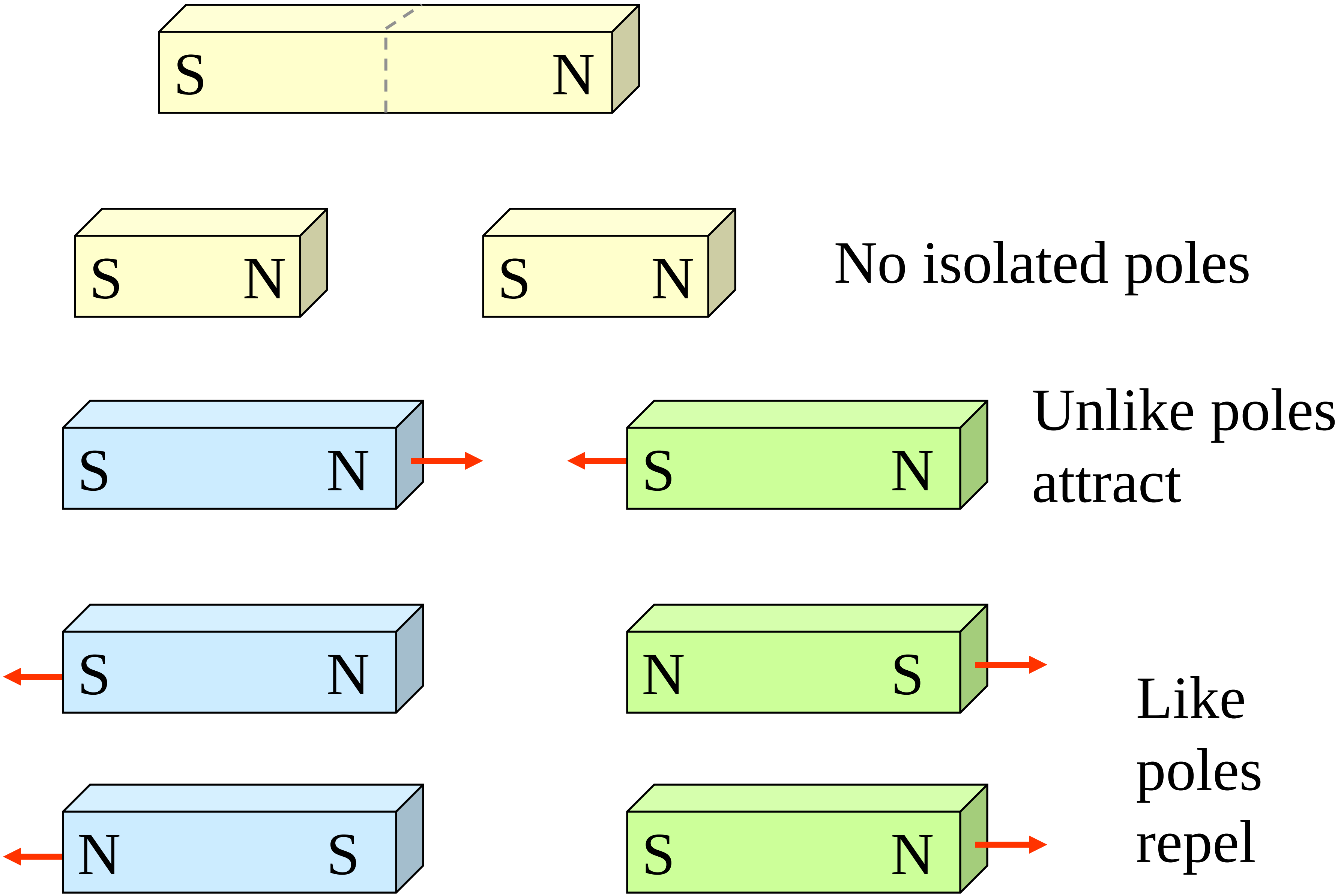
Chapter 14

Magnets and Electromagnetism

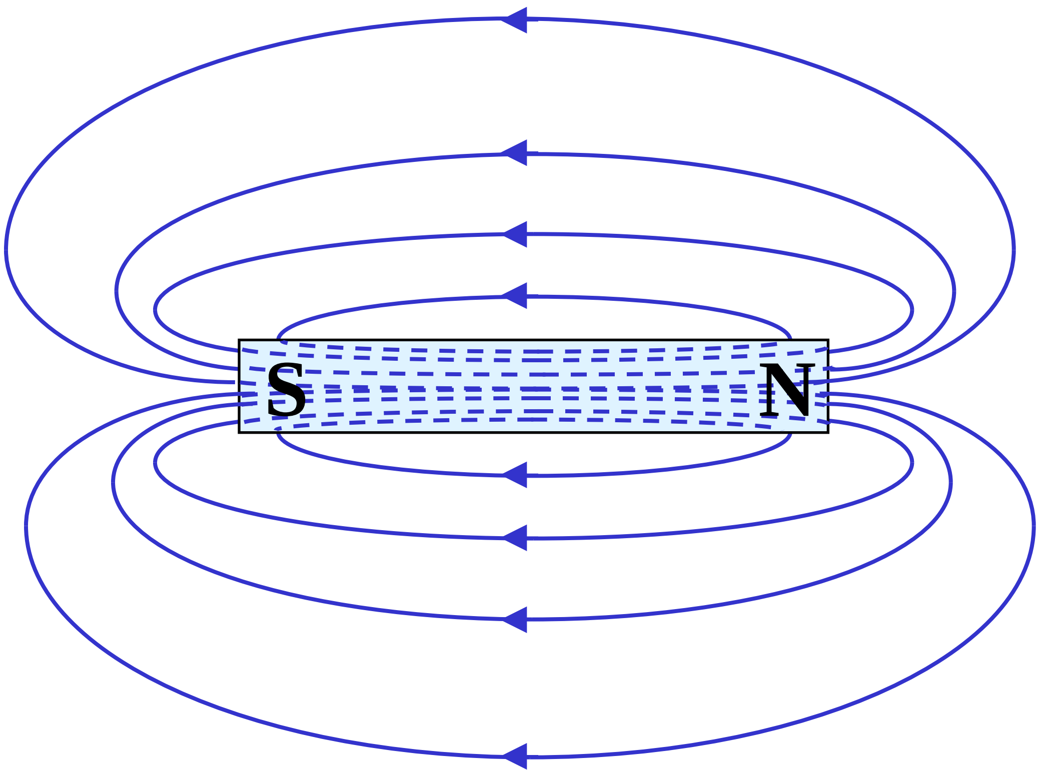
Magnets and Electromagnetism

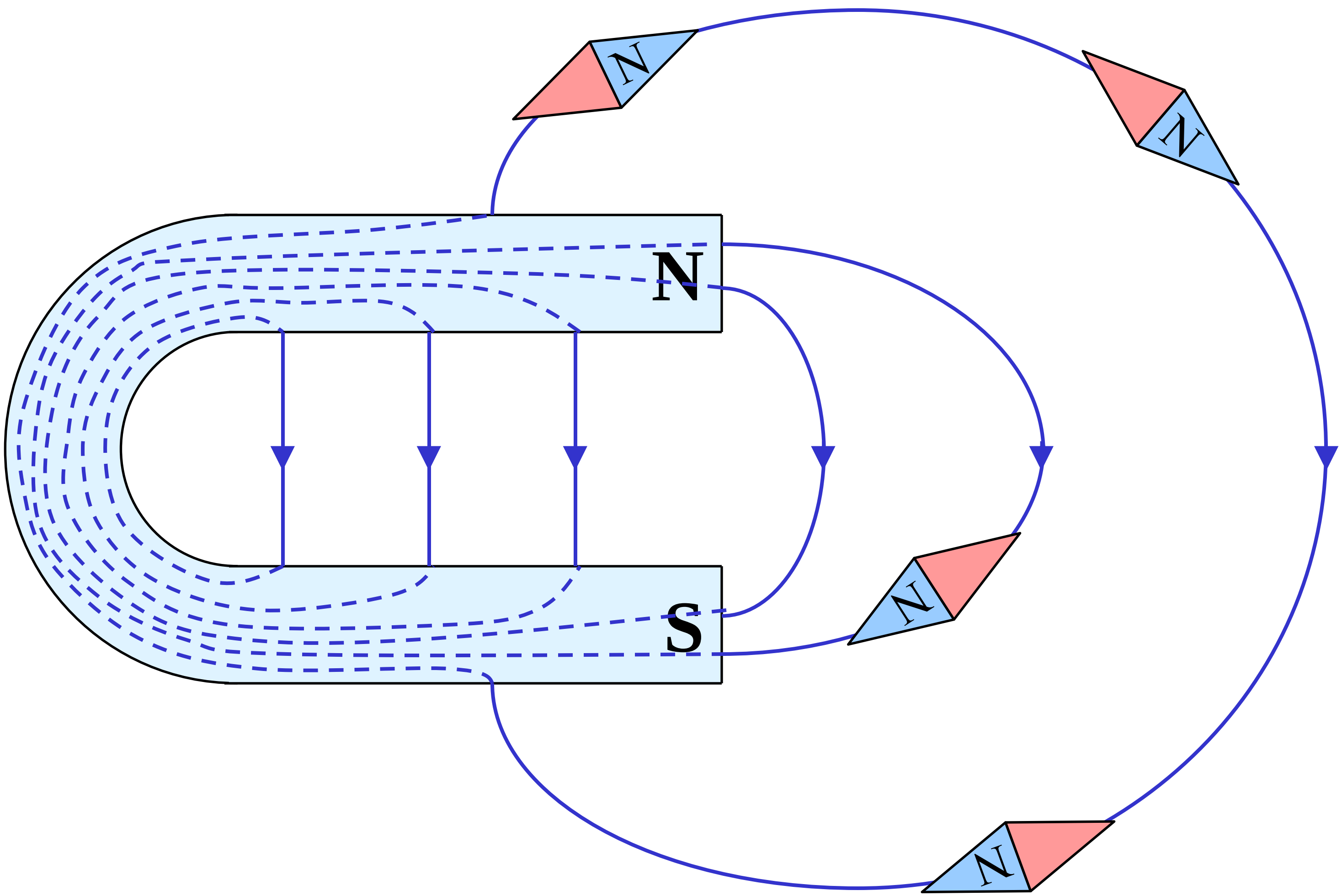
- In the 19th century experiments were done that showed that magnetic and electric effects were just different aspect of one fundamental electromagnetic force.
  - Our understanding of that relationship has led to numerous inventions such as electric motors, electric generators, transformers, etc.
- Magnets attract metallic items made of iron or steel, but not silver, aluminum, copper, or most nonmetallic materials.
  - The three most common magnetic elements are the metals iron, cobalt, and nickel.

Magnetic Poles



- Magnetic field lines show the magnetic field.
  - They form continuous loops which emerge from the north pole and enter through the south pole, outside the magnet.
  - Outside of a magnet they point in the direction the north pole of a compass would point.
  - Inside the magnet, they point the other way

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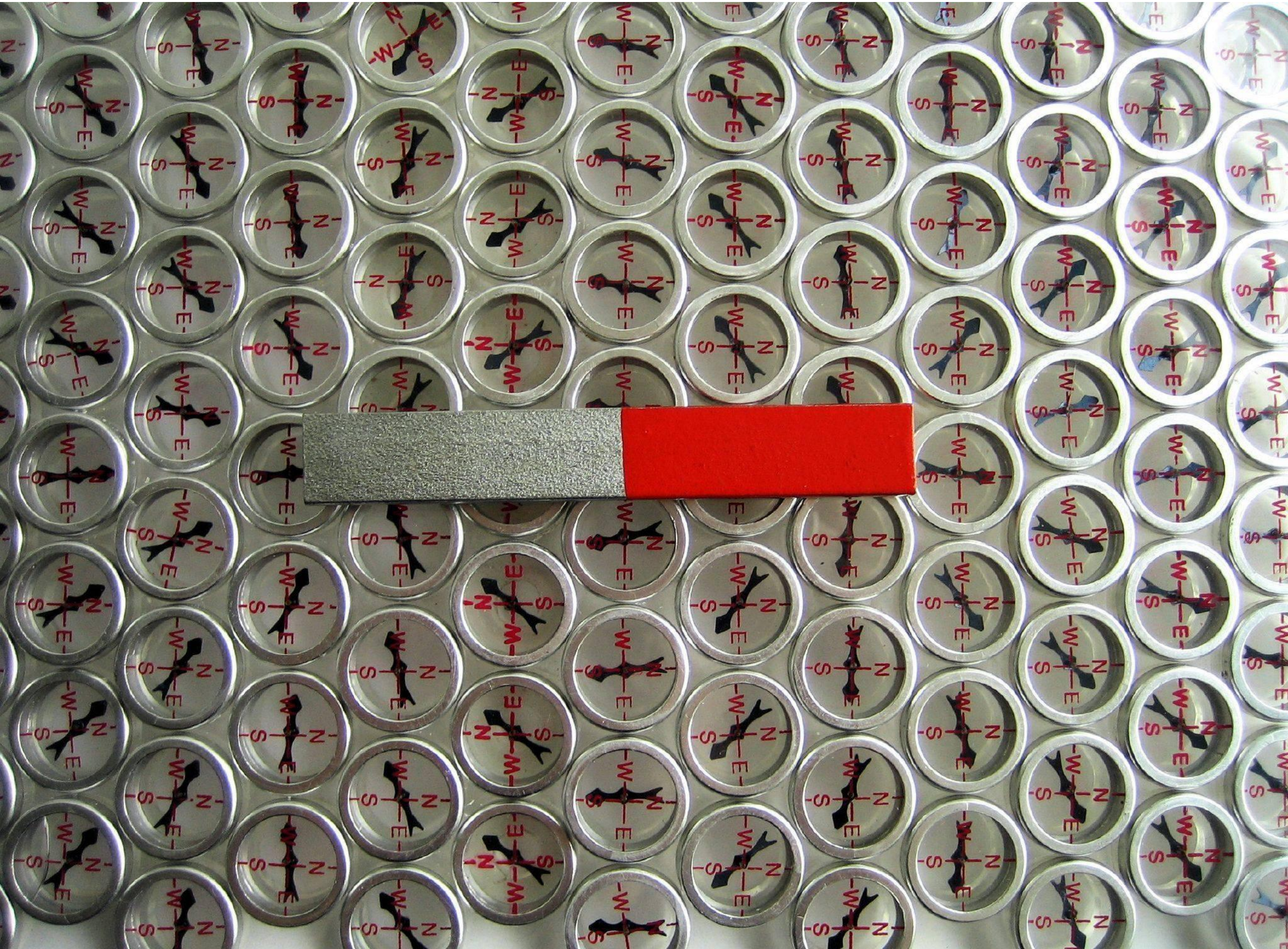
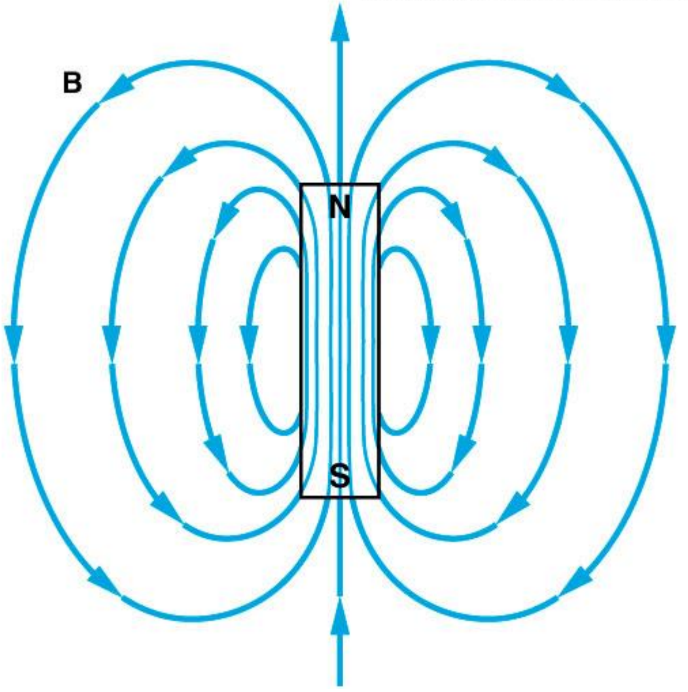
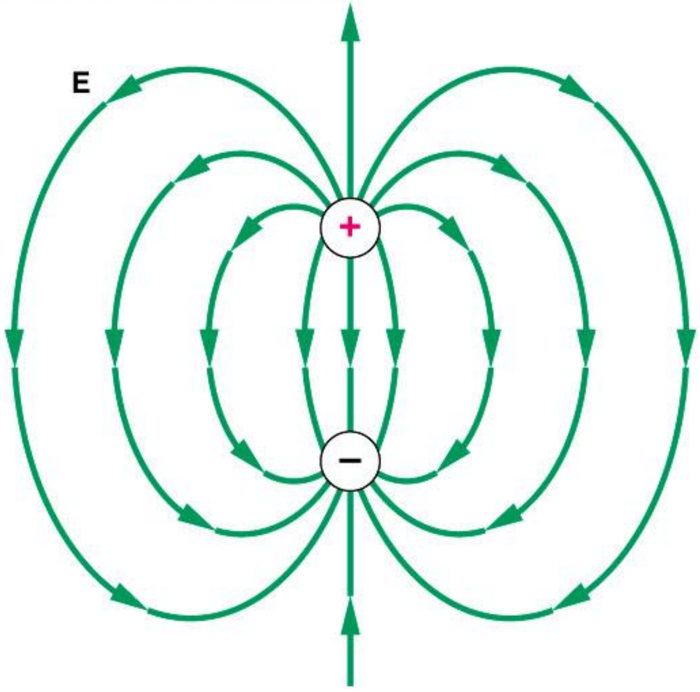


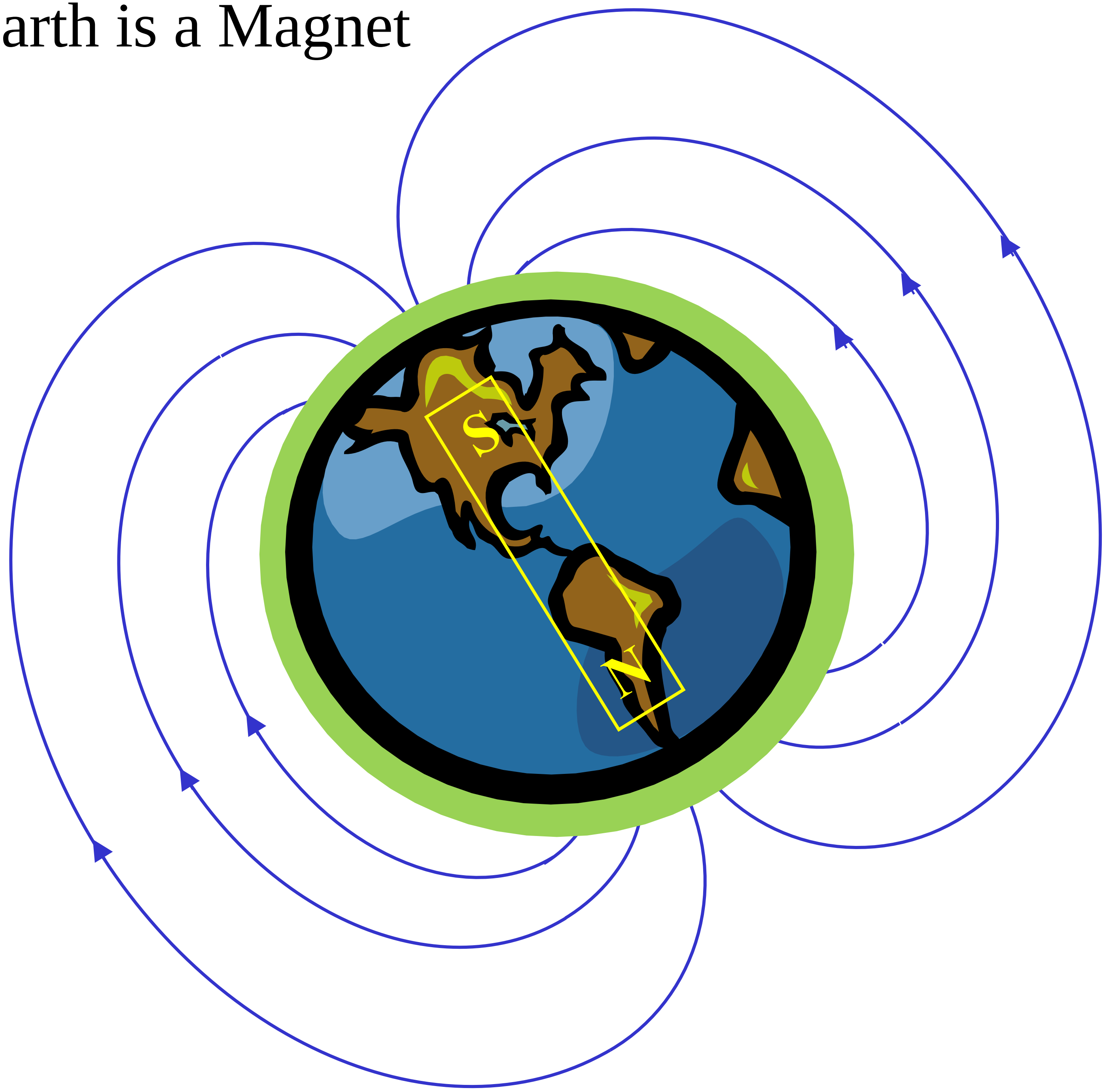




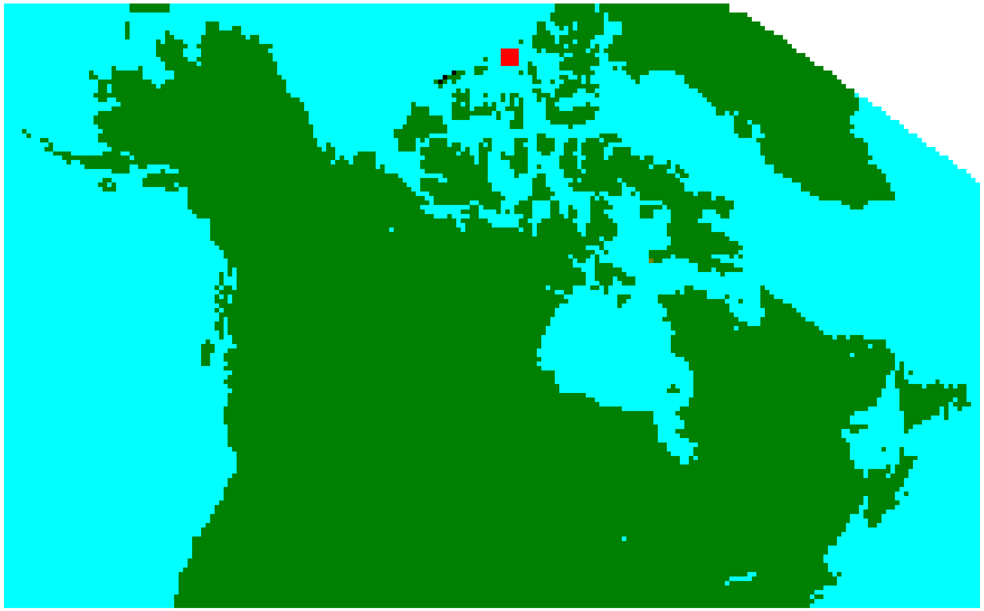
Magnetic fields have similarities to electric fields but they are not the same

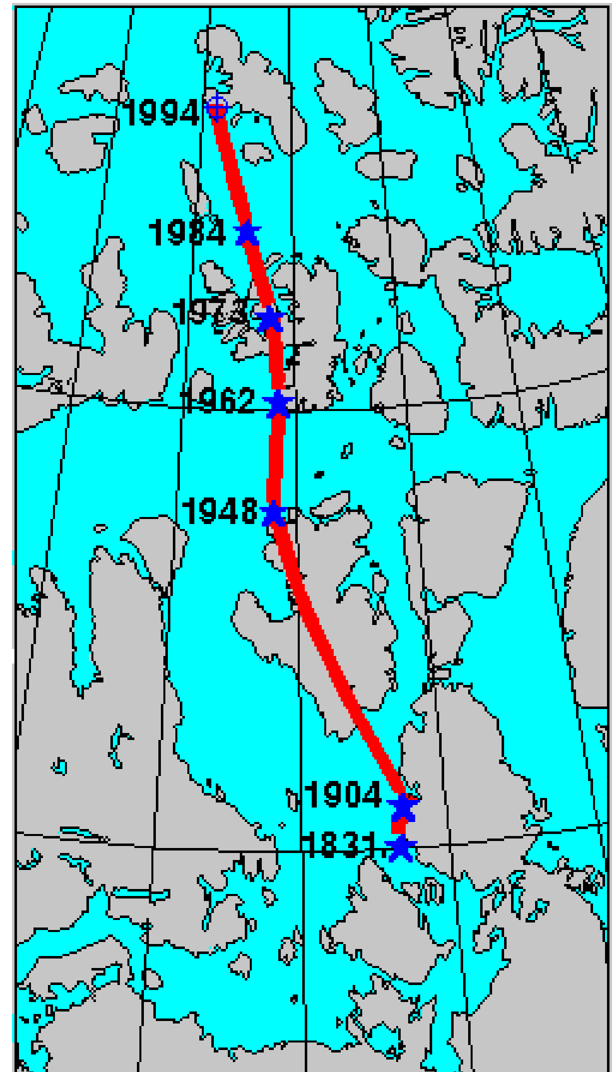
- Electric fields are caused by charged objects; magnetic fields by poles.
- Electric fields end on charged objects; magnetic fields are closed loops.
- Electric fields affect charged objects. Magnetic fields affect poles.

The Earth is a Magnet

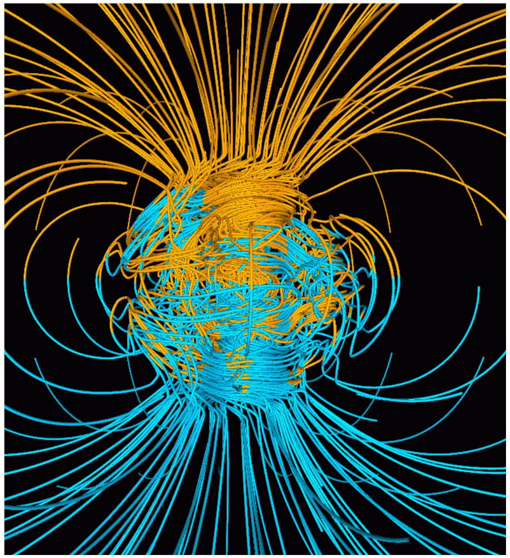


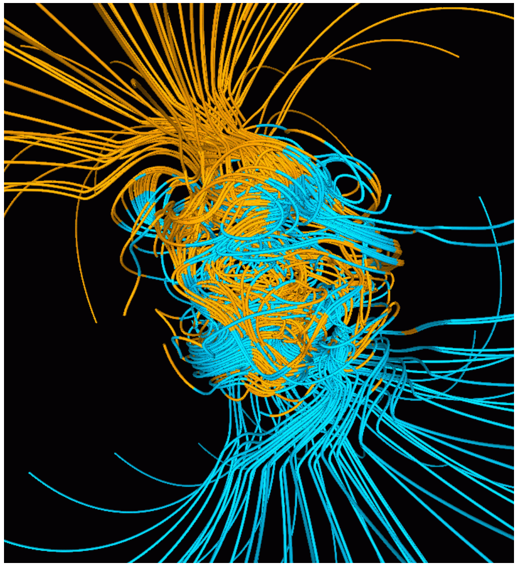
The Earth’s magnetic pole moves

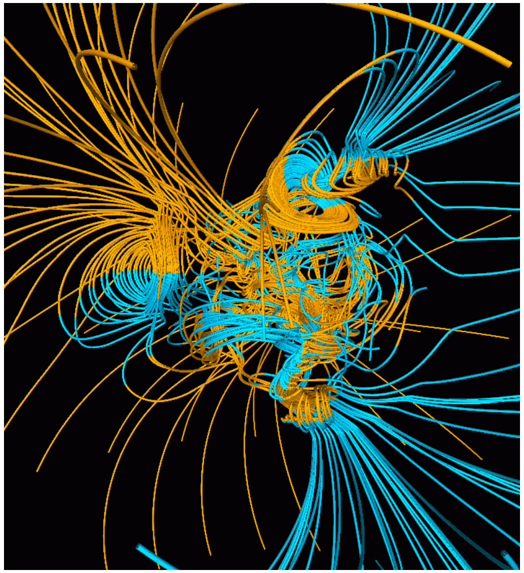


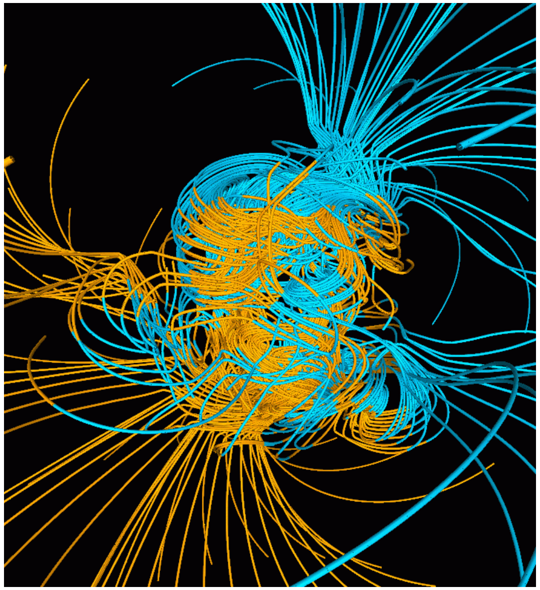


Poles flip about every 300,000 years and take about 1 to 5 thousand years to flip. The last pole reversal was about 780,000 years ago.

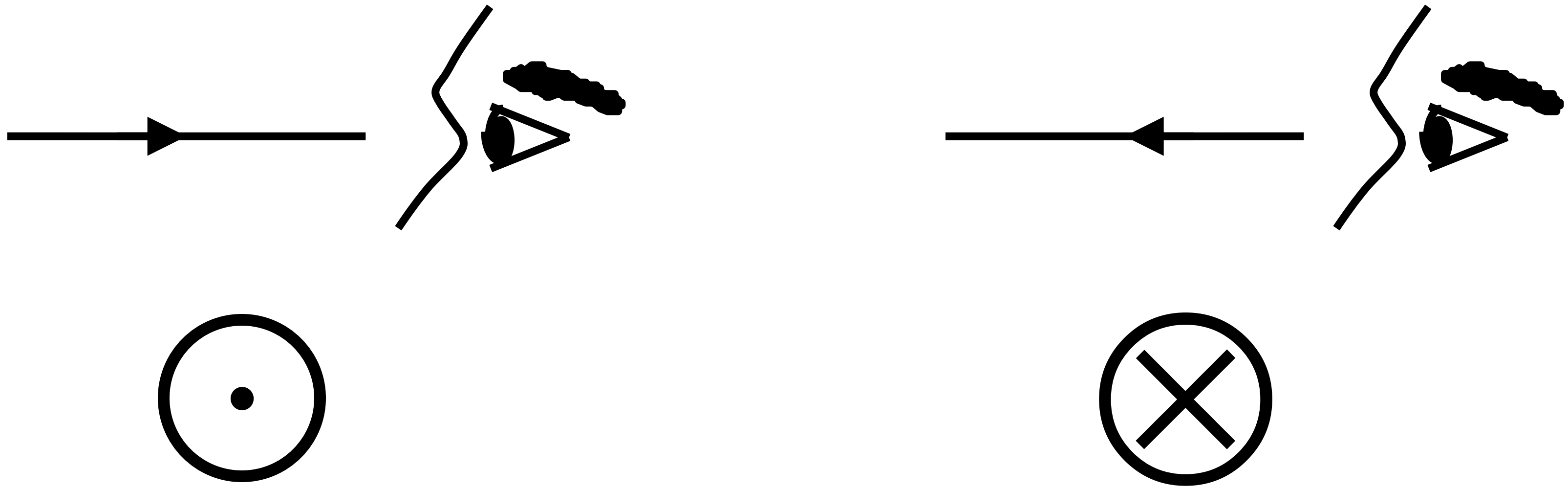






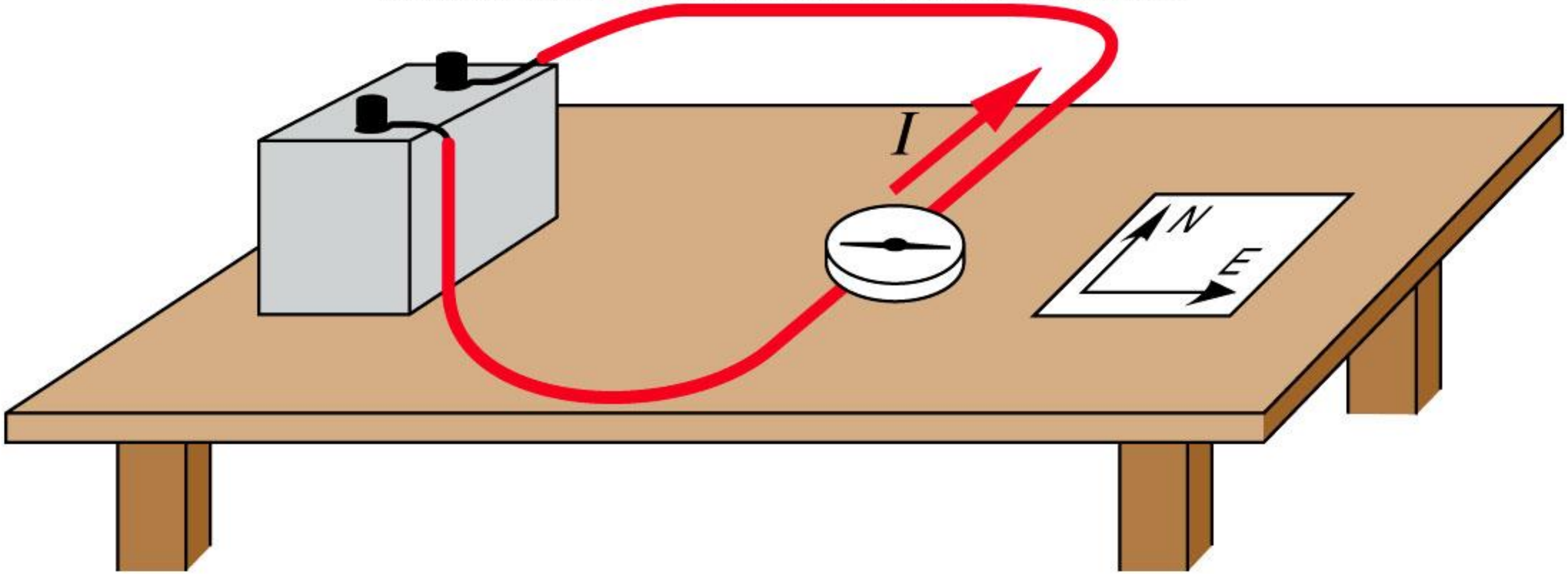


Looking at Vectors

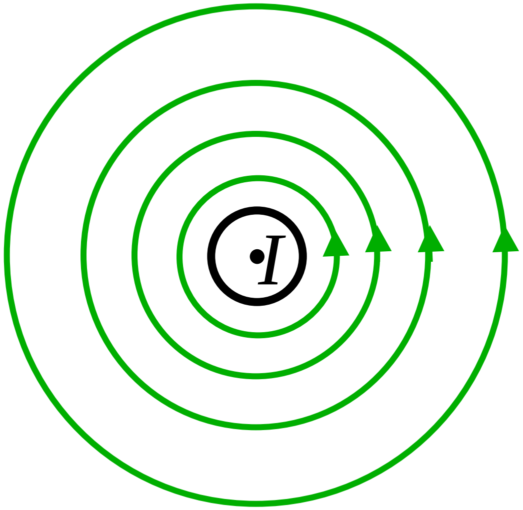


A Relationship between Electricity and Magnetism

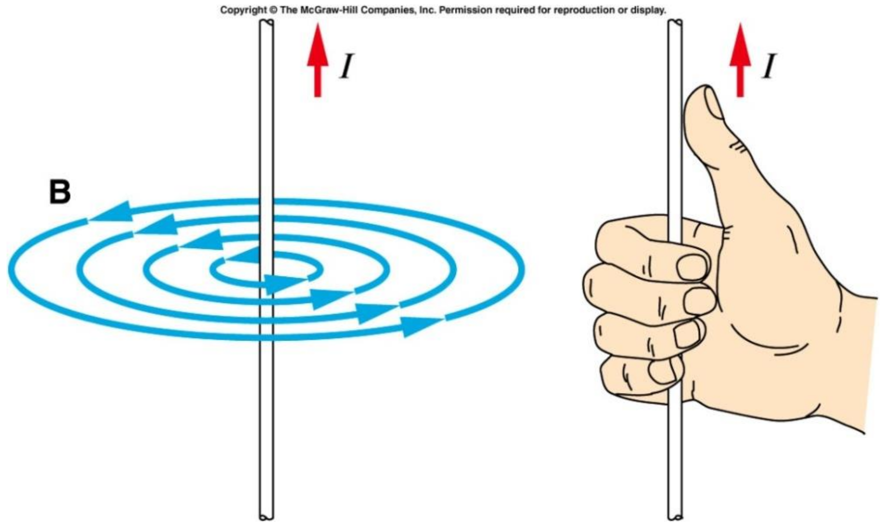
In 1820 the Danish scientist Hans Christian Ørsted (Oersted) discovered that a compass needle was deflected by a current-carrying wire. Electricity could produce magnetic effects.



Magnetic Fields are Produced by Currents



Top view

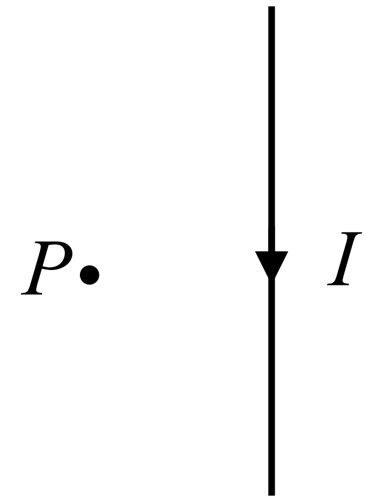


Side View

- A wire with a current moving through it creates a magnetic field in the shape of circles around the wire with orientation given by the right hand rule (RHR-1).
- The field is tangent to the circle at any point.
- The strength of the field decreases farther from the wire.
- The SI Units of magnetic field is a Tesla (T) = 1 N/(A·m)

Interactive Question

A long straight wire has a current going in the direction shown in the figure to the right. Which direction is the magnetic field at point *P*?



$\odot$ (A)

$\otimes$ (B)

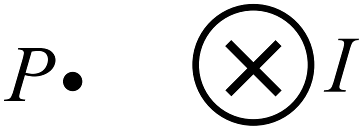
$\uparrow$ (C)

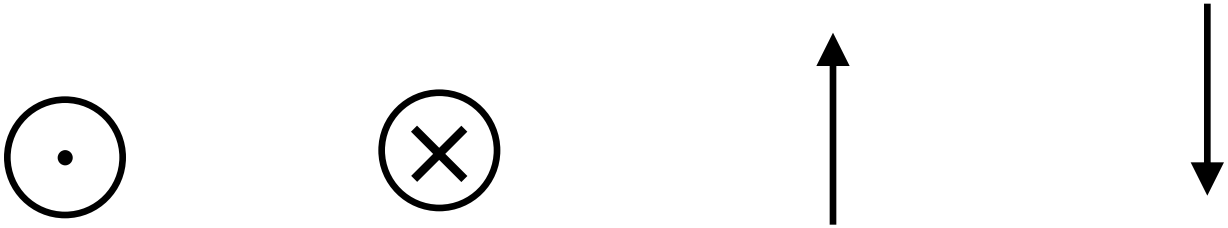
$\downarrow$ (D)

E) None of the above

Interactive Question

A long straight wire has a current going in the direction shown in the figure to the right. Which direction is the magnetic field at point *P*?



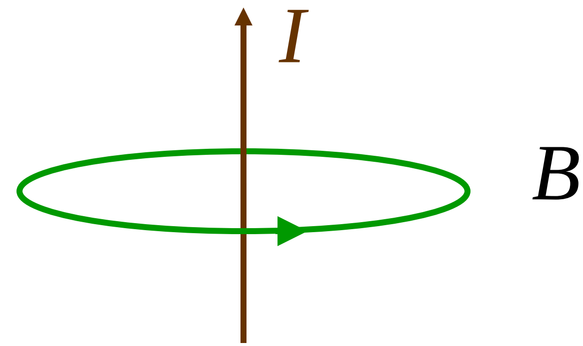


(A) (B) (C) (D)

E) None of the above

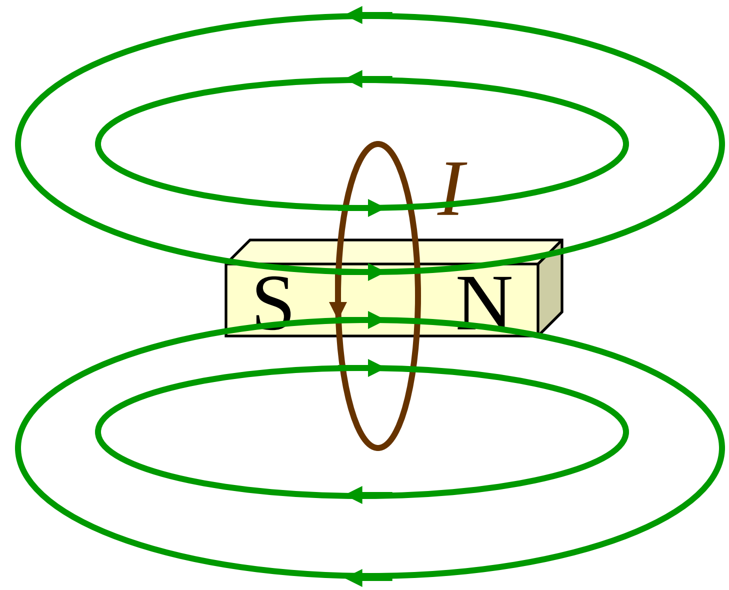
Magnetic field of a wire loop

Take a wire with magnetic field like this:



And twist it in a loop:

To produce a magnetic field like this:

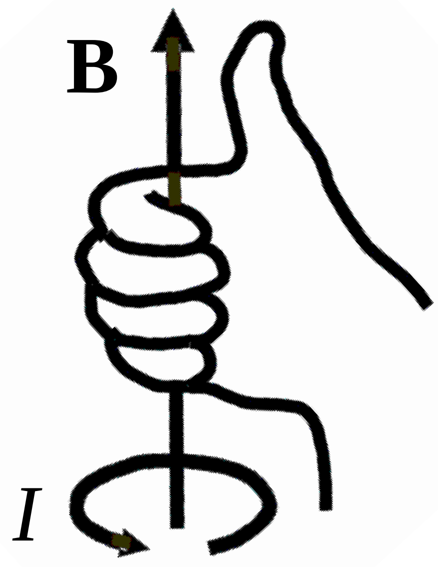


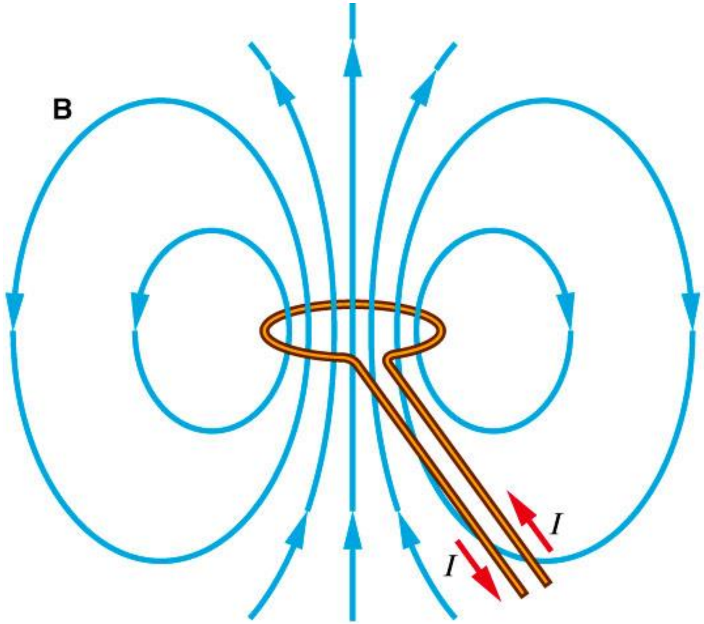
Which looks like the field of a bar magnet.

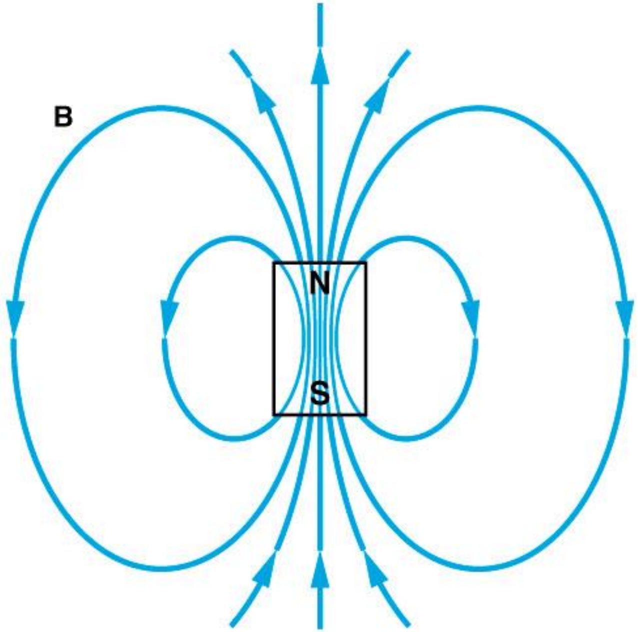
A loop of wire with current creates a magnetic field like a little bar magnet.

Direction of Wire Loop Magnetic Field

The magnetic field of a loop of wire, like a little bar magnet is a complete circle. Inside the loop it points in one direction and outside the loop it points in the other direction. The direction inside the loop can be found using RHR-2.





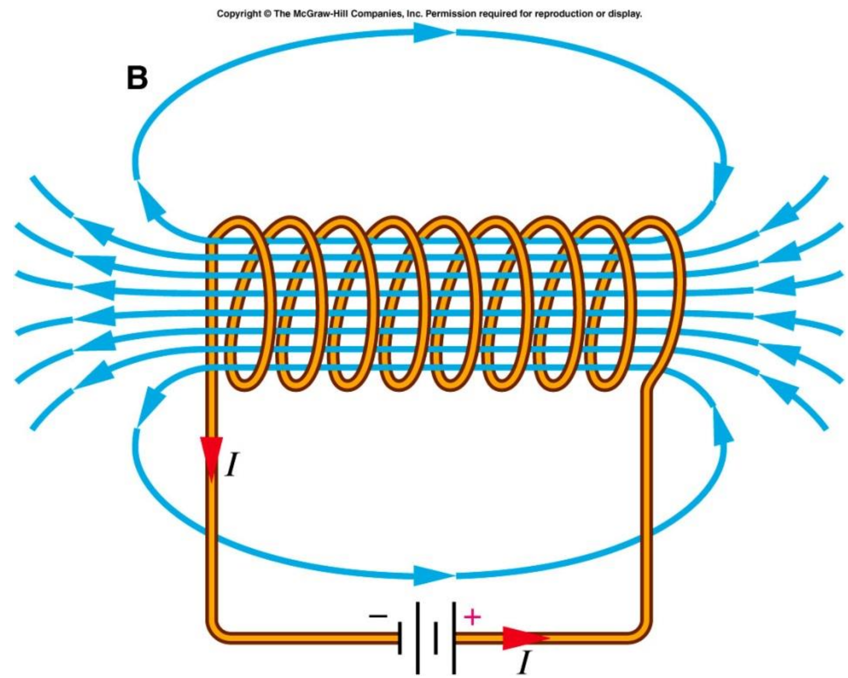


Solenoids and Electromagnets

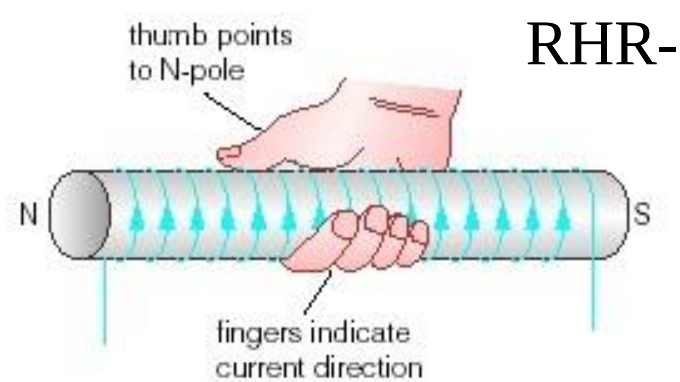
A solenoid has many loops of wire, sometimes wrapped around an iron core.

– The magnetic field produced by a coil of wire will be stronger than one produced by a single loop carrying the same current by a factor equal to the number of turns of coil

– The magnetic field in the solenoid can cause iron atoms inside the solenoid to align their intrinsic magnetic fields. This is an electromagnet



RHR-2



Magnetic Forces on Objects

Magnetic fields (B) will produce a force on an object, if the object satisfies three criteria:

1. The object must have an electric charge (q).
2. The object must be moving (v).
3. The velocity of the object must have a component that is **perpendicular** to the direction of the magnetic field.

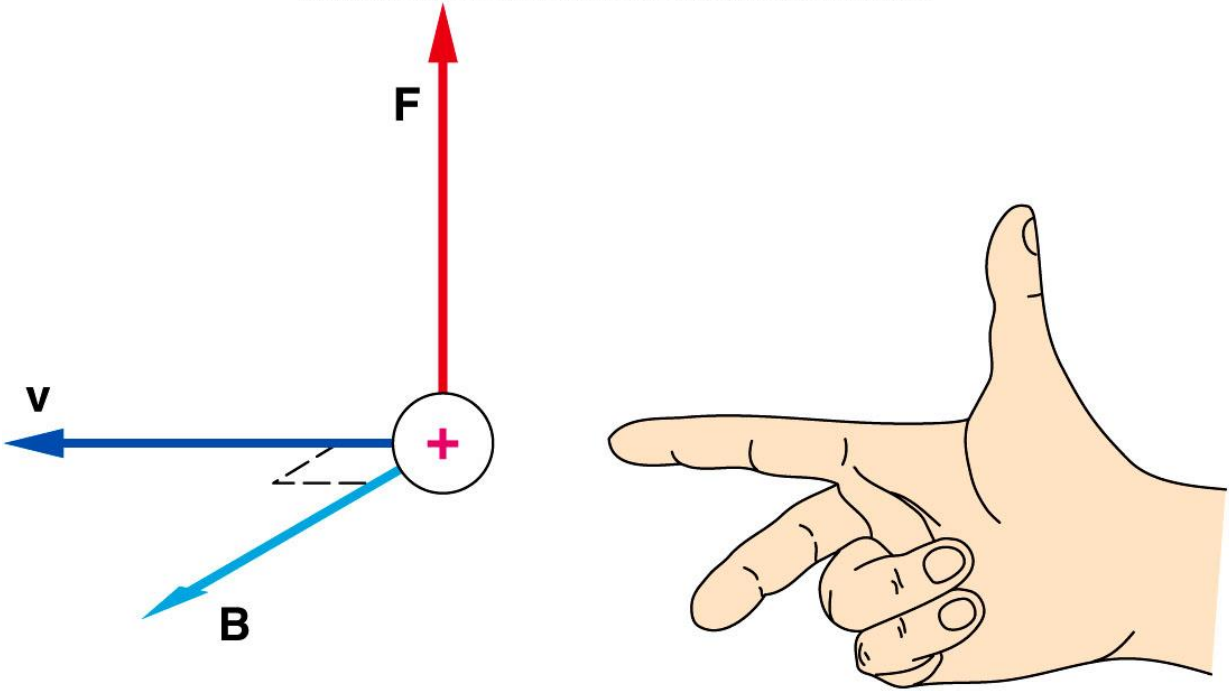
The strength of the force is given by

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

where $v_{\perp}$ is the part of the velocity that is perpendicular to B.

Direction of the Magnetic Forces

The direction of the force on a positive particle is given by RHR-3. A negatively charged particle feels a force in the opposite direction.

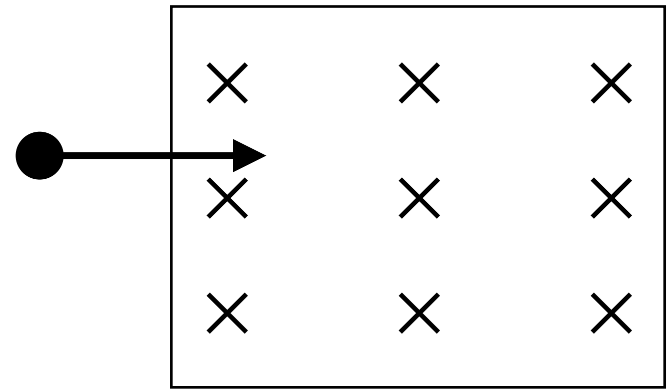


Problem: A proton moves at a speed of 8.0×10^6 m/s directly north in a magnetic field of magnitude 2.5 T directed straight up. At that moment what is the magnitude and direction of the force the proton feels?

Problem: An electron moving directly north at a speed of 1.5×10^7 m/s and feels a force straight down with a magnitude of 2.2×10^{-12} N. If the electron is traveling at a right angle to the magnetic field, what is the magnitude and direction of the magnetic field ?

Interactive Question

A proton enters a region that contains a uniform magnetic field directed into the paper as shown. What is the direction of the magnetic force on the proton when it enters the field

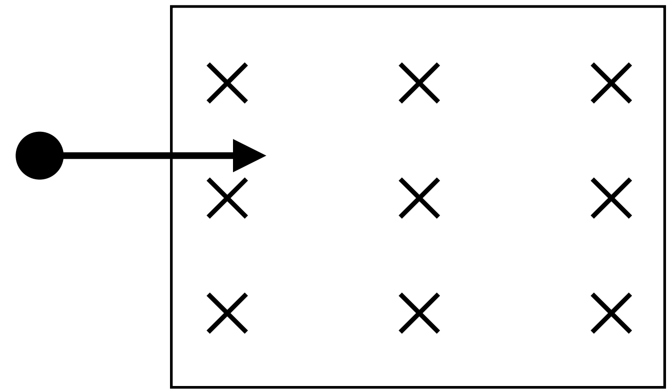


(A) (B) (C) (D)

E) None of the above

Interactive Question

An electron enters a region that contains a uniform magnetic field directed into the paper as shown. What is the direction of the magnetic force on the proton when it enters the field

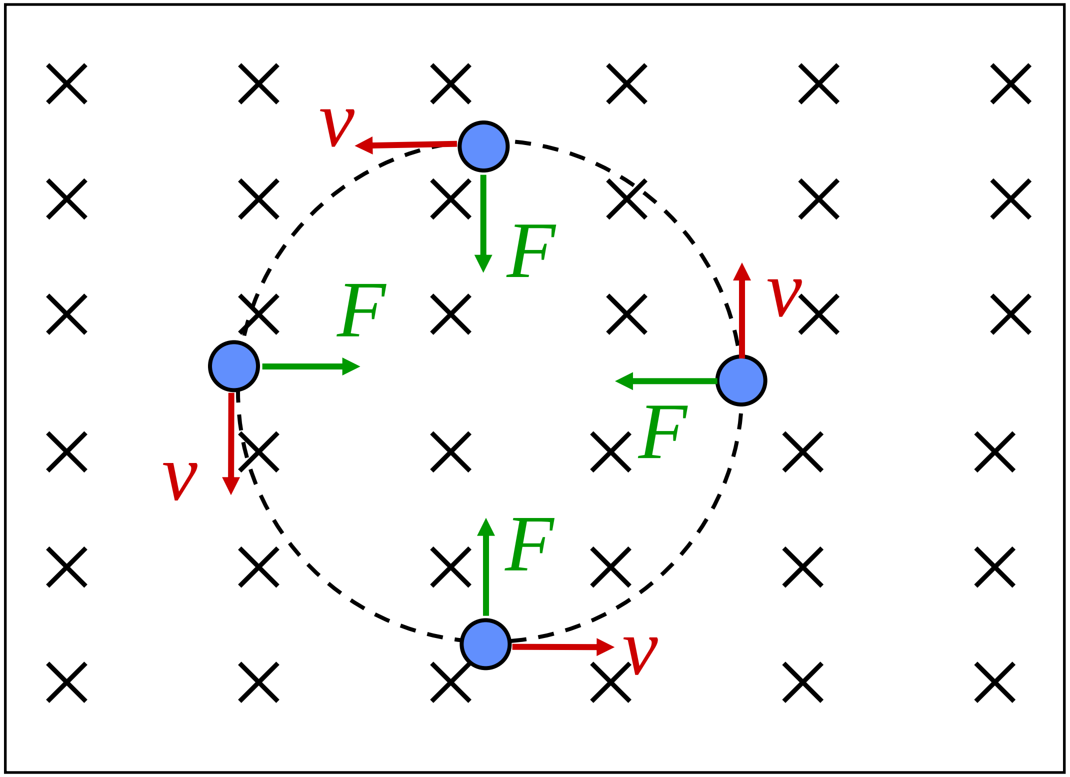


(A) (B) (C) (D)

E) None of the above

Motion of a Charged Particle in a Magnetic Field

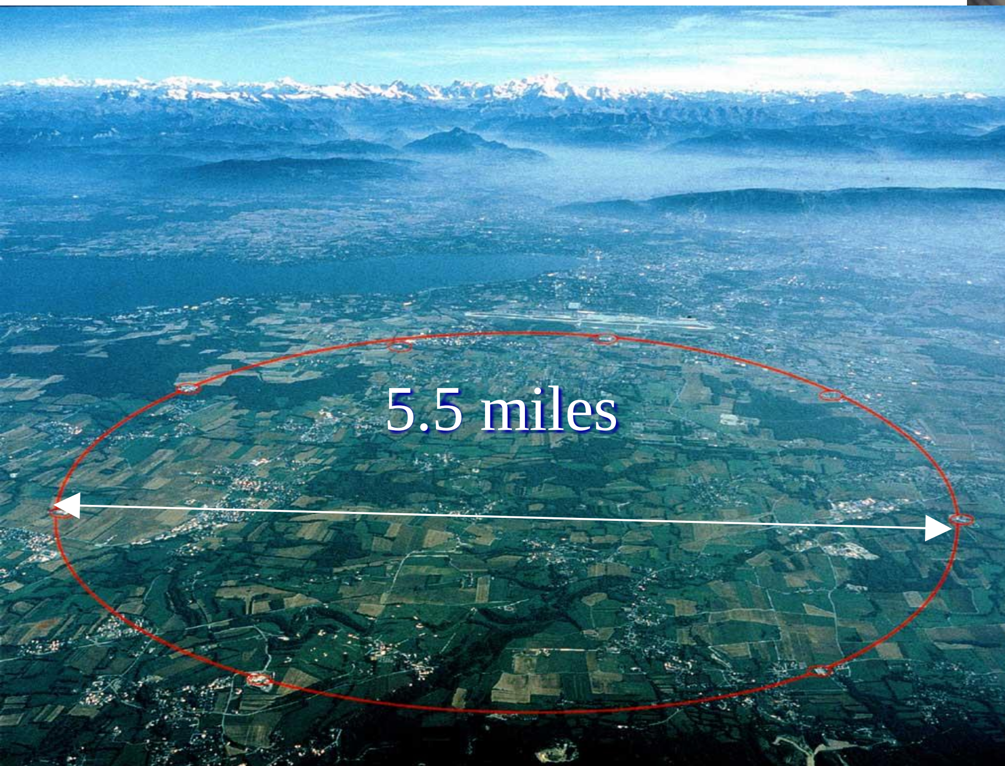
Positive Particle in Magnetic Field



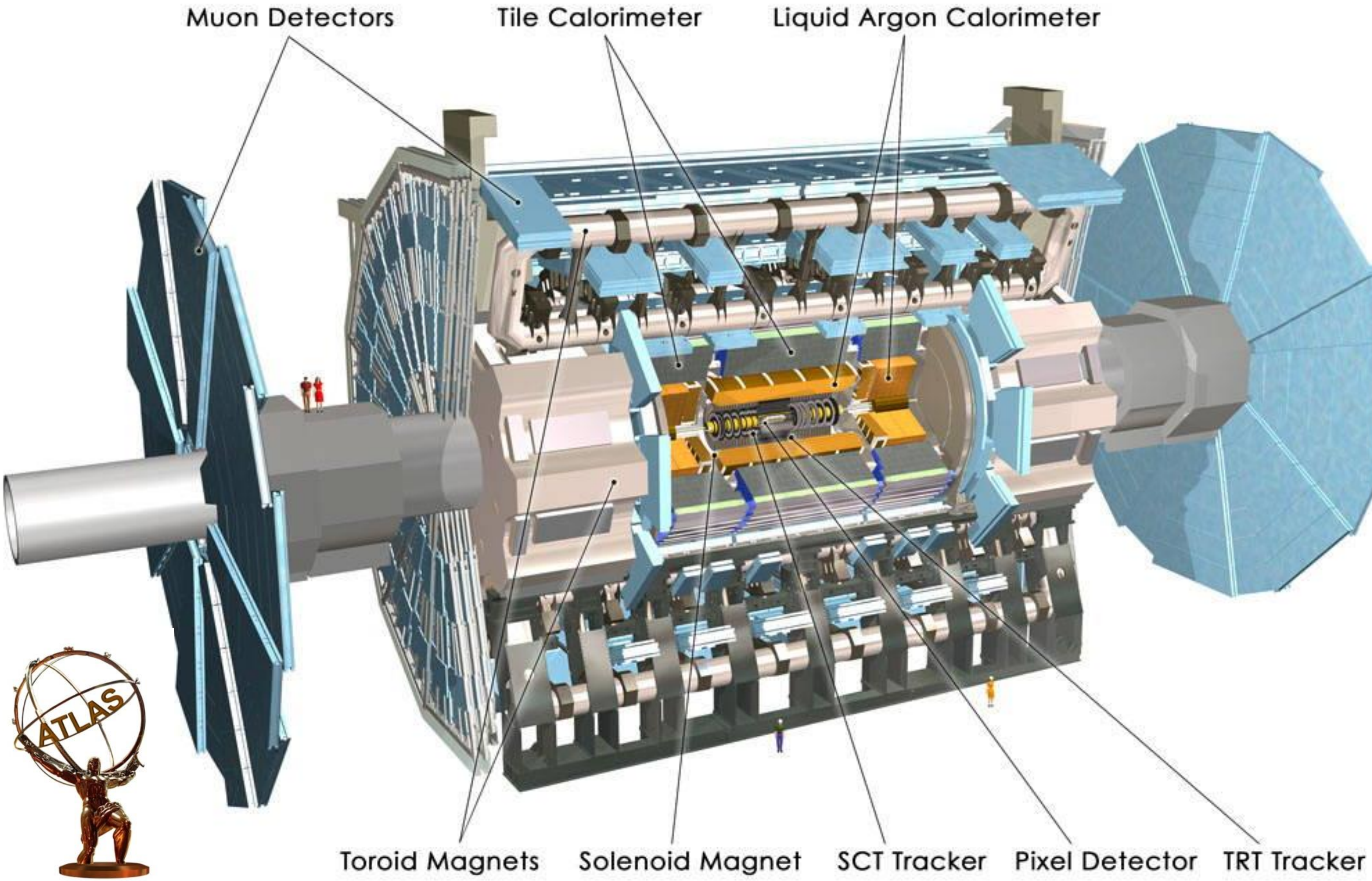
$$F = ma$$
$$Bqv = mv^2/r$$
$$Bq = mv/r$$
$$Bqr = mv$$
$$r = mv/Bq$$
$$r = p/Bq$$

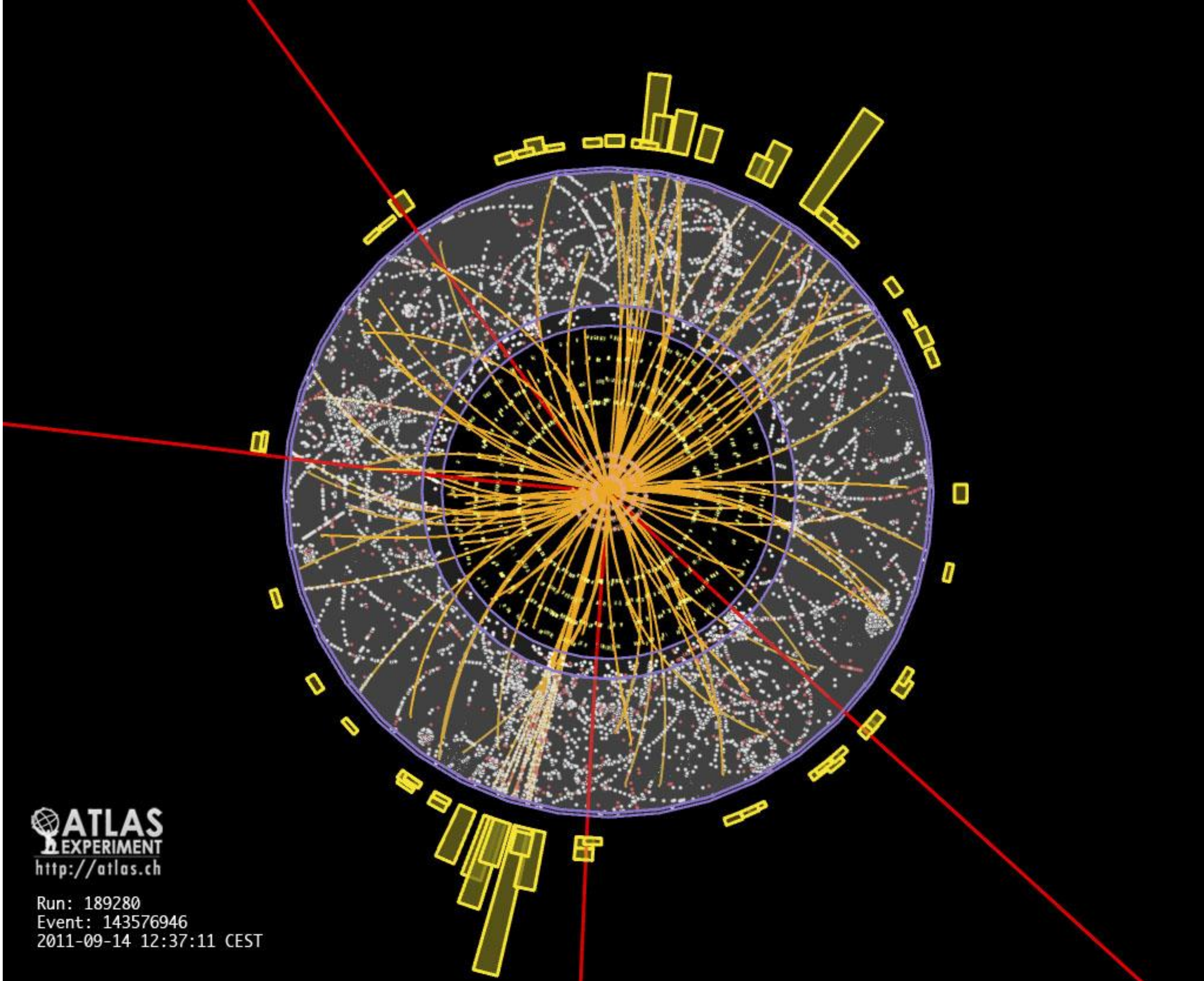
Objects in a uniform magnetic field move in circles with a radius proportional to their momentum.

The Large Hadron Collider at CERN (Geneva, Switzerland)



The ATLAS Detector at the LHC




ATLAS
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Current Carrying Wire in a Magnetic Field

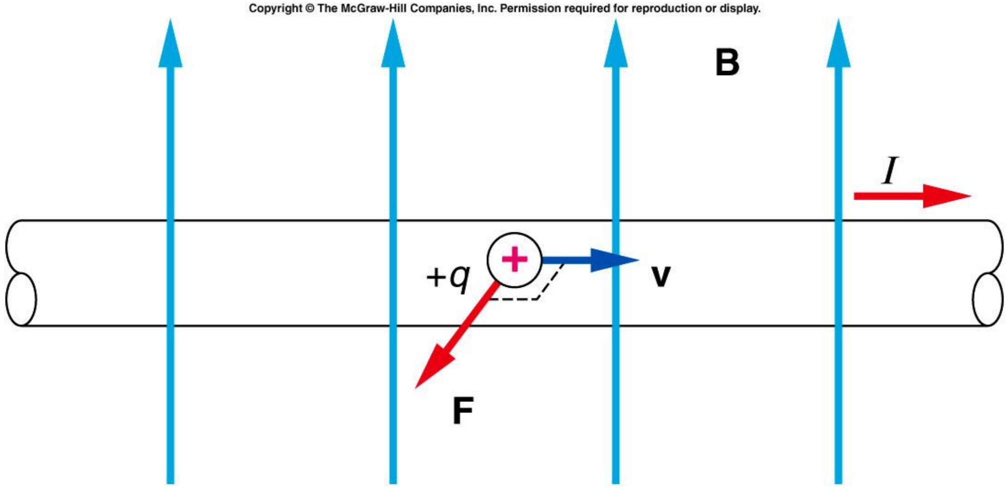
When a wire carries a current, there is charge moving through the wire. Thus a magnetic field will give a force on current carrying wire. The direction of the force is given by RHR-3 with the charges moving in the direction of the current. We can calculate the magnitude of the force for a wire perpendicular to the magnetic field.

$$\begin{aligned} F &= qvB \\ &= (t/t)\, qvB \\ &= (q/t)\,(vt)\, B \end{aligned}$$

$$\boxed{F = ILB}$$

I: current in the wire

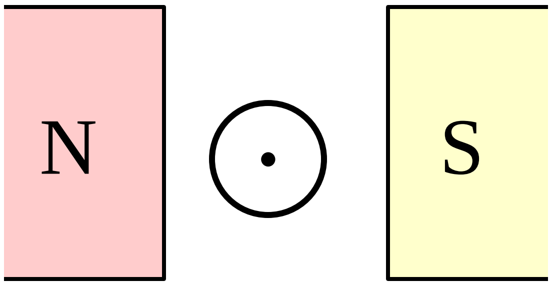
L: length of the wire



Problem: A straight 44 cm wire has an current of 2.3 A flowing east in a 0.65 T magnetic field that points down. What is the magnitude and direction of the force on the wire?

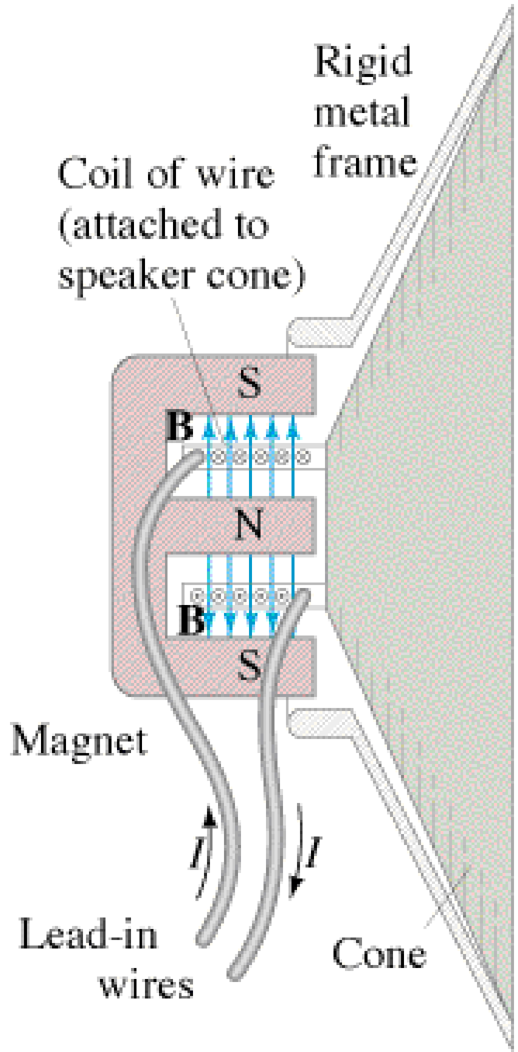
Interactive Question

A long straight wire is placed between the poles of a magnet as shown. When a current is flowing out of the page as shown, the direction of the magnetic force on the wire will be:



A) toward the left
B) toward the right
C) toward the top of the page
D) toward the bottom of the page
E) out of the page

Audio speakers use this principle to create sound



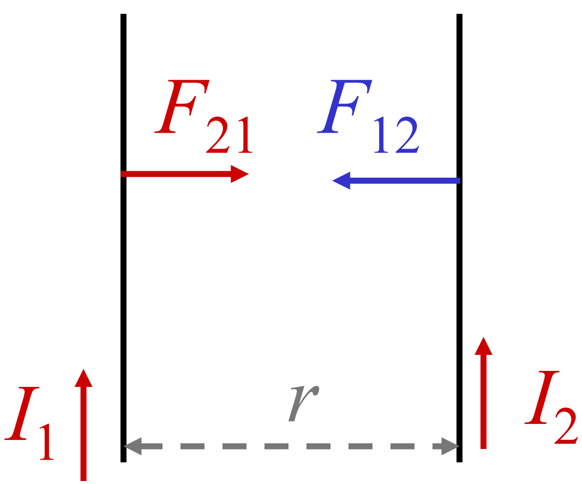
Two Parallel Wires Carrying Current

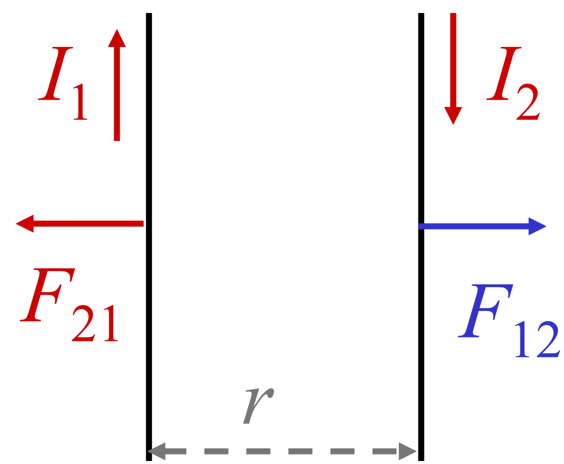
Since wires with current create magnetic fields and wires with current in a magnetic field feel a force, two parallel wires with current will exert a force on each other. If the currents are in the same direction the force will be attractive. If they are in opposite directions the force will be repulsive. The strength of the force is given by

$$F/L = 2k' I_2 I_1 / r$$

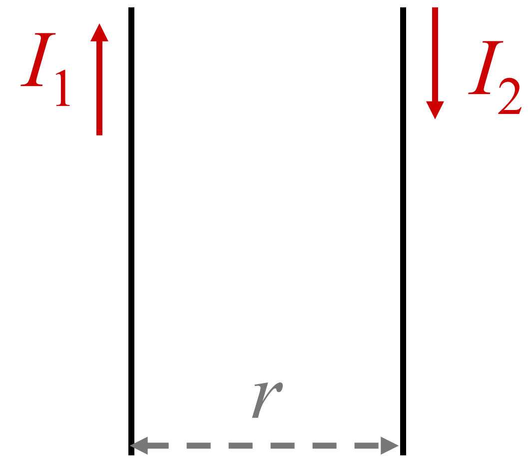
where

$k' = 1\times10^{-7}$ N/A^2





Problem: Two long parallel wires carry currents in opposite direction as shown in the figure with $I_1 = 2.2$ A, $I_2 = 4.4$ A and $r = 3.3$ cm.



A) What is the total force exerted on a 25 cm section of wire 1?

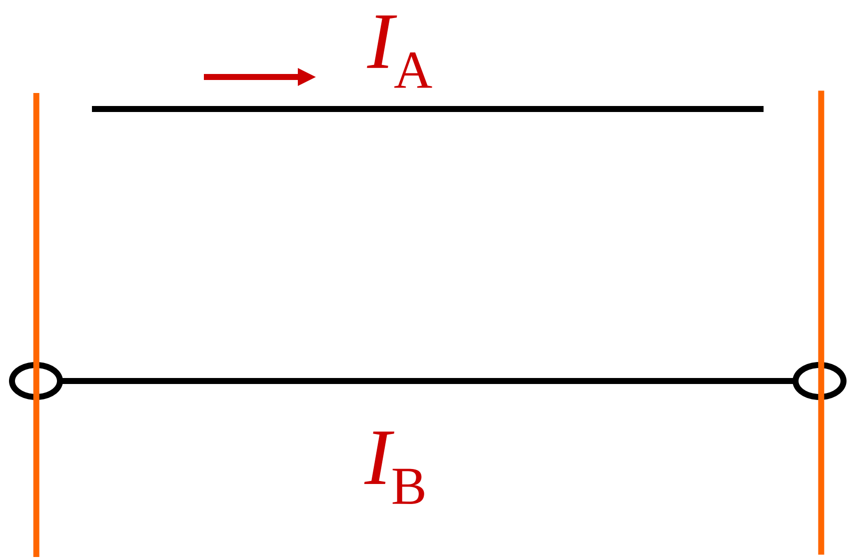
B) What is the direction and strength of the magnetic field produced by wire 2 at the position of wire 1.

C) Knowing the direction of the magnetic field, use the right hand rule to show that the force on wire 1 is repulsive.

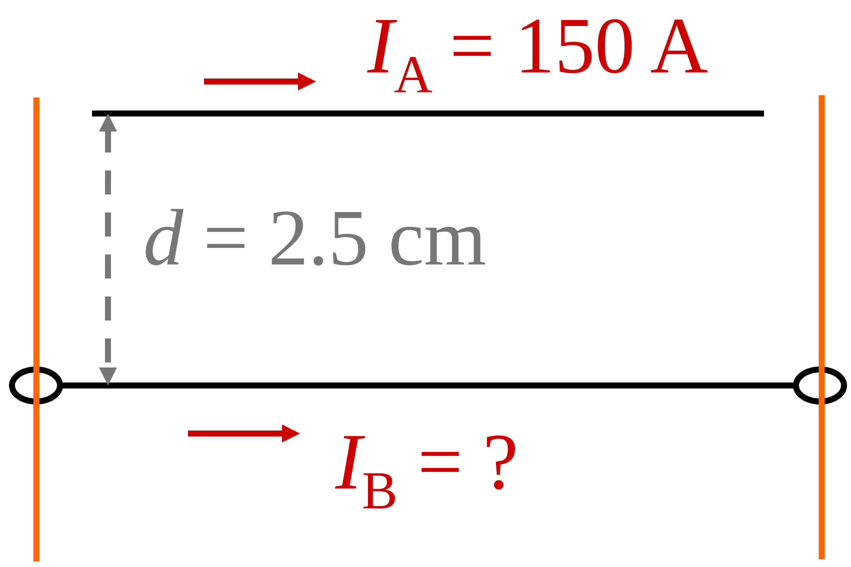
Interactive Question

Wire A carries a current of to the right as shown. Wire B is below and parallel to wire A and allowed to slide freely up and down between a set of nonconducting guides. If wire B is levitating with the magnetic force balancing the gravitational force, which direction does the current flow in wire B?

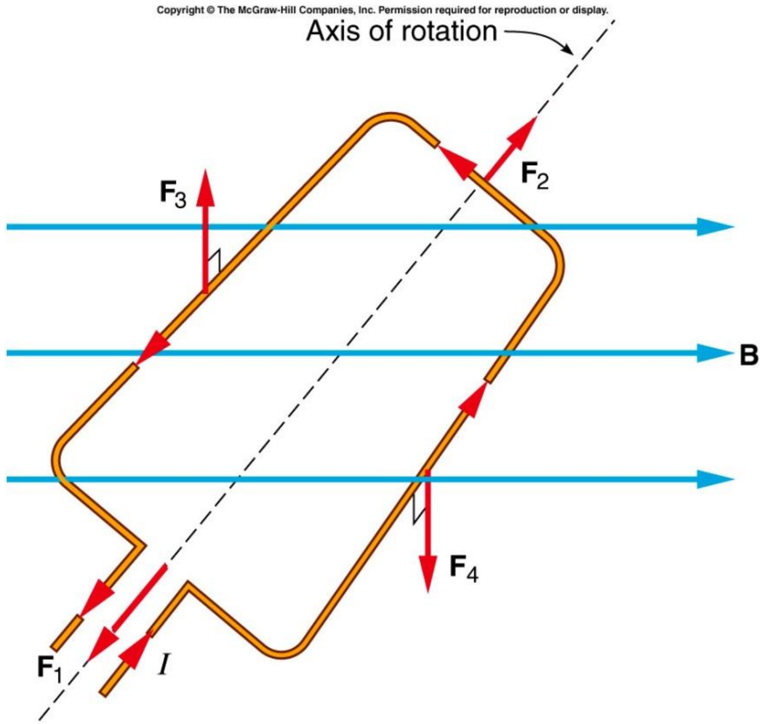
A) To the right
B) To the left
C) There is not enough information to decide.

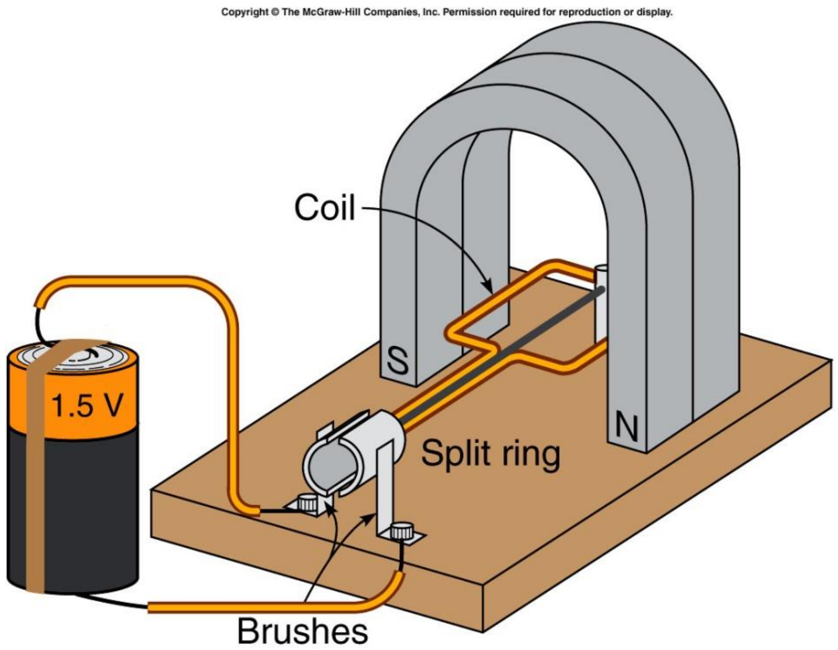


Problem: Two long parallel wires are carrying currents in the same direction. Wire A carries a current of 150 A and is held firmly in position. Wire B carries I_B and is allowed to slide freely up and down parallel to A between a set of nonconducting guides. If the linear mass density of B is 0.010 kg/m, what value of the current I_B will result in wire B levitating when the distance between the conductors is 2.5 cm?



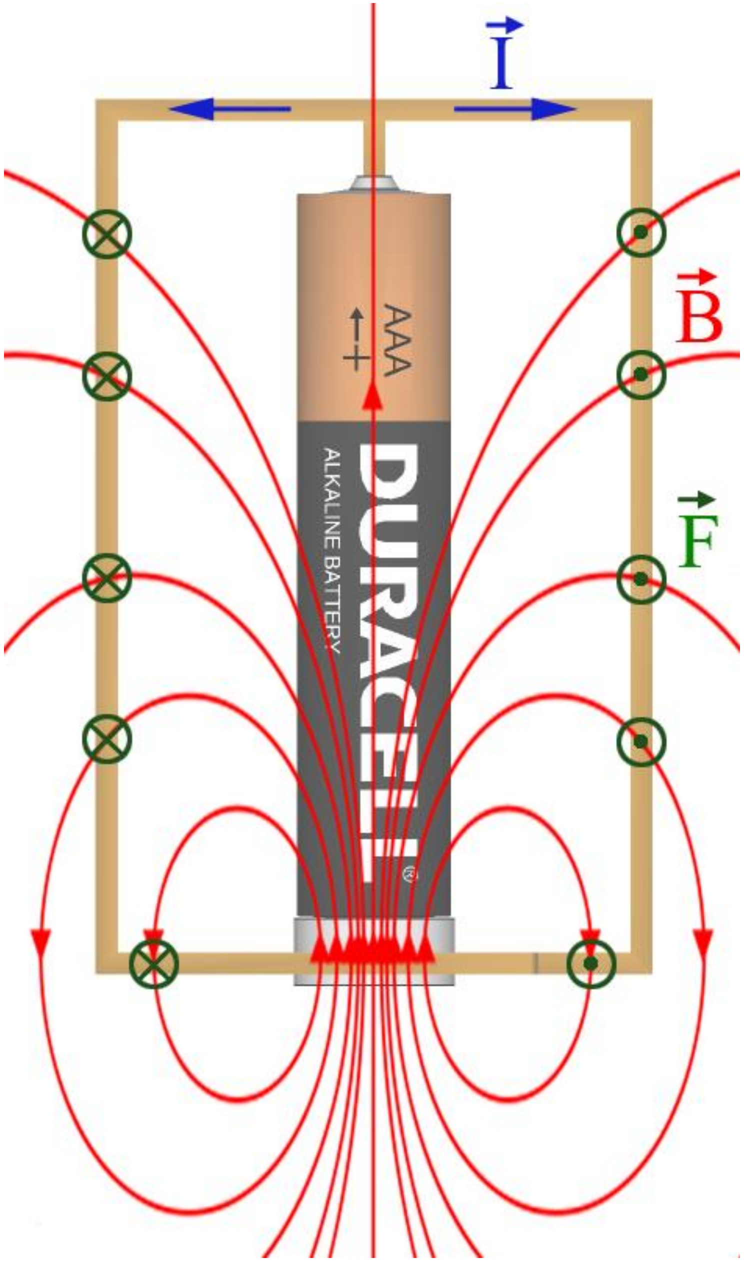
Magnetic Fields Produce a Torque (Rotation) on Current Carrying Wire Loops





This is how an electric motor works. Simply run current through a loop of wire in a magnetic field which causes the loop of wire to rotate due to the magnetic forces on the wire.

Homopolar Motor

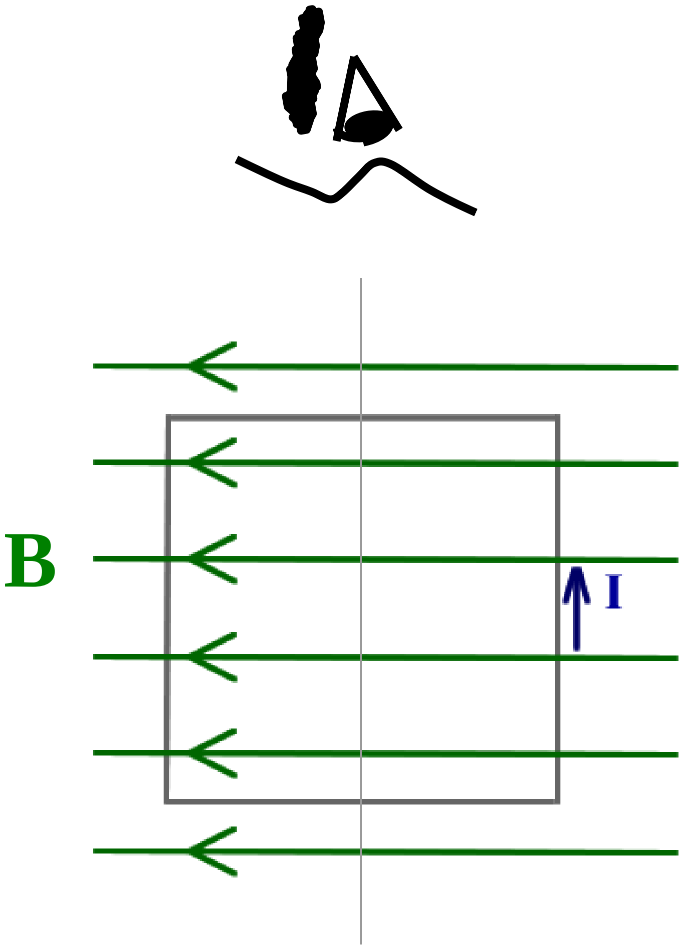


Neodymium
(strong) magnet

Interactive Question

A current loop is placed in a magnetic field as indicated. Will the loop tend to rotate (viewed from above) clockwise, counter-clockwise, or not at all about a vertical axis?

A) Clockwise
B) Counter-clockwise
C) Not at all



Interactive Question

A current loop is placed in a magnetic field as indicated. Will the loop tend to rotate (viewed from above) clockwise, counter-clockwise, or not at all about a vertical axis?

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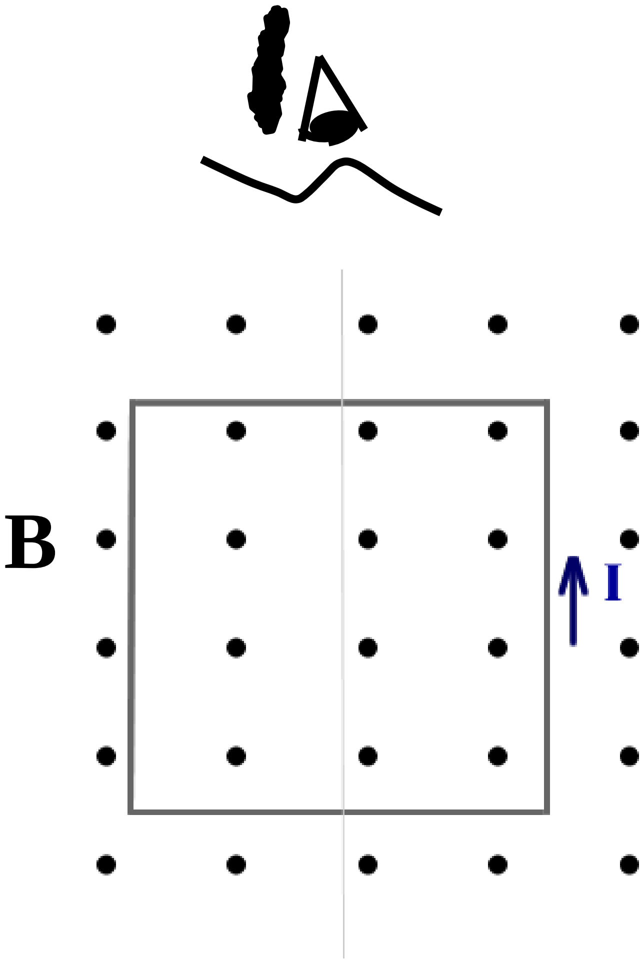


Electromagnetic Induction and Faraday's Law

One of the most important principles that allows us to effectively use electricity was discovered by Michael Faraday. Faraday asked the question, "If electric currents produce magnetic fields, can magnetic fields produce electric currents. The answer turned out to be, "No." But Faraday discovered that *changing* magnetic fields can produce electric currents. Faraday's law states

A changing magnetic flux induces an emf (voltage difference).

To use this law, we need to answer a few questions:

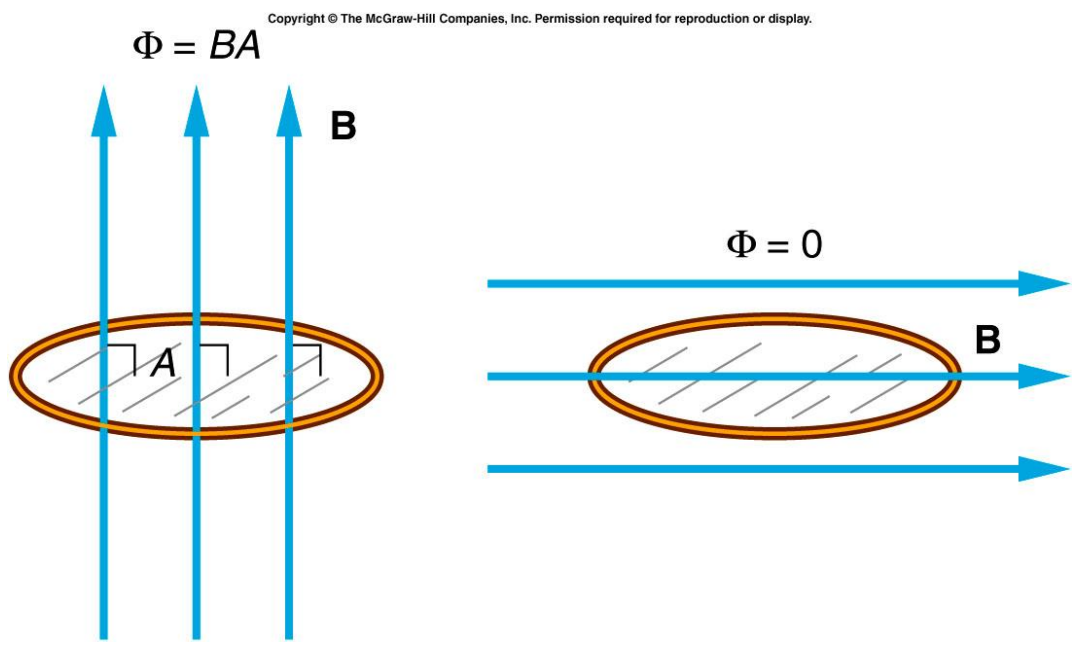
- What is a magnetic flux?
- How do you change it?
- What are the consequences of the induced emf?

Definition of Magnetic Flux

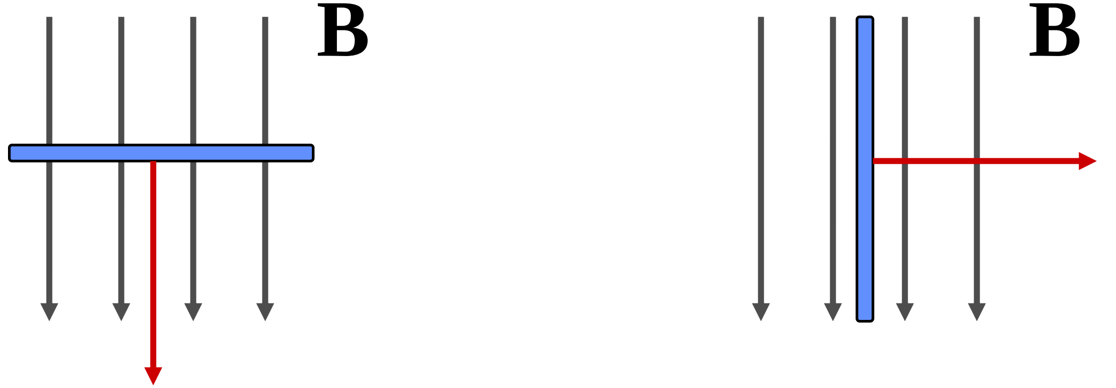
Magnetic flux (Φ) is a measure of how much magnetic field is passing through a loop of wire. SI units = Weber (Wb). It is at a maximum when the field lines are perpendicular to the plane of the loop, and it is zero when the field lines are parallel to the plane of the loop.

$$\boxed{\Phi = NBA}$$

- N is the number of loops of wire
- B is the strength of the magnetic field
- A is the area of the wire loop



Problem: A loop of wire with a radius of .50 m is placed in a magnetic field of .60 Tesla. What is the flux through the wire loop when the face of the loop is (a) perpendicular to the magnetic field, (b) parallel to the magnetic field, (The figure is the view looking down on the wire loop)



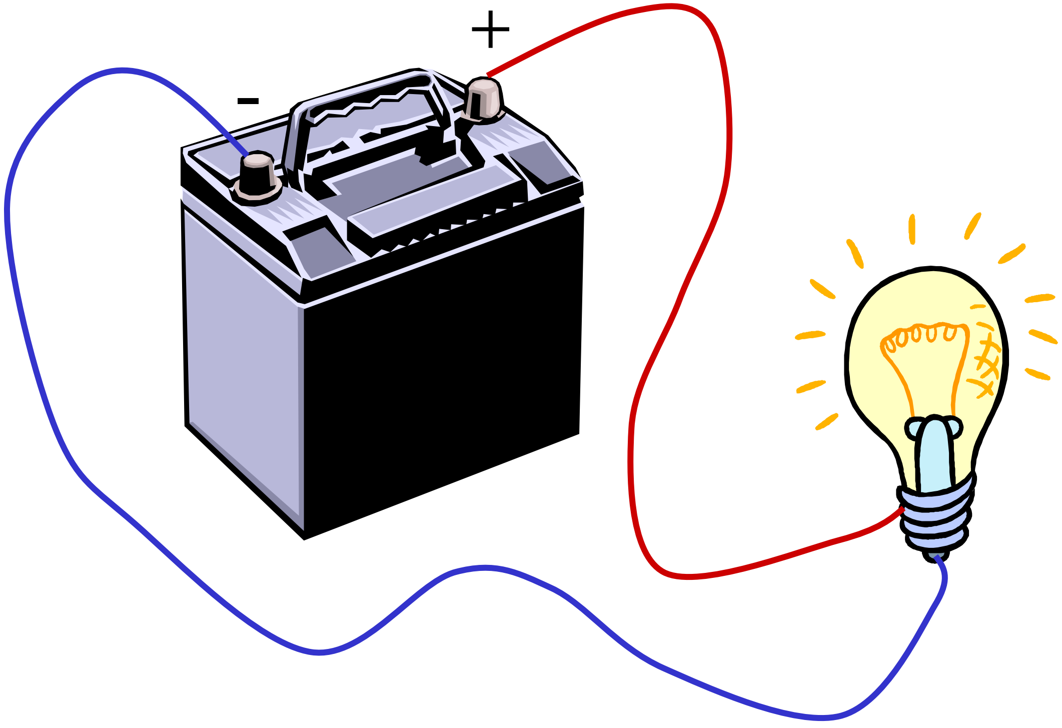
(a) (b)

How can we change the magnetic flux?

$$\Phi = BA$$

1. Change the area, *A*
2. Change the strength of the field, *B*
3. Rotate the wire so that the magnetic field doesn't go through it

What are the consequences of the induced emf (or potential difference)?



So simply changing the magnetic flux creates a potential difference that can produce electricity! This is one practical use of Faraday's law

Faraday's Law gives the magnitude of the induced emf

$$\mathcal{E} = \Delta \Phi / \Delta t$$

$\mathcal{E}$: The induced potential difference

$\Delta \Phi / \Delta t$ is the changing magnetic flux in a certain time

Lenz's Law gives the direction of the induced emf

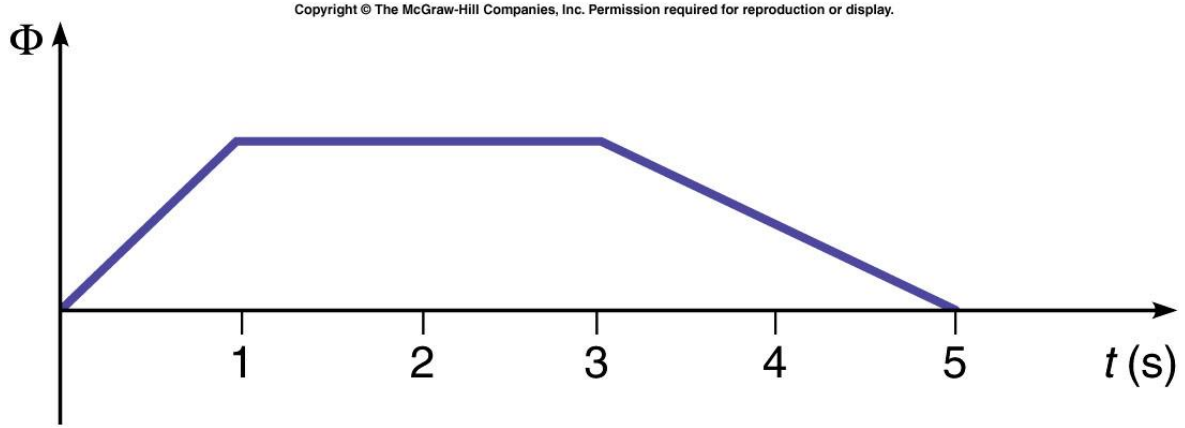
The induced emf always acts to oppose the changing magnetic flux.

Problem: A coil of 200 turns is wrapped on an 18.0 cm by 18.0 cm frame. A magnetic field that is perpendicular to the plane of the coil is change from 0.0 to 0.500 T in 0.800 s. Find the magnitude of the induced voltage

Interactive Question

Suppose that the magnetic flux through a coil of wire varies with time as shown. Where does the induced voltage have its largest magnitude?

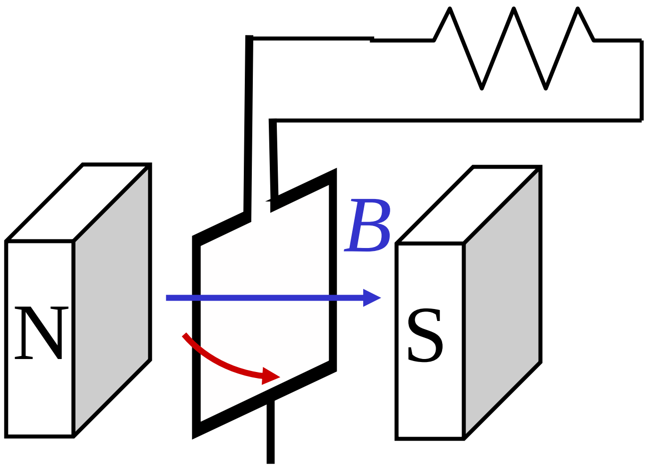
A) From 0 s to 1 s
B) At 1 s
C) From 1 s to 3 s
D) At 3 s
E) From 3 s to 5 s

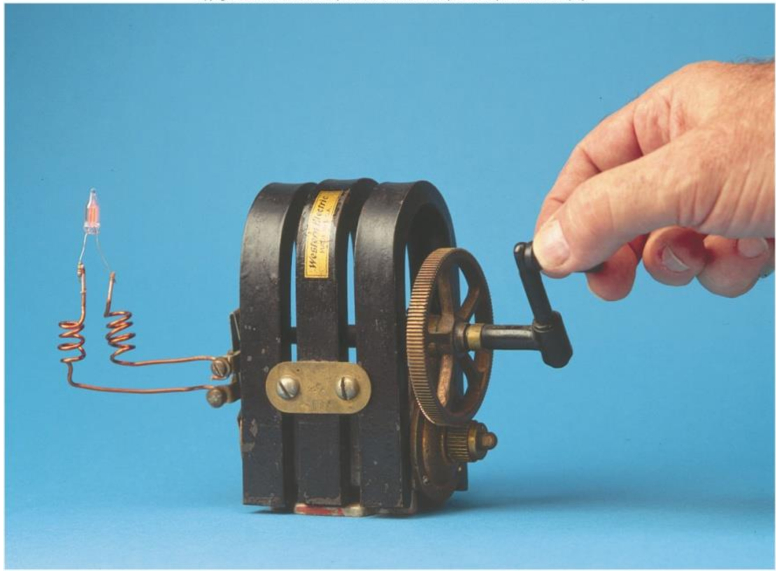


The Electric Generator

A generator converts mechanical energy to electrical energy by electromagnetic induction.

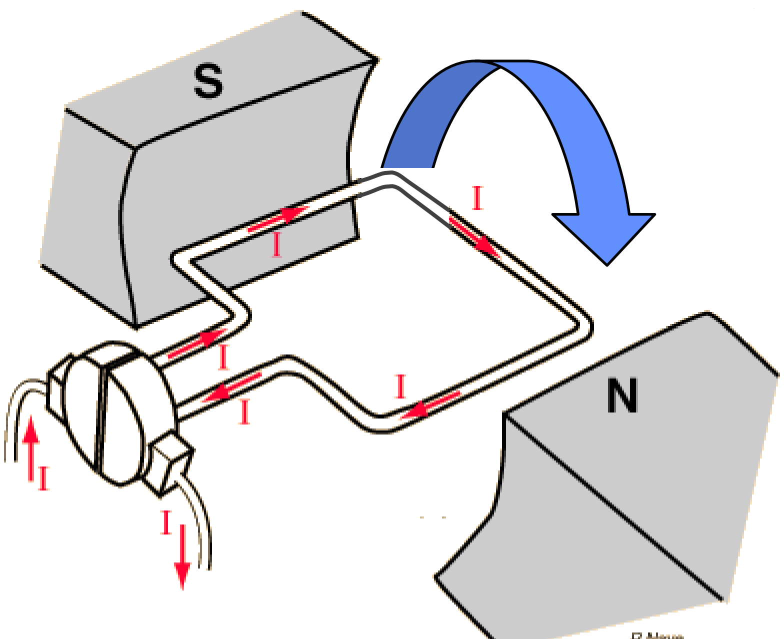
- A simple generator consists of a coil of wire between the pole faces of a permanent magnet.
- The coil's rotation causes the magnetic flux through the coil to change continuously.
- This changing flux produces a voltage difference that can be used to create a current.
- Although it depends on the construction, most generators produce ac current



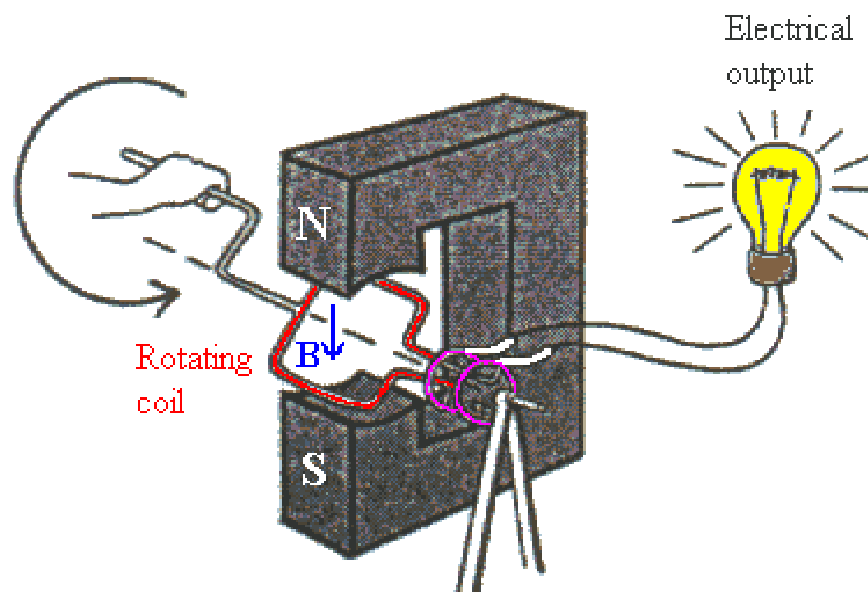


Notice the similarity

Electric Motor: Run a current through a loop of wire in a magnetic field to make the loop turn. (Current in – loop turns)

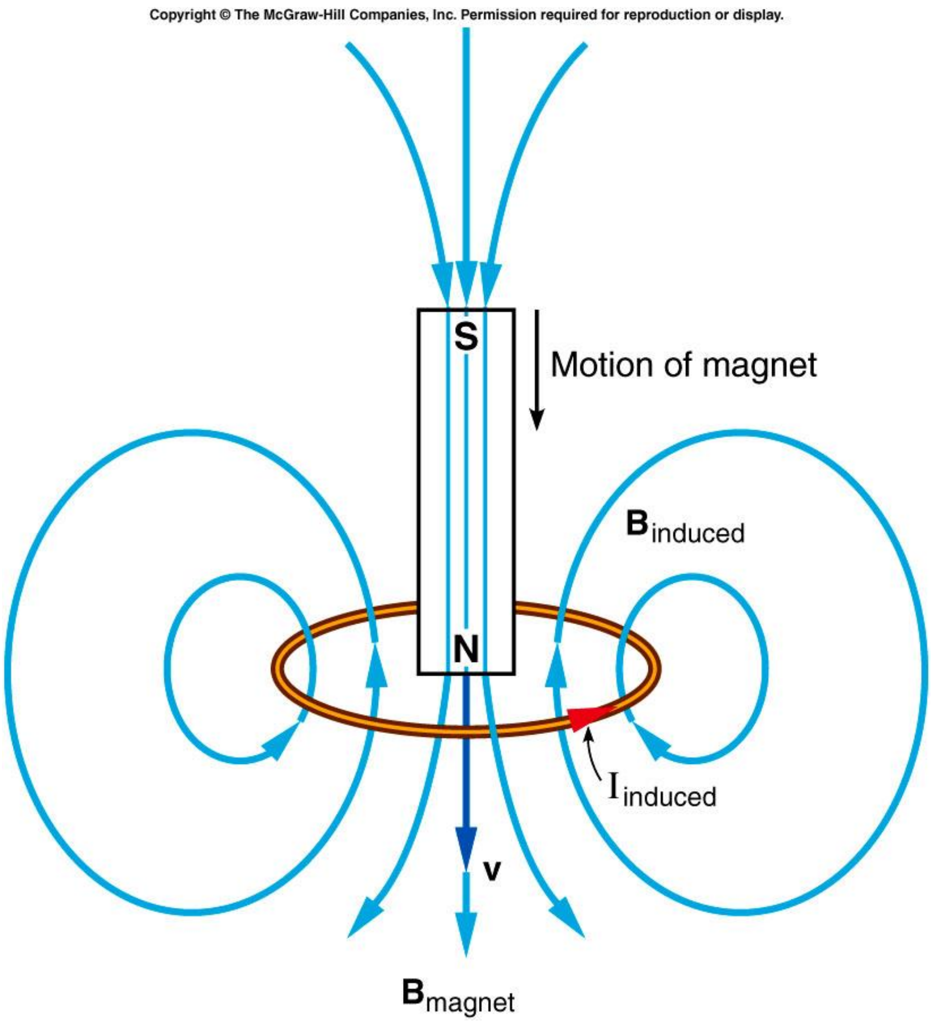


Electric Generator: Using some mechanism, turn a loop of wire in a magnetic field to produce a current. (Turn the loop – current out)



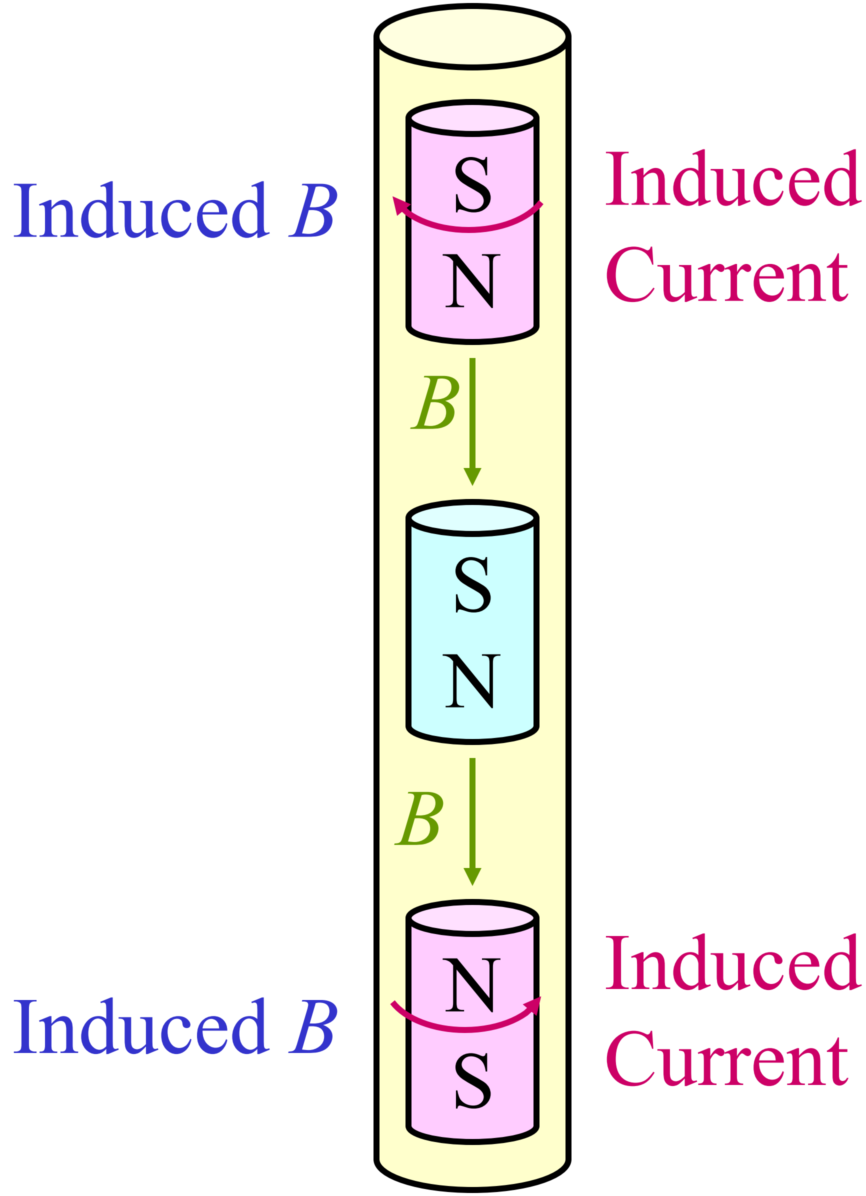
Lenz's Law

The direction of the induced current generated by a changing magnetic flux produces a magnetic field that opposes the change in the original magnetic flux. If the flux is increasing the induced current tries to decrease the flux, and vice versa.



Induced/Eddy Currents

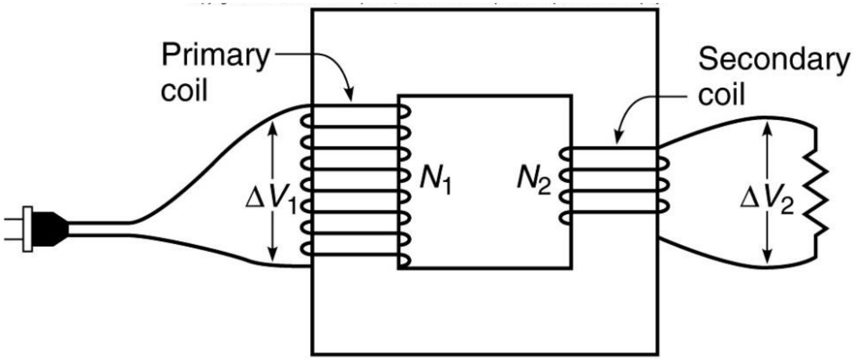
An eddy current is the name given to the current in a conductor due to an induced emf caused by a changing magnetic flux. In many cases, eddy currents do not move through wires, but just through metal plates, tubes, etc.



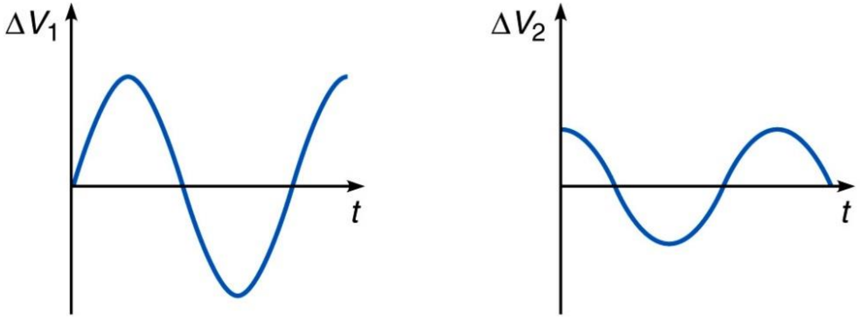
Transformers

- A transformer adjusts the voltage of an ac circuit up or down as needed for a particular application.
- Transformers only work with ac voltage/current.
- Generators and transformers allow alternating current to be used conveniently for large-scale power production and distribution.

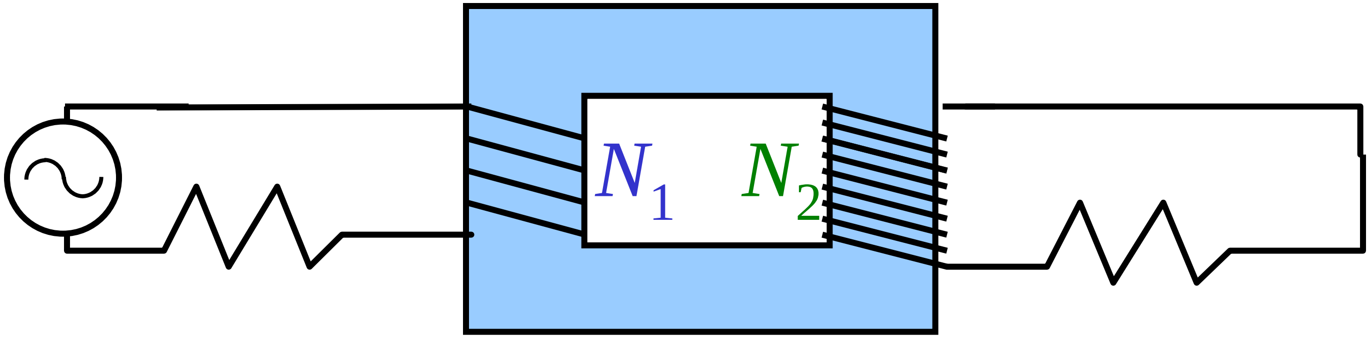
$$\frac{N_1}{\Delta V_1} = \frac{N_2}{\Delta V_2}$$



Transformers can step up (increase) or step down (decrease) the voltage. The power doesn't change, though.



Transformers and Energy



$N_1/\Delta V_1 = N_2/\Delta V_2$

Energy (power) must be conserved. You don't get something for nothing.

When the voltage decreases, the current increases, and vice verse so that the power stays the same.

$P_1 = P_2$

$I_1 \Delta V_1 = I_2 \Delta V_2$

Problem: The input to the primary coil of a transformer is 120 V while the current in the secondary coil is 0.10 A.

(a) When 60.0 W of power are delivered to the circuit attached to the secondary coil, what is the voltage across this coil?

(b) If the primary coil has 20 turns, how many does the secondary coil have?

Problem: Suppose 1 MW of power is being transported over a power line that has a resistance of 20.0 Ω. How much power is lost along the line if the voltage of the line is (a) 240 V (b) 24,000 V?

$$P_R = I\Delta V_R = I^2R$$

$$P = I\,\mathcal{E}$$