# Chapter 2: Introduction to Electrodynamics

## *2.1 Maxwell's differential equations in the time domain*

Whereas the Lorentz force law characterizes the observable effects of electric and magnetic fields on charges, Maxwell's equations characterize the origins of those fields and their relationships to each other. The simplest representation of Maxwell's equations is in differential form, which leads directly to waves; the alternate integral form is presented in Section 2.4.3.

The differential form uses the vector *del operator* $\nabla$:

$$\nabla = \hat{x}\frac{\partial}{\partial x} + \hat{y}\frac{\partial}{\partial y} + \hat{z}\frac{\partial}{\partial z} \tag{2.1.1}$$

where $\hat{x}$, $\hat{y}$, and $\hat{z}$ are defined as unit vectors in cartesian coordinates. Relations involving $\nabla$ are summarized in Appendix D. Here we use the conventional veector *dot product*[1] and *cross product*[2] of $\nabla$ with the electric and magnetic field vectors where, for example:

$$\overline{E} = \hat{x}E_x + \hat{y}E_y + \hat{z}E_z \tag{2.1.2}$$

$$\nabla \bullet \overline{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} \tag{2.1.3}$$

We call $\nabla \bullet \overline{E}$ the *divergence* of $\overline{E}$ because it is a measure of the degree to which the vector field $\overline{E}$ diverges or flows outward from any position. The cross product is defined as:

$$\begin{aligned} \nabla \times \overline{E} &= \hat{x}\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right) + \hat{y}\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right) + \hat{z}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right) \\ &= \det\begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ E_x & E_y & E_z \end{vmatrix} \end{aligned} \tag{2.1.4}$$

which is often called the *curl* of $\overline{E}$. Figure 2.1.1 illustrates when the divergence and curl are zero or non-zero for five representative field distributions.

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[1] The dot product of $\overline{A}$ and $\overline{B}$ can be defined as $\overline{A} \bullet \overline{B} = A_x B_x + A_y B_y + A_z B_z = |A||B|\cos\theta$, where $\theta$ is the angle between the two vectors.

[2] The cross product of $\overline{A}$ and $\overline{B}$ can be defined as $\overline{A} \times \overline{B} = \hat{x}(A_y B_z - A_z B_y) + \hat{y}(A_z B_x - A_x B_z) + \hat{z}(A_x B_y - A_y B_x)$; its magnitude is $|\overline{A}| \bullet |\overline{B}| \sin\theta$. Alternatively, $\overline{A} \times \overline{B} = \det[[A_x, A_y, A_z][B_x, B_y, B_z][\hat{x}, \hat{y}, \hat{z}]]$.

# Electrodynamics A Concise Introduction

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