Solution

The average value of the electric field is found from equation 25.63 as

$$\text{Intensity} = \epsilon_0 c E^2$$

$$E = \sqrt{\frac{\text{Intensity}}{\epsilon_0 c}}$$

$$= \sqrt{\frac{1.38 \times 10^3 \text{ J/(m}^2\text{ s)}}{[8.85 \times 10^{-12} \text{ C}^2\text{/(N m}^2)](3.00 \times 10^8 \text{ m/s})}\left(\frac{\text{N m}}{\text{J}}\right)}$$

$$= 721 \text{ N/C} = 721 \text{ V/m}$$

The average value of B is found from

$$B = \frac{E}{c} = \frac{721 \text{ N/C}}{3.00 \times 10^8 \text{ m/s}} = 2.40 \times 10^{-6} \frac{\text{N}}{\text{A s}}$$

$$= 2.40 \times 10^{-6} \text{ T}$$

Note that the value of B is very much smaller than E, yet each wave contains one half of the total energy of the electromagnetic wave.

The Language of Physics

Maxwell's equations
A set of four equations that completely describe all electromagnetic phenomena (p. 715).

Gaussian surface
An imaginary surface that is placed in space to measure either electric or magnetic flux (p. 715).

Gauss's law for electricity
The electric flux through a Gaussian surface surrounding electric charge is a measure of the amount of electric charge contained within the Gaussian surface. If the charge cannot be measured directly, but the flux can, the charge distribution can be determined by Gauss's law. When the flux is positive, the Gaussian surface surrounds positive charge, and electric flux diverges out of the surface. When the flux is negative, the enclosed charge is negative, and flux converges into the Gaussian surface. For very symmetric problems, Gauss's law can be used to determine the electric field of a particular charge distribution (p. 717).

Gauss's law for magnetism
The magnetic flux passing through a Gaussian surface is always equal to zero because there are no isolated magnetic poles. Thus, magnetic field lines are always continuous, that is, they do not begin or end (p. 720).

Displacement current
A changing electric field in a capacitor is equivalent to a current through the capacitor. This current is called the displacement current (p. 721).

Conduction current
Ordinary current in conducting wires (p. 721).

Ampère's law
A magnetic field can be produced by a conduction current or a changing electric field with time (p. 722).

Faraday's law
An electric field can be produced by changing a magnetic field with time (p. 725).

Electromagnetic waves
Waves that are characterized by a changing electric field and a changing magnetic field. They propagate through space at the speed of light. The electric wave and the magnetic wave are always perpendicular to each other (p. 732).

The electromagnetic spectrum
The complete range of electromagnetic waves, from the longest radio waves down to infrared rays, visible light, ultraviolet light, X rays, and the shortest waves, the gamma rays (p. 736).

Intensity of radiation
The total energy of an electromagnetic wave impinging on a unit area in a unit period of time. It is also represented as the power per unit area (p. 738).

Summary of Important Equations

Electric flux
$\Phi_E = EA \cos\theta$ (25.1)

Gauss's law for electricity
$\Phi_E = \Sigma E\Delta A \cos\theta = \dfrac{q}{\epsilon_0}$ (25.7)

Electric field between the plates of a parallel plate capacitor
$E = \dfrac{\sigma}{\epsilon_0}$ (25.11)

$E = \dfrac{q}{\epsilon_0 A}$ (25.9)

Magnetic flux
$\Phi_M = BA\cos\theta$ (23.1)

Gauss's law for magnetism
$\Phi_M = \Sigma B\Delta A\cos\theta = 0$ (25.13)

The displacement current
$I_D = \epsilon_0 A\dfrac{\Delta E}{\Delta t}$ (25.17)

Ampère's law
$\Sigma B_\parallel \Delta \ell = \mu_0(I_C + I_D)$ (25.18)

$\Sigma B_\parallel \Delta \ell = \mu_0 I_C + \mu_0\epsilon_0 A\dfrac{\Delta E}{\Delta t}$ (25.19)

$\Sigma B_\parallel \Delta \ell = \mu_0 I_C + \mu_0\epsilon_0 \dfrac{\Delta \Phi_E}{\Delta t}$ (25.20)

Faraday's law
$\Sigma E_\parallel \Delta \ell = -\dfrac{\Delta \Phi_M}{\Delta t}$ (25.26)

A changing magnetic field produces an electric field
$E = (\text{constant})\dfrac{\Delta B}{\Delta t}$ (25.33)

A changing electric field produces a magnetic field
$B = (\text{constant})\dfrac{\Delta E}{\Delta t}$ (25.23)

Maxwell's equations

$\Phi_E = \Sigma E\Delta A\cos\theta = \dfrac{q}{\epsilon_0}$ (25.7)

$\Phi_M = \Sigma B\Delta A\cos\theta = 0$ (25.13)

$\Sigma B_\parallel \Delta \ell = \mu_0 I_C + \mu_0\epsilon_0 \dfrac{\Delta \Phi_E}{\Delta t}$ (25.20)

$\Sigma E_\parallel \Delta \ell = -\dfrac{\Delta \Phi_M}{\Delta t}$ (25.26)

Maxwell's equations for charge-free space
$\Sigma E\Delta A\cos\theta = 0$ (25.34)
$\Sigma B\Delta A\cos\theta = 0$ (25.35)

$\Sigma B_\parallel \Delta \ell = \mu_0\epsilon_0 A\dfrac{\Delta E}{\Delta t}$ (25.36)

$\Sigma E_\parallel \Delta \ell = -A\dfrac{\Delta B}{\Delta t}$ (25.37)

Electric plane wave
$E = E_0 \sin(kx - \omega t)$ (25.38)

Magnetic plane wave
$B = B_0 \sin(kx - \omega t)$ (25.39)

Wave number
$k = \dfrac{2\pi}{\lambda}$ (12.9)

Angular frequency
$\omega = 2\pi f$ (12.12)

Speed of light
$c = \dfrac{1}{\sqrt{\mu_0\epsilon_0}}$ (25.57)

Relation of electric field to magnetic field
$E = cB$ (25.56)

Speed of light
$c = \lambda\nu$ (25.58)

Electric energy density
$u_E = \frac{1}{2}\epsilon_0 E^2$ (21.12)

Magnetic energy density
$u_M = \dfrac{1}{2}\dfrac{B^2}{\mu_0}$ (23.50)

Energy density of electromagnetic field
$u = \dfrac{1}{2}\epsilon_0 E^2 + \dfrac{1}{2}\dfrac{B^2}{\mu_0}$ (25.59)

$u = \epsilon_0 E^2$ (25.61)

Intensity of radiation
$\text{Intensity} = \dfrac{\text{Total energy}}{(\text{area})(\text{time})}$ (25.62)

$\text{Intensity} = \epsilon_0 c E^2$ (25.63)

$\text{Intensity} = \dfrac{1}{\mu_0} EB$ (25.64)

Questions for Chapter 25

†1. If an electromagnetic wave has energy, should it also have momentum?

2. According to a news report, a woman once washed her cat and then placed it in the microwave oven to dry. Why was this catastrophic for the cat?

3. How does an antenna receive electromagnetic waves?

4. If a radio wave is 1 km long does the radio antenna have to be this long?

5. A student's automobile antenna was stolen from her car. She then took a metal coat hanger and placed it into the empty antenna mount. Would this work to operate her car radio?

†6. How can you take a picture of people at night with an infrared camera?

7. Most people are concerned about receiving too many X rays, but are not concerned about receiving too much visible radiation. Since both radiations are electromagnetic waves, what is the difference?

8. You have no antenna for your FM radio. Will connecting a 1-m length of TV wire to the FM set act as an antenna?

†9. There is growing concern that the earth may be losing its ozone layer. Why should this concern us?

†10. If you could move at the speed of light, what would an electromagnetic wave look like?

†11. What is the difference between a whip antenna and a loop antenna?

Problems for Chapter 25

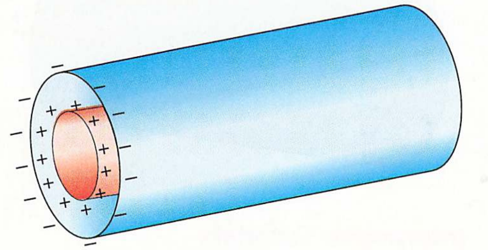
25.2 Gauss's Law for Electricity

1. What is the magnitude of the electric flux from a point charge of 2.00 μC?

2. Find the total flux passing through the sides of a cube 1.00 m on a side if a point charge of 5.00×10^{-6} C is located at its center.

3. Find the electric field between the plates of a parallel plate capacitor of 2.00×10^{-3} m^2 if a charge of 6.00 μC is placed on them.

4. Using Gauss's law find the electric field outside the two concentric cylinders in the diagram, if they are carrying equal but opposite charge.



25.4 The Displacement Current and Ampère's Law

5. A displacement current of 5.00 A exists in a parallel plate capacitor that has an area of 7.50 cm^2. Find the rate at which the electric field changes within the capacitor.

†6. A potential of 100 V is placed across the plates of a parallel plate capacitor rated at 8.50 μF. If it took 0.800 s for this potential to be reached, and if the plates have an area of 25.0×10^{-3} m^2, find (a) the charge deposited on the plates, (b) the conduction current, (c) the displacement current, (d) the rate at which the electric field changed with time.

†7. Show that the displacement current given by equation 25.17 can also be written as

$$I_D = C\frac{\Delta V}{\Delta t}$$

where C is the capacitance of the capacitor and $\Delta V/\Delta t$ is the rate of change of the voltage across the capacitor.

8. For a parallel plate capacitor of 6.00 μF, what should the value of $\Delta V/\Delta t$ be in order that the displacement current be 3.00 mA?

9. A parallel plate capacitor of 6.00 μF has its applied voltage across the plates changing at the rate of 10,000 V/s. What is its displacement current?

10. If the electric field between the plates of a circular parallel plate capacitor changes at the rate of 4.00 $\times$ 10^8 (V/m)/s, and if the radius of the capacitor is 10.0 cm, find the magnetic field at (a) r = 10.0 cm, (b) r = 50.0 cm, and (c) r = 100 cm.

†11. Show that the magnetic field at the distance r from the center of a parallel plate capacitor, equation 25.22, can also be written as

$$B = \frac{\mu_0 C \Delta V/\Delta t}{2\pi r}$$

where C is the capacitance of the capacitor and $\Delta V/\Delta t$ is the rate at which the voltage changes across the capacitor.

12. If the voltage that is applied to the parallel plates of a capacitor varies at the rate of 0.500 V/s, find the magnetic field at a distance of 20.0 cm from the center of a 5.00-μF capacitor.

25.8 The Propagation of an Electromagnetic Wave

13. An electric plane wave has a frequency of 90.0 MHz and an amplitude of 0.85 V/m. Write the equation for the electric wave and the magnetic wave.

25.9 The Speed of an Electromagnetic Wave

14. A radar pulse is sent to the moon when the moon is at its mean distance from the earth. How long does it take the pulse to get to the moon and be reflected back to earth?

15. How long does it take to transmit and receive a reflected signal from a satellite that is orbiting Mars when earth and Mars are aligned?

16. A radar set picks up an aircraft in a time of 3.33×10^{-3} s. How far away is the aircraft?

25.10 The Electromagnetic Spectrum

17. What is the range of frequencies for visible light of wavelengths 380 nm to 720 nm?

18. What is the frequency of a 0.100-nm gamma ray?

19. What is the range of frequencies for infrared radiation lying between 720 nm and 50,000 nm?

20. A diathermy machine generates an electromagnetic wave of 6.00-m wavelength. What frequency does this correspond to?

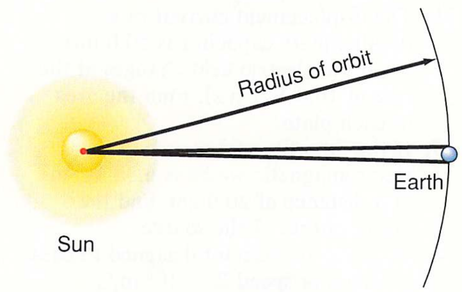
21. An FM radio station broadcasts at 93.4 MHz. What wavelength is associated with this wave?

22. Channel 2 TV operates in a frequency range of 54 to 60 MHz. What range of wavelengths does this represent?

25.11 Energy Transmitted by an Electromagnetic Wave

23. Approximately 60.0% of the solar radiation that impinges on the top of the atmosphere makes it to the surface of the earth. How much energy per square meter hits the surface in 8.00 hr?

†24. If the earth receives 1.38×10^3 J/(m^2 s) of radiation from the sun, how much energy is radiated from the sun per second? What is the percentage of the sun's energy received on the earth to that radiated by the sun?



25. Find the intensity of a 100-W incandescent light bulb at a distance of (a) 20.0 cm, (b) 40.0 cm, (c) 60.0 cm, (d) 80.0 cm, and (e) 100.0 cm from the source.

26. Using the results of problem 25, find the energy density at (a) 20.0 cm, (b) 40.0 cm, (c) 60.0 cm, (d) 80.0 cm, and (e) 100.0 cm.

27. Using the results of problems 25 and 26 find the average value of the electric field and the magnetic field at (a) 20.0 cm, (b) 40.0 cm, (c) 60.0 cm, (d) 80.0 cm, and (e) 100.0 cm.

28. Show that if the distance from the source doubles, the intensity of the radiation decreases by a fourth.

29. Find the average value of the electric and magnetic field a distance of 20.0 m from a 100-W incandescent lamp bulb.

30. What is the maximum intensity of an electromagnetic wave whose maximum electric field is 200 N/C?

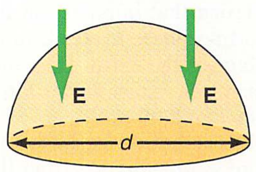
31. A radio station transmits at 1000 W. Find the value of the electric field at a distance of 10.0 km.

32. Find the intensity associated with an electric wave that has a value of 63.0 V/m.

33. What is the intensity on the surface of a wire 5.00 mm in diameter, 5.00 m long, and having a resistance of 100 Ω when it carries a current of 15.0 A?

Additional Problems

34. A hemispherical surface of diameter $d = 10.0$ cm is placed with its flat side down, as shown in the diagram. A uniform electric field of 625 V/m is directed down throughout this region. Find the electric flux passing downward through the surface.



35. The surface charge density of the charge on the plates of a parallel plate capacitor has magnitude $\sigma = 250\ \mu C/m^2$. Find the electric field between the plates.

36. The displacement current in a parallel plate capacitor is 50.0 mA when the electric field changes at the rate of 16.0 V/(m s). Find the area of each plate.

37. If the intensity of a source of electromagnetic waves is 6.38 W/m^2 at a distance of 20.0 cm, find the power output of the source.

38. In a velocity selector designed to pass particles of speed 2×10^6 m/s undeflected, the electric field has a magnitude of 740 N/C. Find the total energy density (due to both electric and magnetic fields).

†39. A radio station emits a power of 50,000 W. Assuming that this power is emitted uniformly in all directions, (a) what would be the power received at a radio antenna of 0.0900 m^2 area, 10.0 miles away? (b) What is the maximum value of the E field picked up by the radio?

†40. You are asked to design a small radio station that will transmit a carrier wave at a frequency of 100 MHz at a power level of 1000 W. (a) If the tuned LC circuit has an inductance of 5.00 mH, what must the value of the capacitance be to generate the 100-MHz signal? (b) What will be the intensity of the radiation at a distance of 20.0 km? (c) What will be the values of E and B at 20.0 km?

†41. If a tuned LC circuit has a capacitance of 7.00×10^{-2} pF and an inductor of 100 μH, (a) what is its natural frequency? (b) If this turned circuit is attached to a dipole antenna, what will the frequency of the electromagnetic wave be? (c) What will its wavelength be?

†42. A ray of light of 400-nm wavelength is traveling in air. It then enters a pool of water where its speed is reduced to 2.26×10^8 m/s. What is the wavelength of the light in the water?

†43. The speed of light in a vacuum was given by equation 25.57. The speed of light in a medium of permittivity ϵ is also given by equation 25.57, but with ϵ_0 replaced by ϵ. Show that the index of refraction, which is defined as the ratio of the speed of light in vacuum to the speed of light in the medium is given by

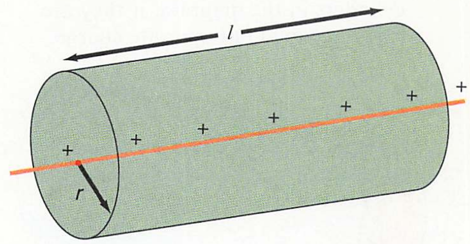
$$n = \frac{c}{v} = \sqrt{\kappa}$$

where κ is the dielectric constant of the medium.

†44. Using Gauss's law, show that the electric filed at a distance r from an infinite line of charge carrying a charge per unit length, $\lambda = q/l$, is given by

$$E = \frac{\lambda}{2\pi\epsilon_0 r}$$

(*Hint:* Draw a cylindrical Gaussian surface around a portion of the infinite line of charge, as shown in the diagram. Then compute $\Sigma E\Delta A \cos\theta$ over the entire cylindrical surface. The entire surface can be broken up into two end caps and the cylindrical surface.)



Interactive Tutorials

45. Wavelength-frequency calculator. (a) Calculate the frequency ν of an electromagnetic wave when the wavelength λ is given and (b) calculate the wavelength λ of an electromagnetic wave when the frequency ν is given.

46. Intensity of an electromagnetic wave. A source is radiating electromagnetic waves at a power output $P = 1000$ W. At a distance $r = 2.00$ m from the source, find (a) the intensity I of the radiation, (b) the energy density u of the radiation, (c) the average value of the electric field E, and (d) the average value of the magnetic field B.