Accurate Understanding of the Physical Picture of Electromagnetic Wave Propagation Velocity

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Abstract

This paper reviews the entire process of deriving the d'Alembert wave equation, where the most important step is using Gauss's law and Ampère's law to respectively derive the d'Alembert wave equations for the scalar potential and vector potential. This paper emphasizes that Gauss's law is the differential form of Coulomb's law, in which the source charge and the observer (i.e., the field point) are relatively stationary; in Ampère's law, the source current carrier and the observer (i.e., the field point) are also relatively stationary. The conclusion of this paper is that both Maxwell's equations and the d'Alembert wave equation are equations under the condition of source-observer relative rest, and the constant 'C' in the d'Alembert wave equation is the propagation speed under conditions of source-observer relative rest in a vacuum environment. Under such special conditions, the propagation space of electromagnetic waves is homogeneous and isotropic; therefore, regardless of propagation distance and directional geometry, and regardless of which planet the source-observer laboratory is located on or its absolute motion, the propagation speed of electromagnetic waves is the same, which is logical. Electromagnetic waves in vacuum emanate from source charges and source currents, propagating to observers everywhere, with source-observer relative rest and a propagation space that is homogeneous and isotropic—this is an accurate physical picture and the physical foundation for accurately understanding the principle of the constancy of the speed of light.

Full Text

Preamble

Accurate Understanding of the Physical Picture of Electromagnetic Wave Propagation

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This paper reviews the complete derivation process of the D'Alembert wave equation, with the most crucial step being the derivation of the D'Alembert wave equations for the scalar and vector potentials using Gauss's law and Ampere's law. We emphasize that Gauss's law is the differential form of Coulomb's law, where the source charge and the observer (i.e., the field point) are relatively at rest; similarly, in Ampere's law, the current source carrier and the observer are also relatively static. The conclusion of this paper is that both Maxwell's equations and the D'Alembert wave equation are formulated under the condition of source-observer relative rest, and the constant 'C' in the D'Alembert wave equation represents the propagation speed under precisely these conditions in a vacuum environment. Under such special conditions, the propagation space of electromagnetic waves is uniform and isotropic; therefore, it is logical that the electromagnetic wave propagation speed remains the same regardless of the distance and geometric orientation between source and observer, and regardless of the absolute motion of the laboratory (on whatever planet) where the source and observer are located. Electromagnetic waves in vacuum are emitted from source charges and currents, propagating to observers everywhere under source-observer relative rest within a uniform, isotropic medium. This constitutes an accurate physical picture and provides the physical foundation for properly understanding the principle of the constancy of the speed of light.

Keywords: field source, observer, source-observer relativity, electromagnetic field, electromagnetic wave, principle of invariance of light speed

Abstract

This paper reviews the complete derivation of the D'Alembert wave equation, highlighting the critical step of deriving the wave equations for scalar and vector potentials from Gauss's law and Ampere's law. We emphasize that Gauss's law represents the differential form of Coulomb's law, where the source charge and observer remain relatively static; likewise, Ampere's law operates under the condition where the current source carrier and observer are relatively at rest. Our central conclusion is that both Maxwell's equations and the D'Alembert wave equation are valid specifically under source-observer relative rest conditions, and the constant 'C' in the D'Alembert wave equation denotes the propagation speed under precisely these conditions in vacuum. In this special scenario, the electromagnetic wave propagation space is uniform and isotropic, making it logically consistent that the propagation speed remains invariant regardless of the distance and azimuthal geometry between source and observer, and irrespective of the absolute motion of the laboratory or its planetary location. The physical picture of electromagnetic waves in vacuum—emitted from source charges and currents, propagating to observers everywhere under source-observer relative rest within a uniform, isotropic medium—provides an accurate conceptual framework and the physical basis for properly understanding the principle of the constancy of the speed of light.

Keywords: field source, observer, source-observer relativity, electromagnetic

field, electromagnetic wave, principle of invariance of light speed

1. Maxwell's Equations with Sources

In vacuum, Maxwell's equations consist of four fundamental equations:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \tag{1.1}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{1.2}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1.3}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{1.4}$$

where ε_0 is the permittivity of free space and μ_0 is the permeability of free space.

The first two equations are source equations. Equation (1.1), Gauss's law, contains the source charge ρ and describes the electric field distribution around it. We emphasize that the source charge and observer are both stationary within the same laboratory, meaning the source-observer system is in a state of relative rest.

Equation (1.2), Ampere's law, contains the source current $\mathbf{j}$ and describes the magnetic field distribution around the current source, including the contribution from displacement current. We emphasize that the current carrier (such as a wire) and the observer are both stationary within the same laboratory, maintaining relative rest between source and observer. The third equation is Faraday's law of induction, and the fourth equation states the non-existence of magnetic monopoles; neither involves source charges or source currents. In summary, Maxwell's equations describe electromagnetic phenomena under the specific condition of source-observer relative rest.

2. Re-deriving the D'Alembert Wave Equation

Through progressive insights, physicists recognized that electric and magnetic fields are interconnected concepts possessing certain symmetries. To describe the electromagnetic field completely and symmetrically, they introduced the scalar potential φ and vector potential $\mathbf{A}$. Based on the source-free equation (1.4), we can introduce the vector potential $\mathbf{A}$, whose relationship with the magnetic field $\mathbf{B}$ is:

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{2.1}$$

Substituting (2.1) into the source-free equation (1.3), we find that $\nabla \times \left(\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t}\right) = 0$, indicating that $\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t}$ is an irrotational field. Since the gradient of any scalar field is irrotational, we can express this as:

$$\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} = -\nabla \varphi \tag{2.2}$$

The negative sign appears because the direction of the electric potential gradient opposes the electric field direction. Thus, the electric field can be described using both scalar and vector potentials:

$$\mathbf{E} = -\nabla \varphi - \frac{\partial \mathbf{A}}{\partial t} \tag{2.3}$$

Substituting (2.3) into Gauss's law (1.1) containing the source charge yields:

$$\nabla^2 \varphi + \frac{\partial}{\partial t}(\nabla \cdot \mathbf{A}) = -\frac{\rho}{\varepsilon_0} \tag{2.5}$$

Substituting (2.1) and (2.3) into Ampere's law (1.2) gives:

$$\nabla^2 \mathbf{A} - \nabla \left(\nabla \cdot \mathbf{A} + \mu_0 \varepsilon_0 \frac{\partial \varphi}{\partial t} \right) - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{j} \tag{2.6}$$

To simplify these equations, we adopt the Lorenz gauge condition:

$$\nabla \cdot \mathbf{A} + \mu_0 \varepsilon_0 \frac{\partial \varphi}{\partial t} = 0 \tag{2.7}$$

With this gauge, equation (2.6) simplifies to:

$$\nabla^2 \mathbf{A} - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{j} \tag{2.8}$$

Applying the Lorenz gauge (2.7) to the scalar potential wave equation (2.5) similarly yields:

$$\nabla^2 \varphi - \mu_0 \varepsilon_0 \frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0} \tag{2.9}$$

Thus, the wave equations for the scalar and vector potentials reduce to two D'Alembert wave equations of identical form:

$$\nabla^2 \varphi - \frac{1}{C^2} \frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0} \tag{2.10}$$

$$\nabla^2 \mathbf{A} - \frac{1}{C^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{j} \tag{2.11}$$

where the constant C represents the electromagnetic wave propagation speed:

$$C = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \tag{2.12}$$

This speed depends entirely on the permittivity ε_0 and permeability μ_0 of the propagation environment. Here, ε_0 and μ_0 are the vacuum permittivity and permeability between source and observer.

We emphasize that these values correspond to the permittivity and permeability of the vacuum environment between source and observer under the condition of source-observer relative rest. Consequently, C represents the propagation speed of electromagnetic fields or waves under this specific condition. In vacuum, under source-observer relative rest, the propagation environment for electromagnetic fields or waves is uniform and isotropic, with ε_0 and μ_0 being truly constant. Therefore, regardless of the distance and geometric orientation between observer and source charge or current, and irrespective of the absolute motion of the laboratory (whether on Earth or elsewhere), the propagation speed should be identical. This is a reasonable conclusion that presents no logical difficulties. The physical picture of electromagnetic waves in vacuum—emitted from source charges and currents, propagating to observers everywhere under source-observer relative rest within a uniform, isotropic space—provides an accurate foundation for understanding the principle of the constancy of the speed of light.

3. On Einstein's Scientific Principles

Humanity has continuously explored the scientific laws of nature, and throughout the history of modern science, various debates have persisted. In fact, both scientific experiments and scientific controversies serve as dual drivers of scientific progress. Vigorous debates surrounding Galileo's principle of relativity, Newton's laws of mechanics and gravitation, Einstein's theory of relativity, and Bohr's quantum theory have profoundly advanced the development of mechanics, electromagnetism, gravitational physics, relativity, and quantum mechanics.

Einstein was a profound thinker and great scientist. This paper contends that Einstein's greatest scientific contribution lies in proposing two objective criteria for judging scientific theories: First, a theory must not contradict empirical facts—though one must avoid the pitfall that "people can often, and indeed always, adapt theories to facts through artificial supplementary hypotheses, thereby maintaining a universal theoretical foundation." Second, a proposition is correct if it is derived within a logical system according to accepted logical rules.

The discussions in this paper regarding Maxwell's equations, the scalar and vector potentials, the derivation of the D'Alembert wave equation, the permittivity and permeability of the propagation environment, and the generation and propagation of electromagnetic fields and waves are all natural, reasonable, and consistent with Einstein's scientific principles, and therefore should constitute correct theory.

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Note: Figure translations are in progress. See original paper for figures.