THE BIG IDEA

Magnetism can produce electric current, and electric current can produce magnetism.

In 1831, two physicists, Michael Faraday in England and Joseph Henry in the United States, independently discovered that magnetism could produce an electric current in a wire. Their discovery was to change the world by making electricity so commonplace that it would power industries by day and light up cities by night.

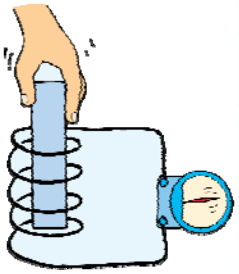
37.1 Electromagnetic Induction

Electric current can be produced in a wire by simply moving a magnet into or out of a wire coil.

37.1 Electromagnetic Induction

No battery or other voltage source was needed to produce a current—only the motion of a magnet in a coil or wire loop.

Voltage was induced by the relative motion of a wire with respect to a magnetic field.

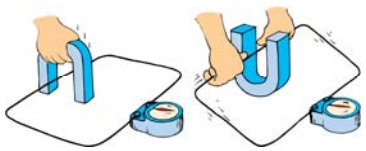


37.1 Electromagnetic Induction

The production of voltage depends only on the relative motion of the conductor with respect to the magnetic field.

Voltage is induced whether the magnetic field moves past a conductor, or the conductor moves through a magnetic field.

The results are the same for the same *relative* motion.



37.1 Electromagnetic Induction

The amount of voltage induced depends on how quickly the magnetic field lines are traversed by the wire.

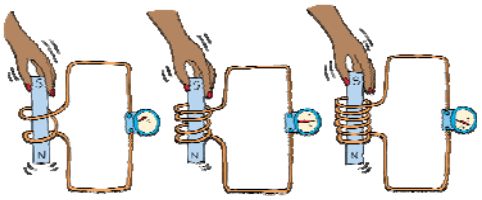
- Very slow motion produces hardly any voltage at all.
- Quick motion induces a greater voltage.

Increasing the number of loops of wire that move in a magnetic field increases the induced voltage and the current in the wire.

Pushing a magnet into twice as many loops will induce twice as much voltage.

37.1 Electromagnetic Induction

Twice as many loops as another means twice as much voltage is induced. For a coil with three times as many loops, three times as much voltage is induced.



37.1 Electromagnetic Induction

We don't get something (energy) for nothing by simply increasing the number of loops in a coil of wire.

Work is done because the induced current in the loop creates a magnetic field that repels the approaching magnet.

If you try to push a magnet into a coil with more loops, it requires even more work.

37.1 Electromagnetic Induction

Work must be done to move the magnet.

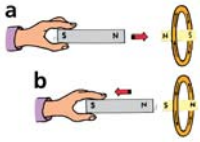
a. Current induced in the loop produces a magnetic field (the imaginary yellow bar magnet), which repels the bar magnet.

37.1 Electromagnetic Induction

Work must be done to move the magnet.

a. Current induced in the loop produces a magnetic field (the imaginary yellow bar magnet), which repels the bar magnet.

b. When the bar magnet is pulled away, the induced current is in the opposite direction and a magnetic field attracts the bar magnet.



37.1 Electromagnetic Induction

The law of energy conservation applies here.

The force that you exert on the magnet multiplied by the distance that you move the magnet is your input work.

This work is equal to the energy expended (or possibly stored) in the circuit to which the coil is connected.

37.1 Electromagnetic Induction

If the coil is connected to a resistor, more induced voltage in the coil means more current through the resistor.

That means more energy expenditure.

Inducing voltage by changing the magnetic field around a conductor is **electromagnetic induction.**

37.1 Electromagnetic Induction

CONCEPT CHECK

How can you create a current using a wire and a magnet?

37.2 Faraday's Law

Faraday's law states that the induced voltage in a coil is proportional to the product of the number of loops, the cross-sectional area of each loop, and the rate at which the magnetic field changes within those loops.

37.2 Faraday's Law

Faraday's law describes the relationship between induced voltage and rate of change of a magnetic field:

The induced voltage in a coil is proportional to the product of the number of loops, the cross-sectional area of each loop, and the rate at which the magnetic field changes within those loops.

37.2 Faraday's Law

The current produced by electromagnetic induction depends upon

- the induced voltage,
- the resistance of the coil, and the circuit to which it is connected.

For example, you can plunge a magnet in and out of a closed rubber loop and in and out of a closed loop of copper.

The voltage induced in each is the same but the current is quite different—a lot in the copper but almost none in the rubber.

37.2 Faraday's Law

think!

If you push a magnet into a coil connected to a resistor you'll feel a resistance to your push. For the same pushing speed, why is this resistance greater in a coil with more loops?

37.2 Faraday's Law

think!

If you push a magnet into a coil connected to a resistor you'll feel a resistance to your push. For the same pushing speed, why is this resistance greater in a coil with more loops?

Answer:

More work is required because more voltage is induced, producing more current in the resistor and more energy transfer. When the magnetic fields of two magnets overlap, the two magnets are either forced together or forced apart. When one of the fields is induced by motion of the other, the polarity of the fields is always such as to force the magnets apart. Inducing more current in more coils increases the induced magnetic field and the resistive force.

37.2 Faraday's Law

CONCEPT CHECK **What does Faraday's law state?**

37.3 Generators and Alternating Current

Whereas a motor converts electrical energy into mechanical energy, a generator converts mechanical energy into electrical energy.

37.3 Generators and Alternating Current

A current can be generated by plunging a magnet into and out of a coil of wire.

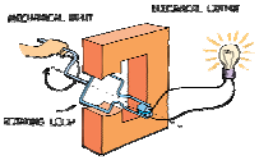
- As the magnet enters, the magnetic field strength inside the coil increases and induced voltage in the coil is directed one way.
- As the magnet leaves, the magnetic field strength diminishes and voltage is induced in the opposite direction.
- Greater frequency of field change induces greater voltage.
- The frequency of the alternating voltage is the frequency of the changing magnetic field within the loop.

37.3 Generators and Alternating Current

It is more practical to move the coil instead of moving the magnet, by rotating the coil in a stationary magnetic field.

A machine that produces electric current by rotating a coil within a stationary magnetic field is called a **generator.**

A generator is essentially the opposite of a motor, converting mechanical energy into electrical energy.



37.3 Generators and Alternating Current

Simple Generators

Starting perpendicular to the field, the loop has the largest number of lines inside.

As it rotates, the loop encircles fewer of the field lines until it lies along the field lines, when it encloses none at all.

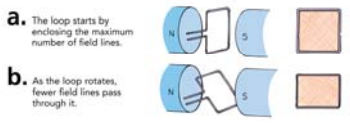
As rotation continues, it encloses more field lines, reaching a maximum when it has made a half revolution.

The magnetic field inside the loop changes in cyclic fashion.

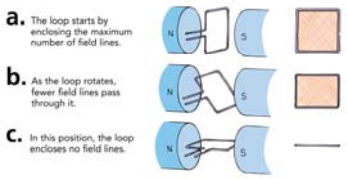
37.3 Generators and Alternating Current

a. The loop starts by enclosing the maximum number of field lines.

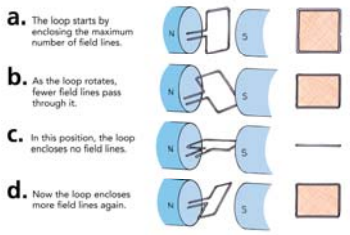
37.3 Generators and Alternating Current



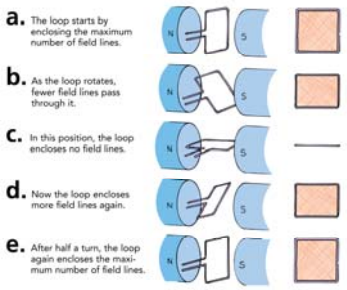
37.3 Generators and Alternating Current



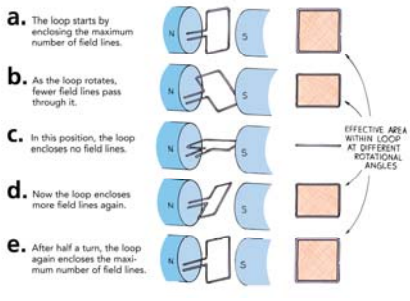
37.3 Generators and Alternating Current



37.3 Generators and Alternating Current

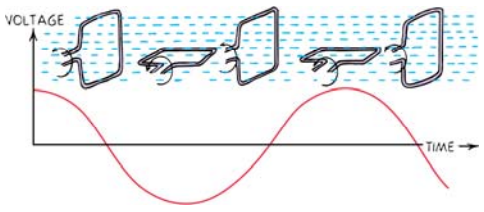


37.3 Generators and Alternating Current



37.3 Generators and Alternating Current

As the loop rotates, the magnitude and direction of the induced voltage (and current) change. One complete rotation of the loop produces one complete cycle in voltage (and current).

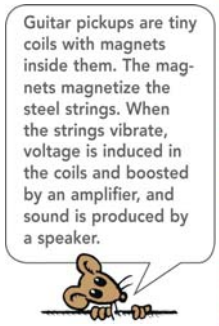


37.3 Generators and Alternating Current

The voltage induced by the generator alternates, and the current produced is alternating current (AC).

The current changes magnitude and direction periodically.

The standard AC in North America changes magnitude and direction during 60 complete cycles per second—60 hertz.



37.3 Generators and Alternating Current

Complex Generators

The generators used in power plants are much more complex than the model discussed here.

Huge coils made up of many loops of wire are wrapped on an iron core, to make an armature much like the armature of a motor.

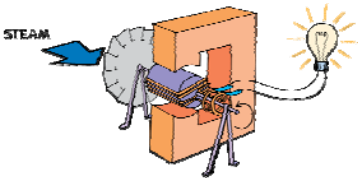
They rotate in the very strong magnetic fields of powerful electromagnets.

37.3 Generators and Alternating Current

The armature is connected externally to an assembly of paddle wheels called a turbine.

While wind or falling water can be used to produce rotation of the turbine, most commercial generators are driven by moving steam.

At the present time, a fossil fuel or nuclear fuel is used as the energy source for the steam.



37.3 Generators and Alternating Current

An energy source of some kind is required to operate a generator.

Some fraction of energy from the source is converted to mechanical energy to drive the turbine.

The generator converts most of this to electrical energy.

Some people think that electricity is a source of energy. It is not. It is a *form* of energy that must have a source.

37.3 Generators and Alternating Current

CONCEPT CHECK **How is a generator different from a motor?**

37.4 Motor and Generator Comparison

Moving charges experience a force that is perpendicular to both their motion and the magnetic field they traverse.

37.4 Motor and Generator Comparison

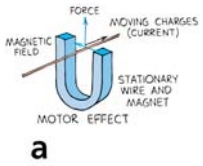
An electric current is deflected in a magnetic field, which underlies the operation of the motor.

Electromagnetic induction underlies the operation of a generator.

We will call the deflected wire the motor effect and the law of induction the generator effect.

37.4 Motor and Generator Comparison

a. When a current moves to the right, there is a force on the electrons, and the wire is tugged upward.

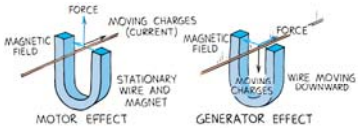


a

37.4 Motor and Generator Comparison

a. When a current moves to the right, there is a force on the electrons, and the wire is tugged upward.

b. When a wire with no current is moved downward, the electrons in the wire experience a force, creating current.



a b

37.4 Motor and Generator Comparison

The motor effect occurs when a current moves through a magnetic field.

- The magnetic field creates a perpendicular upward force on the electrons.
- Because the electrons can't leave the wire, the entire wire is tugged along with the electrons.

37.4 Motor and Generator Comparison

In the generator effect, a wire with no current is moved downward through a magnetic field.

- The electrons in this wire experience a force perpendicular to their motion, which is along the wire.
- A current begins to flow.

37.4 Motor and Generator Comparison

A striking example of a device functioning as both motor and generator is found in hybrid automobiles.

- When extra power for accelerating or hill climbing is needed, this device draws current from a battery and acts as a motor.
- Braking or rolling downhill causes the wheels to exert a torque on the device so it acts as a generator and recharges the battery.
- The electrical part of the hybrid engine is both a motor and a generator.

37.4 Motor and Generator Comparison

CONCEPT CHECK

How does a magnetic field affect a moving charge?

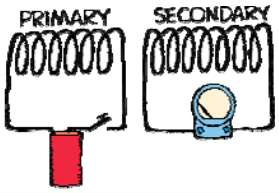
37.5 Transformers

A transformer works by inducing a changing magnetic field in one coil, which induces an alternating current in a nearby second coil.

37.5 Transformers

Consider a pair of coils, side by side, one connected to a battery and the other connected to a galvanometer.

It is customary to refer to the coil connected to the power source as the *primary* (input), and the other as the *secondary* (output).



37.5 Transformers

As soon as the switch is closed in the primary and current passes through its coil, a current occurs in the secondary.

When the primary switch is opened, a surge of current again registers in the secondary but in the opposite direction.

Whenever the primary switch is opened or closed, voltage is induced in the secondary circuit.

37.5 Transformers

The magnetic field that builds up around the primary extends into the secondary coil.

Changes in the magnetic field of the primary are sensed by the nearby secondary.

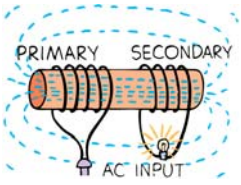
These changes of magnetic field intensity at the secondary induce voltage in the secondary, in accord with Faraday's law.

37.5 Transformers

If we place an iron core inside both coils, alignment of its magnetic domains intensifies the magnetic field within the primary.

The magnetic field is concentrated in the core, which extends into the secondary, so the secondary intercepts more field change.

The galvanometer will show greater surges of current when the switch of the primary is opened or closed.



37.5 Transformers

Instead of opening and closing a switch to produce the change of magnetic field, an alternating current can power the primary.

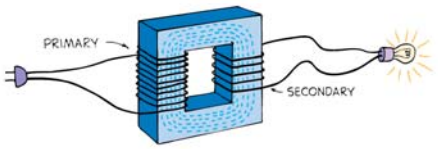
Then the rate of magnetic field changes in the primary (and in the secondary) is equal to the frequency of the alternating current.

Now we have a **transformer,** a device for increasing or decreasing voltage through electromagnetic induction.

37.5 Transformers

If the iron core forms a complete loop, guiding all magnetic field lines through the secondary, the transformer is more efficient.

All the magnetic field lines within the primary are intercepted by the secondary.



37.5 Transformers

Voltage

Voltages may be stepped up or stepped down with a transformer.

Suppose the primary consists of one loop connected to a 1-V alternating source.

- Consider the arrangement of a one-loop secondary that intercepts all the changing magnetic field lines of the primary.
- Then a voltage of 1 V is induced in the secondary.

37.5 Transformers

If another loop is wrapped around the core, the induced voltage will be twice as much, in accord with Faraday's law.

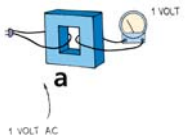
If the secondary has a hundred times as many turns as the primary, then a hundred times as much voltage will be induced.

This arrangement of a greater number of turns on the secondary than on the primary makes up a step-up transformer.

Stepped-up voltage may light a neon sign or operate the picture tube in a television receiver.

37.5 Transformers

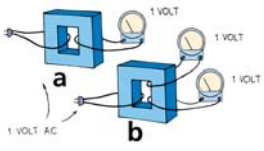
a. 1 V induced in the secondary equals the voltage of the primary.



37.5 Transformers

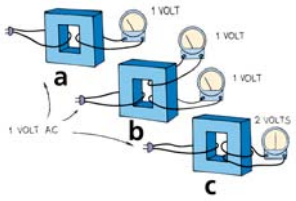
a. 1 V induced in the secondary equals the voltage of the primary.

b. 1 V is induced in the added secondary also because it intercepts the same magnetic field change from the primary.



37.5 Transformers

a. 1 V induced in the secondary equals the voltage of the primary.
b. 1 V is induced in the added secondary also because it intercepts the same magnetic field change from the primary.
c. 2 V is induced in a single two-turn secondary.



37.5 Transformers

If the secondary has fewer turns than the primary, the alternating voltage in the secondary will be *lower* than that in the primary.

The voltage is said to be stepped down.

If the secondary has half as many turns as the primary, then only half as much voltage is induced in the secondary.

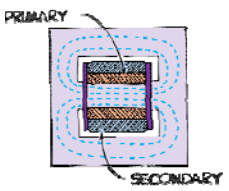
37.5 Transformers

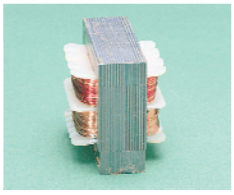
The relationship between primary and secondary voltages with respect to the relative number of turns is

$$\frac{\text{primary voltage}}{\text{number of primary turns}} = \frac{\text{secondary voltage}}{\text{number of secondary turns}}$$

37.5 Transformers

A practical transformer uses many coils. The relative numbers of turns in the coils determines how much the voltage changes.





37.5 Transformers

Power

You don't get something for nothing with a transformer that steps up the voltage, for energy conservation is always in control.

The transformer actually transfers energy from one coil to the other. The rate at which energy is transferred is the power.

The power used in the secondary is supplied by the primary.

37.5 Transformers

The primary gives no more power than the secondary uses.

If the slight power losses due to heating of the core are neglected, then the power going in equals the power coming out.

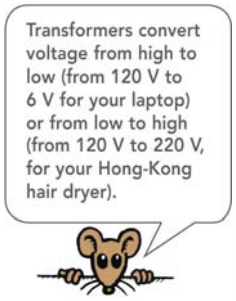
Electric power is equal to the product of voltage and current:

$(\text{voltage} \times \text{current})_{\text{primary}} = (\text{voltage} \times \text{current})_{\text{secondary}}$

37.5 Transformers

If the secondary has more voltage, it will have less current than the primary.

If the secondary has less voltage, it will have more current than the primary.



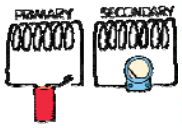
37.5 Transformers

This transformer lowers 120 V to 6 V or 9 V. It also converts AC to DC by means of a *diode* that acts as a one-way valve.

37.5 Transformers

think!

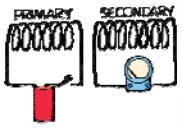
When the switch of the primary is opened or closed, the galvanometer in the secondary registers a current. But when the switch remains closed, no current is registered on the galvanometer of the secondary. Why?



37.5 Transformers

think!

When the switch of the primary is opened or closed, the galvanometer in the secondary registers a current. But when the switch remains closed, no current is registered on the galvanometer of the secondary. Why?



Answer:

A current is only induced in a coil when there is a *change* in the magnetic field passing through it. When the switch remains in the closed position, there is a steady current in the primary and a steady magnetic field about the coil.

37.5 Transformers

think!

If the voltage in a transformer is stepped up, then the current is stepped down. Ohm's law says that increased voltage will produce increased current. Is there a contradiction here, or does Ohm's Law not apply to transformers?

37.5 Transformers

think!

If the voltage in a transformer is stepped up, then the current is stepped down. Ohm's law says that increased voltage will produce increased current. Is there a contradiction here, or does Ohm's Law not apply to transformers?

Answer:

Ohm's law still holds, and there is no contradiction. The voltage induced across the secondary circuit, divided by the load (resistance) of the secondary circuit, equals the current in the secondary circuit. The current is stepped down in comparison with the larger current that is drawn in the *primary* circuit.

37.5 Transformers

CONCEPT CHECK **How does a transformer work?**

37.6 Power Transmission

Almost all electric energy sold today is in the form of alternating current because of the ease with which it can be transformed from one voltage to another.

37.6 Power Transmission

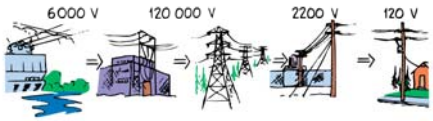
Power is transmitted great distances at high voltages and correspondingly low currents.

This reduces energy losses due to the heating of the wires.

Power may be carried from power plants to cities at about 120,000 volts or more, stepped down to about 2400 volts in the city, and finally stepped down again to 120 volts.

37.6 Power Transmission

Power transmission uses transformers to increase voltage for long-distance transmission and decrease it before it reaches your home.

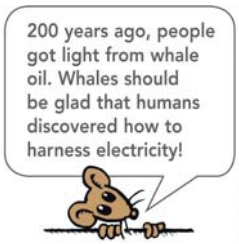


37.6 Power Transmission

Energy, then, is transformed from one system of conducting wires to another by electromagnetic induction.

The same principles account for sending energy from a radio-transmitter antenna to a radio receiver many kilometers away.

The effects of electromagnetic induction are very far-reaching.



37.6 Power Transmission

CONCEPT CHECK **Why is almost all electrical energy sold today in the form of alternating current?**

37.7 Induction of Electric and Magnetic Fields

A magnetic field is created in any region of space in which an electric field is changing with time.

37.7 Induction of Electric and Magnetic Fields

Electromagnetic induction has thus far been discussed in terms of the production of voltages and currents.

The more fundamental way to look at it is in terms of the induction of electric *fields.*

The electric fields, in turn, give rise to voltages and currents.

37.7 Induction of Electric and Magnetic Fields

Induction takes place whether or not a conducting wire or any material medium is present.

Faraday's law states that an electric field is created in any region of space in which a magnetic field is changing with time.

The magnitude of the created electric field is proportional to the rate at which the magnetic field changes.

The direction of the created electric field is at right angles to the changing magnetic field.

37.7 Induction of Electric and Magnetic Fields

If electric charge happens to be present where the electric field is created, this charge will experience a force.

- For a charge in a wire, the force could cause it to flow as current, or to push the wire to one side.
- For a charge in the chamber of a particle accelerator, the force can accelerate the charge to high speeds.

37.7 Induction of Electric and Magnetic Fields

There is a second effect, which is the counterpart to Faraday's law.

It is just like Faraday's law, except that the roles of electric and magnetic fields are interchanged.

37.7 Induction of Electric and Magnetic Fields

A magnetic field is created in any region of space in which an electric field is changing with time.

- The magnitude of the magnetic field is proportional to the rate at which the electric field changes.
- The direction of the created magnetic field is at right angles to the changing electric field.

37.7 Induction of Electric and Magnetic Fields

CONCEPT CHECK

How can an electric field create a magnetic field?

37.8 Electromagnetic Waves

An electromagnetic wave is composed of oscillating electric and magnetic fields that regenerate each other.

37.8 Electromagnetic Waves

Shake the end of a stick back and forth in still water and you will produce waves on the water surface.

Similarly shake a charged rod back and forth in empty space and you will produce electromagnetic waves in space.

37.8 Electromagnetic Waves

The shaking charge can be considered an electric current.

- A magnetic field surrounds an electric current.
- A changing magnetic field surrounds a *changing* electric current.
- A changing magnetic field creates a changing electric field.
- The changing electric field creates a changing magnetic field.

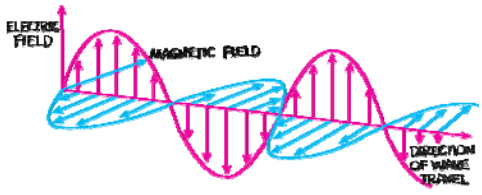
37.8 Electromagnetic Waves

An electromagnetic wave is composed of oscillating electric and magnetic fields that regenerate each other.

No medium is required. The oscillating fields emanate from the vibrating charge.

At any point on the wave, the electric field is perpendicular to the magnetic field.

Both are perpendicular to the direction of motion of the wave.



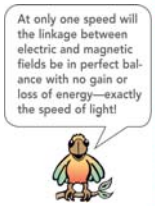
37.8 Electromagnetic Waves

Speed of Electromagnetic Waves

For electromagnetic radiation, there is only one speed—the speed of light—no matter what the frequency or wavelength or intensity of the radiation.

The changing electric field induces a magnetic field. The changing magnetic field acts back to induce an electric field.

Only one speed could preserve this harmonious balance of fields.



37.8 Electromagnetic Waves

If the wave traveled at less than the speed of light, the fields would rapidly die out.

The electric field would induce a weaker magnetic field, which would induce a still weaker electric field.

If the wave traveled at more than the speed of light, the fields would build up in a crescendo of ever greater magnitudes.

At some critical speed, however, mutual induction continues indefinitely, with neither a loss nor a gain in energy.

37.8 Electromagnetic Waves

From his equations of electromagnetic induction, Maxwell calculated the value of this critical speed and found it to be 300,000 kilometers per second.

He used only the constants in his equations determined by simple laboratory experiments with electric and magnetic fields.

He didn't *use* the speed of light. He *found* the speed of light!

37.8 Electromagnetic Waves

Nature of Light

Maxwell quickly realized that he had discovered the solution to one of the greatest mysteries of the universe—the nature of light.

Maxwell realized that radiation of any frequency would propagate at the same speed as light.

37.8 Electromagnetic Waves

This radiation includes radio waves, which can be generated and received by antennas.

- A rotating device in the sending antenna alternately charges the upper and lower parts of the antenna positively and negatively.
- The charges accelerating up and down the antenna transmit electromagnetic waves.
- When the waves hit a receiving antenna, the electric charges inside vibrate in rhythm with the variations of the field.

37.8 Electromagnetic Waves

CONCEPT CHECK

What makes up an electromagnetic wave?

Assessment Questions

1. A voltage will be induced in a wire loop when the magnetic field within that loop
   a. changes.
   b. aligns with the electric field.
   c. is at right angles to the electric field.
   d. converts to magnetic energy.

Assessment Questions

1. A voltage will be induced in a wire loop when the magnetic field within that loop
   a. changes.
   b. aligns with the electric field.
   c. is at right angles to the electric field.
   d. converts to magnetic energy.

Answer: A

37 Electromagnetic Induction
Conceptual Physics

Assessment Questions

2. If you change the magnetic field in a closed loop of wire, you induce in the loop a
   a. current.
   b. voltage.
   c. electric field.
   d. all of these

37 Electromagnetic Induction
Conceptual Physics

Assessment Questions

2. If you change the magnetic field in a closed loop of wire, you induce in the loop a
   a. current.
   b. voltage.
   c. electric field.
   d. all of these

Answer: D

37 Electromagnetic Induction
Conceptual Physics

Assessment Questions

3. The essential concept in an electric motor and a generator is
   a. Coulomb's law.
   b. Ohm's law.
   c. Faraday's law.
   d. Newton's second law.

37 Electromagnetic Induction
Conceptual Physics

Assessment Questions

3. The essential concept in an electric motor and a generator is
   a. Coulomb's law.
   b. Ohm's law.
   c. Faraday's law.
   d. Newton's second law.

Answer: C

37 Electromagnetic Induction
Conceptual Physics

Assessment Questions

4. A motor and a generator are
   a. similar devices.
   b. very different devices with different applications.
   c. only found in hybrid cars.
   d. energy sources.

Assessment Questions

4. A motor and a generator are
   a. similar devices.
   b. very different devices with different applications.
   c. only found in hybrid cars.
   d. energy sources.

Answer: A

Assessment Questions

5. A step-up transformer in an electrical circuit can
   a. increase voltage.
   b. decrease energy.
   c. increase current.
   d. increase energy.

Assessment Questions

5. A step-up transformer in an electrical circuit can
   a. increase voltage.
   b. decrease energy.
   c. increase current.
   d. increase energy.

Answer: A

Assessment Questions

6. To keep heat losses down when power is carried across the countryside, it is best that current in the wires is
   a. low.
   b. high.
   c. not too low and not too high.
   d. replaced with voltage.

Assessment Questions

6. To keep heat losses down when power is carried across the countryside, it is best that current in the wires is
   a. low.
   b. high.
   c. not too low and not too high.
   d. replaced with voltage.

Answer: A

Assessment Questions

7. According to James Clerk Maxwell, if the magnitude of the created magnetic field increases, the change in the electric field will
   a. stay the same.
   b. increase.
   c. decrease.
   d. always disappear.

Assessment Questions

7. According to James Clerk Maxwell, if the magnitude of the created magnetic field increases, the change in the electric field will
   a. stay the same.
   b. increase.
   c. decrease.
   d. always disappear.

Answer: B

Assessment Questions

8. Electricity and magnetism connect to form
   a. mass.
   b. energy.
   c. ultra high-frequency sound.
   d. light.

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Assessment Questions

8. Electricity and magnetism connect to form
   a. mass.
   b. energy.
   c. ultra high-frequency sound.
   d. light.

Answer: D