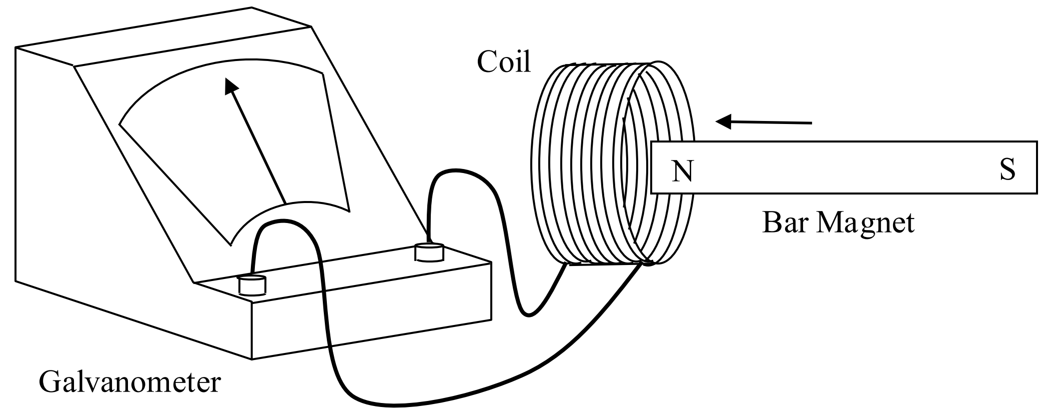
Magnetic Induction
&
Faraday’s Law

Experiment #1

Consider a wire coil connected to a galvanometer (which is a sensitive current measuring device.



Move a magnet slowly into the coil. Observe the meter.
Hold the magnet stationary in the coil. Observe the meter.
Slowly back the magnet out. Observe the meter.
Repeat with reversed polarity of the magnet.
Repeat moving the magnet more quickly.

Results of Experiment #1

- Current appears ONLY when there is relative motion between the loop and the magnet (i.e., when either moves toward or away from the other).
- The current vanishes when the motion ceases.
- Faster motion produces greater current.
- An approaching N-pole toward the loop and a receding N-pole from the loop produce opposite currents.
- Moving a S-pole toward and away also produces currents, but in reversed direction as compared to the N-pole.

Experiment #2

Instead of a bar magnet, have a second coil that is connected to a power source via a switch. Place this second coil near the first coil that is still connected to the galvanometer.

Close the switch to power coil 2. Observe the meter.

Keep the switch closed. Observe the meter.

Open the switch to disengage coil 2. Observe the meter.

Results of Experiment #2

- Induced current appears ONLY when the current in the powered coil is changing (i.e., turning "on" or turning "off").
- There is no induced current when the current in the powered coil is constant.
- Turning "on" and turning "off" produce opposite currents.
- Reversing the direction of the current in the power coil produces induced currents in the opposite.

Summarizing Results of Experiments

- The induced current (& induced EMF) is apparently caused when the "amount of magnetic field" passing through the coil changes.
- The "amount of magnetic field" (which can be thought of as the # of magnetic field lines) passing through the loop is just the *magnetic flux*, Φ_B.

Qualitative punchline:

An EMF (and therefore a current) is induced in a conducting loop when the magnetic flux passing through that loop changes.

Faraday's Law & Lenz's Law

Faraday's Law:

The EMF induced in a closed conducting loop is determined by the rate at which the magnetic flux through the loop changes.

That is: $\varepsilon = -\frac{d\Phi_B}{dt}$,

where the magnetic flux: $\Phi_B = \int \vec{B} \cdot d\vec{A}$.

The minus sign comes from Lenz's law:

The induced current will have a direction such that the magnetic field due to the induced current opposes the change in magnetic flux that induced that current.

General ways to change Φ_B through a coil:

1. Change the magnitude of the $\vec{B}$-field within the coil.

$$\varepsilon = -\frac{d\Phi_B}{dt} = -A\frac{dB}{dt}$$

2. Change the area of the coil or the portion of the area within the $\vec{B}$-field.

$$\varepsilon = -\frac{d\Phi_B}{dt} = -B\frac{dA}{dt}$$

3. Change the angle between $\vec{B}$ and the area of the coil.

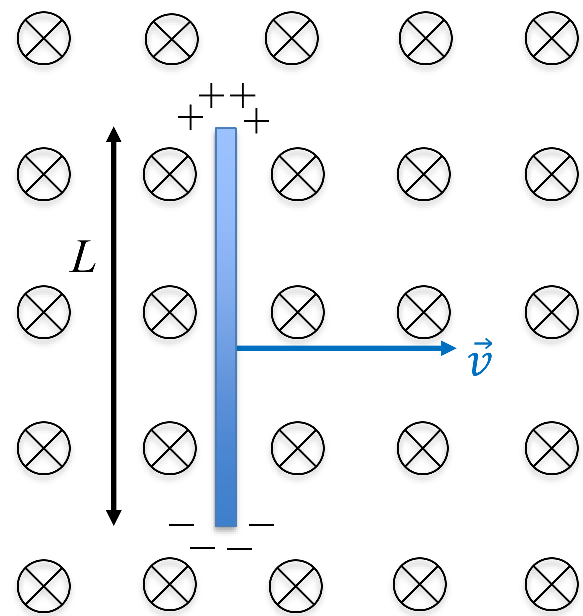
$$\varepsilon = -\frac{d\Phi_B}{dt} = -B\frac{dA}{dt} = -BA\frac{d}{dt}(\cos[\theta(t)])$$

4. Perform any combination of the ways described above.

$$\varepsilon = -\frac{d\Phi_B}{dt} = -(B\frac{dA}{dt} + A\frac{dB}{dt})$$

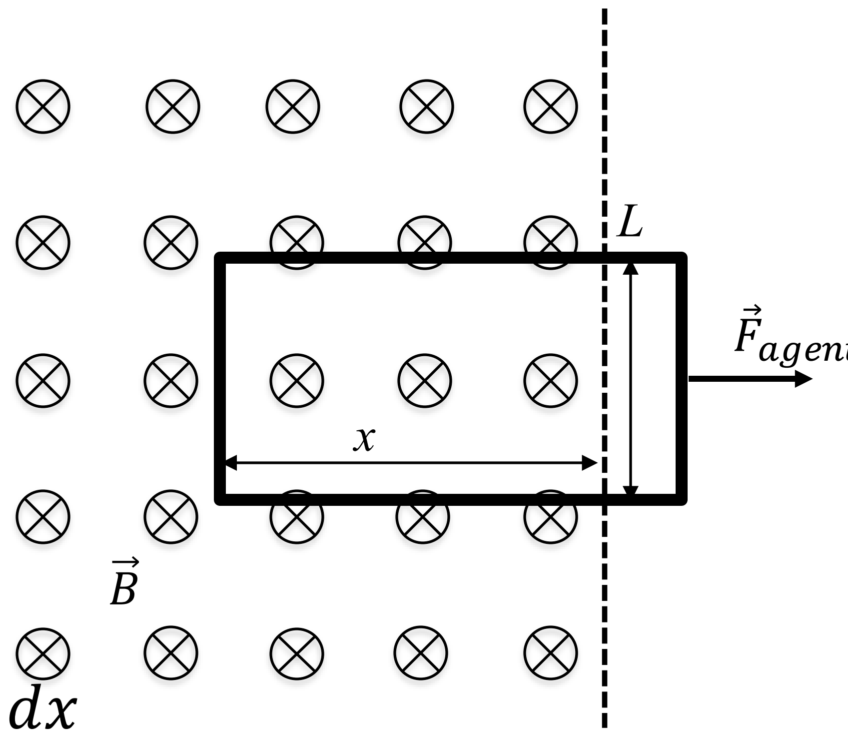
Motional EMF

A conducting bar is pulled through a uniform magnetic field as shown. (Free) electrons in the metal moving through the magnetic field experience a (downward) force leaving resulting in a charge separation of the bar with (+) charges at the top and (–) charges at the bottom: $\vec{F}_B = -e(\vec{v} \times \vec{B})$.



This continues until the electric force opposing the the charge separation balances the magnetic force creating the charge separation: $F_E = F_B$. Then, $eE = evB$. The result is a potential difference $\Delta V = EL$ across the bar. With $E = vB$, then $\Delta V = BvL$.

Induction & Energy Transfer



Consider a conducting loop being pulled out of a magnetic field by some external agent. The agent is doing work to pull the loop out. (Why?)

The rate at this work is done is the power output of the agent.

$$P = \frac{dW}{dt} = F\frac{dx}{dt} = Fv$$

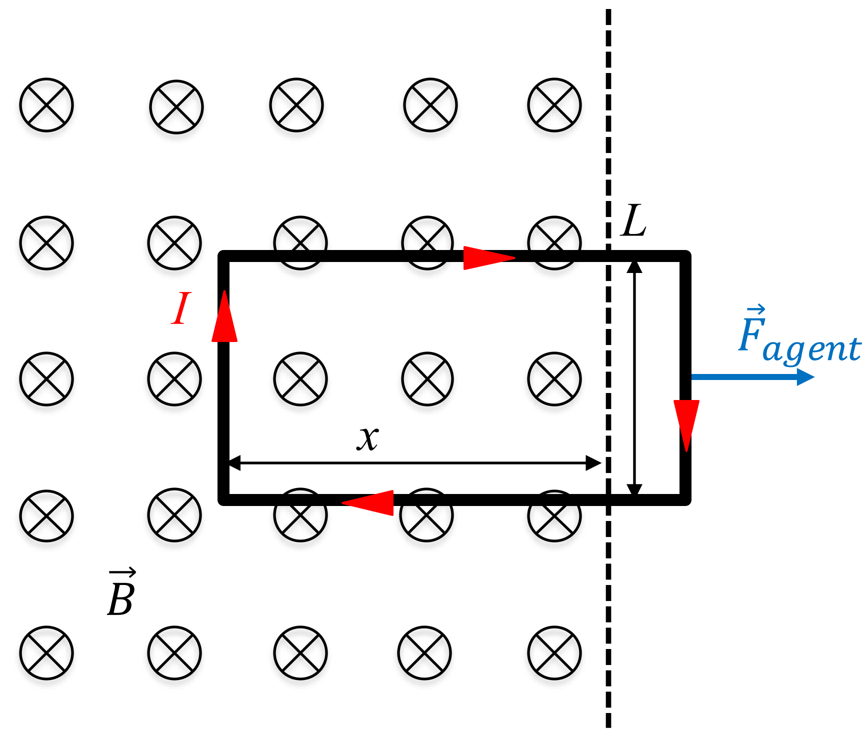
Note that $\Phi_B = \int \vec{B} \cdot d\vec{A} = BA = BLx$

and is decreasing (into the screen).

Induction & Energy Transfer (cont'd)

$$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BLx) = -BL\frac{dx}{dt} = -BLv$$

The (–) sign reminds us that the induced EMF in the loop opposes the change in Φ_B. Since Φ_B out of the screen through the loop is decreasing as the loop moves out of the field, this EMF generates a clockwise current, I , in the loop given by $I = \frac{|\varepsilon|}{R} = \frac{BLv}{R}$, where R is the resistance of the loop.

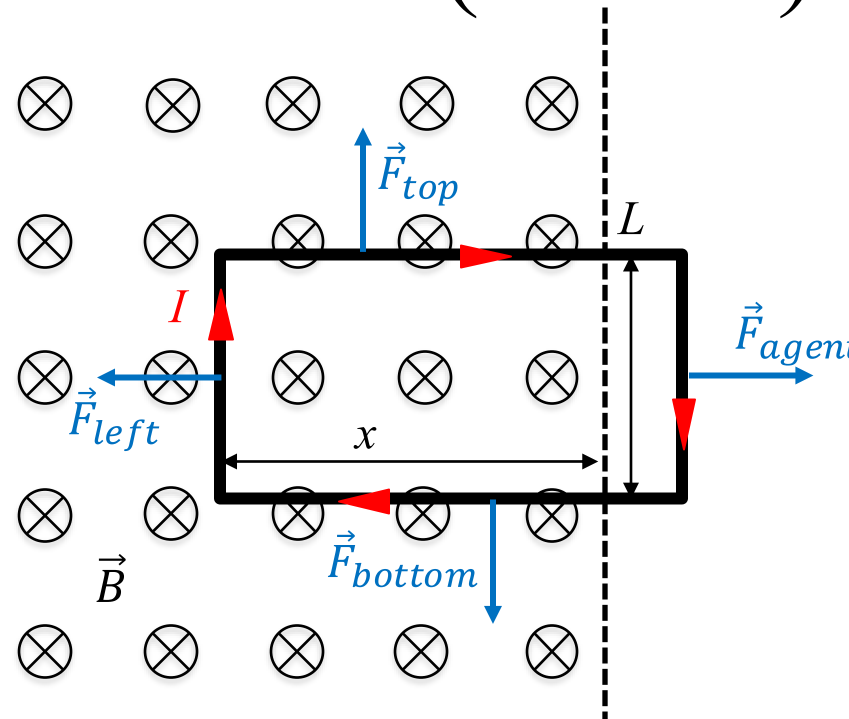


Induction & Energy Transfer (cont'd)

The left segment of the loop experience a magnetic force, $\vec{F} = I\vec{L} \times \vec{B} = ILB$ to the left.

The top and bottom segments of the loop experience opposite forces and cancel out.

Only $\vec{F}_{left}$ opposes $\vec{F}_{agent}$.



To pull the loop out of the field at a constant speed, $|\vec{F}_{agent}| = |\vec{F}_{left}|$.

Power expended = $F_{agent}v = IBLv = \left(\frac{BLv}{R}\right) BvL = \frac{B^2L^2v^2}{R} = I^2R$.

That is, the rate at which the agent does work to pull the loop of the $\vec{B}$-field equals the rate at which thermal energy appears in the loop.