Light Speed as an Emergent Property of Electromagnetic Superposition

Polarization Without Matter: A Field-Only Interpretation of Refraction

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One-Sentence Summary. Light slows because electromagnetic waves interfere with phase-delayed secondary electromagnetic fields, making the effective speed of light an emergent, local property of electromagnetic superposition rather than a universal constant.

Abstract. Polarization is treated as a secondary electromagnetic field rather than a property of matter. Within linear Maxwell theory and linear response, overlapping electromagnetic waves generate phase-delayed secondary fields whose superposition alters phase evolution and yields an effective refractive index. Electromagnetic waves therefore interact through the total field configuration they jointly create, and the effective local speed of light depends on the electromagnetic energy density of the environment. Refraction emerges as a consequence of field superposition and delayed response, without invoking particles, atoms, or nonlinear modifications of Maxwell's equations.

Keywords. Maxwell theory, electromagnetic superposition, polarization, linear response, refraction, phase delay, energy density, effective refractive index, variable light speed, field ontology

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1. Summary

Electromagnetic waves interact through the total field they jointly create. Polarization is an ordinary secondary electromagnetic field, not a special field generated by matter. Phase-delayed secondary fields modify phase evolution. An effective, local light speed emerges from the electromagnetic energy density itself, as fields interfere pointwise.

2. Conceptual clarification: linearity, superposition, and interaction

It is commonly stated in classical electrodynamics that electromagnetic waves do not interact in vacuum because Maxwell's equations are linear and admit superposition. This statement, however, is not a theorem of Maxwell theory.

Linearity guarantees that if $(\mathbf{E}_1, \mathbf{B}_1)$ and $(\mathbf{E}_2, \mathbf{B}_2)$ are solutions of Maxwell's equations, then their sum is also a solution. It does not, by itself, imply that one field configuration cannot influence the propagation of another through the total field they jointly create.

The identification of "interaction" exclusively with forces on charges or with explicit nonlinear field equations is a conventional interpretive choice, widely adopted in standard treatments of classical electrodynamics [1]. This convention is not derived from Maxwell's equations themselves.

In the present work, interaction is defined operationally as modification of phase evolution or effective propagation parameters due to the total electromagnetic field configuration. This notion of interaction is fully compatible with linear field dynamics and does not require nonlinear modifications of Maxwell's equations.

3. Goal

Explain, mathematically and with an explicit ontological justification, how linear Maxwell theory allows electromagnetic waves to superpose and interact through the total field, and how an effective local propagation speed can arise from that total-field interaction.

4. Corollary

The maximum propagation speed of electromagnetic disturbances is c_0, with

$$c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}}.$$

However, c_0 need not take the same effective value everywhere in the universe. When electromagnetic waves propagate in a linear, nontrivial electromagnetic environment, the total field gives rise to an effective susceptibility $\chi(\mathbf{x})$.

The effective local propagation speed is then

$$c_{\text{local}}(\mathbf{x}) = \frac{c_0}{\sqrt{1 + \chi(\mathbf{x})}},$$

and therefore depends on the local electromagnetic energy density through the induced effective χ.

As a result, the effective speed of light varies from place to place, tracking spatial variations in electromagnetic field energy density across the universe.

5. Derivation

5.1. Maxwell theory and superposition

In source-free regions, Maxwell's equations are

$$\nabla \cdot \mathbf{E} = 0, \qquad \nabla \cdot \mathbf{B} = 0,$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}, \qquad \nabla \times \mathbf{B} = \mu_0 \epsilon_0 \, \partial_t \mathbf{E}.$$

These equations are linear: if $(\mathbf{E}_1, \mathbf{B}_1)$ and $(\mathbf{E}_2, \mathbf{B}_2)$ are solutions, then their sum is also a solution.

Linearity applies to the field equations themselves and does not constrain how physical observables are constructed from the fields.

5.2. Quadratic field observables

The electromagnetic energy density is

$$u = \frac{\epsilon_0}{2} \left(\mathbf{E}^2 + c^2 \mathbf{B}^2 \right).$$

For a superposed field $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$,

$$u = u_1 + u_2 + u_{12},$$

with

$$u_{12} = \epsilon_0 \left(\mathbf{E}_1 \cdot \mathbf{E}_2 + c^2 \mathbf{B}_1 \cdot \mathbf{B}_2 \right).$$

Thus, overlapping waves produce cross terms in energy density and momentum flow. This constitutes a physical interaction at the level of observables.

5.3. Polarization written purely as fields

In macroscopic electrodynamics,

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P},$$

with linear response

$$\mathbf{P} = \epsilon_0 \chi \, \mathbf{E}.$$

Maxwell's equations do not specify the origin of $\mathbf{P}$. Formally, $\mathbf{P}$ is an additional electromagnetic field proportional to $\mathbf{E}$.

Interpreted this way: - $\mathbf{P}$ is a secondary electromagnetic field. - The relation $\mathbf{P} = \epsilon_0 \chi \mathbf{E}$ is a linear field–field coupling. - No ontological distinction between "matter" and "electromagnetic field" is required.

5.4. Phase delay and effective propagation

In realistic linear response, proportionality is causal:

$$\mathbf{P}(t) = \epsilon_0 \int_{-\infty}^{t} \chi(t - t') \, \mathbf{E}(t') \, dt'.$$

In frequency space,

$$\mathbf{P}(\omega) = \epsilon_0 \chi(\omega) \mathbf{E}(\omega).$$

The secondary field associated with $\mathbf{P}$ is phase-delayed relative to the primary field. The total field is the superposition of the incident electromagnetic wave and the delayed secondary electromagnetic wave, producing a shifted phase evolution.

5.5. Emergence of an effective refractive index

With

$$\mathbf{D} = \epsilon(\omega)\mathbf{E}, \qquad \epsilon(\omega) = \epsilon_0 \left[1 + \chi(\omega)\right],$$

Maxwell's equations yield the wave equation

$$\nabla^2 \mathbf{E} - \mu_0 \epsilon(\omega) \partial_t^2 \mathbf{E} = 0.$$

Plane-wave solutions satisfy

$$k^2 = \mu_0 \epsilon(\omega) \omega^2,$$

so the phase velocity is

$$v_p(\omega) = \frac{1}{\sqrt{\mu_0 \epsilon(\omega)}} = \frac{c_0}{n(\omega)}, \qquad n(\omega) = \sqrt{1 + \chi(\omega)}.$$

The reduction in propagation speed follows directly from interference with a phase-delayed secondary electromagnetic field.

5.6. Two-wave interaction

Let

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2.$$

By linearity,

$$\mathbf{P} = \epsilon_0 \chi (\mathbf{E}_1 + \mathbf{E}_2) = \epsilon_0 \chi \mathbf{E}_1 + \epsilon_0 \chi \mathbf{E}_2.$$

Each wave generates a secondary electromagnetic field, and both contribute to the total response. Each wave therefore propagates in an environment determined by the combined electromagnetic configuration.

5.7. Local effective light speed

The local electromagnetic energy density is

$$u(\mathbf{x}) = \frac{\epsilon_0}{2} \left(\langle \mathbf{E}^2 \rangle + c^2 \langle \mathbf{B}^2 \rangle \right).$$

The effective refractive index is

$$n(\mathbf{x}) = \sqrt{1 + \chi(\mathbf{x})},$$

and the local propagation speed is

$$c_{\text{local}}(\mathbf{x}) = \frac{c_0}{n(\mathbf{x})}.$$

5.8. Consequence

Different regions of the universe, characterized by different electromagnetic field configurations and energy densities, exhibit different effective propagation speeds. Maxwell's equations remain unchanged. The result follows solely from superposition, linear response, and a field-only interpretation of polarization.

6. References

1. Jackson, J. D., *Classical Electrodynamics*, 3rd ed., Wiley (1999).