, fingers curl in direction of B-field

both will work, check with the pictures

Solenoids

Solenoid – long continuous wire, shaped into several closely spaced coils.

Running current through a solenoid will make an electromagnet.

Solenoids act as several current loops spaced closely together, and centered on a common axis.

See pictures on pages 682 and 683.

Magnetic Field of a Solenoid

$B = \mu_0 n I$ $n = N/L$ turns per unit length

Inside of a long solenoid, the B-field is uniform.

The B-field is parallel to the axis of the solenoid.

Outside the solenoid, the B-field is weaker.
We will only care about inside a solenoid.

For a solenoid that is very long compared to its radius, we assume the magnetic field is zero outside the solenoid.

Therefore, when working with solenoids, we will only care about the field inside the solenoid.

Work out example 19.9

See figure 19.36

Magnetic Domains

Individual atoms may act like tiny magnets because of the motion of the electrons around the nucleus. Act like a tiny current loop.

If another electron orbits in opposite direction, the magnetic fields cancel out.

Electrons also spin. This produces a noticeable B-field.

When electrons have opposite spins, they also cancel out. Most electrons are paired. Most of the magnetic field will again cancel out.

Magnetic fields due to electron motion is zero or very small for most materials.

Since most electrons are paired, most materials are not magnetic.

However in some materials, there are **unpaired electrons**.
(iron, cobalt, nickel)

Because of the **unpaired electrons**, the magnetic fields don’t cancel out.

These materials are magnetic.
We call them ferromagnetic.

In ferromagnetic materials, coupling occurs between neighboring atoms.
Nearby atoms have spins that tend to be aligned.

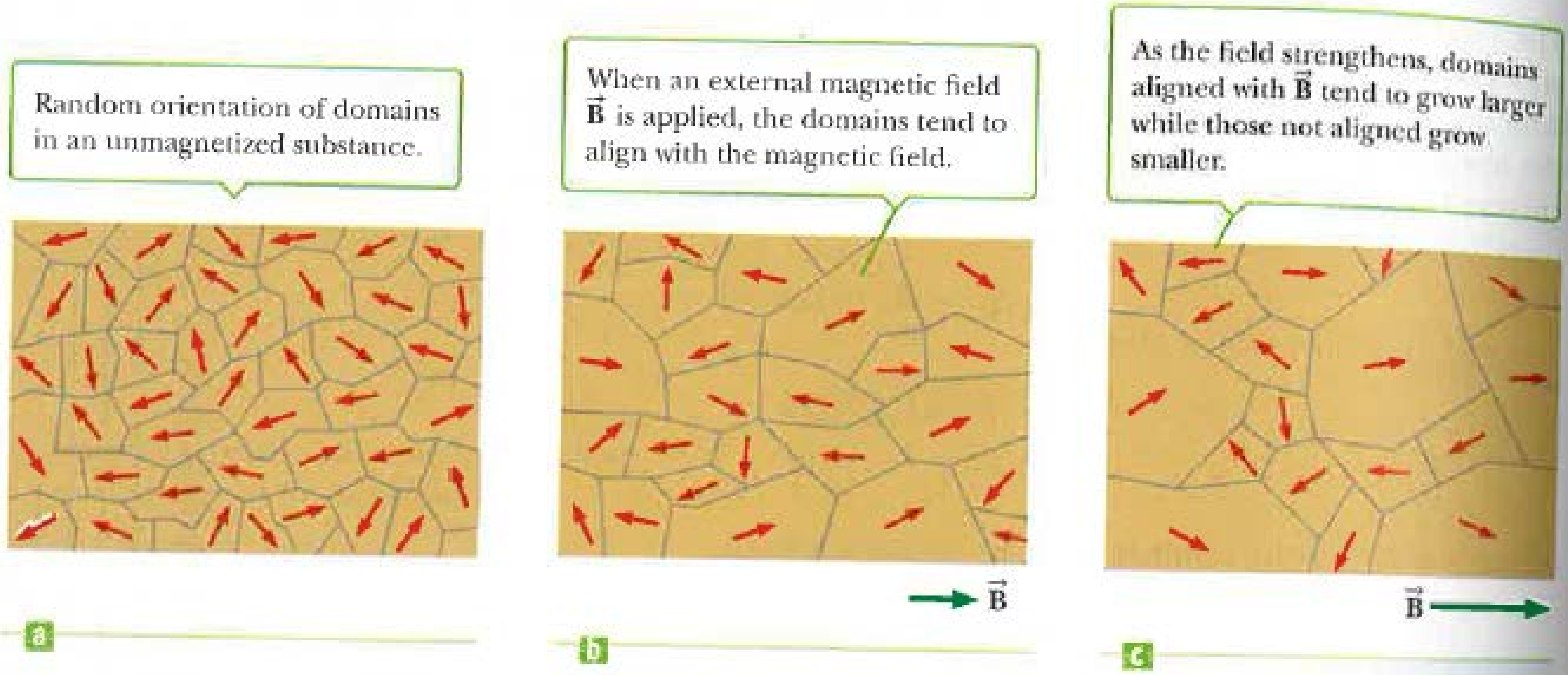
In ferromagnetic materials where there are large groups of atoms whose spins are aligned, strong magnetic fields are formed.

Regions of adjacent atoms whose spins are aligned are called domains.

See figure 19.38

Ferromagnetic materials have large domains.

Un-magnetized materials have smaller domains.



Random orientation of domains in an unmagnetized substance.

When an external magnetic field $\vec{\mathbf{B}}$ is applied, the domains tend to align with the magnetic field.

As the field strengthens, domains aligned with $\vec{\mathbf{B}}$ tend to grow larger while those not aligned grow smaller.

Figure 19.38 Orientation of magnetic dipoles before and after a magnetic field is applied to a ferromagnetic substance.

Apply a magnetic field to the material.

In the presence of magnetic field, the domains want to align with the field.

Permanent magnets are formed when the domains remain aligned even if no external field is present. (Ferromagnetic materials)

Paramagnetic – materials that have a weak response to a magnetic field.

Examples are aluminum, calcium, platinum