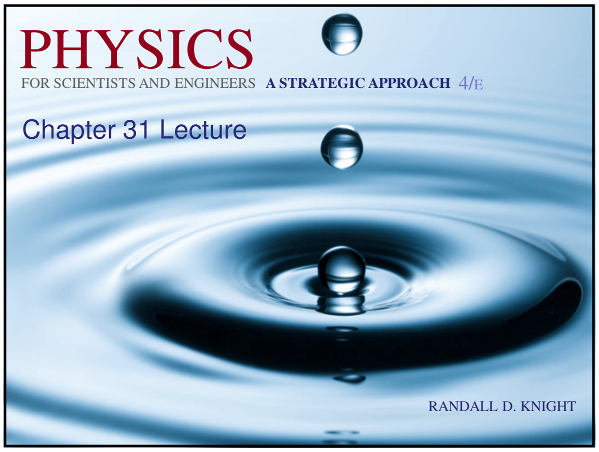
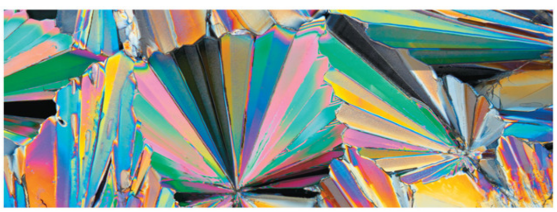


Chapter 31 Electromagnetic Fields and Waves



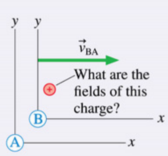
IN THIS CHAPTER, you will study the properties of electromagnetic fields and waves.

 Slide 31-2

Chapter 31 Preview

How do fields transform?

Whether the field at a point is electric or magnetic depends, surprisingly, on your motion relative to the charges and currents. You'll learn how to transform the fields measured in one reference frame to a second reference frame moving relative to the first.



« LOOKING BACK Section 4.3 Relative motion

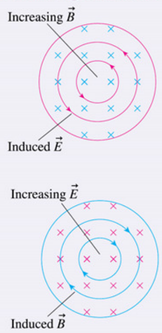
 Slide 31-3

Chapter 31 Preview

What is Maxwell's theory of electromagnetism?

Electricity and magnetism can be summarized in four equations for the fields, called Maxwell's equations, and one equation that tells us how charges respond to fields.

- Gauss's law: Charges create electric fields.
- Gauss's law for magnetism: There are no isolated magnetic poles.
- Faraday's law: Electric fields can also be created by changing magnetic fields.
- Ampère-Maxwell law: Magnetic fields can be created either by currents or by changing magnetic fields.



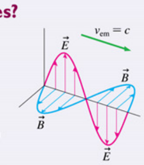
« LOOKING BACK Section 24.4 Gauss's law
« LOOKING BACK Section 29.6 Ampère's law
« LOOKING BACK Section 30.5 Faraday's law

 Slide 31-4

Chapter 31 Preview

What are electromagnetic waves?

Maxwell's equations predict the existence of self-sustaining oscillations of the electric and magnetic fields—electromagnetic waves—that travel through space without the presence of charges or currents.



- In a vacuum, all electromagnetic waves—from radio waves to x rays—travel with the *same* speed $v_{em} = 1/\sqrt{\epsilon_0\mu_0} = c$, the speed of light.
- The fields $\vec{E}$ and $\vec{B}$ are perpendicular to each other and to the direction of travel.
- Electromagnetic waves are launched by an oscillating dipole, called an antenna.
- Electromagnetic waves transfer energy.
- Electromagnetic waves also transfer momentum and exert radiation pressure.

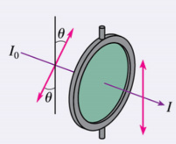
« LOOKING BACK Section 16.4 The wave equation

 Slide 31-5

Chapter 31 Preview

What is polarization?

An electromagnetic wave is polarized if the electric field always oscillates in the same plane—the plane of polarization. Polarizers both create and analyze polarized light. You will learn to calculate the intensity of light transmitted through a polarizer and will see that light is completely blocked by crossed polarizers. Polarization is used in many types of modern optical instrumentation.



 Slide 31-6

Chapter 31 Reading Questions

Reading Question 31.1

Experimenter A creates a magnetic field in the laboratory. Experimenter B moves relative to A. Experimenter B sees

A. Just the same magnetic field.
B. A magnetic field of different strength.
C. A magnetic field pointing the opposite direction.
D. Just an electric field.
E. Both a magnetic and an electric field.

Reading Question 31.1

Experimenter A creates a magnetic field in the laboratory. Experimenter B moves relative to A. Experimenter B sees

A. Just the same magnetic field.
B. A magnetic field of different strength.
C. A magnetic field pointing the opposite direction.
D. Just an electric field.
✔**E. Both a magnetic and an electric field.**

Reading Question 31.2

Maxwell's equations are a set of how many equations?

A. Two
B. Three
C. Four
D. Five
E. Six

Reading Question 31.2

Maxwell's equations are a set of how many equations?

A. Two
B. Three
✔ **C. Four**
D. Five
E. Six

Reading Question 31.3

Maxwell introduced the *displacement current* as a correction to

A. Coulomb's law.
B. Gauss's law.
C. Biot-Savart's law.
D. Ampère's law.
E. Faraday's law.

Reading Question 31.3

Maxwell introduced the *displacement current* as a correction to

A. Coulomb's law.
B. Gauss's law.
C. Biot-Savart's law.
✔**D. Ampère's law.**
E. Faraday's law.

Reading Question 31.4

The law that characterizes polarizers is called

A. Malus's law.
B. Maxwell's law.
C. Poynting's law.
D. Lorentz's law.

Reading Question 31.4

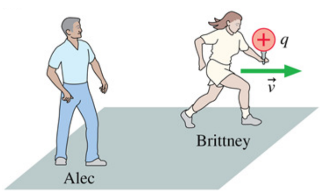
The law that characterizes polarizers is called

✔**A. Malus's law.**
B. Maxwell's law.
C. Poynting's law.
D. Lorentz's law.

Chapter 31 Content, Examples, and QuickCheck Questions

Slide 31-16

E or *B*? It Depends on Your Perspective

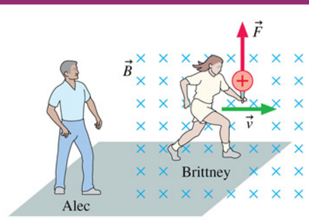


Charge q moves with velocity $\vec{v}$ relative to Alec.

- Alec sees a moving charge, and he knows that this creates a magnetic field.
- From Brittney's perspective, the charge is at rest, so the magnetic field is zero.
- Is there, or is there not, a magnetic field?

Slide 31-17

E or *B*? It Depends on Your Perspective

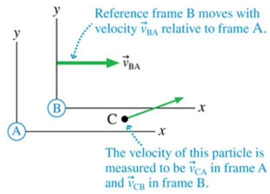


Charge q moves through a magnetic field established by Alec.

- Alec predicts an upward magnetic force on the moving charge, which will accelerate it.
- From Brittney's perspective, the charge is at rest, so there can be no magnetic force on the charge.
- Does the charge accelerate or not?

Slide 31-18

Reference Frames



- The figure shows a charged particle C, which can be measured by experimenters in two different reference frames, A and B.
- The particle's velocity relative to frame A is *different* than the velocity in frame B:

$$\vec{v}_{CA} = \vec{v}_{CB} + \vec{v}_{BA}$$

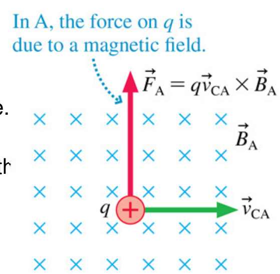
- The particle's acceleration is the *same* in both frames:

$$\vec{a}_{CA} = \vec{a}_{CB}$$

 Slide 31-19

The Transformation of Electric and Magnetic Fields

- According to Alec (frame A), a charged particle moves through a magnetic field and experiences a magnetic force.
- Suppose Brittney (frame B) runs alongside the charge with the same velocity.
- Since the accelerations are the same in both frames, the force must also be the same.



The situation in frame A

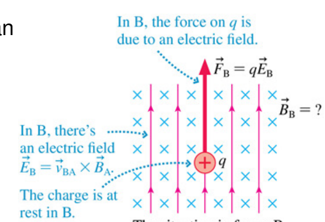
 Slide 31-20

The Transformation of Electric and Magnetic Fields

- Brittney must observe an electric field:

$$\vec{E}_B = \vec{v}_{BA} \times \vec{B}_A$$

- As Brittney runs past Alec, she finds part of Alec's magnetic field has become an electric field!



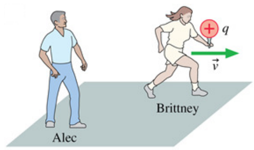
The situation in frame B

- **Whether a field is seen as "electric" or "magnetic" depends on the motion of the reference frame relative to the sources of the field.**

 Slide 31-21

QuickCheck 31.1

Brittney runs past Alec while holding a positive charge q. In Alec's reference frame, there is (or are)

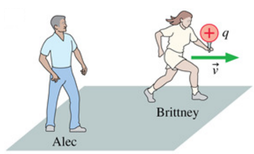


A. Only an electric field.
B. Only a magnetic field.
C. An electric and a magnetic field.
D. No fields.

Slide 31-22

QuickCheck 31.1

Brittney runs past Alec while holding a positive charge q. In Alec's reference frame, there is (or are)

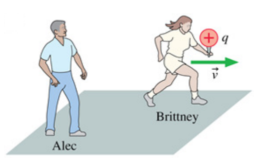


A. Only an electric field.
B. Only a magnetic field.
✔**C. An electric and a magnetic field.**
D. No fields.

Slide 31-23

QuickCheck 31.2

Brittney runs past Alec while holding a positive charge q. In Brittney's reference frame, there is (or are)

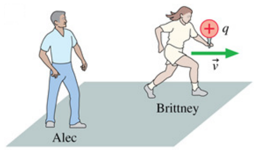


A. Only an electric field.
B. Only a magnetic field.
C. An electric and a magnetic field.
D. No fields.

Slide 31-24

QuickCheck 31.2

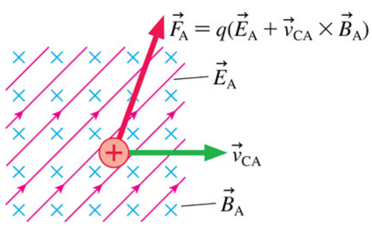
Brittney runs past Alec while holding a positive charge q. In Brittney's reference frame, there is (or are)



- ✔ **A. Only an electric field.**
- B. Only a magnetic field.
- C. An electric and a magnetic field.
- D. No fields.

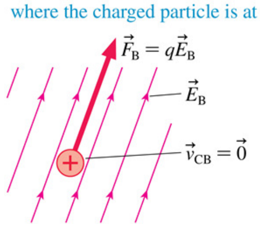
No moving charges in Brittney's frame

The Transformation of Electric and Magnetic Fields



- A charge in reference frame A experiences electric and magnetic forces.

The Transformation of Electric and Magnetic Fields



- The charge experiences the same force in frame B, but it is due only to an electric field.

Example 31.1 Transforming the Electric Field

EXAMPLE 31.1 **Transforming the electric field**

A laboratory experimenter has created the parallel electric and magnetic fields $\vec{E} = 10{,}000\,\hat{\imath}$ V/m and $\vec{B} = 0.10\,\hat{\imath}$ T. A proton is shot into these fields with velocity $\vec{v} = 1.0 \times 10^5\,\hat{\jmath}$ m/s. What is the electric field in the proton's reference frame?

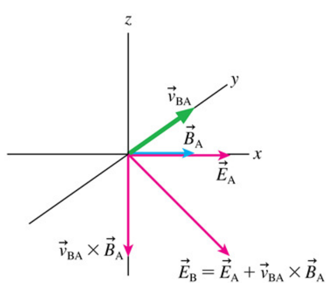
MODEL Let the laboratory be reference frame A and a frame moving with the proton be reference frame B. The relative velocity is $\vec{v}_{BA} = 1.0 \times 10^5\,\hat{\jmath}$ m/s.

Slide 31-28

Example 31.1 Transforming the Electric Field

EXAMPLE 31.1 **Transforming the electric field**

VISUALIZE FIGURE 31.6 shows the geometry. The laboratory fields, now labeled A, are parallel to the x-axis while $\vec{v}_{BA}$ is in the y-direction. Thus $\vec{v}_{BA} \times \vec{B}_A$ points in the negative z-direction.



Slide 31-29

Example 31.1 Transforming the Electric Field

EXAMPLE 31.1 **Transforming the electric field**

SOLVE $\vec{v}_{BA}$ and $\vec{B}_A$ are perpendicular, so the magnitude of $\vec{v}_{BA} \times \vec{B}_A$ is $(1.0 \times 10^5$ m/s$)(0.10$ T$)(\sin 90°) = 10{,}000$ V/m. Thus the electric field in frame B, the proton's frame, is

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A = (10{,}000\,\hat{\imath} - 10{,}000\,\hat{k})\ \text{V/m}$$
$$= (14{,}000\ \text{V/m},\ 45° \text{ below the } x\text{-axis})$$

ASSESS The force on the proton is the same in both reference frames. But in the proton's reference frame that force is due entirely to an electric field tilted 45° below the x-axis.

Slide 31-30

The Transformation of Electric and Magnetic Fields

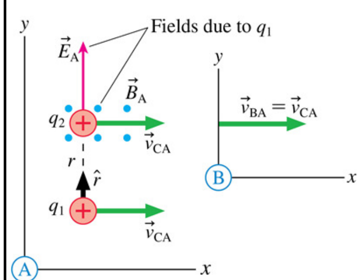
- The **Galilean field transformation equations** are

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$
$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$

  where $\vec{v}_{BA}$ is the velocity of reference frame B relative to frame A.
- The fields are measured *at the same point in space* by experimenters *at rest* in each reference frame.
- These equations are only valid if $v_{BA} << c$.

Slide 31-31

Galilean Field Transformation Equations

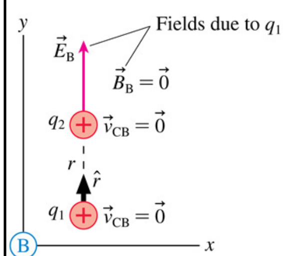


Fields seen in frame A

- The figure shows two positive charges moving side by side through frame A.
- Charge q_2 experiences both an electric and magnetic field due to charge q_1.

Slide 31-32

Galilean Field Transformation Equations



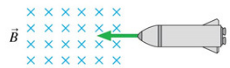
Fields seen in frame B

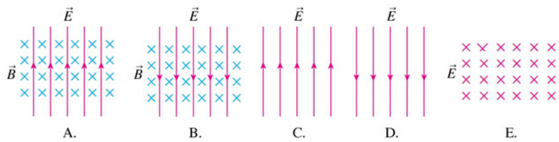
- In the reference frame in which the charges are both at rest, charge q_1 experiences only an electric field due to charge q_2.
- The magnitude of the electric field in frame B as predicted by the Galilean field transformation equations is too high by a factor of $(1 - v_{BA}^2/c^2)$.
- When $v_{BA} << c$, this difference can be neglected.

Slide 31-33

QuickCheck 31.3

Experimenters on earth have created the magnetic field shown. A rocket flies through the field, from right to left. Which are the field (or fields) in the rocket's reference frame?

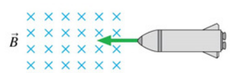


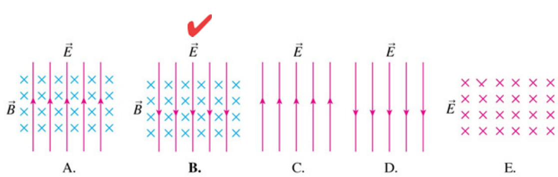


Slide 31-34

QuickCheck 31.3

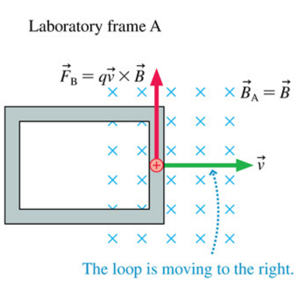
Experimenters on earth have created the magnetic field shown. A rocket flies through the field, from right to left. Which are the field (or fields) in the rocket's reference frame?





Slide 31-35

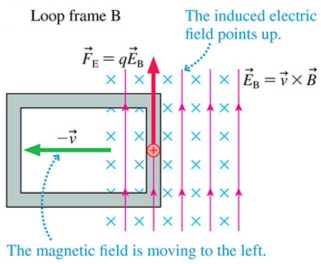
Faraday's Law Revisited



- The figure shows a laboratory reference frame A in which a conducting loop is moving into a static magnetic field.
- The magnetic field exerts an upward magnetic force on the charges in the leading edge of the wire.
- This induces a current in the loop.
- We call this a *motional emf*.

Slide 31-36

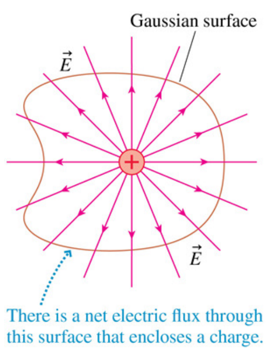
Faraday's Law Revisited



- An experimenter in the loop's frame sees not only a magnetic field but also an electric field, which is what drives the current.
- This is the *induced electric field* of Faraday's law.
- The induced electric field only exists in the loop frame of reference, in which the magnetic field is moving.

Slide 31-37

The Field Laws Thus Far: 1. Gauss's Law



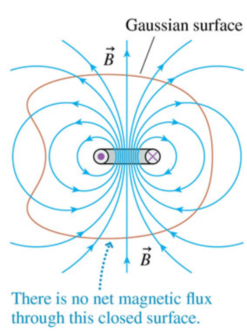
- Gauss's law for the electric field says that for any closed surface enclosing total charge Q_{in}, the net electric flux through the surface is

$$(\Phi_e)_{\text{closed surface}} = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\epsilon_0}$$

- The circle on the integral sign indicates that the integration is over a closed surface.

Slide 31-38

The Field Laws Thus Far: 2. Gauss's Law for Magnetic Fields



- Magnetic field lines form continuous curves: Every field line leaving a surface at some point must reenter it at another.
- Gauss's law for the magnetic field states that the net magnetic flux through a closed surface is *zero*:

$$(\Phi_m)_{\text{closed surface}} = \oint \vec{B} \cdot d\vec{A} = 0$$

Slide 31-39

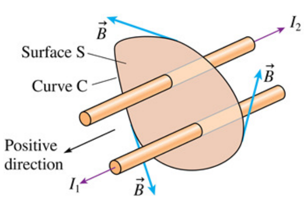
The Field Laws Thus Far: 3. Faraday's Law

- Faraday's law states that a changing magnetic flux through a closed loop creates an induced emf around the loop:

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$$

- Where the line integral of $\vec{E}$ is around the closed curve that bounds the surface through which the magnetic flux is calculated.
- This equation means that an electric field can be created by a changing magnetic field.

Ampère's Law



- Ampère's law states that whenever total current $I_{through}$ passes through an area bounded by a closed curve, the line integral of the magnetic field around the curve is

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{through}$$

- Ampère's law is the formal statement that currents create magnetic fields.

Tactics: Determining the Signs of Flux and Current

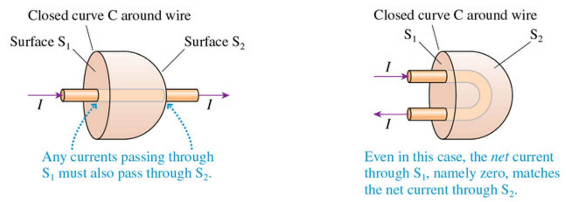
TACTICS BOX 31.1

Determining the signs of flux and current

1. For a surface S bounded by a closed curve C, choose either the clockwise (cw) or counterclockwise (ccw) direction around C.
2. Curl the fingers of your *right* hand around the curve in the chosen direction, with your thumb perpendicular to the surface. Your thumb defines the positive direction.
   - A flux Φ through the surface is positive if the field is in the same direction as your thumb, negative if the field is in the opposite direction.
   - A current through the surface in the direction of your thumb is positive, in the direction opposite your thumb is negative.

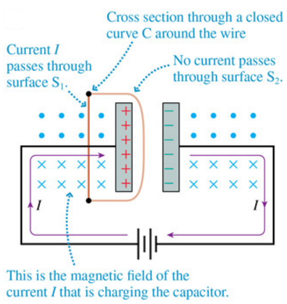
Exercises 4–6

Ampère's Law



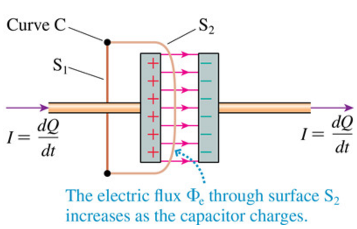
- Ampère's law may be applied to the current I_{through} passing through any surface S that is bounded by curve C.

Maxwell's Correction to Ampère's Law



- The figure shows a capacitor being charged.
- Curve C is a closed curve encircling the wire on the left.
- Surface S_1 has $I_{\text{through}} = I$, but surface S_2 has $I_{\text{through}} = 0$!
- Ampère's law is either wrong or incomplete.

Maxwell's Correction to Ampère's Law



- The rate at which the electric flux is changing through surface S_2 is

$$\frac{d\Phi_e}{dt} = \frac{1}{\epsilon_0}\frac{dQ}{dt} = \frac{I}{\epsilon_0}$$

- Maxwell added a correction term to Ampère's law using what he called the **displacement current**:

$$I_{\text{disp}} = \epsilon_0 \frac{d\Phi_e}{dt}$$

The Field Laws Thus Far: 4. The Ampère-Maxwell Law

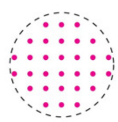
- The Ampère-Maxwell law states that a changing electric flux through a closed loop or an electric current through the loop creates a magnetic field around the loop:

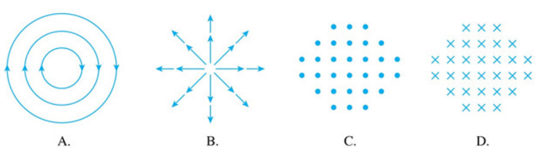
$$\oint \vec{B} \cdot d\vec{s} = \mu_0(I_{\text{through}} + I_{\text{disp}}) = \mu_0\left(I_{\text{through}} + \epsilon_0 \frac{d\Phi_e}{dt}\right)$$

- Where the line integral of $\vec{B}$ is around the closed curve that bounds the surface through which the electric flux and current are flowing.
- This equation means that a magnetic field can be created either by an electric current or by a changing electric field.

QuickCheck 31.4

The electric field is increasing.
Which is the induced magnetic field?

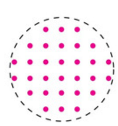


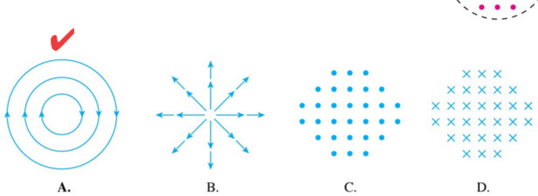


E. There's no induced field in this case.

QuickCheck 31.4

The electric field is increasing.
Which is the induced magnetic field?

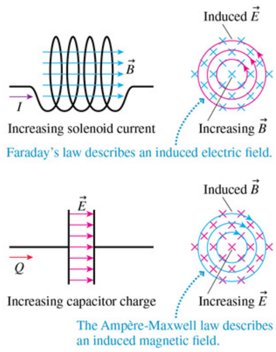




E. There's no induced field in this case.

Induced Fields

- An increasing solenoid current causes an increasing magnetic field, which induces a circular electric field.
- An increasing capacitor charge causes an increasing electric field, which induces a circular magnetic field.



 Slide 31-49

Maxwell's Equations

- Electric and magnetic fields are described by the four **Maxwell's Equations**:

$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\epsilon_0}$	Gauss's law
$\oint \vec{B} \cdot d\vec{A} = 0$	Gauss's law for magnetism
$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$	Faraday's law
$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{through} + \epsilon_0 \mu_0 \frac{d\Phi_e}{dt}$	Ampère-Maxwell law

 Slide 31-50

The Lorentz Force Law

- In addition to Maxwell's equations, which describes the fields, a fifth equation is needed to tell us how matter responds to these fields:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \qquad \text{(Lorentz force law)}$$

- There are a total of 11 fundamental equations describing classical physics:
- Newton's first law
- Newton's second law
- Newton's third law
- Newton's law of gravity
- Gauss's law
- Gauss's law for magnetism
- Faraday's law
- Ampère-Maxwell law
- Lorentz force law
- First law of thermodynamics
- Second law of thermodynamics

 Slide 31-51

The Fundamental Ideas of Electromagnetism

- Let's summarize the physical meaning of the five electromagnetic equations:

- **Gauss's law:** Charged particles create an electric field.
- **Faraday's law:** An electric field can also be created by a changing magnetic field.
- **Gauss's law for magnetism:** There are no isolated magnetic poles.
- **Ampère-Maxwell law, first half:** Currents create a magnetic field.
- **Ampère-Maxwell law, second half:** A magnetic field can also be created by a changing electric field.
- **Lorentz force law, first half:** An electric force is exerted on a charged particle in an electric field.
- **Lorentz force law, second half:** A magnetic force is exerted on a charge moving in a magnetic field.

 Slide 31-52

Advanced Topic: Electromagnetic Waves

- Maxwell was the first to understand that light is an oscillation of the electromagnetic field.
- Maxwell was able to predict that electromagnetic waves can exist at any frequency, not just at the frequencies of visible light.
- This prediction was the harbinger of radio waves.

Large radar installations like this one are used to track rockets and missiles.

 Slide 31-53

Advanced Topic: Electromagnetic Waves

- Maxwell's equations lead to a wave equation for the electric and magnetic fields.
- The source-free Maxwell's equations, with no charges or currents, are

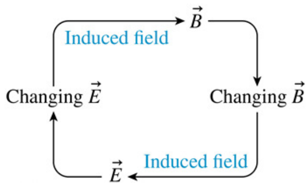
$$\oint \vec{E} \cdot d\vec{A} = 0 \qquad \oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$$

$$\oint \vec{B} \cdot d\vec{A} = 0 \qquad \oint \vec{B} \cdot d\vec{s} = \epsilon_0 \mu_0 \frac{d\Phi_e}{dt}$$

 Slide 31-54

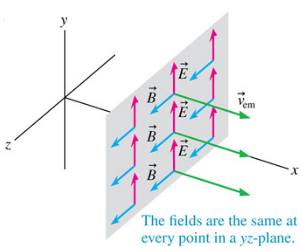
Advanced Topic: Electromagnetic Waves

- A changing magnetic field creates an induced electric field, and a changing electric field creates an induced magnetic field.
- If a changing magnetic field creates an electric field that, in turn, happens to change in just the right way to recreate the original magnetic field, then the fields can exist in a self-sustaining mode.



Slide 31-55

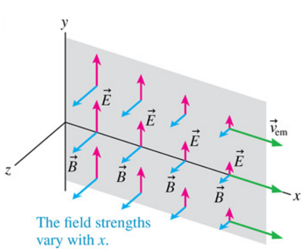
Advanced Topic: Electromagnetic Waves



- This figure shows the fields due to a plane wave, traveling to the right along the x-axis.
- The fields are the same everywhere in any yz-plane perpendicular to x.

Slide 31-56

Advanced Topic: Electromagnetic Waves

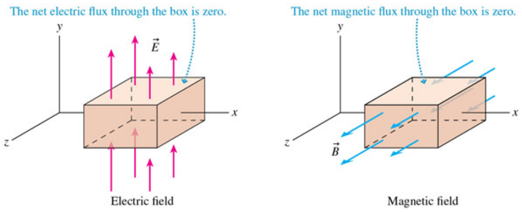


- This figure shows that the fields—at one instant of time—do change along the x-axis.
- These changing fields are the disturbance that is moving down the x-axis at speed v_{em}, so $\vec{E}$ and $\vec{B}$ of a plane wave are functions of the two variables x and t.

Slide 31-57

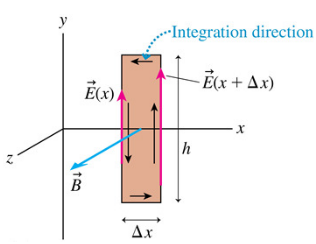
Advanced Topic: Electromagnetic Waves

- Consider an imaginary box, a Gaussian surface, centered on the x-axis.
- There is no charge in the box, and for a plane wave the net electric and magnetic flux through the box is zero, so the plane wave is consistent with the first two of Maxwell's equations.



 Slide 31-58

Advanced Topic: Faraday's Law



- Let's apply Faraday's law to the narrow rectangle in the xy-plane shown.
- The magnetic field $\vec{B}$ is perpendicular to the rectangle, so the magnetic flux is $\Phi_m = B_z A_{rectangle} = B_z h\Delta x$.
- As the wave moves, the flux *changes* at the rate

$$\frac{d\Phi_m}{dt} = \frac{d}{dt}(B_z h \Delta x) = \frac{\partial B_z}{\partial t} h \Delta x$$

 Slide 31-59

Advanced Topic: Faraday's Law

- The electric field points in the y-direction; hence at all points on the top and bottom edges the contribution to the integral is zero.
- Along the left edge of the loop, at position x, E_y has the same value at every point.
- We can write Faraday's law as

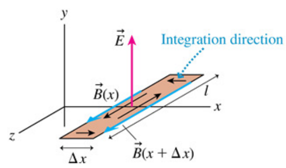
$$\oint \vec{E} \cdot d\vec{s} = \frac{\partial E_y}{\partial x} h \Delta x = -\frac{d\Phi_m}{dt} = -\frac{\partial B_z}{\partial t} h \Delta x$$

- The area $h\,\Delta x$ of the rectangle cancels, and we're left with

$$\frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t}$$

 Slide 31-60

Advanced Topic: The Ampère-Maxwell Law



- Let's apply the Ampère-Maxwell law to the narrow rectangle in the xz-plane shown.
- The electric field is perpendicular to the rectangle, so the electric flux is $\Phi_e = E_y A_{rectangle} = E_y l \Delta x$.
- As the wave moves, the flux *changes* at the rate

$$\frac{d\Phi_e}{dt} = \frac{d}{dt}(E_y l \Delta x) = \frac{\partial E_y}{\partial t} l \Delta x$$

 Slide 31-61

Advanced Topic: The Ampère-Maxwell Law

- We can write the Ampère-Maxwell law as

$$\oint \vec{B} \cdot d\vec{s} = -\frac{\partial B_z}{\partial x} l \Delta x = \epsilon_0 \mu_0 \frac{d\Phi_e}{dt} = \epsilon_0 \mu_0 \frac{\partial E_y}{\partial t} l \Delta x$$

- The area of the rectangle cancels, and we're left with

$$\frac{\partial B_z}{\partial x} = -\epsilon_0 \mu_0 \frac{\partial E_y}{\partial t}$$

 Slide 31-62

Advanced Topic: The Wave Equation

- If we start with the Faraday's law requirement for any electromagnetic wave, we can take the second derivative with respect to x, and combine this with the Ampère-Maxwell law requirement to obtain a wave equation

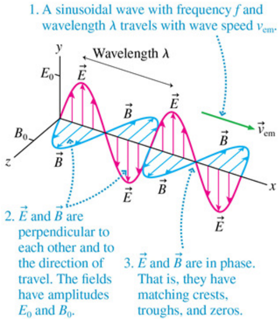
$$\frac{\partial^2 E_y}{\partial t^2} = \frac{1}{\epsilon_0 \mu_0} \frac{\partial^2 E_y}{\partial x^2} \quad \text{(the wave equation for electromagnetic waves)}$$

- Comparing this with the general wave equation studied in Chapter 16, we see that an electromagnetic wave must travel (in vacuum) with speed

$$v_{em} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \text{ m/s} = c$$

 Slide 31-63

Properties of Electromagnetic Waves



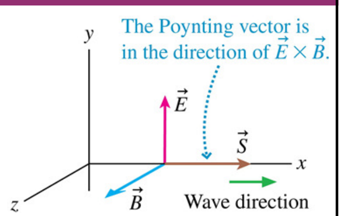
- This figure shows the electric and magnetic fields at points along the x-axis, due to a passing electromagnetic wave.
- The field strengths are related by $E = cB$ at every point on the wave.

 Slide 31-64

The Poynting Vector

- The energy flow of an electromagnetic wave is described by the **Poynting vector**:

$$\vec{S} \equiv \frac{1}{\mu_0}\vec{E} \times \vec{B}$$



- The Poynting vector points in the direction in which an electromagnetic wave is traveling.
- The units of S are W/m^2; the magnitude S of the Poynting vector measures the instantaneous rate of energy transfer per unit area of the wave.

 Slide 31-65

Intensity of Electromagnetic Waves

- The Poynting vector is a function of time, oscillating from zero to $S_{max} = E_0^2/c\mu_0$ and back to zero twice during each period of the wave's oscillation.
- Of more interest is the *average* energy transfer, averaged over one cycle of oscillation, which is the wave's **intensity** I.
- The intensity of an electromagnetic wave is

$$I = \frac{P}{A} = S_{avg} = \frac{1}{2c\mu_0}E_0^2 = \frac{c\epsilon_0}{2}E_0^2$$

- The intensity of electromagnetic waves at a distance r away from an isotropic source with power P_{source} is

$$I = \frac{P_{source}}{4\pi r^2}$$

 Slide 31-66

QuickCheck 31.5

To double the intensity of an electromagnetic wave, you should increase the amplitude of the electric field by a factor of

A. 0.5
B. 0.707
C. 1.414
D. 2
E. 4

Slide 31-67

QuickCheck 31.5

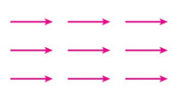
To double the intensity of an electromagnetic wave, you should increase the amplitude of the electric field by a factor of

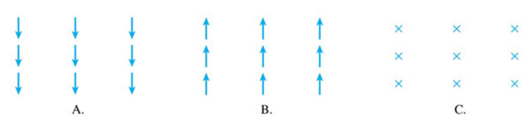
A. 0.5
B. 0.707
✔**C. 1.414** $I \propto E_0^2$
D. 2
E. 4

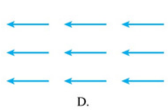
Slide 31-68

QuickCheck 31.6

An electromagnetic plane wave is coming toward you, out of the screen. At one instant, the electric field looks as shown. Which is the wave's magnetic field at this instant?





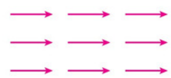


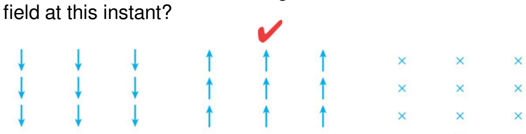
E. The magnetic field is instantaneously zero.

Slide 31-69

QuickCheck 31.6

An electromagnetic plane wave is coming toward you, out of the screen. At one instant, the electric field looks as shown. Which is the wave's magnetic field at this instant?





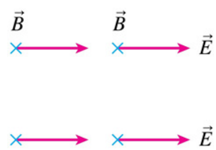
$\vec{E} \times \vec{B}$ is in the direction of motion.

E. The magnetic field is instantaneously zero.

Slide 31-70

QuickCheck 31.7

In which direction is this electro-magnetic wave traveling?

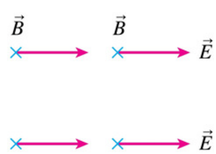


A. Up
B. Down.
C. Into the screen
D. Out of the screen
E. These are not allowable fields for an electromagnetic wave.

Slide 31-71

QuickCheck 31.7

In which direction is this electro-magnetic wave traveling?



✔ **A. Up** $\vec{E} \times \vec{B}$ is in the direction of motion.
B. Down
C. Into the screen
D. Out of the screen
E. These are not allowable fields for an electromagnetic wave.

Slide 31-72

Example 31.4 Fields of a Cell Phone

EXAMPLE 31.4 Fields of a cell phone

A digital cell phone broadcasts a 0.60 W signal at a frequency of 1.9 GHz. What are the amplitudes of the electric and magnetic fields at a distance of 10 cm, about the distance to the center of the user's brain?

MODEL Treat the cell phone as a point source of electromagnetic waves.

Example 31.4 Fields of a Cell Phone

EXAMPLE 31.4 Fields of a cell phone

SOLVE The intensity of a 0.60 W point source at a distance of 10 cm is

$$I = \frac{P_{source}}{4\pi r^2} = \frac{0.60\text{ W}}{4\pi(0.10\text{ m})^2} = 4.78\text{ W/m}^2$$

We can find the electric field amplitude from the intensity:

$$E_0 = \sqrt{\frac{2I}{c\epsilon_0}} = \sqrt{\frac{2(4.78\text{ W/m}^2)}{(3.00\times10^8\text{ m/s})(8.85\times10^{-12}\text{ C}^2/\text{N m}^2)}} = 60\text{ V/m}$$

The amplitudes of the electric and magnetic fields are related by the speed of light. This allows us to compute

$$B_0 = \frac{E_0}{c} = 2.0\times10^{-7}\text{ T}$$

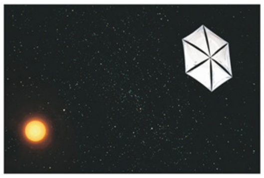
Example 31.4 Fields of a Cell Phone

EXAMPLE 31.4 Fields of a cell phone

ASSESS The electric field amplitude is modest; the magnetic field amplitude is very small. This implies that the interaction of electromagnetic waves with matter is mostly due to the electric field.

Radiation Pressure

- Electromagnetic waves transfer not only energy but also momentum.



Artist's conception of a future spacecraft powered by radiation pressure from the sun.

- Suppose we shine a beam of light on an object that completely absorbs the light energy.
- The momentum transfer will exert an average **radiation pressure** on the surface:

$$p_{rad} = \frac{F}{A} = \frac{P/A}{c} = \frac{I}{c}$$

where I is the intensity of the light wave.

 Slide 31-76

Example 31.5 Solar Sailing

EXAMPLE 31.5 Solar sailing

A low-cost way of sending spacecraft to other planets would be to use the radiation pressure on a solar sail. The intensity of the sun's electromagnetic radiation at distances near the earth's orbit is about 1300 W/m^2. What size sail would be needed to accelerate a 10,000 kg spacecraft toward Mars at 0.010 m/s^2?

MODEL Assume that the solar sail is perfectly absorbing.

 Slide 31-77

Example 31.5 Solar Sailing

EXAMPLE 31.5 Solar sailing

SOLVE The force that will create a 0.010 m/s^2 acceleration is $F = ma = 100$ N. We can use Equation 31.42 to find the sail area that, by absorbing light, will receive a 100 N force from the sun:

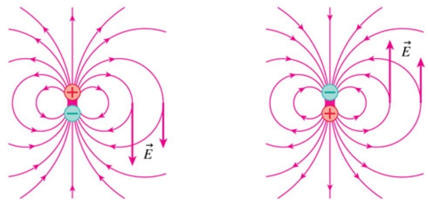
$$A = \frac{cF}{I} = \frac{(3.00 \times 10^8 \text{ m/s})(100 \text{ N})}{1300 \text{ W/m}^2} = 2.3 \times 10^7 \text{ m}^2$$

ASSESS If the sail is a square, it would need to be 4.8 km × 4.8 km, or roughly 3 mi × 3 mi. This is large, but not entirely out of the question with thin films that can be unrolled in space. But how will the crew return from Mars?

 Slide 31-78

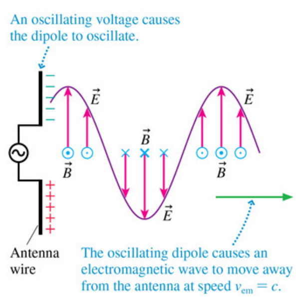
Generating Electromagnetic Waves

- An electric dipole creates an electric field that reverses direction if the dipole charges are switched.
- An oscillating dipole can generate an electromagnetic wave.



Slide 31-79

Antennas

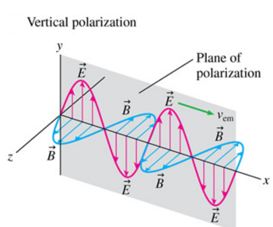


- An antenna acts like an oscillating electric dipole, involving both moving charge and a current.
- A self-sustaining electromagnetic wave is produced.

Slide 31-80

Polarization

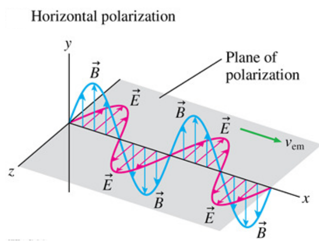
- The plane of the electric field vector $\vec{E}$ and the Poynting vector $\vec{S}$ is called the **plane of polarization**.
- The electric field in the figure below oscillates vertically, so this wave is *vertically polarized*.



Slide 31-81

Polarization

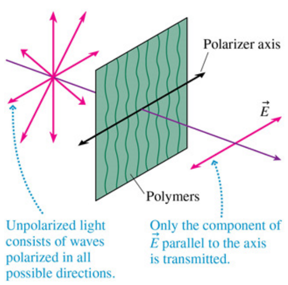
- The electric field in the figure below is *horizontally polarized.*



- Most natural sources of light are unpolarized, emitting waves whose electric fields oscillate randomly with all possible orientations.

 Slide 31-82

Polarization



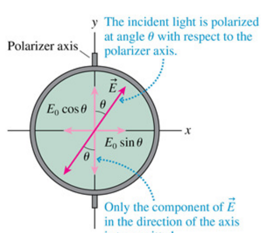
- The most common way of artificially generating polarized visible light is to send unpolarized light through a *polarizing filter*.

 Slide 31-83

Malus's Law

- Suppose *polarized* light of intensity I_0 approaches a polarizing filter.
- The component of the incident electric field that is polarized *parallel* to the axis is transmitted:

$$\vec{E}_{\text{transmitted}} = E_{\parallel}\hat{j} = E_0 \cos\theta\,\hat{j}$$



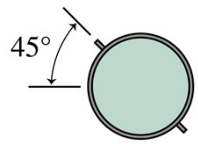
- The transmitted intensity depends on the square of the electric field amplitude:

$$I_{\text{transmitted}} = I_0 \cos^2\theta \quad \text{(incident light polarized)}$$

 Slide 31-84

QuickCheck 31.8

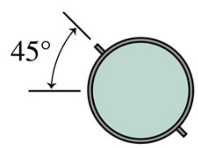
A vertically polarized light wave of intensity $1000\ \text{mW/m}^2$ is coming toward you, out of the screen. After passing through this polarizing filter, the wave's intensity is



A. $707\ \text{mW/m}^2$
B. $500\ \text{mW/m}^2$
C. $333\ \text{mW/m}^2$
D. $250\ \text{mW/m}^2$
E. $0\ \text{mW/m}^2$

QuickCheck 31.8

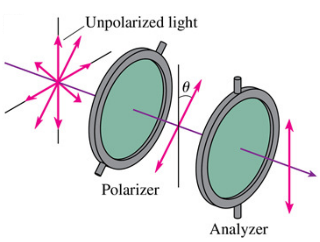
A vertically polarized light wave of intensity $1000\ \text{mW/m}^2$ is coming toward you, out of the screen. After passing through this polarizing filter, the wave's intensity is



A. $707\ \text{mW/m}^2$
✔ **B. $500\ \text{mW/m}^2$** $I = I_0 \cos^2 \theta$
C. $333\ \text{mW/m}^2$
D. $250\ \text{mW/m}^2$
E. $0\ \text{mW/m}^2$

Polarizers and Analyzers

- Malus's law can be demonstrated with two polarizing filters.
- The first, called the *polarizer*, is used to produce polarized light of intensity I_0.

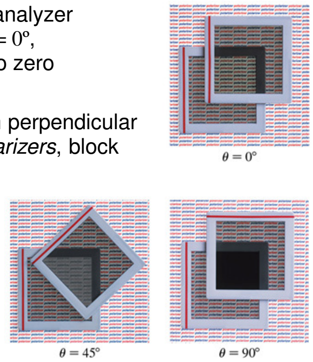


- The second, called the *analyzer*, is rotated by angle θ relative to the polarizer.

Polarizing Filters

- The transmission of the analyzer is (ideally) 100% when $\theta = 0°$, and steadily decreases to zero when $\theta = 90°$.
- Two polarizing filters with perpendicular axes, called *crossed polarizers*, block all the light.
- If the incident light on a polarizing filter is *unpolarized*, half the intensity is transmitted:

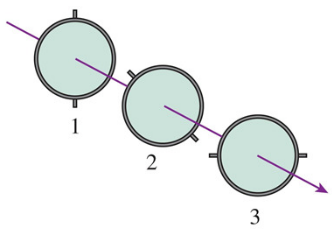
$$I_{\text{transmitted}} = \frac{1}{2}I_0$$



QuickCheck 31.9

Unpolarized light, traveling in the direction shown, is incident on polarizer 1. Does any light emerge from polarizer 3?

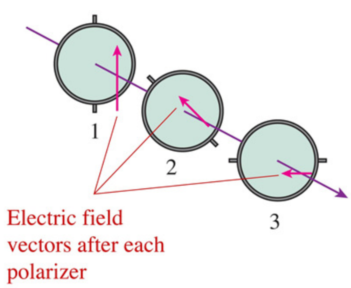
A. Yes
B. No.



QuickCheck 31.9

Unpolarized light, traveling in the direction shown, is incident on polarizer 1. Does any light emerge from polarizer 3?

✔ **A. Yes**
B. No



Polarizing Sunglasses

- *Glare*—the reflection of the sun and the skylight from roads and other horizontal surfaces—has a strong horizontal polarization.
- This light is almost completely blocked by a vertical polarizing filter.
- Vertically polarizing sunglasses can "cut glare" without affecting the main scene you wish to see.

Slide 31-91

Chapter 31 Summary Slides

Slide 31-92

General Principles

Maxwell's Equations

These equations govern electromagnetic fields:

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\epsilon_0}$$ Gauss's law

$$\oint \vec{B} \cdot d\vec{A} = 0$$ Gauss's law for magnetism

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt}$$ Faraday's law

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{through} + \epsilon_0 \mu_0 \frac{d\Phi_e}{dt}$$ *Ampère-Maxwell law*

Maxwell's equations tell us that:

An electric field can be created by

- Charged particles
- A changing magnetic field

A magnetic field can be created by

- A current
- A changing electric field

Slide 31-93

General Principles

Lorentz Force

This force law governs the interaction of charged particles with electromagnetic fields:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- An electric field exerts a force on any charged particle.
- A magnetic field exerts a force on a moving charged particle.

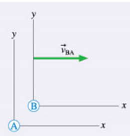
General Principles

Field Transformations

Fields measured in reference frame A to be $\vec{E}_A$ and $\vec{B}_A$ are found in frame B to be

$$\vec{E}_B = \vec{E}_A + \vec{v}_{BA} \times \vec{B}_A$$

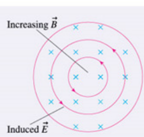
$$\vec{B}_B = \vec{B}_A - \frac{1}{c^2}\vec{v}_{BA} \times \vec{E}_A$$



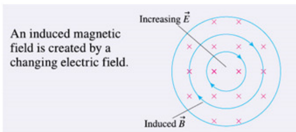
Important Concepts

Induced fields

An induced electric field is created by a changing magnetic field.



Important Concepts



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Important Concepts

An **electromagnetic wave** is a self-sustaining electromagnetic field.

- An em wave is a transverse wave with $\vec{E}$, $\vec{B}$, and $\vec{v}_{em}$ mutually perpendicular.
- An em wave propagates with speed $v_{em} = c = 1/\sqrt{\epsilon_0 \mu_0}$.
- The electric and magnetic field strengths are related by $E = cB$.
- The **Poynting vector** $\vec{S} = (\vec{E} \times \vec{B})/\mu_0$ is the energy transfer in the direction of travel.
- The wave **intensity** is $I = P/A = (1/2c\mu_0)E_0^2 = (c\epsilon_0/2)E_0^2$.

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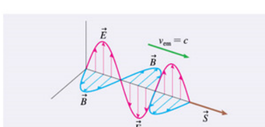
Important Concepts



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Applications

Polarization

The electric field and the Poynting vector define the **plane of polarization**. The intensity of polarized light transmitted through a polarizing filter is given by Malus's law:

$$I = I_0 \cos^2 \theta$$

where θ is the angle between the electric field and the polarizer axis.