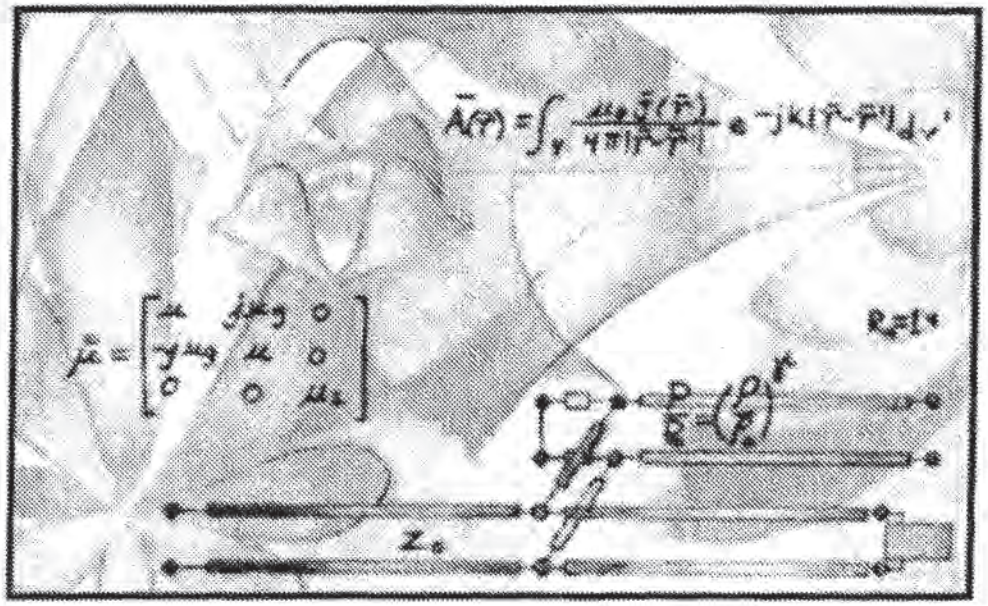
ELECTROMAGNETIC WAVES



David H. Staelin • Ann W. Morgenthaler • Jin Au Kong

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David H. Staelin

Ann W. Morgenthaler

Jin Au Kong

Massachusetts Institute of Technology

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RADIATION BY CURRENTS AND CHARGES IN FREE SPACE

2.1 STATIC SOLUTIONS TO MAXWELL'S EQUATIONS

In this chapter, we consider how electromagnetic disturbances are created and how they propagate in free space. In Chapter 1, we saw that Maxwell's equations predicted the existence of electromagnetic waves, even in vacuum where no currents or charges were present (though sources **outside** the region of interest were of course necessary to generate these waves). We shall now consider the case where the sources ρ and $\overline{J}$ are not zero, resulting in an *inhomogeneous wave equation*. Knowledge of the exact current and charge distributions on an object (antenna) located in free space is then sufficient to predict the field distributions at every point in space.

Before developing the inhomogeneous wave equation, we first discuss the simpler *static field* solutions to Maxwell's equations. Static fields do not change in time and therefore cannot produce waves. We shall see that the static field solutions to a particular problem are quite similar to the *dynamic field* solutions to the same problem with a time-dependent source, but the dynamic solutions must take into account the finite propagation velocity of electromagnetic waves. Because information does not propagate instantaneously from one point in space to another, this retardation effect must be included in the description of radiation. Section 2.2 describes the dynamics of radiating fields, but for now we consider only the simpler static fields.

If we let $\partial/\partial t \rightarrow 0$ in the time-varying Maxwell's equations (1.2.1)–(1.2.4), or let $\omega \rightarrow 0$ in the time-harmonic Maxwell's equations (1.4.4)–(1.4.7), we see that the four basic equations of electromagnetism immediately decouple into two pairs.

Faraday's law and Gauss's law in free space become

$$\nabla \times \overline{E} = 0 \tag{2.1.1}$$

$$\nabla \cdot \overline{E} = \rho/\epsilon_0 \tag{2.1.2}$$

and this pair of *electrostatic* equations, along with appropriate boundary conditions, uniquely determines the electric field. The charge density ρ is assumed to be specified.

Likewise, Ampere's law and Gauss's magnetic law in free space are

$$\nabla \times \overline{H} = \overline{J} \tag{2.1.3}$$

$$\nabla \cdot \mu_0 \overline{H} = 0 \tag{2.1.4}$$

where again this pair of *magnetostatic* equations with boundary conditions specifies $\overline{H}$ completely if $\overline{J}$ is known. Because $\overline{E}$ and $\overline{H}$ are decoupled, it is impossible to have wave propagation, since it is the interaction between the time derivatives of $\overline{E}$ and the space derivatives of $\overline{H}$ and vice versa which leads to electromagnetic radiation. We may solve (2.1.1) and (2.1.2) for the electric field by noticing that the vector identity $\nabla \times (\nabla\Phi) = 0$ holds for any scalar field Φ. Since $\nabla \times \overline{E} = 0$, we can write

$$\overline{E} = -\nabla\Phi \tag{2.1.5}$$

where Φ is called the *scalar electric potential*, and the negative sign is chosen so that electric field lines point from regions of high potential to regions of low potential (i.e., in the direction that a positive charge would move if it were placed in the field). The electric potential is a particularly useful quantity because it is a **scalar** which contains complete information about the three components of the **vector** electric field. Substitution of (2.1.5) into (2.1.2) yields the *scalar Poisson equation* in vacuum:

$$\nabla^2\Phi = -\rho/\epsilon_0 \tag{2.1.6}$$

It is Poisson's equation, an inhomogeneous second-order partial differential equation, which we should like to solve, and since it is a linear equation, we shall use the method of *superposition*.

Consider, first, the simplest charge distribution, namely a point charge q located at the origin. There are two ways to find the scalar electric potential; the first makes use of Gauss's law directly. The differential form of Gauss's law (2.1.2) may be converted to an integral representation by using *Gauss's divergence theorem* (1.6.7) discussed in Chapter 1:

$$\int_V (\nabla \cdot \overline{G})\, dv = \oint_A \overline{G} \cdot \hat{n}\, da \tag{2.1.7}$$

The quantities V, A, $\hat{n}$, da, and dv have been defined in Section 1.6.

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