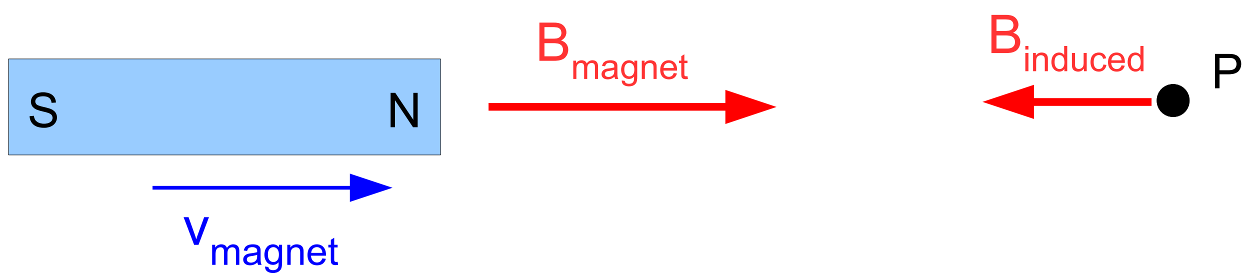
ELECTROMAGNETIC INDUCTION

Electromagnetic Induction

- Magnetic fields resist changes to their state
  - Similar to a large mass resisting changes in velocity
- When a change is made to a B field
  - A new B field is "induced" → direction opposes change
  - Any moving magnet feels a resisting force



B_{magnet} is getting stronger at point P

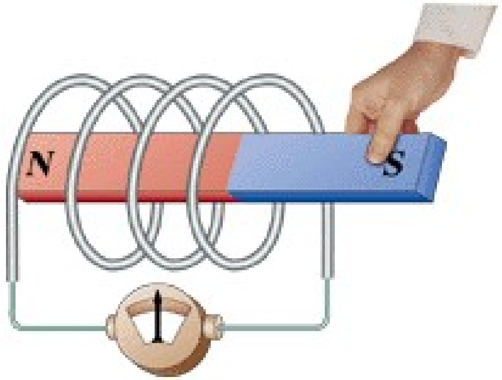
Therefore $B_{induced}$ opposes B_{magnet}

- This process is called electromagnetic induction
  - The resisting nature of the force is called "Lenz's Law"

Induced Current

- Does $B_{induced}$ have an electric current source?
  - Experiment: A moving magnet near a conducting metal
  - $B_{induced}$ is stronger due to induced current in the metal
  - Conclusion: Changing B field → electric current → $B_{induced}$

- Can now produce current without a battery!

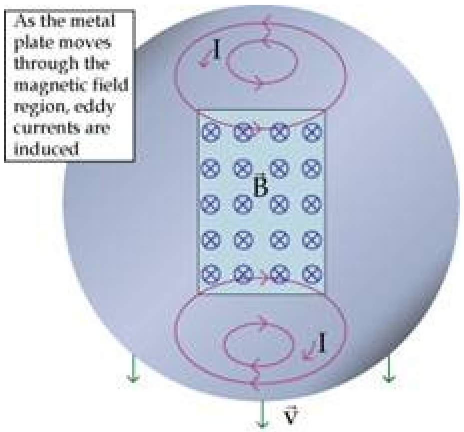


This is called "alternating current" (AC) because the current switches direction...

Batteries produce direct current (DC), which moves in a constant direction

Eddy Currents

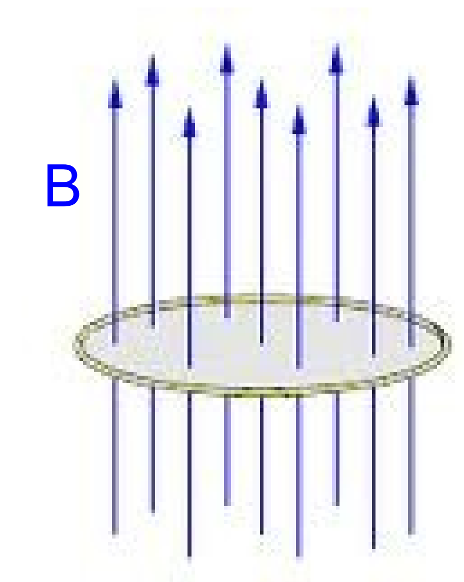
- Current can be induced in any conducting material
  - Not just iron, and not just wire loops!



- Induced currents resemble "whirlpools"
  - And are called "eddy" currents
- Metal detectors
  - Move an electromagnet past a metal
  - And detect the eddy currents

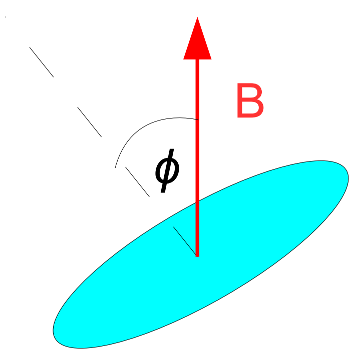
Magnetic Flux

- To calculate the induced current in a wire loop:
  - Must measure the changing B field around the whole loop
  - Mathematically, there is a simpler way:



- Magnetic Flux (ϕ_B)
  - Measure of how B field penetrates a loop

$$\Phi_B = B_\perp A = B A \cos(\phi)$$



  - Unit: 1 Weber (W) = 1 T m^2

Faraday's Law

- General rule covering electromagnetic induction

- Changing magnetic flux produces an EMF
  - Which can produce a current (if a conductor is nearby)
  - EMF measured in Volts (but no actual ΔV – no battery)

$$\epsilon = \left| \frac{\Delta \Phi_B}{\Delta t} \right|$$

For a coil instead of a loop:

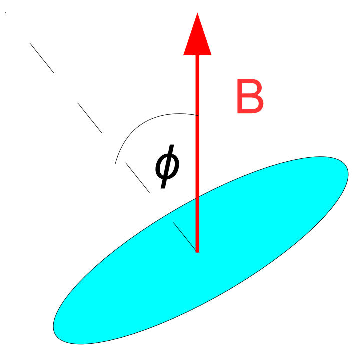
$$\epsilon = N \left| \frac{\Delta \Phi_B}{\Delta t} \right|$$

Ways to produce a changing magnetic flux:

1) Change strength of B field

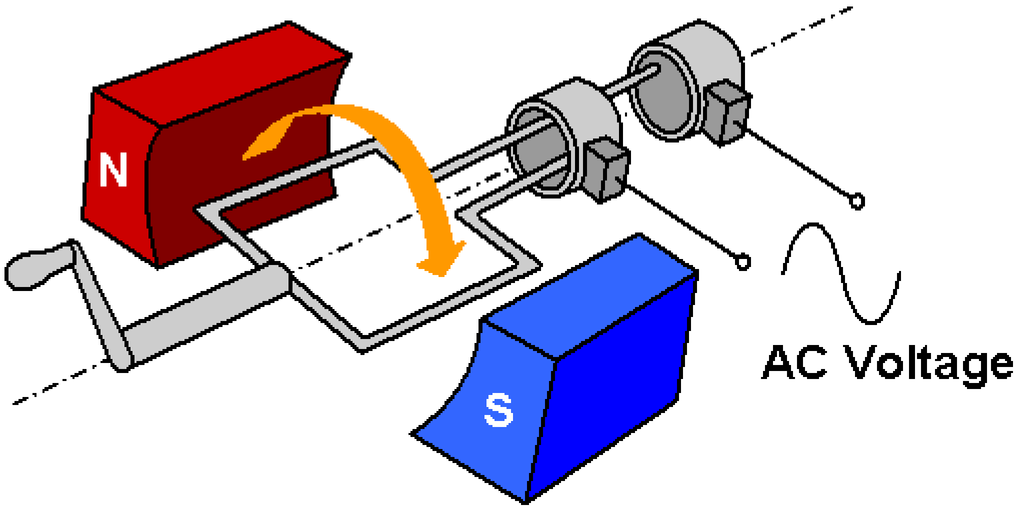
2) Change area of loop

3) Change the angle ϕ by rotating the loop



Generators

- Ingredients: Magnet, Wire loop/coil
  - Same ingredients as an electric motor!

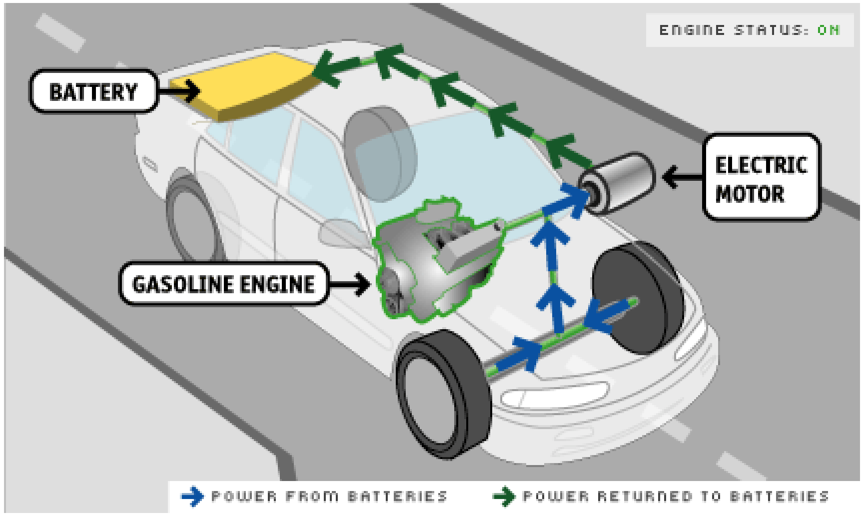


Changing flux through the loop/coil → EMF (pushes AC through the wires). Force to turn coil can be provided:

1) by hand
2) by pressure produced by burning fuel
3) by wind

Regenerative Braking

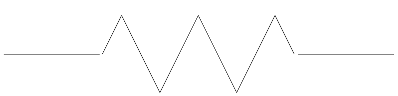
- Traditional (friction-based) brakes waste fuel
  - Braking: converts energy of burned fuel → heat
- Instead, we can save this energy in a battery
  - By using the spinning wheels as generators
- Electric cars and hybrids
  - Can use stored energy later...
  - ...to drive the car via a motor



Inductance

- Induced EMF (ε) for a loop or coil of wire
  - Depends on how quickly the current in the loop changes
  - And the "inductance" (L) of the loop/coil – Unit: Henry (H)
  - Compare a loop/coil with a resistor:

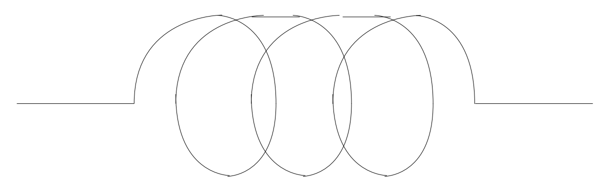
Resistors



$$I = \frac{V}{R} = \frac{\epsilon}{R}$$

(Current is proportional to EMF)

Wire loops/coils – "Inductors"



$$\frac{\Delta i}{\Delta t} = \frac{\epsilon}{L}$$

(Change in current is proportional to EMF)

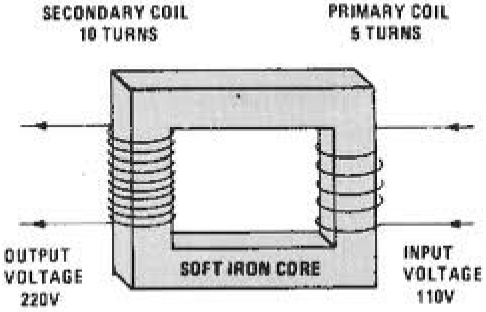
$$\epsilon = L\left|\frac{\Delta i}{\Delta t}\right|$$

Transformers

- Transporting electrical energy is inefficient
  - Due to long wires from power plant to destination
  - Long wire → large resistance → lots of heat loss

- Electrical power: $P_{\text{from power plant}} = VI$
  - For a given amount of power, there is some flexibility:
  - (Low Voltage, High Current) or (High Voltage, Low Current)

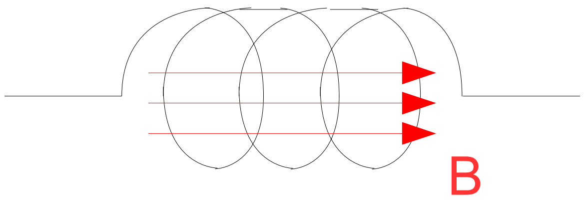
- Transformers
  - Convert (Low V, High I) to (High V, Low I)
  - Low I cuts down on heat loss
  - Low V safer for the end user



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

Storing Magnetic Energy

- Inductor can store energy in its B field
  - Similar to a capacitor storing energy in its E field



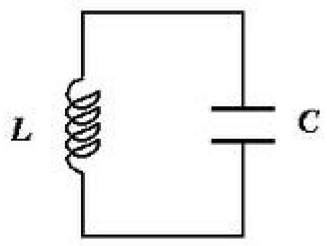
$$U = \frac{1}{2} L I^2$$

$$u = \frac{Energy}{Volume} = \frac{B^2}{2\mu_0}$$

- This energy resists abrupt changes
  - A light bulb in series with an inductor:
  - Will turn on slowly after switch is turned on
  - Will fade out slowly after switch is turned off

Electrical Oscillations

- Inductors and capacitors both store energy
  - Connect them → energy "oscillates" from one to the other
  - Just like KE and PE in a mass-spring system



- LC circuits are "electrical oscillators"
  - With a "resonance" angular frequency:

$$\omega = \sqrt{\frac{1}{LC}}$$

- Basis for our wireless communications
  - Radio, cell phones, bluetooth, wi-fi, etc.
  - Adjust L and/or C → can "tune" to a specific frequency