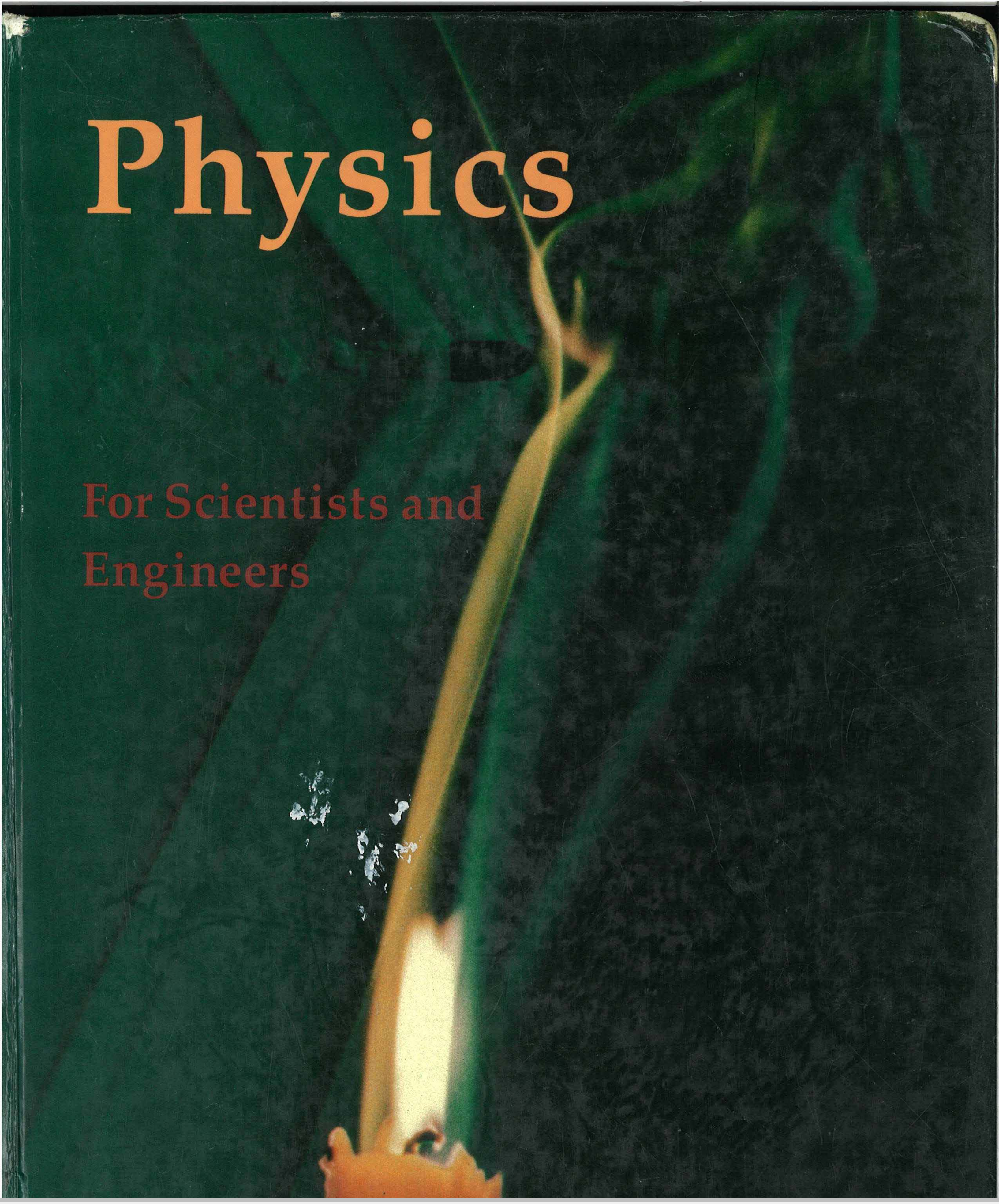
Physics

For Scientists and Engineers



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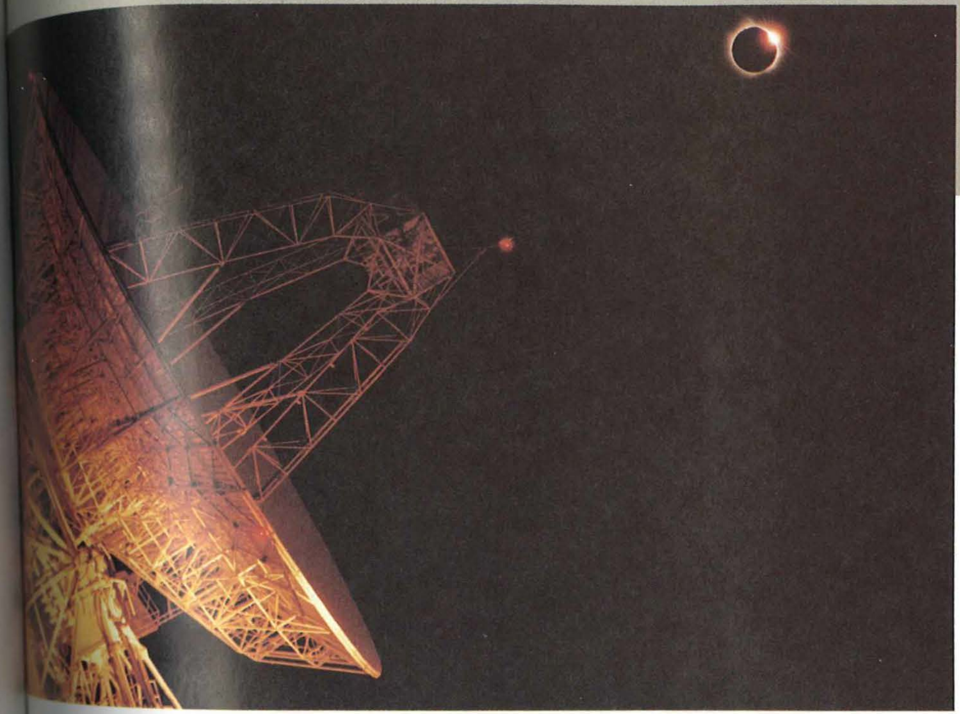
Chapter 29

Maxwell's Equations and Electromagnetic Waves



A multiple-exposure view showing the 26-m tracking antenna at Wallops Station, Virginia, and a total solar eclipse. Electromagnetic radiation at radio wavelengths, like that at optical wavelengths, is not readily absorbed by the earth's atmosphere—making it a viable means of communication between two distant points on the ground or between a point on the ground and a plane, satellite, or spacecraft. Objects are tracked by aiming a continuous radar beam at them and receiving the reflected beam.

About 1860, the great Scottish physicist James Clerk Maxwell found that the experimental laws of electricity and magnetism—the laws of Coulomb, Gauss, Biot–Savart, Ampère, and Faraday, which we have studied in Chapters 18 through 28—could be summarized in a concise mathematical form now known as Maxwell's equations. One of the laws, Ampère's law, contained an inconsistency, which Maxwell was able to remove with the invention of the displacement current (Section 29-1). The new consistent set of equations predicts the possibility of electromagnetic waves.

Maxwell's equations relate the electric- and magnetic-field vectors **E** and **B** to their sources, which are electric charges, currents, and changing fields. These equations play a role in classical electromagnetism analogous to that of Newton's laws in classical mechanics. In principle, all problems in classical electricity and magnetism can be solved using Maxwell's equations, just as all problems in classical mechanics can be solved using Newton's laws. Maxwell's equations are considerably more complicated than Newton's laws, however, and their application to most problems involves mathematics beyond the scope of this book. Nevertheless, Maxwell's equations are of great theoretical importance.

Maxwell showed that these equations could be combined to yield a wave equation for the electric- and magnetic-field vectors **E** and **B**. Such electromagnetic waves are caused by accelerating charges, for example, the charges in an alternating current in an antenna. They were first produced in the laboratory by Heinrich Hertz in 1887. Maxwell showed that the speed of electromagnetic waves in free space should be

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \tag{29-1}$$

where ϵ_0, the permittivity of free space, is the constant appearing in Coulomb's and Gauss's laws and μ_0, the permeability of free space, is that in the Biot–Savart law and Ampère's law. When the measured value of ϵ_0 and the defined value of μ_0 are put into Equation 29-1, the speed of electromagnetic waves is found to be about 3×10^8 m/s, the same as the measured speed of light. Maxwell noted this "coincidence" with great excitement and correctly surmised that light itself is an electromagnetic wave.

In this chapter we begin by showing that Ampère's law as stated in Chapter 25 does not hold for discontinuous currents. We then show how Maxwell generalized Ampère's law by adding a term now called Maxwell's displacement current. After stating Maxwell's equations and relating them to the laws of electricity and magnetism that we have already studied, we will show that these equations imply that electric and magnetic field vectors obey a wave equation that describes waves that propagate through free space with speed $c = 1/\sqrt{\mu_0 \epsilon_0}$. Finally, we will illustrate how electromagnetic waves carry energy and momentum, and discuss the electromagnetic spectrum.

29-1 Maxwell's Displacement Current

As we studied in Chapter 25, Ampère's law (Equation 25-15) relates the line integral of the magnetic field around some closed curve C to the current that passes through any area bounded by that curve:

$$\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I \qquad \text{for any closed curve } C \tag{29-2}$$

We noted that this equation holds only for continuous currents. We can see that it does not hold for discontinuous currents by considering the charging of a capacitor (Figure 29-1). According to Ampère's law, the line integral of the magnetic field **B** around a closed curve equals μ_0 times the total current through any surface bounded by the curve. Such a surface need not be a plane. Two surfaces bounded by the curve C are indicated in Figure 29-1.

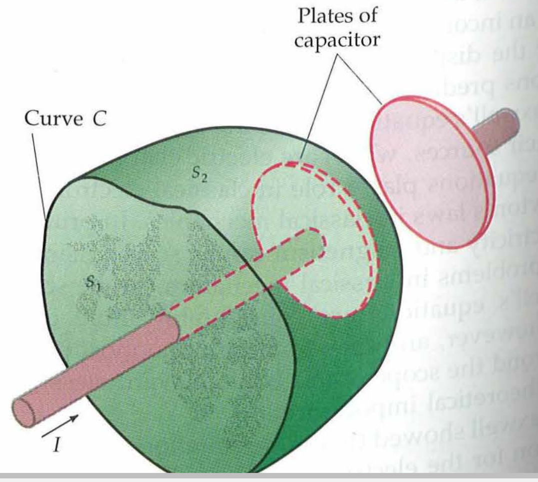


Figure 29-1 Two surfaces S_1 and S_2 bounded by the same curve C. The current I passes through surface S_1 but not S_2. Ampère's law, which relates the line integral of the magnetic field **B** around the curve C to the total current passing through any surface bounded by C, is not valid when the current is not continuous, as

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