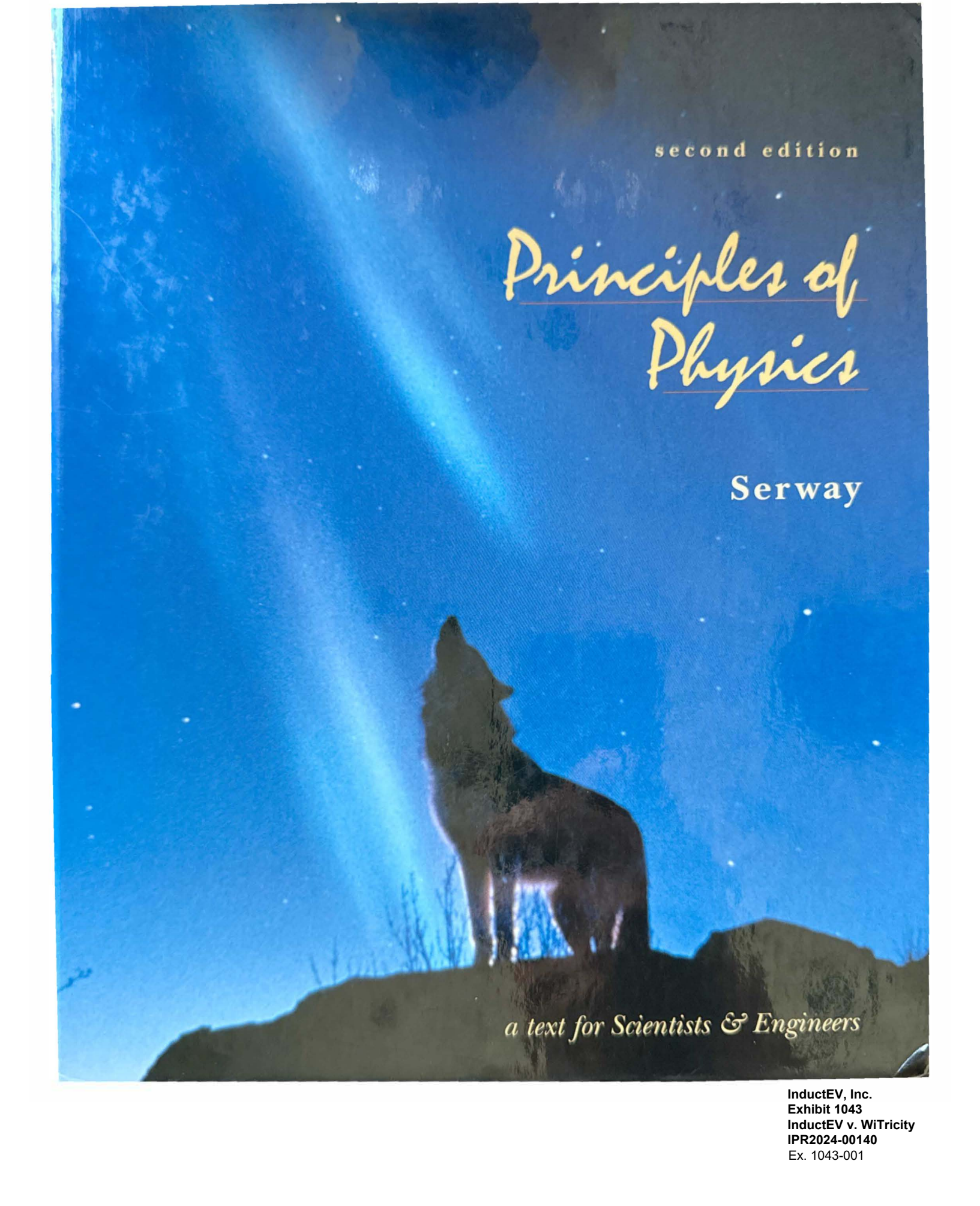




second edition

Principles of Physics

Serway

a text for Scientists & Engineers

Principles of Physics

SECOND EDITION

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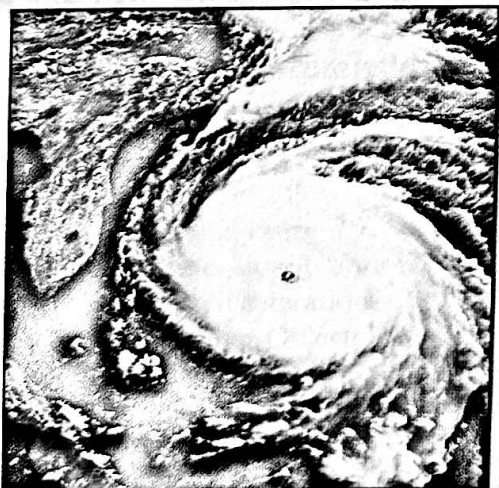
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NASA

receiver when the resonance frequency of the receiver was adjusted to match that of the transmitter.⁴ The energy transfer was detected when the voltage across the spheres in the receiver circuit became high enough to ionize air molecules, which caused sparks to appear in the air gap separating the spheres. Hertz's experiment is analogous to the mechanical phenomenon in which one tuning fork picks up the vibrations from an identical vibrating fork.

Hertz assumed that the energy transferred from the transmitter to the receiver was carried in the form of waves, which are now known to have been electromagnetic waves. In a series of experiments, he also showed that the radiation generated by the transmitter exhibited the wave properties of interference, diffraction, reflection, refraction, and polarization. As we shall see shortly, all of these properties are exhibited by light. Thus, it became evident that the waves observed by Hertz had properties similar to those of light waves and differed only in frequency and wavelength.

Perhaps Hertz's most convincing experiment was his measurement of the speed of the waves from the transmitter. Waves of known frequency from the transmitter were reflected from a metal sheet so that an interference pattern was set up, much like the standing wave pattern on a stretched string. As we saw in our discussion of standing waves, the distance between nodes is $\lambda/2$, and so Hertz was able to determine the wavelength, λ . Using the relationship $v = f\lambda$, Hertz found that v was close to 3×10^8 m/s, the known speed of visible light. Thus, Hertz's experiments provided the first evidence in support of Maxwell's theory.

24.5 • PRODUCTION OF ELECTROMAGNETIC WAVES BY AN ANTENNA

Electromagnetic waves are radiated by *any* circuit carrying an alternating current. The fundamental mechanism responsible for this radiation is the acceleration of a charged particle. **Whenever a charged particle undergoes an acceleration, it must radiate energy by electromagnetic radiation.**

An alternating voltage applied to the wires of an antenna forces an electric charge in the antenna to oscillate. This is a common technique for accelerating charged particles and is the source of the radio waves emitted by the antenna of a radio station.

Figure 24.9 illustrates how an electromagnetic wave is produced by oscillating electric charges in an antenna. Two metal rods are connected to an ac generator, which causes charges to oscillate between the two rods. The output voltage of the generator is sinusoidal. At $t = 0$, the upper rod is given a maximum positive charge and the bottom rod an equal negative charge, as in Figure 24.9a. The electric field near the antenna at this instant is also shown in Figure 24.9a. As the charges oscillate, the rods become less charged, the field near the rods decreases in strength, and the downward-directed maximum electric field produced at $t = 0$ moves away from the rod. When the charges are neutralized, as in Figure 24.9b, the electric field has dropped to zero. This occurs at a time equal to one quarter of the period of oscillation. Continuing in this fashion, the upper rod soon obtains a maximum negative charge and the lower rod becomes positive, as in Figure 24.9c, resulting

⁴Following Hertz's discoveries, Guglielmo Marconi succeeded in developing a practical, long-range radio communication system.

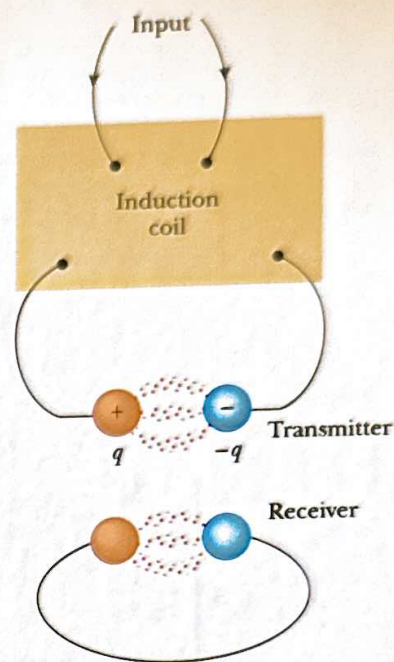


Figure 24.8 Schematic diagram of Hertz's apparatus for generating and detecting electromagnetic waves. The transmitter consists of two spherical electrodes connected to an induction coil, which provides short voltage surges to the spheres, setting up oscillations in the discharge. The receiver is a nearby loop containing a second spark gap.

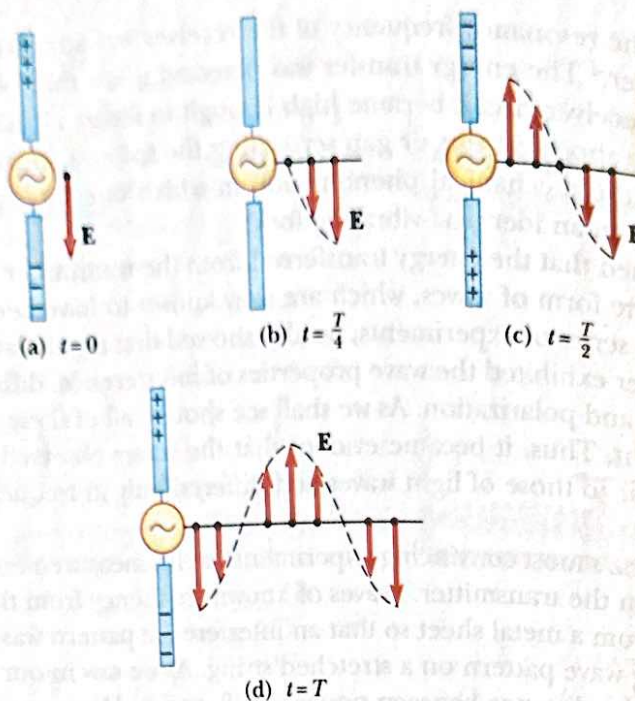


Figure 24.9 The electric field set up by charges oscillating in an antenna. The field moves away from the antenna with the speed of light.

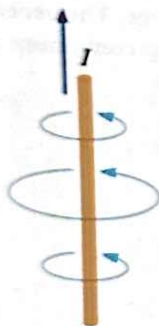


Figure 24.10 Magnetic field lines around an antenna carrying a changing current. Why do the circles have different radii?

in an electric field directed upward. This occurs after a time equal to one half the period of oscillation. The oscillations continue as indicated in Figure 24.9d.

The electric field near the antenna oscillates in phase with the charge distribution. That is, the field points down when the upper rod is positive and up when the upper rod is negative. Furthermore, the magnitude of the field at any instant depends on the amount of charge on the rods at that instant. As the charges continue to oscillate (and accelerate) between the rods, the electric field set up by the charges moves away from the antenna at the speed of light. One cycle of charge oscillation produces one full wavelength in the electric field pattern.

Because the oscillating charges create a current in the rods, a magnetic field is also generated when the current in the rods is upward, as shown in Figure 24.10. The magnetic field lines circle the antenna and are *perpendicular to the electric field at all points*. As the current changes with time, the magnetic field lines spread out from the antenna. At great distances from the antenna, the electric and magnetic fields become very weak. However, at these great distances, it is necessary to take into account the facts that (1) a changing magnetic field produces a changing electric field and (2) a changing electric field produces a changing magnetic field, as predicted by Maxwell. These induced electric and magnetic fields are in phase: At any point, the two fields reach their maximum values at the same instant. This is illustrated for one instant of time in Figure 24.11.

CONCEPTUAL PROBLEM 1

Radio antennas can be in the form of conducting lines or loops. What should the orientation of each of these types of antennas be, relative to a linear broadcasting antenna?

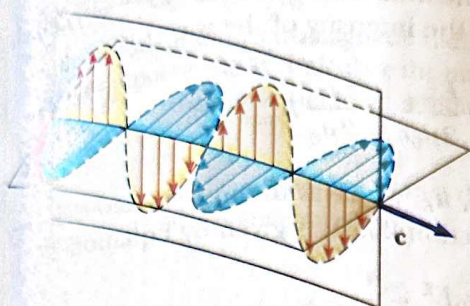


Figure 24.11 An electromagnetic wave sent out by oscillating charges in an antenna. This drawing represents the wave at one instant of time.

CONCEPTUAL PROBLEM 2

In radio transmission, a radio wave serves as a carrier wave, and the sound wave is superimposed on the carrier wave. In amplitude modulation (AM radio), the amplitude of the carrier wave varies according to the sound wave. In frequency modulation (FM radio), the frequency of the carrier wave varies according to the sound wave. The navy sometimes uses flashing lights to send Morse code to neighboring ships, a process that has similarities to radio broadcasting. Is this AM or FM? What is the carrier frequency? What is the signal frequency? What is the broadcasting antenna? What is the receiving antenna?

24.6 • ENERGY CARRIED BY ELECTROMAGNETIC WAVES

Electromagnetic waves carry energy, and as they propagate through space they can transfer energy to objects placed in their path. The intensity of an electromagnetic wave is described by a vector $\mathbf{S}$, called the **Poynting vector**, defined by the expression

$$\mathbf{S} \equiv \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \quad [24.19]$$

The magnitude of the Poynting vector represents the rate at which energy flows through a unit surface area perpendicular to the flow and its direction is along the direction of wave propagation (Fig. 24.12). The SI units of the Poynting vector are $\text{J/s} \cdot \text{m}^2 = \text{W/m}^2$. (These are the units $\mathbf{S}$ must have because it represents the power per unit area, where the unit area is oriented at right angles to the direction of wave propagation.)

As an example, let us evaluate the magnitude of $\mathbf{S}$ for a plane electromagnetic wave where $|\mathbf{E} \times \mathbf{B}| = EB$. In this case

$$S = \frac{EB}{\mu_0} \quad [24.20]$$

Because $B = E/c$, we can also express this as

$$S = \frac{E^2}{\mu_0 c} = \frac{c}{\mu_0} B^2$$

These equations for S apply at any instant of time.

What is of more interest for a sinusoidal plane electromagnetic wave is the time average of S over one or more cycles, called the wave intensity, I . When this average

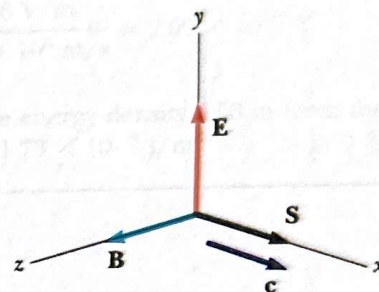


Figure 24.12 The Poynting vector $\mathbf{S}$ for a plane electromagnetic wave is along the direction of propagation.

• **Poynting vector**

• **Poynting vector for a plane wave**

is taken, we obtain an expression involving the time average of $\cos^2(kx - \omega t)$, which equals $\frac{1}{2}$. Hence, the average value of S (or the intensity of the wave) is

$$I = S_{av} = \frac{E_{\max} B_{\max}}{2\mu_0} = \frac{E_{\max}^2}{2\mu_0 c} = \frac{c}{2\mu_0} B_{\max}^2 \quad [24.21]$$

Recall that the energy per unit volume, u_E , which is the instantaneous energy density associated with an electric field (Section 20.9), is given by Equation 20.31:

$$u_E = \frac{1}{2} \epsilon_0 E^2$$

and that the instantaneous energy density u_B associated with a magnetic field (Section 23.7) is given by Equation 23.22:

$$u_B = \frac{B^2}{2\mu_0} \quad [24.23]$$

Because E and B vary with time for an electromagnetic wave, the energy densities also vary with time. Using the relationships $B = E/c$ and $c = 1/\sqrt{\epsilon_0 \mu_0}$, Equation 24.23 becomes

$$u_B = \frac{(E/c)^2}{2\mu_0} = \frac{\epsilon_0 \mu_0}{2\mu_0} E^2 = \frac{1}{2} \epsilon_0 E^2$$

Comparing this result with the expression for u_E , we see that

$$u_B = u_E = \frac{1}{2} \epsilon_0 E^2 = \frac{B^2}{2\mu_0}$$

That is, for an electromagnetic wave, the instantaneous energy density associated with the magnetic field equals the instantaneous energy density associated with the electric field. Hence, in a given volume the energy is equally shared by the two fields.

The total instantaneous energy density, u , is equal to the sum of the energy densities associated with the electric and magnetic fields:

$$u = u_E + u_B = \epsilon_0 E^2 = \frac{B^2}{\mu_0}$$

When this is averaged over one or more cycles of an electromagnetic wave, we again get a factor of $\frac{1}{2}$. Hence, the total average energy per unit volume of an electromagnetic wave is

$$u_{av} = \epsilon_0 (E^2)_{av} = \frac{1}{2} \epsilon_0 E_{\max}^2 = \frac{B_{\max}^2}{2\mu_0} \quad [24.24]$$

Comparing this result with Equation 24.21 for the average value of S , we see that

$$I = S_{av} = cu_{av} \quad [24.25]$$

In other words, the intensity of an electromagnetic wave equals the average energy density multiplied by the speed of light.