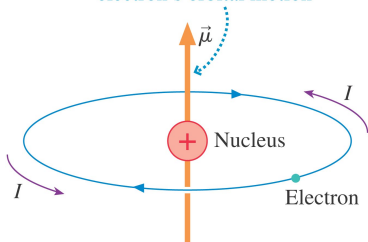


Magnetic Properties of Matter

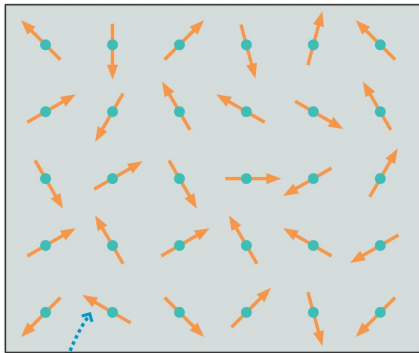
Magnetic moment due to the electron's orbital motion



- Now it is time to use what we have learned to explain the properties of permanent magnets.
- The orbital motion of atomic electrons resembles a current loop! Apparently every little atom is an electromagnet!

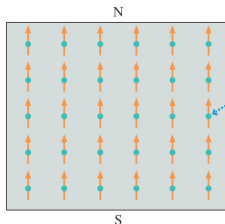
- However, most atoms have many electrons with some moving clockwise and some counter-clockwise. So, the net magnetic moment is close to zero.
- In 1922 it was discovered that electrons themselves have an intrinsic magnetic moment called **spin**. Each electron is really a microscopic bar magnet.
- In most substances these little bar magnets are randomly oriented with respect to each other.

Spin and Ferromagnetism



The atomic magnetic moments due to unpaired spins point in random directions. The sample has no net magnetic moment.

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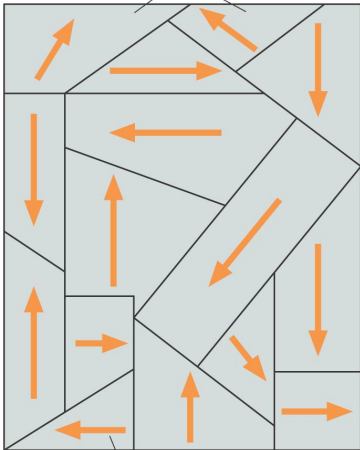


The atomic magnetic moments are aligned. The sample has north and south magnetic poles.

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Induced Magnetic Dipoles

Magnetic domains



Magnetic moment of the domain

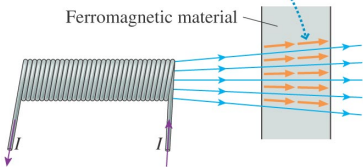
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- Iron is a magnetic material but not all iron acts like a magnet. **Magnetic domains** form inside the iron.
- Each domain (0.1 mm) is a strong magnet but they are randomized with respect to each other.

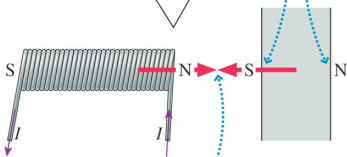
Induced Magnetic Dipoles

The magnetic domains align with the solenoid's magnetic field.

Ferromagnetic material



The induced magnetic dipole has north and south magnetic poles.



The attractive force between the opposite poles pulls the ferromagnetic material toward the solenoid.

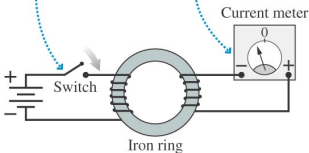
- We can line-up the domains using an electromagnet. This is an **induced magnetic dipole**.
- We have made a chunk of iron into a permanent magnet.

Chapter 34: Electromagnetic Induction

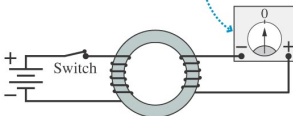
- We are done with Chapter 33 - time to move on to **electromagnetic induction**.
- We have seen that moving charges (currents) induce a magnetic field. It is natural to wonder if you can use a magnetic field to induce a current.
- In terms of practical impact, the discovery of how to do this must be highly ranked in terms of the great discoveries of the 19th century.
- The age of electricity depends on induced currents. Further, devices we use every day (eg. magnetic storage) are not possible without it.
- Worth spending our last couple of classes on...

Faraday's Discovery

Closing the switch ... causes a momentary current in the right circuit.

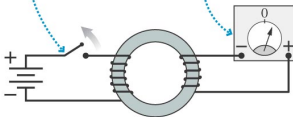


No current flows while the switch stays closed.



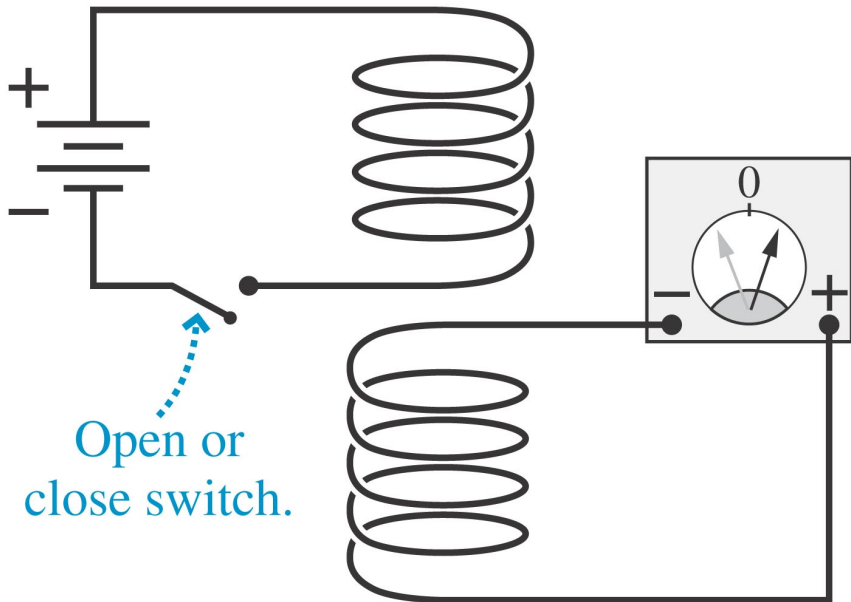
Opening the switch ...

... causes a momentary current in the opposite direction.

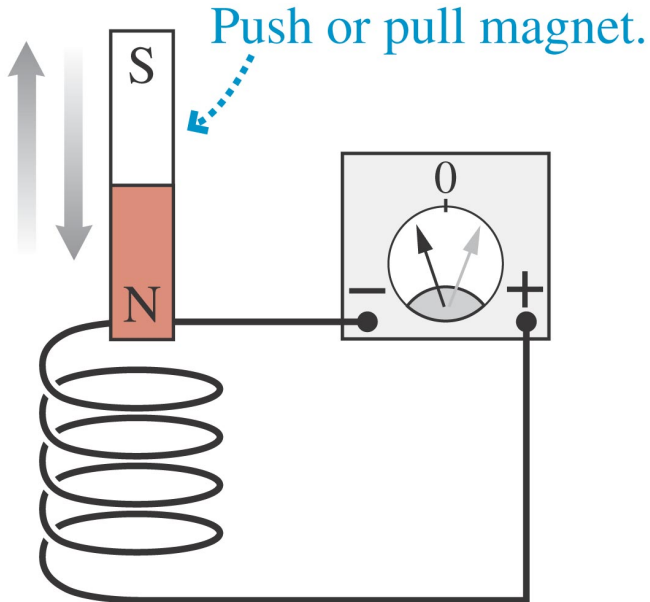


- Faraday set up the experiment on the left.
- He was attempting to use the left-most circuit to magnetize the iron ring, which he thought would induce a current on the right-most coil. It didn't work.
- However, he noticed that he got a small current just at the moment he either turned the circuit on or off. Apparently the **change** in magnetic field induced the current.
- He set up a series of experiments to test this.

Faraday's Discovery

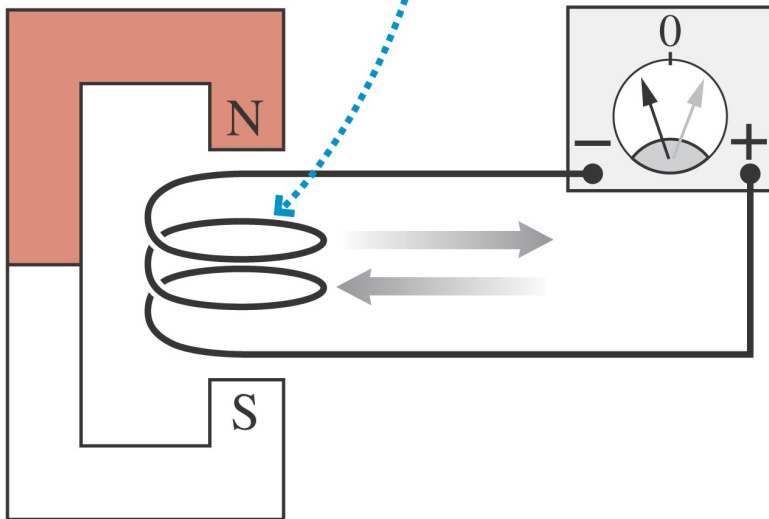


Faraday's Discovery



Faraday's Discovery

Push or pull coil.

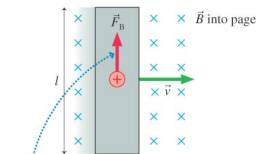


Faraday's Law

- So, Faraday discovered that there is only current in the coil in the magnetic field through the coil is changing.
- It doesn't matter whether the change is “turning on” or “turning off” or changing direction or strength. The change is the important thing.
- We call this an **induced current**

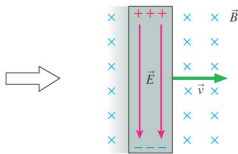
Motional EMF

- An induced current can be created by
 - ① changing the size or orientation of a circuit in a stationary magnetic field
 - ② changing the magnetic field through a stationary circuit
- Consider moving a conductor of length L through a magnetic field \vec{B} at velocity \vec{v} .
- The force on a charge inside is $\vec{F} = q\vec{v} \times \vec{B}$

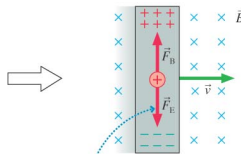


Charge carriers in the wire experience an upward force of magnitude $F_B = qvB$. Being free to move, positive charges flow upward (or, if you prefer, negative charges downward).

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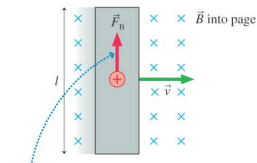


The charge separation creates an electric field in the conductor. \vec{E} increases as more charge flows.



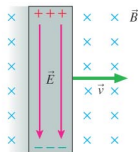
The charge flow continues until the downward electric force \vec{F}_E is large enough to balance the upward magnetic force \vec{F}_B . Then the net force on a charge is zero and the current ceases.

Motional EMF

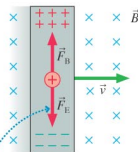


Charge carriers in the wire experience an upward force of magnitude $F_B = qvB$. Being free to move, positive charges flow upward (or, if you prefer, negative charges downward).

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The charge separation creates an electric field in the conductor. \vec{E} increases as more charge flows.



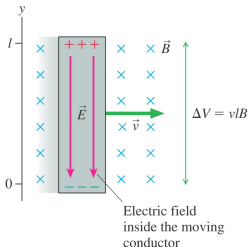
The charge flow continues until the downward electric force \vec{F}_E is large enough to balance the upward magnetic force \vec{F}_B . Then the net force on a charge is zero and the current ceases.

- The force on the charges cause positive charges to move to the top and a potential difference to exist between top and bottom.
- They stop accumulating at the top when the electric repulsive forces balance the magnetic force pushing the charges.
- The potential difference is

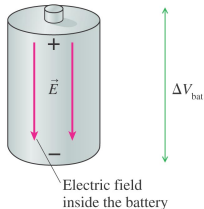
$$\Delta V = V_{top} - V_{bottom} = - \int_0^l E_y dy = - \int_0^l (-vB) dy = vLB$$

Motional EMF

- (a) Magnetic forces separate the charges and cause a potential difference between the ends. This is a motional emf.



- (b) Chemical reactions separate the charges and cause a potential difference between the ends. This is a chemical emf.

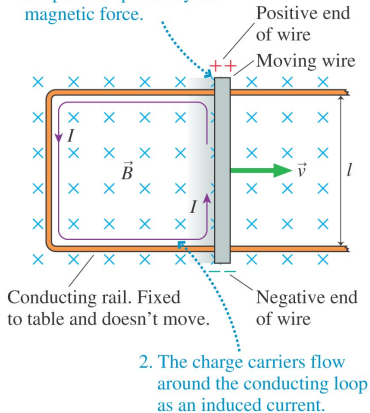


- For a battery we use a charge escalator model for **chemical emf**
- Now we can also generate a potential difference from mechanical energy - **motional emf**
- The motional emf created by a conductor of length L moving with velocity v perpendicular to a magnetic field B is

$$\mathcal{E} = vLB$$

Induced Current in a Circuit

1. The charge carriers in the wire are pushed upward by the magnetic force.



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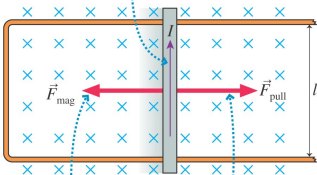
- Now we should include that moving conductor in a circuit!
- If we hook-up a conducting rail we can get a current flowing through the circuit.
- The current induced in the circuit of resistance R is given by Ohm's Law as

$$I = \frac{\mathcal{E}}{R} = \frac{vLB}{R}$$

(induced by magnetic forces on moving charges - charges moving left to right)

Induced Current in a Circuit

The induced current flows through the moving wire.



The magnetic force on the current-carrying wire is opposite the motion.

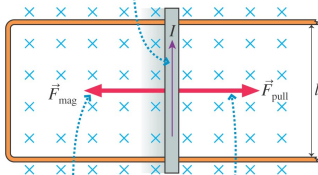
A pulling force to the right must balance the magnetic force to keep the wire moving at constant speed. This force does work on the wire.

- We assumed the conductor was moving at constant velocity. However, there is a force opposing the motion!
- As the conductor moves through the magnetic field the charges inside are moved by the field, creating a current. However, that current is now a flow of charges from bottom to top in a magnetic field!!

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Induced Current in a Circuit

The induced current flows through the moving wire.



The magnetic force on the current-carrying wire is opposite the motion.

A pulling force to the right must balance the magnetic force to keep the wire moving at constant speed. This force does work on the wire.

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- Now we do another $q\vec{v} \times \vec{B}$ with the direction of \vec{v} being along the conductor. The force works against the motion.
- If you reverse the direction (turn your pull into a push) then the new magnetic force also turns around. It always is opposite to the motion and has magnitude

$$F_{\text{pull}} = F_{\text{mag}} = ILB = \left(\frac{vIB}{R} \right) LB = \frac{vL^2 B^2}{R}$$

Energy Considerations

- Of course, to keep the conductor moving we have to supply energy. How much?
- Let's do it in terms of power. The power exerted by a force pushing or pulling an object with velocity v is $P = Fv$, so the power is

$$P_{input} = F_{pull}v = \frac{v^2 L^2 B^2}{R}$$

- How much energy is dissipated by the circuit?

$$P_{dissipated} = I^2 R = \frac{v^2 L^2 B^2}{R}$$

- Energy is conserved!