PHYS12 CH:20 The Invisible Force That Powers Your Life

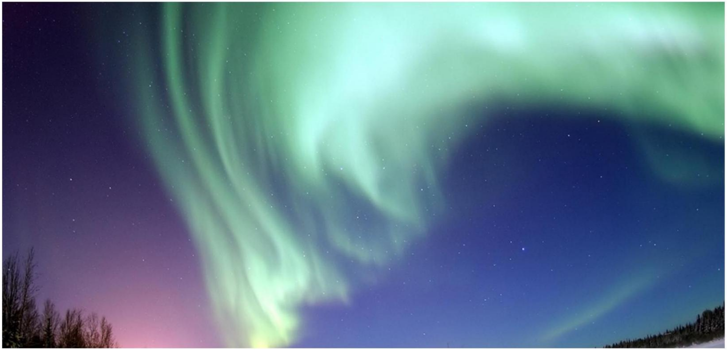
From Aurora to Electric Motors

Mr. Gullo

December 2025

Outline

The Aurora's Secret



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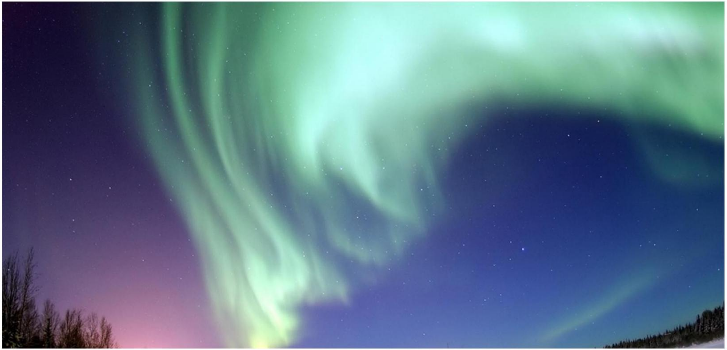

The Connection

Same physics that creates northern lights powers your phone, lights your home, and makes your car move.

Learning Objectives

By the end of this lesson, you will be able to:

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- **20.3:** Calculate induced electromotive force and current

20.1 Magnetic Poles

Every magnet has two poles:

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The Paradox

Civilian: "Opposites attract, same poles repel."
Physicist: "True, but you can NEVER isolate a single pole."

Nature's Rule for Moving Charges

$$\boxed{F = qvB\sin\theta}$$

Force on a charge moving through a magnetic field.

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Variables:

- F = force (N)
- q = charge (C)
- v = velocity (m/s)
- B = magnetic field strength (T, tesla)
- θ = angle between $\vec{v}$ and $\vec{B}$

20.1 Right-Hand Rule for Force

To find force direction on positive charge:

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To find force direction on positive charge:

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2. Curl fingers toward magnetic field $\vec{B}$
3. Thumb points in direction of force $\vec{F}$

Key Insight

For negative charges, force is OPPOSITE the thumb direction.

20.1 Maximum Force Condition

When is Force Maximum?

$\sin\theta$ is maximum when $\theta = 90$

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The Mental Model

Charge moving parallel to field lines feels no force. Moving perpendicular to field lines feels maximum force.

20.2 The Force on Current in Magnetic Field

Universal Law: Magnetic Force on Wire

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Current-carrying wire in magnetic field experiences force.

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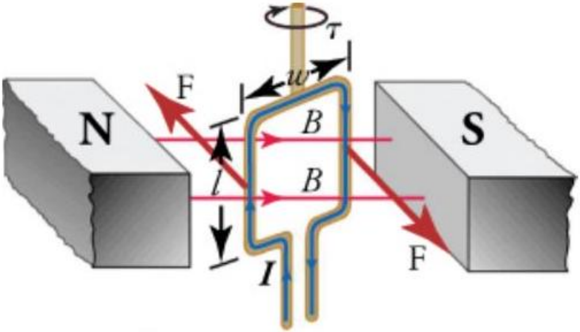
Current-carrying wire in magnetic field experiences force.

The Mental Model

Think of electricity as water flowing through a hose. Put that hose in a magnetic field, and the field *pushes* the hose sideways.

20.2 Electric Motor: Converting Energy



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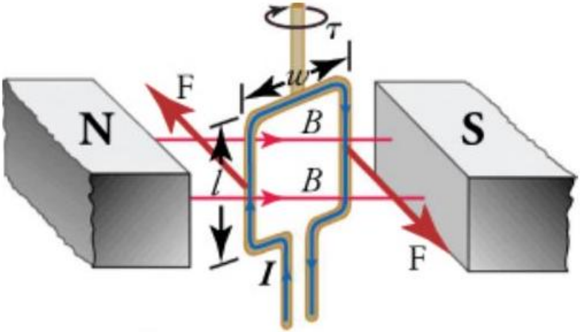
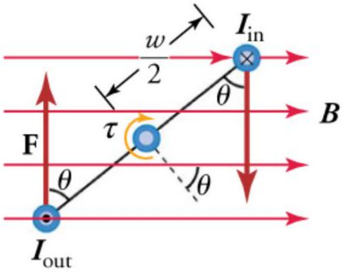


The Paradox

Civilian: "Motors are complicated machines."
Physicist: "Just a current loop in a magnetic field."

20.2 Motor Torque Analysis



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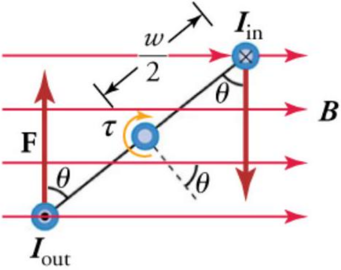
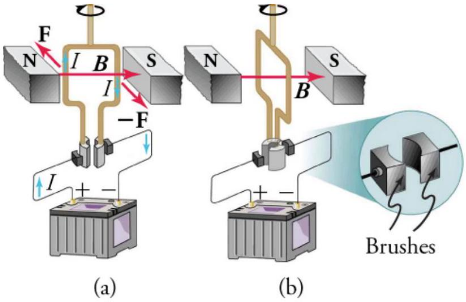


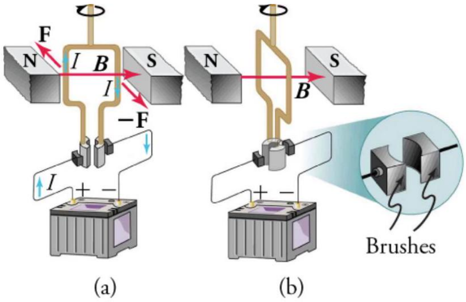
Universal Law: Torque on Current Loop

$$\boxed{\tau = NIAB \sin \theta}$$

Where N = turns, I = current, A = loop area, B = magnetic field

20.2 Keeping the Motor Spinning

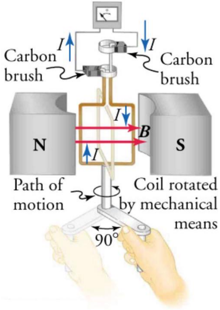




The Problem

Torque reverses every half turn. Without **brushes** to reverse current, motor oscillates instead of rotating.

20.2 Run Motor in Reverse: Generator



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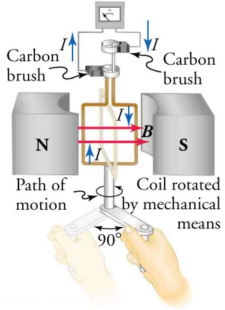


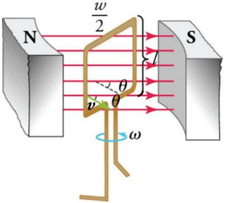
The Symmetry

Motor: Electrical energy $\rightarrow$ Mechanical energy

Generator: Mechanical energy $\rightarrow$ Electrical energy

20.2 Generator: The Math

Velocity of wire makes angle θ with magnetic field:



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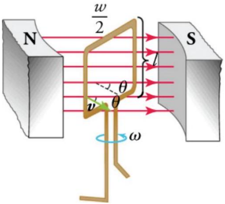
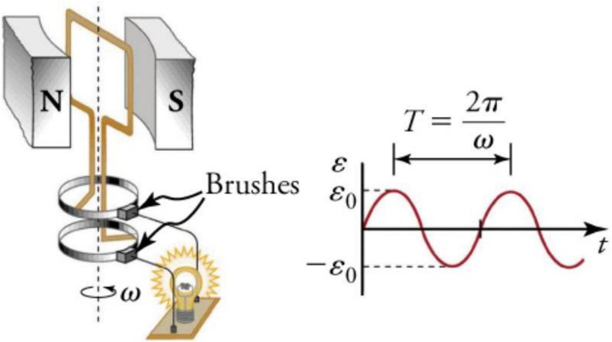


Universal Law: Generator EMF

$$\boxed{\varepsilon = NAB\omega \sin \omega t}$$

Peak emf: $\varepsilon_0 = NAB\omega$

20.2 AC Power from Generator



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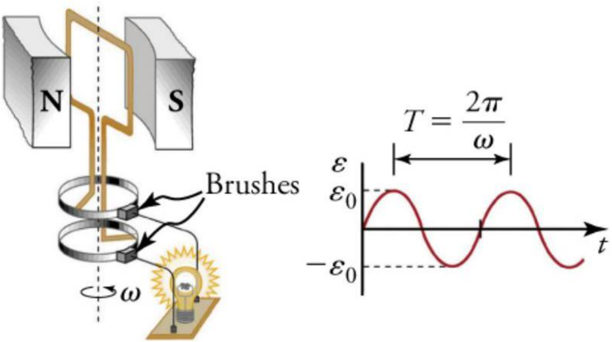
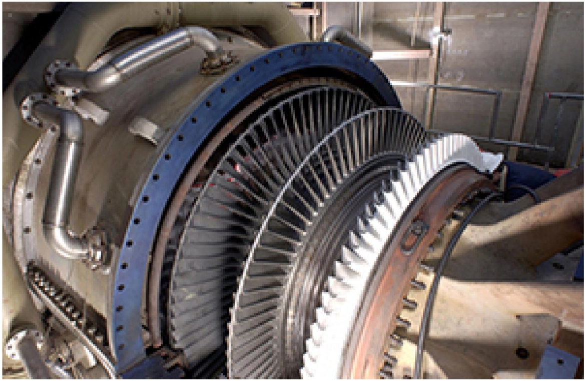


Civilian View vs. Reality

Civilian: "Why don't lights flicker 120 times per second?"
Physicist: "Faster than eye refresh rate. We don't notice."

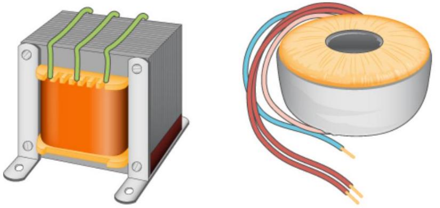
20.2 Real Generators: Steam Turbines



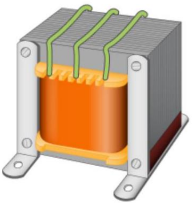
Energy Chain

Coal/Nuclear/Gas → Heat → Steam → Turbine → Generator → Electricity

20.2 Transformers: Changing Voltage



(a) (b)



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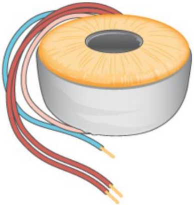


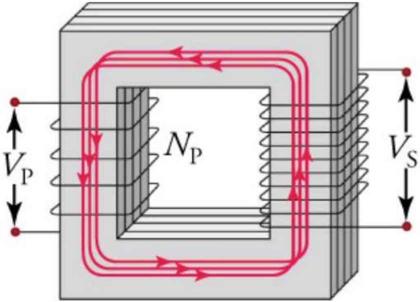
(b)

What Transformers Do

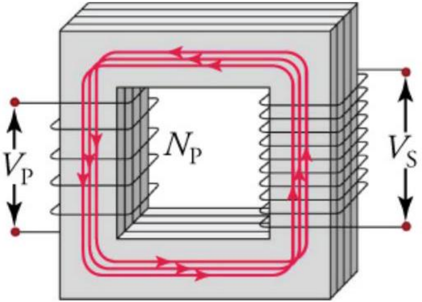
Change AC voltage from one value to another

Phone chargers, laptop adapters, power tools

20.2 How Transformers Work



20.2 How Transformers Work



The Principle

1. AC current in primary coil creates changing magnetic field
2. Iron core traps and amplifies magnetic field
3. Changing field passes through secondary coil
4. Induces AC voltage in secondary coil

20.2 Transformer Equation

Universal Law: Voltage Transformation

$$\boxed{\frac{V_S}{V_P} = \frac{N_S}{N_P}}$$

Secondary voltage / Primary voltage = Turns ratio

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Step-Up vs. Step-Down

Step-Up: $N_S > N_P \rightarrow$ Increases voltage (power transmission)
Step-Down: $N_S < N_P \rightarrow$ Decreases voltage (home delivery)

20.2 Power Transmission: Why High Voltage?

Power Transmitted

$$P_{\text{transmitted}} = I_{\text{transmitted}} V_{\text{transmitted}}$$

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The Problem: Joule Losses

$$P_{\text{lost}} = I^2_{\text{transmitted}} R_{\text{wire}}$$

Power lost as heat proportional to **current squared**

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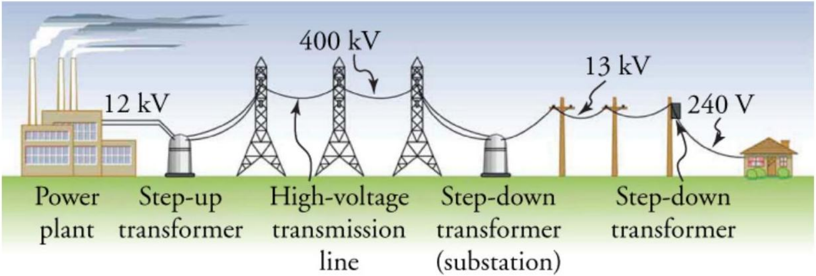
The Solution

Increase voltage $\rightarrow$ Decrease current $\rightarrow$ Minimize losses


400 kV
13 kV
12 kV
240 V
Power plant
Step-up transformer
High-voltage transmission line
Step-down transformer (substation)
Step-down transformer

20.3 Nature's Symmetry

We Already Know

Electric current creates magnetic field (electromagnet)

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Faraday's Question (1831)

Can magnetic field create electric current?

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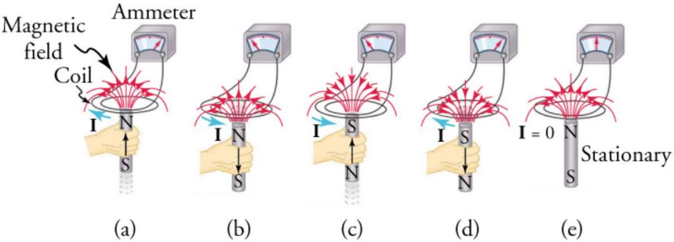
Faraday's Question (1831)

Can magnetic field create electric current?

The Answer

Yes - but only when magnetic field *changes*

20.3 Faraday's Experiment



20.3 What is EMF?

Terrible Name

Electromotive Force is NOT a force
It's a *potential difference* (voltage)

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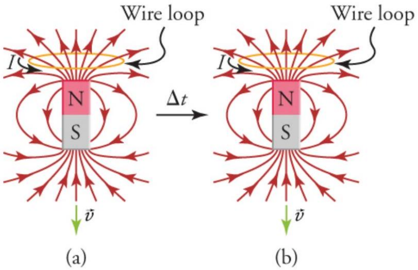
Universal Law: EMF Definition

Energy added per unit charge by source

Symbol: ε Units: Volts (V)

20.3 Understanding Magnetic Flux



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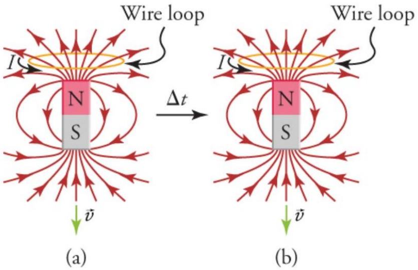
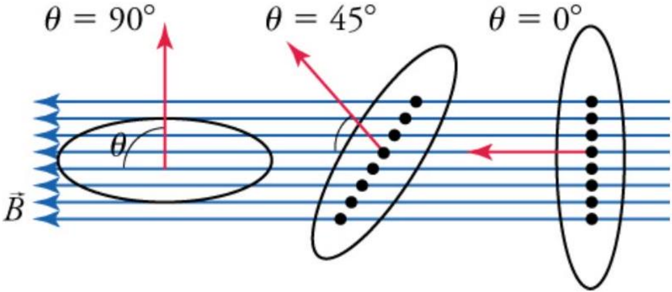


Universal Law: Magnetic Flux

$$\boxed{\Phi = BA\cos\theta}$$

Number of field lines perpendicular through area A
Unit: Weber (Wb) $= \text{T}\cdot\text{m}^2 = \text{V}\cdot\text{s}$

20.3 Flux and Loop Orientation



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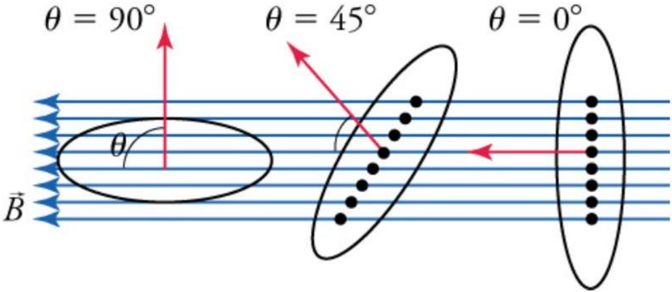

The Sail Analogy

Loop = Sail, Magnetic Field = Wind

Maximum flux when perpendicular ($\theta = 0$)

Zero flux when parallel ($\theta = 90$)

20.3 Faraday's Law of Induction

Universal Law: Faraday's Law

$$\boxed{\varepsilon = -N\frac{\Delta\Phi}{\Delta t}}$$

EMF induced equals rate of change of magnetic flux

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Three Ways to Induce EMF

1. Change magnetic field strength B
2. Change loop area A
3. Change orientation angle θ

20.3 Lenz's Law: The Minus Sign

Universal Law: Lenz's Law

Induced current flows in direction that *opposes* the change in flux

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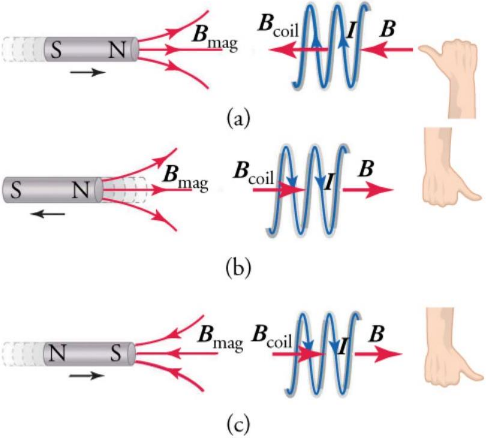
Nature Resists Change

Flux increasing? $\rightarrow$ Induced field opposes increase
Flux decreasing? $\rightarrow$ Induced field opposes decrease

20.3 Applying Lenz's Law



Attempt: EMF in Moving Coil

Try this on your own (3 min, silent):

A magnetic field passes through a 16-turn coil with diameter 2.0 cm. The magnetic field decreases from 0.020 T to 0.010 T in 34 s. The coil has resistance 0.1 Ω.

Given:

- $N = 16$ turns
- $d = 0.020$ m
- $\Delta B = -0.010$ T
- $\Delta t = 34$ s
- $R = 0.1\ \Omega$

Find: Magnitude and direction of induced current

Work individually. It's okay to get stuck.

Compare: EMF in Moving Coil

Turn and talk (2 min):

1. What equation did you use for EMF?
2. How did you calculate the magnetic flux?
3. How did you find current from EMF?
4. What direction does current flow?

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Name wheel: One pair share your approach (not your answer).

Reveal: Solution

Self-correct in a different color:
G - Given: See problem

Reveal: Solution

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Reveal: Solution

Self-correct in a different color:

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E - Equations:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = -N\frac{\Delta B\pi d^2}{4\Delta t}$$

$$I = \frac{\varepsilon}{R}$$

Reveal: Solution

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S - Substitute:

$$I = -16\frac{(-0.010\text{ T})\pi(0.020\text{ m})^2}{4(0.10\,\Omega)(34\text{ s})} = 15\,\mu\text{A}$$

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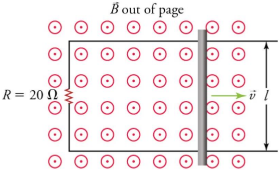
S - Statement: $\boxed{I = 15\,\mu\mathrm{A}}$ to the right (opposes decrease in field)

Attempt: Sliding Rod Circuit

Try this on your own (3 min, silent):

A U-shaped wire with a 20 Ω resistor has a conducting rod sliding on it at 0.50 m/s. The circuit is in a constant 0.010 T magnetic field pointing into the page. The rod is 0.10 m long.



Given: $B = 0.010$ T, $v = 0.50$ m/s, $\ell = 0.10$ m, $R = 20\,\Omega$
Find: Current magnitude and direction

Work individually. It's okay to get stuck.

Compare: Sliding Rod Circuit

Turn and talk (2 min):

1. What changes: B, A, or θ?
2. How fast does area change?
3. What's the rate of flux change?
4. Direction of induced current?

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S - Substitute:

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$$\boxed{I = 25\,\mu\mathrm{A}}$$

flowing **clockwise**

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$$\boxed{I = 25\,\mu\text{A}}$$

flowing **clockwise**

Check: Lenz's law - flux into page increasing, so induced field out of page (counterclockwise current would point out, but we have sign... current is clockwise)

Key Equations Summary

Motors and Generators

$$F = I\ell B \sin\theta \quad \text{(Force on wire)}$$
$$\tau = NIAB \sin\theta \quad \text{(Motor torque)}$$
$$\varepsilon = NAB\omega \sin\omega t \quad \text{(Generator EMF)}$$

Transformers and Power

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad \text{(Transformer equation)}$$
$$P_{\text{lost}} = I^2 R \quad \text{(Joule heating)}$$

Key Equations Summary (continued)

Electromagnetic Induction

$$\Phi = BA\cos\theta \quad \text{(Magnetic flux)}$$

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \quad \text{(Faraday's Law)}$$

$$\varepsilon = B\ell v \quad \text{(Motional EMF)}$$

Lenz's Law (Direction)

Induced current opposes the change in magnetic flux

The Big Picture

Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

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Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)

The Big Picture

Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)
- Changing magnetic field creates electric current (induction)

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Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)
- Changing magnetic field creates electric current (induction)
- Motors convert electrical $\rightarrow$ mechanical energy

The Big Picture

Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)
- Changing magnetic field creates electric current (induction)
- Motors convert electrical $\rightarrow$ mechanical energy
- Generators convert mechanical $\rightarrow$ electrical energy

The Big Picture

Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)
- Changing magnetic field creates electric current (induction)
- Motors convert electrical $\rightarrow$ mechanical energy
- Generators convert mechanical $\rightarrow$ electrical energy
- Transformers change voltage using induction

The Big Picture

Symmetry of Electromagnetism

Electricity $\leftrightarrow$ Magnetism

- Electric current creates magnetic field (electromagnet)
- Changing magnetic field creates electric current (induction)
- Motors convert electrical $\rightarrow$ mechanical energy
- Generators convert mechanical $\rightarrow$ electrical energy
- Transformers change voltage using induction
- Power grid uses transformers to transmit energy efficiently

Homework

Complete the assigned problems

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