Rethinking Electricity:
A Wave-Based Interpretation of Electrical Energy Transport

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17 May 2026

Abstract: This work revisits Oliver Heaviside's interpretation of electricity within modern electromagnetic theory, presenting electrical energy transport as a fundamentally wave-based phenomenon. Electrical energy is transmitted primarily as electromagnetic fields propagating through the dielectric medium surrounding the conductors; the motion of charges within the conductors plays a secondary, dissipative role. Building on transmission line theory, Maxwell's equations, and Poynting's theorem, the paper introduces the concepts of supracurrent and infracurrent to distinguish field-mediated energy flux from dissipative material response. The telegrapher's equations are then interpreted as a macroscopic description of propagation and loss in real transmission lines.

1 Introduction

Electricity is commonly compared to water flowing through a pipe, an idea known as the "hydraulic analogy". This analogy was already widely used in the early days of the telegraph. The discovery of the electron strengthened this view and led to the Drude model [1], which describes electricity as a flow of free electrons through a conductor. Despite its intuitive appeal, the hydraulic analogy has important limitations. These limitations motivate a closer examination of how electrical energy is actually transmitted.

2 Hydraulic Analogy

2.1 Velocity of Electricity

A key limitation of the hydraulic analogy is its inability to explain the propagation speed of electrical energy. Electrical energy is known to propagate at a significant fraction of the speed of light; however, accelerating electrons to such velocities would require particle accelerators and extremely large amounts of energy. On the other hand, electron drift velocities in copper wires are many orders of magnitude smaller than the energy propagation velocity, typically on the order of millimeters per second.

The propagation speed of electrical signals is not determined by the conductor material or its geometry, but primarily by the properties of the surrounding dielectric medium, namely its permittivity and magnetic permeability.

$$v = \frac{c}{\sqrt{\epsilon_r \, \mu_r}} \tag{1}$$

When the medium between conductors is air, the propagation speed is approximately equal to the speed of light. In a coaxial cable, however, the effective propagation speed is typically reduced to about two-thirds of the speed of light because of the dielectric properties of materials such as polyethylene. This discrepancy raises a conceptual difficulty for models that interpret electricity purely as a physical flow of electrons.

2.2 Veritasium thought experiment

This conceptual limitation is not only theoretical but also appears in modern interpretations of electricity. A well-known example is the Veritasium thought experiment [2], which argues that electrical energy propagates through electromagnetic fields in the space surrounding conductors rather than through their interior.

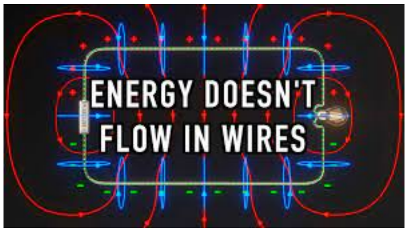

Figure 1: Veritasium's YouTube video.

In many elementary explanations, electromagnetic fields are acknowledged but are treated as secondary to the intuitive picture of charges moving through wires.

This equivalence is challenged by a thought experiment in which a light bulb is placed one meter from a battery, while the connecting wires extend over a distance of 0.5 light-seconds. If energy were transported through the wire as electron flow, the signal would take about 1 s to reach the bulb. In contrast, if energy propagates through the surrounding fields, it would arrive in approximately 3 ns. This result indicates that the two interpretations are not strictly equivalent.

Figure 2: Veritasium's thought experiment.

This interpretation that electrical energy is mainly transmitted through surrounding electromagnetic fields is consistent with classical electromagnetism and with standard high-frequency engineering practice.

2.3 High-Frequency PCB

While thought experiments reveal conceptual inconsistencies, their physical relevance becomes clearer in real engineering systems. In modern high-frequency circuit design, electrical energy is not treated as flowing through conductors, but as propagating through electromagnetic fields.

This is evident in Printed Circuit Boards (PCBs), where increasing operating frequencies led to effects such as electromagnetic interference (EMI), arising from field coupling rather than conduction through wires. In 1967, Morrison showed that EMI cannot be explained within a purely electron motion framework and requires a field-based interpretation. In this view, PCB traces do not transport energy themselves, but guide its propagation through the surrounding dielectric.

> *"Buildings have walls and halls. People travel in the halls, not the walls. Circuits have traces and spaces. Energy and signals travel in the spaces, not the traces." [3]*

This perspective is reflected in modern engineering practice, where many design problems arise from interpreting signals as currents in wires instead of fields in space.

> *"I spend most of my consulting time solving EMI problems because most of the engineers I meet have no clue about any of this. My job is so easy and I make such a ridiculous amount of money doing it. It's just unbelievable; I solve most EMI problems by simply adding return path vias to boards or changing the positions of decoupling caps, [...]. It's not that electronic engineers don't know to consider coupling between signal lines, but because most of them persist in thinking that signals travel in wires, rather than in the fields, they don't understand when coupling will occur and when it won't". [4]*

From this standpoint, energy in a PCB propagates as coupled electric (E) and magnetic (H) fields in the dielectric, while conductors guide and constrain this propagation. The structure acts as a waveguide, directing energy along field distributions determined by the geometry and boundary conditions. Thus, what is commonly interpreted as current flow in copper is more accurately described as field-guided energy transport. [5]

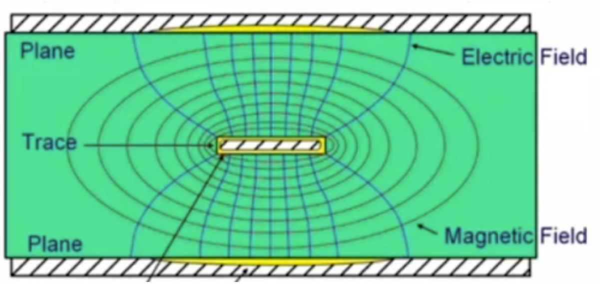

Figure 3: PCB electromagnetic fields.

2.4 Circuit Theory

To formalize these observations, it is useful to revisit the theoretical frameworks traditionally used to describe electrical systems. Circuit theory provides a simplified framework for analyzing and designing electrical circuits at low frequencies. It is based on an approximation of electromagnetic theory in which energy propagation is assumed to be instantaneous. Under this assumption, the geometry and length of conductors can be neglected, allowing the direct application of Kirchhoff's laws.

A key condition for the validity of this approach is that the physical dimensions of the circuit are much smaller than the wavelength of the signal:

$$L_{\text{circuit}} \ll \lambda \tag{2}$$

When this condition is satisfied, voltage and current can be treated as lumped quantities, and propagation effects such as delay, reflection, and wave behavior can usually be ignored. In this limited regime, the hydraulic analogy can be a useful approximation. However, as frequency increases or circuit dimensions grow, this approximation breaks down.

2.5 Transmission Line Theory

When the length of conductors becomes comparable to the wavelength, or when operating at higher frequencies, Circuit theory is no longer adequate and transmission line theory must be applied.

In this framework, conductors are treated as waveguides, and their electrical properties are described by distributed parameters: resistance (R), inductance (L), capacitance (C), and conductance (G). This model allows electromagnetic waves to propagate along the line in both directions.

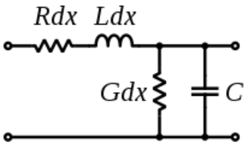

Figure 4: Transmission Line Model.

A central concept is the characteristic impedance Z_0, which defines the relationship between voltage and current for waves traveling without reflection:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{3}$$

When the load impedance matches Z_0, energy is transmitted efficiently without reflection. If the load differs, part of the wave is reflected, generating reflected waves and potentially standing waves, which reduce transmission efficiency. This principle is fundamental in the design of coaxial cables, microstrip lines, antennas, and high-frequency systems.

When a transmission line is excited, energy propagates as an electromagnetic wave along the conductors. Initially, the wave is determined solely by the characteristic impedance of the line, as it has not yet encountered the load. Upon reaching the termination, part of the wave may be reflected depending on the load impedance. The interaction between incident and reflected waves leads to a transient regime, which eventually evolves into a steady state.

At sufficiently high frequencies, the transient regime may dominate the system behavior, preventing the establishment of a steady state. In this regime, propagation effects become essential, and simple circuit approximations fail. At even higher frequencies, such as in the microwave or optical regimes, electromagnetic energy propagates primarily through the dielectric medium, while the conductors primarily serve as waveguides to confine the fields.

2.6 Thought experiment solution

To clarify the conceptual issues raised in the Veritasium thought experiment [2], we interpret it under idealized conditions, where the source, transmission line, and load are assumed to be linear and well-defined. When the source is switched on, the system enters a transient regime governed by electromagnetic propagation guided by the conductor geometry, as described by transmission line theory. A disturbance travels along the line at a velocity set by the surrounding medium.

At this stage, the power delivered is determined by the local impedance encountered by the propagating wave. If the load is matched to the characteristic impedance of the relevant transmission path, a significant fraction of the energy reaches the load after approximately 3 ns. The remaining energy is redistributed through subsequent propagation and reflections at impedance discontinuities, progressively establishing the global boundary conditions. After a round-trip time of about one second, the system approaches the steady-state behavior predicted by conventional circuit theory.

This interpretation shows that, even in an ideal system, energy transfer is initially governed by electromagnetic propagation and only later by steady-state circuit behavior.

3 Contemporary theory of electricity

Up to this point, electricity has been discussed from a macroscopic and engineering perspective. To assess its consistency, it is useful to situate it within the current theoretical framework. Electrical phenomena are currently understood through a hierarchy of effective theories, each valid at a different scale. Rather than a single unified model, it is currently assumed that electricity emerges from progressively simpler descriptions obtained by averaging microscopic details, a process commonly referred to as “coarse-graining.”

3.1 Fundamental Level

At the most fundamental level, electrical phenomena arise from Quantum Electrodynamics (QED), where electrons and electromagnetic fields are treated as interacting quantum fields mediated by photons. Although QED provides the conceptual foundation, it is too complex for direct application to real materials, serving instead as the basis for effective theories.

3.2 Microscopic Level

At the scale of solids, this complexity is reduced through condensed matter physics. Electrons in periodic lattices form energy bands that determine electrical properties: metals conduct due to partially filled bands, while insulators and semiconductors exhibit band gaps. In metals, this is often interpreted in terms of metallic bonding, where valence electrons are delocalized and shared across the lattice. Conduction arises from electron and hole dynamics and depends on band structure and scattering processes. In practice, these systems are described using effective approaches such as density functional theory (DFT) and simplified lattice models. [6]

3.3 Emergent Level

To connect microscopic behavior with observable currents, transport theory is introduced. In general, conductivity can be described by quantum linear response theory (Kubo formalism). In many ordinary macroscopic conductors, scattering destroys coherence, and transport becomes diffusive, well described by semiclassical models such as Boltzmann or Drude. In contrast, when coherence is preserved (mesoscopic regime), transport is described in terms of quantum transmission, as in the Landauer-Büttiker formalism. [7]

3.4 Macroscopic Level

At larger scales, electrical phenomena are described by Maxwell's equations in matter, with microscopic details encoded in effective parameters such as conductivity and permittivity. Under the quasistatic approximation, these reduce to circuit theory, while at higher frequencies transmission line theory is required to account for propagation, delay, and reflections. This represents a coarse-grained description in which currents and charges appear as continuous quantities.

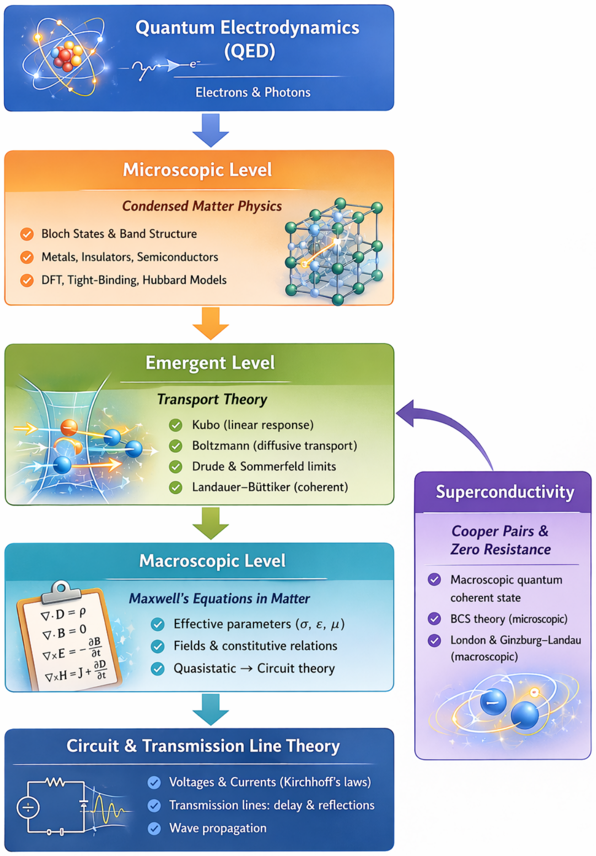

Figure 5: Effective theories of electricity.

3.5 Superconductivity

While this hierarchy describes most electrical phenomena, some regimes require special branches within this hierarchy, most notably superconductivity. At low temperatures, electrons form Cooper pairs that condense into a coherent quantum state, leading to zero resistance and magnetic field expulsion. In this regime, conduction is no longer described by diffusive transport but by a macroscopic wavefunction. Superconductivity thus illustrates how new collective phases emerge, requiring distinct effective descriptions at different scales.

3.6 Summary

This layered description of electricity, based on a hierarchy of emergent theories, provides an effective framework for research and engineering, allowing different levels of description to be applied according to scale without requiring explicit derivations from more fundamental theories.

However, this plurality comes at the cost of conceptual fragmentation. From a philosophical standpoint, a unified and physically transparent interpretation is preferable to a collection of scale-dependent models whose connections remain implicit. In particular, it obscures the distinction between fundamental mechanisms and effective approximations.

These examples suggest that conventional transport-based interpretations of current are not fundamental, but regime-dependent. For this reason, it is natural to reconsider the ontological status of electrical current. Rather than treating it as a primary entity, we interpret it as an emergent manifestation of electromagnetic field dynamics, where energy transport, rather than charge flow, plays the central role.

4 Oliver Heaviside

4.1 Reinterpreting the current

Focusing on the macroscopic level of this theoretical hierarchy, we propose that electrical energy in a circuit is mainly transmitted as a guided electromagnetic wave confined between the conducting wires. In this picture, electron motion inside the conductor appears as a secondary effect of the wave, arising from the fact that real conductors are not perfect [8]. One of the earliest researchers to propose this idea was Oliver Heaviside in the late 19th century.

> *"Is there such a thing as an electric current? Not that it is intended to cast any doubt upon the existence of a phenomenon so called; but is it a current?, that is, something moving through a wire […]. Now, in Maxwell's theory there is the potential energy of the displacement produced in the dielectric parts by the electric force, and there is the kinetic or magnetic energy of the magnetic force in all parts of the field, including the conducting parts. They are supposed to be set up by the current in the wire. We reverse this: the current in the wire is set up by the energy transmitted through the medium around it". [9]*

4.2 Telegraphy

To understand the origin and physical intuition behind this field-based interpretation, it is useful to revisit the historical development of Heaviside's work. The invention of the telegraph in 1844 marked the beginning of modern telecommunications, developed largely without a solid theoretical foundation and guided mainly by empirical knowledge. In parallel, Maxwell published *A Treatise on Electricity and Magnetism* in 1873 [10], unifying electricity, magnetism, and optics. Oliver Heaviside, a largely self-taught telegrapher, reformulated and extended Maxwell's theory after his death [11]. He introduced vector methods, replacing Maxwell's component-based formulation with a more compact representation, and reformulated the theory into the four equations that are currently regarded as its standard form:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \tag{4}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{5}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{6}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{7}$$

The first transatlantic submarine cable was laid in 1858, but it failed due to severe signal distortion that was not yet understood. Attempts to compensate by increasing the transmission power further damaged the cable's insulation and contributed to its failure. A more successful system was established in 1866, incorporating improvements informed by the work of Lord Kelvin. Heaviside reformulated the theory of transmission lines using the telegrapher's equations. He showed that signal distortion is minimized when $RC = GL$, the so-called distortionless condition, and proposed increasing line inductance using loading coils to approximate this regime, significantly improving transmission performance.

Heaviside worked largely outside academia, publishing extensively in *The Electrician* [12]. Although initially overlooked, his contributions later became fundamental to modern electrical theory.

4.3 Energy Current

After reformulating Maxwell's theory into a more practical framework, Heaviside turned his attention to energy transport in electrical systems. This energy flow is directed from the source toward regions where it is dissipated, rather than circulating through the conductors. Heaviside described this transfer as an "energy current", now formalized as the electromagnetic energy flux. This electromagnetic energy flux is formalized by the Poynting vector [13]:

$$\vec{S} = \vec{E} \times \vec{H} \tag{8}$$

Within this framework, electrical signals in transmission lines can be interpreted as electromagnetic waves guided by conductors. Energy propagates primarily through the surrounding dielectric, while conductors guide and confine the fields.

> *"The battery acts upon the dielectric primarily, producing electric displacement and magnetic induction. These disturbances are propagated through the dielectric at the speed of light. The electrical conductors act [...] not as conductors but rather as obstructors, [...] by guiding the electromagnetic waves along definite paths in space." [9]*

The motion of electrons within the conductor is a response to the electromagnetic fields and contributes to energy dissipation through resistive losses rather than being the primary transport mechanism.

> *"There is a necessary waste of energy involved in the process, according to Joule's law of the generation of heat by the existence of electric current in conducting matter. Thus two things happen when the degree of conductivity is not infinite. First, the reflection is imperfect at the boundary of the conductor, a portion of an incident disturbance being transmitted into it. Next, in the act of transmission and the attenuation involved, there is a loss of energy from the electromagnetic field." [9]*

In this interpretation, a perfect conductor does not transmit energy through its interior but instead guides electromagnetic waves along its surface.

> *"A perfect conductor [...] allows electromagnetic waves to slip along its surface [...]. Though perfectly obstructive internally, it is perfectly conductive superficially. It merely guides the waves". [9]*

Heaviside's view contrasted with the hydraulic interpretation of current as a flow of substance, and led to important developments such as the design of coaxial cables to confine electromagnetic energy.

4.4 Infracurrent and Supracurrent

Building on this interpretation, we introduce a conceptual framework that distinguishes between energy transport and material dissipation within electrical systems:

- **Electricity**: The transfer of electromagnetic energy from a source to a receiver, mediated by electric and magnetic fields and guided by the conductor wires.

- **Supracurrent**: The field-mediated component of this process, associated with the propagation of electromagnetic energy through the dielectric. It represents the organized flow of energy described by the Poynting vector.
- **Infracurrent**: The material response within conductors, associated with the motion of charge carriers and responsible for energy dissipation due to finite conductivity.

In this framework, what is traditionally described as electrical current can be reinterpreted as a composite phenomenon, in which energy transport and charge motion play fundamentally different roles. This distinction provides an alternative perspective in which the primacy is assigned to field dynamics rather than to charge flow.

4.5 Poynting's Theorem

The distinction between supracurrent and infracurrent can be expressed more precisely through Poynting's theorem, which gives the local conservation law for electromagnetic energy. For a linear, nondispersive medium, the electromagnetic energy density is

$$u = \frac{1}{2}(\vec{E} \cdot \vec{D} + \vec{B} \cdot \vec{H}) \tag{9}$$

They satisfy the local conservation law

$$\frac{\partial u}{\partial t} = -\nabla \cdot \vec{S} - \vec{J} \cdot \vec{E} \tag{10}$$

In this equation, $\vec{S}$ represents the electromagnetic energy flux, while $\nabla \cdot \vec{S}$ measures the net flow of electromagnetic energy out of a region. The vector $\vec{S}$ therefore corresponds to the supracurrent: the organized, field-mediated transport of energy through space. The term $\vec{J} \cdot \vec{E}$, by contrast, represents the rate at which electromagnetic field energy is transferred to matter. In ordinary resistive conductors, where $\vec{J} = \sigma \vec{E}$, this term becomes σE^2 and corresponds to Joule heating. It therefore provides the energetic signature of the infracurrent: the material response associated with charge motion and dissipation.

Poynting's theorem thus shows that electrical systems contain two coupled but physically distinct aspects: the transport of energy by electromagnetic fields, described by $\vec{S}$, and the conversion of part of that energy into material excitation or heat, described by $\vec{J} \cdot \vec{E}$. This provides a formal basis for the distinction introduced above between supracurrent and infracurrent.

4.6 Skin Effect

The skin effect, described by Heaviside, states that at high frequencies electric current concentrates near the surface of a conductor, while at low frequencies it is more uniformly distributed. In this framework, a perfect conductor would prevent electromagnetic fields from penetrating its interior, forcing energy to propagate through the surrounding dielectric. In real conductors, finite conductivity allows partial field penetration, inducing electron motion that leads to resistive losses and energy dissipation as heat.

4.7 Hertzian waves

Maxwell's theory predicted that electromagnetic waves could propagate through space without the need for conductors. This was experimentally confirmed by Hertz in 1888 [14], demonstrating that electrical energy can be transmitted as free-space waves. In this context, electromagnetic energy guided along conductors can be radiated into space, or conversely, incoming waves can be captured and guided by conductors. This highlights the continuity between guided waves in transmission lines and radiated waves in free space.

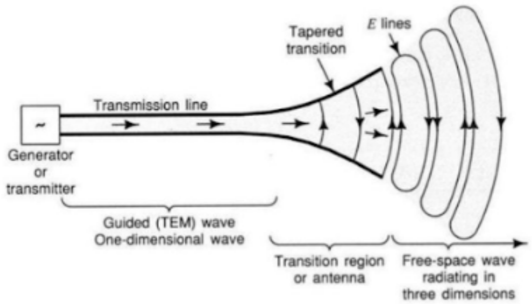

Figure 6: Antenna emission.

4.8 Two different currents

This distinction is closely related to the classical separation between conduction current and displacement current in Maxwell's equations [15]. Both contribute to the generation of magnetic fields, but they arise from different physical mechanisms: conduction current corresponds to the motion of charge carriers in matter, whereas displacement current originates from the time variation of the electric field and can exist even in regions without free charges.

$$\nabla \times \mathbf{B} = \underbrace{\mu_0 \mathbf{J}}_{\text{conduction}} + \underbrace{\mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}}_{\text{displacement}} \tag{11}$$

Maxwell introduced the displacement current to ensure consistency with charge conservation, resolving apparent contradictions such as those arising in a charging capacitor. This extension also made it possible to derive electromagnetic wave equations and to describe wave propagation in both vacuum and material media.

Within this perspective, the distinction introduced in this work can be understood as follows: infracurrent corresponds to the material response associated with conduction processes and losses, while supracurrent refers to the field-mediated transport of energy supported by the coupled evolution of electric and magnetic fields.

4.9 Wave, Diffusion and Absorption

This conceptual distinction can be formalized mathematically by decomposing the dynamics into three fundamental processes: wave propagation, dissipative diffusion, and local absorption.

The wave equation describes the propagation of energy through a medium at finite speed without intrinsic loss, preserving the structure of the signal:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} \tag{12}$$

In contrast, dissipative processes introduce attenuation. The heat (or diffusion) equation models the progressive loss of structure due to resistive effects:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{D}\frac{\partial u}{\partial t} \tag{13}$$

Finally, a Helmholtz-type equation describes a local attenuation mechanism, in which the field amplitude decreases exponentially due to energy absorption by the medium, without redistribution or propagation:

$$\frac{\partial^2 u}{\partial x^2} = k^2\, u \tag{14}$$

According to this framework, electrical energy transport may be interpreted as the superposition of a propagating field component and material response mechanisms. The propagating component corresponds to the supracurrent, associated with the guided electromagnetic wave, while the dissipative and absorptive contributions are linked to the infracurrent, arising from the interaction between fields and matter.

Consequently, the phenomenon of electricity may be modeled as the combined effect of these contributions:

$$\frac{\partial^2 u}{\partial x^2} = \underbrace{a\,\frac{\partial^2 u}{\partial t^2}}_{\text{wave}} + \underbrace{b\,\frac{\partial u}{\partial t}}_{\text{diffusion}} + \underbrace{c\,u}_{\text{absorption}} \tag{15}$$

The telegrapher's equations, developed by Heaviside [16], can be interpreted within this framework as describing the coupled evolution of these processes for both voltage and current:

$$\frac{\partial^2 V}{\partial x^2} = \underbrace{LC\,\frac{\partial^2 V}{\partial t^2}}_{\text{wave}} + \underbrace{(RC + LG)\,\frac{\partial V}{\partial t}}_{\text{diffusion}} + \underbrace{GR\,V}_{\text{absorption}} \tag{16}$$

$$\frac{\partial^2 I}{\partial x^2} = \underbrace{LC\,\frac{\partial^2 I}{\partial t^2}}_{\text{wave}} + \underbrace{(RC + LG)\,\frac{\partial I}{\partial t}}_{\text{diffusion}} + \underbrace{GR\,I}_{\text{absorption}} \tag{17}$$

In this interpretation, the wave term captures the field-mediated transport of energy (supracurrent), while the remaining terms account for the material response and associated losses (infracurrent).

5 Conclusions

The analysis presented in this work supports the view that electrical energy is mainly transported through electromagnetic fields rather than by charge motion.

In this picture, electric current can be interpreted as the combination of two coupled contributions: a field-mediated component (supracurrent), responsible for energy transport guided by conductors, and a material component associated with charge motion and dissipation (infracurrent). Infracurrent is not the fundamental carrier of electrical energy, but a secondary effect that arises in real materials due to their finite conductivity.

By interpreting the telegrapher's equations as a unified description of propagation and loss, this work provides a conceptually coherent framework that clearly distinguishes energy transport, dissipation, and material response.

This interpretation is deeply rooted in the work of Oliver Heaviside, who first emphasized that electromagnetic energy propagates through the surrounding medium and that the role of conductors is primarily to guide this propagation.

In the ideal lossless limit, the dissipative contribution associated with infracurrent vanishes, suggesting a possible conceptual pathway for reinterpreting superconductivity within the present framework. This identification, however, must be made with caution: superconductors are not merely perfect conductors, since they exhibit not only zero resistance, but also characteristic phenomena such as the Meissner effect, flux quantization, and persistent currents. Therefore, although superconductivity cannot be reduced simply to the absence of infracurrent, the distinction between field-mediated energy transport and dissipative material response provides a promising starting point for a deeper reinterpretation of the superconducting state.

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