Substantial Spacetime Dynamics (I) Beyond Einstein’s Light Speed Postulate: The Mechanical Mechanism of the Light Speed Limit and the C_s^2 Framework of Substantial Spacetime

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February 13, 2026

Abstract

This paper provides the mechanical answer to why the speed of light is the universal limit, a fact that was previously only assumed as a postulate by Einstein. Recent gravitational wave detections demand a shift from geometric abstractions to a mechanical ontology of spacetime. While the constancy of the speed of light (c) has long been a foundational postulate, its physical origin and numerical relation to other constants remain unresolved. In this work, we propose that the observed speed c is not the ultimate limit, but a manifestation of a deeper structural bound determined by the intrinsic constitutive strength of spacetime, denoted as C_s.

Based on the definitive natural verdict of gravitational wave experiments, this work identifies C_s as a newly discovered fundamental constant. Crucially, C_s is revealed as the ”Meta-constant” of the universe, which serves as the primary sovereign governing the electromagnetic constants (ϵ_0, μ_0), the gravitational constant G, and the emergence of universal physical scales. We demonstrate that the true invariant limit resides in a quadratic structural threshold C_s^2, representing the maximal structural stress or response capacity of spacetime as a physical entity.

Our CSSD framework proves that the structural response C_s is the true primary limit, while c is its secondary representative. This perspective resolves the conceptual ambiguity between photon propagation and spacetime causality, unifies disparate constants within a single structural ontology, and reveals that quantities such as Planck units and vacuum impedance are coordinated manifestations of this common Meta-constant C_s. This work establishes Cui’s Substantial Spacetime Dynamics (CSSD) as the foundational pathway toward resolving the architecture of the universe through its constitutive strength.

Keywords: Spacetime Entity, Meta-constant (C_s), C_s^2 Structural Threshold, CSSD Framework, Gravitational Wave Verdict

1 Introduction

1.1 The enduring mystery of the speed of light

Since Newton, physics has evolved from "gravity as force" to "gravity as geometry." However, the detection of gravitational waves declares the end of this journey. As Einstein himself suggested, solutions to deep problems must be sought at a higher level of understanding. This paper formally demonstrates that spacetime is neither an empty background nor an abstract geometric metric, but a **physical substantial entity** with a finite strength limit C_s^2 and an intrinsic response speed C_s. By establishing the mechanical attributes of the spacetime entity, this research not only deciphers the underlying logic of the constancy of the speed of light but also marks the transition of physics from an era describing "shadows" to a new epoch of analyzing the universe's ontology: **Cui's Substantial Spacetime Dynamics (CSSD)**.

Among all constants in physics, none has occupied a more central or enigmatic role than the speed of light in vacuum, c. It appears simultaneously as a property of electromagnetic radiation, a limiting velocity for material objects, a conversion factor between space and time, and a defining parameter of relativistic causality. Since Einstein's formulation of special relativity in 1905, the constancy of c has been elevated to the status of a postulate, forming the cornerstone of modern spacetime theory.

Yet, despite more than a century of empirical confirmation and theoretical success, fundamental questions persist:

- Why does light propagate at this particular speed?
- Why is this speed invariant for all inertial observers?
- Why does this same constant govern both electromagnetic waves and spacetime causal structure?
- Why does the vacuum admit no signal faster than this speed, while matter waves and fields in media propagate more slowly?
- Why do unrelated constants—ϵ_0, μ_0, G, Planck units—conspire numerically around this same value?

Modern physics typically accepts c as a primitive postulate or as a structural feature of spacetime geometry, but not as a derived physical consequence of spacetime's material constitution. This approach, while mathematically elegant, leaves unanswered the deeper ontological question: what is spacetime such that it possesses a universal speed limit at all?

Historically, similar puzzles have arisen in other domains. For example, the elastic modulus of a material determines the speed of sound within it; the tensile strength of a bridge determines its load-bearing capacity. In each case, the observable response speed reflects an underlying structural property. By contrast, spacetime is typically treated as an abstract geometric manifold rather than a physical medium with intrinsic constitutive strength.

This paper argues that this omission lies at the heart of the conceptual opacity surrounding the speed of light. The fundamental departure of SSD from General Relativity is the recognition that the vacuum is not a void geometric stage, but a physical lattice with a definitive constitutive limit. We define C_s^2 as the primary **invariant structural threshold** where the energy density of the spacetime medium reaches its saturation point, dictating the coupling strength of all physical fields. The fundamental departure of SSD from General Relativity is the recognition that the vacuum is not a void geometric stage, but a physical lattice with a definitive constitutive limit.

By identifying the near-simultaneity of gravitational and electromagnetic signals as a final natural verdict, we establish C_s not merely as a velocity bound, but as the fundamental Meta-constant of physical ontology. We define C_s^2 as the primary invariant structural threshold where the energy density of the spacetime medium reaches its saturation point, dictating the coupling strength of all physical fields.

1.2 From geometric postulate to physical explanation

Einstein's great achievement was to recognize that the invariance of c reflects a fundamental symmetry of spacetime itself, not merely a property of light as a physical object. However, the geometric formalism of Minkowski spacetime reframes the phenomenon rather than explaining its physical origin. The metric structure encodes c by construction, but it does not clarify why spacetime should possess precisely this causal slope, nor why this slope is numerically connected to electromagnetic properties of the vacuum.

The situation is analogous to describing the rigidity of a crystal lattice using geometric constraints without specifying the interatomic forces that generate them. Geometry captures structure, but not the underlying physical reason for that structure.

Over the decades, many approaches have attempted to address this gap, including:

- Electromagnetic aether models and their relativistic successors,
- Quantum vacuum fluctuation interpretations,
- Emergent spacetime scenarios in quantum gravity,
- Holographic and entropic gravity proposals,
- Varying speed of light cosmologies.

Yet none has succeeded in deriving the observed value of c from a physically grounded structural principle applicable across electromagnetism, gravitation, and spacetime dynamics simultaneously.

This work proposes that the resolution lies in recognizing that the speed of light is not itself the fundamental bound, but rather the observable linear response speed of spacetime under electromagnetic excitation. The true invariant limit is instead associated with a deeper structural threshold of spacetime itself, denoted C_s^2, which governs not only light propagation but the entire constitutive architecture of the universe.

1.3 Core thesis and conceptual shift

The central claim of this paper is:

The speed of light c is not the ultimate speed limit of spacetime, but rather a representative manifestation of a deeper spacetime structural response bound C_s, whose square C_s^2 defines a fundamental constitutive strength of spacetime.

In this framework:

- C_s^2 represents the maximal structural stress or response capacity of spacetime as a physical entity.
- $C_s = \sqrt{C_s^2}$ defines the maximal linear propagation speed of disturbances in spacetime.

- The photon speed c satisfies $c \leq C_s$, and in vacuum reaches this bound due to the unique structural coupling between electromagnetism and spacetime.
- Other propagation modes in matter or fields propagate at $v < c$ because they encounter additional structural constraints imposed by material media.

This distinction resolves a long-standing conceptual ambiguity: why light is both a particle phenomenon and a spacetime limit. In this theory, light is not the origin of the limit, but rather its most transparent physical representative.

More profoundly, we argue that this same structural constant C_s^2 governs:

- The electromagnetic constants ϵ_0 and μ_0,
- The gravitational constant G,
- The Planck units,
- The emergence of universal scales in cosmology.

Thus, constants previously treated as independent empirical parameters are unified as coordinated expressions of spacetime's intrinsic constitutive strength.

1.4 Position within the broader research program

This paper serves as the foundational work of a series, establishing **Cui's Substantial Spacetime Dynamics I** as the unique mechanical pathway to resolving the following major challenges in physics (detailed physical analyses are reserved for subsequent papers):

Cosmological Core: The black hole singularity dilemma, the cosmological constant conflict, the nature of dark matter, the essence of dark energy, the mechanism of cosmic inflation, and the Hubble constant crisis.

Physical Origin and Microscopic Mechanisms: The dynamical origin of mass, the physical rhythm of time, matter-antimatter asymmetry, the vacuum catastrophe (zero-point energy density), the mechanical correlation of quantum states, and the fundamental mechanism of quantum wavefunction collapse.

All these challenges find logically self-consistent, ultimate mechanical solutions within the CSSD framework. This paper focuses solely on establishing the underlying mechanical logic, without delving into specific branches, to ensure the purity and security of the theoretical core [18]. The fundamental departure of SSD from General Relativity is the recognition that the vacuum is not a void geometric stage, but a physical lattice with a definitive constitutive limit. We define C_s^2 as the primary **invariant structural threshold** where the energy density of the spacetime medium reaches its saturation point, dictating the coupling strength of all physical fields.

2 From Newtonian Space to Einsteinian Spacetime: Achievements and Limits

2.1 Newtonian absolute space and time

In classical mechanics, space and time were regarded as absolute, immutable backgrounds. Space provided a fixed geometric arena within which objects moved, while time flowed uniformly and independently of physical processes. Velocities were relative to absolute space, but acceleration was absolute, reflecting motion with respect to this background.

Within this framework, there was no intrinsic upper limit on speed. In principle, arbitrarily large velocities were conceivable, constrained only by the forces available. The speed of light was simply one among many measurable velocities, albeit one that appeared constant across diverse experimental conditions.

However, this framework encountered profound difficulties with the emergence of Maxwell's equations, which predicted electromagnetic waves propagating at a fixed speed determined by the vacuum permittivity and permeability:

$$c = 1/\sqrt{\epsilon_0 \mu_0}.$$

This raised the question: relative to what medium or frame does light propagate at this speed? Attempts to resolve this through the luminiferous aether failed experimentally, most notably in the Michelson–Morley experiment.

2.2 Einsteinian relativity and geometric spacetime

Einstein's resolution was radical and transformative. He abandoned absolute space and time and instead postulated that:

- The laws of physics are invariant in all inertial frames.
- The speed of light in vacuum is the same for all inertial observers, independent of the motion of the source or observer.

From these postulates, the Lorentz transformations and Minkowski spacetime geometry follow. Time and space become intertwined, and the invariant interval replaces absolute measures.

This framework achieved extraordinary empirical success, explaining time dilation, length contraction, relativistic energy-momentum relations, and the causal structure of spacetime. It further generalized into general relativity, where gravitation arises from spacetime curvature.

Yet, despite these successes, the physical origin of the invariant speed remained obscure. Why should spacetime possess precisely this invariant slope? Why should this slope numerically match the electromagnetic wave speed? Why should it be universal across all interactions?

Einstein himself acknowledged this conceptual gap. While relativity explains how spacetime behaves given the invariance of c, it does not explain why spacetime possesses this property in the first place.

2.3 Geometric postulates versus physical ontology

Modern physics typically treats spacetime as a geometric manifold endowed with a metric tensor whose signature and scale encode causal structure. The invariant speed c enters as a conversion factor between temporal and spatial coordinates. In natural units, it is often set to unity, effectively absorbed into the geometry.

This approach is mathematically efficient, but ontologically thin. It describes spacetime's behavior but not its physical nature. It is analogous to describing the bending of a beam by specifying its curvature without identifying the elastic modulus or molecular structure that generates that curvature.

Moreover, this geometric formalism blurs an important conceptual distinction: the difference between signal propagation and spacetime response. Light propagation is a physical process involving electromagnetic fields and photons, while causal structure is a property of spacetime itself. The traditional identification of the two conflates these distinct levels.

This conflation becomes particularly problematic when considering:

- Media in which light travels slower than c,
- Massive particles approaching but never reaching c,
- Hypothetical superluminal phenomena in quantum entanglement (without causal signaling),
- The emergence of spacetime itself in quantum gravity.

These phenomena suggest that c is not merely a geometric artifact but reflects a deeper physical constraint governing spacetime's capacity to transmit disturbances.

2.4 The unresolved problem of physical constants

Beyond c, physics contains numerous dimensionful constants: ϵ_0, μ_0, $G,\hbar$, k_B, and others. Traditionally, these are treated as independent empirical parameters whose values must be measured rather than derived.

However, several striking patterns hint at deeper structure:

- The electromagnetic constants combine to produce c.
- Planck units combine c, G, and $\hbar$ into universal scales of length, time, and mass.
- Vacuum impedance $Z_0 = \sqrt{\mu_0/\epsilon_0}$ appears as a characteristic of free space itself.
- Gravitational and electromagnetic interactions, though vastly different in strength, appear coordinated through shared dimensional structures.

These numerical relationships strongly suggest that these constants are not arbitrary but reflect underlying structural properties of spacetime. Yet no existing theory derives them from a common physical principle.

This paper argues that the missing principle is the constitutive strength of spacetime itself.

3 Spacetime as a Physical Entity: Structural Ontology

3.1 From geometric arena to physical medium

In classical and relativistic physics alike, spacetime is typically treated as an abstract geometric arena in which physical fields and particles evolve. Even in general relativity, where spacetime becomes dynamical, its dynamics are encoded geometrically rather than materially. Curvature replaces force, but spacetime itself remains ontologically thin: it curves, but what it is made of remains unspecified.

However, multiple lines of evidence suggest that spacetime possesses physical properties analogous to those of a medium:

- It supports wave propagation (electromagnetic and gravitational waves).
- It exhibits causal response limits.

- It stores energy and momentum (as in gravitational waves).
- It undergoes structural deformations (curvature).
- It exhibits characteristic impedance (vacuum impedance).

These features are difficult to reconcile with the notion of spacetime as a purely abstract manifold. Instead, they suggest that spacetime behaves as a structured physical entity with constitutive properties, response thresholds, and mechanical limits.

This motivates the central ontological shift of this work: spacetime is not merely geometry, but a physically structured entity capable of storing, transmitting, and responding to disturbances according to intrinsic laws.

3.2 Structural response and constitutive strength

In materials science, the response of a medium to external perturbations is governed by its constitutive relations. For example:

- The speed of sound in a solid depends on its elastic modulus and density.
- The refractive index of a medium depends on its electromagnetic polarizability.
- The yield strength of a material defines the stress beyond which it deforms irreversibly.

In each case, observable propagation speeds and response behaviors reflect deeper structural properties.

We propose that spacetime, as a physical entity, similarly possesses constitutive parameters governing its response to disturbances. Among these, the most fundamental is its maximum structural response capacity, which we denote C_s^2.

This quantity represents the maximal two-dimensional stress or strain rate that spacetime can sustain without structural breakdown. Its square root $C_s = \sqrt{C_s^2}$ defines the maximal linear propagation speed of disturbances within spacetime.

Crucially, this maximal response speed is a property of spacetime itself, not of any particular field or particle.

3.3 Distinguishing spacetime limit from photon speed

Traditional physics identifies the speed of light with the ultimate speed limit of nature. However, this identification conflates two distinct concepts:

- The speed at which photons propagate in vacuum.
- The maximal speed at which spacetime can transmit causal influence.

In the present framework, these are related but not identical. The photon speed c represents the maximal propagation speed of electromagnetic disturbances in vacuum. But the deeper limit is the maximal structural response speed of spacetime itself, C_s.

We therefore posit the inequality:

$$c \leq C_s.$$

In vacuum, due to the unique coupling between electromagnetism and spacetime structure, this bound is saturated:

$$c = C_s.$$

However, this equality is contingent, not fundamental. In principle, other fields or modes could approach but not exceed C_s, and in material media, electromagnetic waves propagate at $v < c$ due to additional structural constraints imposed by matter.

This distinction resolves a deep conceptual tension: why light is both a particle phenomenon and a spacetime limit. Light is not the source of the limit; it is its most transparent representative.

3.4 The significance of the square: why C_s^2 is fundamental

A central and novel claim of this work is that the truly fundamental quantity is not C_s itself, but its square C_s^2. This reflects the fact that spacetime's constitutive strength is fundamentally a two-dimensional stress or response capacity rather than a one-dimensional velocity.

To see this, note that:

- Velocity measures linear response along a single dimension.
- Structural strength measures the capacity to sustain deformations across spatial-temporal surfaces.
- Physical action, energy density, and curvature are inherently quadratic in nature.

In elasticity theory, yield strength depends on stress tensors rather than velocities. In electromagnetism, energy density scales as the square of field amplitudes. In gravitation, curvature invariants involve quadratic combinations of metric derivatives.

Analogously, we argue that the true invariant limit of spacetime is a quadratic structural threshold C_s^2, which constrains all linear response phenomena via:

$$v^2 \leq C_s^2,$$

from which:

$$v \leq C_s$$

follows.

This insight explains why the speed of light appears squared in many fundamental relations, including relativistic energy-momentum relations, electromagnetic energy density, and Planck-scale constructions. It is not velocity itself that is fundamental, but the underlying structural capacity from which velocity bounds emerge.

3.5 Spacetime entity theory: conceptual summary

We summarize the core ontological commitments of Spacetime Entity Theory as follows:

1. Spacetime is a physically structured entity, not merely a geometric manifold.
2. It possesses intrinsic constitutive properties governing its response to disturbances.
3. The most fundamental of these is a quadratic structural strength C_s^2.
4. The maximal linear propagation speed C_s emerges as the square root of this structural limit.
5. The photon speed c is a representative manifestation of C_s in vacuum, not its ontological origin.

6. Electromagnetic, gravitational, and inertial phenomena are unified expressions of this same structural capacity.

With this foundation, we now turn to the derivation and interpretation of the inequality $c \leq C_s$ and its physical consequences.

4 Deriving the Structural Bound: Why $c \leq C_s$

4.1 Propagation as spacetime response

It is crucial to recognize that the contemporary academic understanding of gravitational wave detection remains at a remarkably superficial and preliminary stage. The current consensus merely stops at confirming Einstein's century-old prediction and measuring the consistency of its speed with that of light. This study contends that such a perception falls far short of grasping the true, profound significance of gravitational wave experiments. **Gravitational waves do not propagate *through* spacetime; they are the mechanical elastic vibrations *of* the spacetime entity itself.** The observed near-simultaneity is, in essence, a **"final verdict"** delivered by nature: it reveals that spacetime possesses substantial attributes, and its intrinsic response speed C_s is the universe's primary sovereign, while the speed of light c is merely its representative in the material realm. Neglecting this core implication is the root cause of the stagnation of modern physics within the illusion of geometry.

In any physical medium, wave propagation represents the medium's response to localized disturbances. The maximal propagation speed is determined not by the disturbance itself, but by the medium's intrinsic response capacity. For example, the speed of sound in a material is determined by its elastic modulus and density, not by the properties of the sound source.

By analogy, electromagnetic waves propagating through vacuum represent spacetime's response to electromagnetic field oscillations. The speed at which this response propagates is therefore governed by spacetime's constitutive properties.

In conventional electromagnetism, this speed is given by:

$$c = 1/\sqrt{\epsilon_0 \mu_0}.$$

However, this expression merely shifts the question: why do ϵ_0 and μ_0 possess the particular values that they do? Why do they combine to produce this speed? What determines their numerical magnitude?

In Spacetime Entity Theory, these constants are not independent parameters but derived expressions of spacetime's structural strength C_s^2. The speed of light emerges as the maximal electromagnetic response permitted by spacetime's constitutive architecture.

Why the Photon Speed is a Perfectly Valid Representative in Vacuum: The universal success of experiments in vacuum—including all foundational tests of general and special relativity—in utilizing c arises from a profound **coincidence of necessity**. Electromagnetic waves represent the most pristine mode of excitation for the spacetime entity, coupling directly to its constitutive degrees of freedom without the inertial load of mass or the dissipative complexity of material media. In vacuum, the photon's propagation encounters **only** the ultimate structural limit C_s, making its speed c a direct, **saturated mapping** of that limit: $c = C_s$. Consequently, all mathematical formalisms and experimental predictions based on c in vacuum are not merely effective approximations; they are **precisely equivalent** to those formulated in terms of the more fundamental C_s, accounting perfectly for the observed causal structure and relativistic kinematics.

4.2 Linear versus quadratic constraints

To understand why the deeper constraint is quadratic, consider the following:

- Velocity is a first-order quantity relating spatial and temporal increments.
- Stress, energy density, and curvature involve second-order quantities.
- Physical stability and breakdown thresholds are governed by stress or energy density, not velocity per se.

In a material medium, the maximal wave speed is determined by the square root of the ratio of elastic modulus to density. The modulus itself represents a stress-response capacity—a quadratic structural property.

Similarly, spacetime's maximal linear propagation speed C_s arises as the square root of a deeper structural strength C_s^2.

Thus, the inequality:

$$v^2 \leq C_s^2$$

is the fundamental constraint, from which:

$$v \leq C_s$$

follows.

Light in vacuum saturates this bound, yielding $c = C_s$, but this equality is a contingent outcome of spacetime's electromagnetic coupling, not a defining postulate of spacetime itself.

4.3 Why light uniquely saturates the bound

A key question arises: why does light, among all known physical phenomena, reach this maximal propagation speed?

In Spacetime Entity Theory, this is because electromagnetic disturbances interact directly with spacetime's fundamental structural degrees of freedom without requiring the mediation of massive carriers or internal material relaxation processes. As a result, electromagnetic waves in vacuum propagate at the maximal rate permitted by spacetime's intrinsic response capacity.

By contrast:

- Massive particles carry inertia and rest mass, which impose additional response constraints.
- Waves in material media encounter molecular or lattice structures that introduce further delays.
- Gravitational perturbations, while also propagating at c, represent distortions of spacetime geometry itself and therefore also saturate the structural limit.

Thus, light and gravitational waves both propagate at C_s because they couple directly to spacetime's fundamental structure, whereas other phenomena propagate more slowly due to additional structural layers.

4.4 Resolving the media paradox

A long-standing puzzle in physics concerns the fact that light propagates at different speeds in different media, while remaining subject to the same relativistic causal structure. How can light slow down in glass or water without violating the universal speed limit?

In the present framework, this paradox dissolves. The universal speed limit is C_s, not c. The photon speed c represents the maximal electromagnetic propagation speed in vacuum, but in media, effective propagation involves repeated absorption, re-emission, and polarization processes that introduce additional structural constraints.

Thus:

$$v_{\text{medium}} < c \leq C_s.$$

No violation of spacetime causality occurs because the deeper limit C_s remains intact. The speed of light in vacuum is merely one empirical projection of this deeper structural bound.

4.5 Implications for superluminal phenomena

Certain quantum phenomena, such as entanglement correlations, appear to exhibit instantaneous or superluminal behavior. However, these do not transmit usable information and therefore do not violate relativistic causality.

Within the present framework, such phenomena do not challenge the structural bound C_s because they do not involve propagating disturbances within spacetime's causal medium. Instead, they reflect nonlocal correlations within the quantum state space, which does not directly map onto spacetime propagation channels.

Thus, Spacetime Entity Theory preserves relativistic causality while clarifying its physical origin: causality arises not from abstract geometric postulates but from spacetime's intrinsic structural response limits.

5 Electromagnetism as Spacetime Constitutive Response

5.1 Vacuum permittivity and permeability as spacetime properties

In classical electromagnetism, the vacuum permittivity ϵ_0 and permeability μ_0 are treated as empirical constants characterizing the electromagnetic properties of empty space. Historically, they were introduced to describe how electric and magnetic fields propagate and interact in vacuum.

However, their physical interpretation remains obscure. What does it mean for empty space to possess permittivity and permeability? Why should these constants have the numerical values they do? Why should their product yield the square of the speed of light?

In Spacetime Entity Theory, ϵ_0 and μ_0 are not properties of an abstract vacuum but constitutive parameters of spacetime itself. They encode spacetime's electromagnetic response characteristics, analogous to how dielectric constants describe material media.

From this perspective, the relation:

$$c = 1/\sqrt{\epsilon_0 \mu_0}$$

becomes a constitutive identity rather than a coincidence. It expresses the fact that spacetime's electromagnetic response speed is governed by its intrinsic structural strength C_s, such that:

$$\epsilon_0 \mu_0 = 1/C_s^2.$$

Thus, the product $\epsilon_0\mu_0$ is not an independent parameter but a manifestation of spacetime's quadratic response capacity.

5.2 Vacuum impedance and structural stiffness

Another fundamental electromagnetic quantity is the vacuum impedance:

$$Z_0 = \sqrt{\mu_0/\epsilon_0} \approx 376.7\,\Omega.$$

This quantity characterizes the ratio of electric to magnetic field amplitudes in electromagnetic waves propagating in vacuum. Its physical meaning has long been mysterious, as it appears to describe a resistive property of empty space.

In Spacetime Entity Theory, Z_0 is interpreted as a measure of spacetime's electromagnetic stiffness or resistance to field deformation. Just as mechanical impedance characterizes a medium's resistance to motion, vacuum impedance characterizes spacetime's resistance to electromagnetic field oscillations.

Together, ϵ_0, μ_0, and Z_0 encode spacetime's electromagnetic constitutive response, all ultimately governed by the deeper structural strength C_s^2.

5.3 Energy density and quadratic structure

The electromagnetic energy density in vacuum is given by:

$$u = \frac{1}{2}\left(\epsilon_0 E^2 + \frac{B^2}{\mu_0}\right).$$

This quadratic dependence on field amplitudes reflects the deeper quadratic nature of spacetime's structural response. Energy storage corresponds to structural deformation of spacetime's electromagnetic degrees of freedom, governed by its constitutive stiffness.

The appearance of c^2 in relativistic energy-momentum relations:

$$E^2 = p^2c^2 + m^2c^4$$

likewise reflects the quadratic structural limit C_s^2 rather than a mere velocity parameter. In this view, c^2 functions as a conversion factor between structural energy density and linear momentum flow, rooted in spacetime's intrinsic response capacity.

5.4 Why electromagnetic waves are special

Electromagnetic waves propagate through vacuum without requiring a material carrier. This distinguishes them from sound waves, water waves, or lattice vibrations, all of which require material substrates. The absence of a material substrate suggests that electromagnetic waves propagate through spacetime itself.

In Spacetime Entity Theory, this is taken literally: electromagnetic waves are oscillations of spacetime's electromagnetic structural degrees of freedom. Their propagation speed is therefore governed by spacetime's intrinsic constitutive response limits, yielding $c = C_s$ in vacuum.

This interpretation dissolves the historical aether controversy by recognizing spacetime itself as the medium, while preserving relativistic invariance because spacetime's structure is itself invariant.

5.5 Why c is invariant

The invariance of the speed of light across inertial frames is traditionally treated as a postulate. In the present framework, it becomes a physical consequence of spacetime's intrinsic structural response capacity.

Because C_s is a property of spacetime itself, not of any particular observer or source, all observers measure the same maximal propagation speed for disturbances that couple directly to spacetime's structure. Light, as such a disturbance, therefore exhibits invariant speed.

This explains why c is invariant without requiring it to be a primitive axiom: invariance arises from the universality of spacetime's constitutive properties.

6 Gravitation as Structural Response of Spacetime

6.1 Curvature as structural deformation

In general relativity, gravitation is described not as a force but as curvature of spacetime induced by mass-energy. Objects follow geodesics determined by this curvature, and gravitational waves propagate as ripples in spacetime geometry.

This geometric description, while empirically successful, leaves open the physical nature of curvature. What does it mean for spacetime to curve? What physical entity is deforming, and what resists that deformation?

In Spacetime Entity Theory, curvature is interpreted as structural deformation of spacetime's constitutive fabric. Mass-energy induces stress in spacetime, and spacetime responds according to its intrinsic structural strength C_s^2.

Thus, gravitation becomes not merely geometric but mechanical: it is the manifestation of spacetime's structural response to energy-momentum loading.

6.2 The gravitational constant as constitutive parameter

The gravitational constant G governs the strength of gravitational interactions. In Newtonian gravity:

$$F = G\frac{m_1 m_2}{r^2},$$

and in general relativity, it appears as the coupling constant between spacetime curvature and energy-momentum:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}.$$

Why does G have its particular value? Why is gravity so weak compared to electromagnetism? Why does G combine with c and $\hbar$ to define Planck scales?

In Spacetime Entity Theory, G is not a fundamental parameter but a derived constitutive coefficient reflecting spacetime's resistance to curvature. Specifically, G encodes the ratio between applied energy density and resulting structural deformation of spacetime.

More precisely, we propose that:

$$G \sim \frac{1}{C_s^2} \times (\text{spacetime density scale}),$$

where the precise proportionality depends on spacetime's internal structural degrees of freedom. While a full derivation of this relation lies beyond the scope of this paper and is developed in subsequent works, the essential insight is that G emerges from the same structural capacity C_s^2 that governs electromagnetic propagation.

Thus, gravity and electromagnetism are unified not by force unification but by shared dependence on spacetime's constitutive strength.

6.3 Gravitational wave propagation

Gravitational waves propagate at the speed of light, as confirmed by observations of binary mergers. This has often been cited as evidence that gravity and electromagnetism share the same causal structure.

In the present framework, this equality arises because both gravitational and electromagnetic waves couple directly to spacetime's fundamental structure. They therefore propagate at the maximal response speed C_s permitted by spacetime's constitutive capacity.

This reinforces the interpretation that c is not an electromagnetic artifact but a spacetime structural property.

6.4 Energy, inertia, and spacetime resistance

Inertia measures an object's resistance to acceleration. In Newtonian mechanics, it is encoded in mass; in relativity, mass-energy equivalence relates inertia to energy via:

$$E = mc^2.$$

This relation has long been regarded as a mysterious numerical coincidence linking mass and energy through the square of the speed of light.

In Spacetime Entity Theory, this relation acquires structural meaning. The factor $c^2 = C_s^2$ represents spacetime's structural resistance to energy localization. Mass-energy curves spacetime and induces structural deformation; the conversion factor between mass and energy reflects the constitutive strength of spacetime itself.

Thus, inertia is reinterpreted as spacetime's resistance to deformation by energy-momentum loading, and mass-energy equivalence becomes a structural identity rather than a numerical accident.

6.5 Toward a unified structural interpretation

Taken together, these considerations suggest that electromagnetism, gravitation, and inertia are not independent phenomena but different manifestations of spacetime's structural response to disturbances.

Electromagnetic waves represent oscillatory responses, gravitational fields represent static or quasi-static deformations, and inertia represents resistance to acceleration. All are governed by the same underlying structural capacity C_s^2.

This unification does not require additional dimensions, hidden variables, or exotic fields. It arises naturally from treating spacetime itself as a physically structured entity with intrinsic mechanical limits.

7 Planck Units, Universal Scales, and the Architecture of Constants

7.1 The mystery of Planck units

Planck units are constructed from three constants: c, G, and $\hbar$. They define characteristic scales of length, time, mass, and energy:

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}}, \quad t_P = \sqrt{\frac{\hbar G}{c^5}}, \quad m_P = \sqrt{\frac{\hbar c}{G}}.$$

These scales are often interpreted as marking the onset of quantum gravitational effects or the breakdown of classical spacetime. Yet their deeper physical meaning remains elusive. Why do these particular combinations of constants define universal scales? Why do these constants combine in precisely these ways?

In Spacetime Entity Theory, these relations are no longer mysterious. Since $c^2 = C_s^2$ represents spacetime's structural strength and G encodes its resistance to curvature, the Planck units naturally emerge as scales at which quantum action $\hbar$ interacts with spacetime's constitutive response limits.

Thus, Planck scales are not arbitrary but reflect the intrinsic architecture of spacetime itself.

7.2 Vacuum energy density and structural limits

The energy density associated with electromagnetic fields, gravitational fields, and quantum vacuum fluctuations is constrained by spacetime's structural response capacity. Excessive energy density would exceed spacetime's structural strength C_s^2, leading to breakdown phenomena such as black hole formation or singular behavior.

This interpretation suggests that black holes represent regions where spacetime's structural capacity is saturated or exceeded, leading to extreme curvature and causal trapping. Rather than being mere geometric curiosities, black holes become structural failure modes of spacetime itself.

This perspective will be developed in detail in subsequent papers, but it already highlights the unifying role of C_s^2 across electromagnetic, gravitational, and quantum domains.

7.3 Why constants appear finely tuned

Modern cosmology often invokes fine-tuning arguments to explain why physical constants take values compatible with life and structure formation. Small changes in constants such as c, G, or α (the fine-structure constant) would dramatically alter cosmic evolution.

In the present framework, this fine-tuning is reinterpreted as structural coherence. The constants are not independently adjustable parameters but coordinated manifestations of a single underlying spacetime architecture. Altering one constant independently of the others would violate the structural consistency of spacetime and lead to physically incoherent regimes.

Thus, the apparent fine-tuning of constants reflects not anthropic coincidence but the intrinsic coherence of spacetime's constitutive structure.

7.4 Universal scaling relations

Beyond Planck units, numerous scaling relations appear throughout physics, including:

- The Rydberg constant in atomic spectra,
- The Compton wavelength of particles,
- The Schwarzschild radius of black holes,
- The Hubble scale in cosmology.

These scales all involve combinations of c, G, and$\hbar$, suggesting deep structural interrelations. In Spacetime Entity Theory, these relations arise because all such scales reflect different modes of interaction between quantum action, spacetime structural strength, and energy-momentum loading. These scaling behaviors extend to the galactic level, where the spacetime entity's response characteristics provide a mechanical alternative to dark matter hypotheses [19].

Rather than treating each scale as an independent coincidence, this framework unifies them as structural expressions of a single spacetime architecture.

7.5 Toward a structural cosmology

Cosmology traditionally treats spacetime geometry as evolving according to Einstein's equations, with matter and energy driving expansion and curvature. In the present framework, cosmic expansion and large-scale structure formation are reinterpreted as global structural responses of spacetime to energy-momentum distributions.

This suggests that cosmological phenomena such as inflation, dark energy, and cosmic acceleration may ultimately reflect deeper constitutive properties of spacetime rather than requiring new exotic fields or modifications of gravity.

While these implications lie beyond the scope of this paper, they motivate the broader research program of Spacetime Entity Theory.

8 Philosophical and Physical Implications

8.1 From postulates to physical necessity

One of the most striking features of modern physics is the reliance on foundational postulates that resist deeper explanation. The invariance of the speed of light, the form of quantum commutation relations, and the structure of spacetime geometry are typically accepted as axioms rather than derived from physical necessity.

Spacetime Entity Theory seeks to reverse this pattern by grounding these principles in the physical constitution of spacetime itself. Instead of postulating c as an invariant, we derive it as a manifestation of spacetime's structural response capacity. Instead of treating constants as arbitrary inputs, we interpret them as expressions of spacetime's intrinsic architecture.

This shift transforms physics from a collection of formal postulates into a coherent structural ontology.

8.2 Reinterpreting relativity

The present framework does not contradict special or general relativity; rather, it provides a deeper physical interpretation of their mathematical structure. Lorentz invariance, time dilation, length contraction, and causal cones remain intact, but their origin is reinterpreted.

In this view:

- Lorentz invariance arises because spacetime's constitutive structure is isotropic and homogeneous.
- The invariant speed c arises because spacetime possesses a maximal response speed C_s.
- The Minkowski metric encodes spacetime's structural response properties rather than arbitrary geometric conventions.

Thus, relativity emerges naturally from spacetime's physical constitution rather than being imposed axiomatically.

8.3 Reinterpreting quantum constants

The appearance of $\hbar$ in Planck units and quantum relations has long been regarded as mysterious. In Spacetime Entity Theory, $\hbar$ represents the minimal quantum of action associated with spacetime's discrete or granular response structure.

When combined with spacetime's structural strength C_s^2 and curvature resistance encoded by G, $\hbar$ yields natural scales at which spacetime's response behavior transitions between classical and quantum regimes.

Thus, quantum mechanics and relativity become structurally unified through spacetime's constitutive properties rather than remaining formally separate frameworks.

8.4 Implications for cosmology and origin questions

Perhaps the most profound implication of this framework is its relevance to questions of cosmic origin and structure. If spacetime possesses intrinsic constitutive strength, then the emergence of the universe itself may reflect structural instabilities, phase transitions, or boundary conditions of spacetime's own architecture.

Phenomena such as the Big Bang, inflation, dark energy, and cosmic acceleration may ultimately be understood not as arbitrary initial conditions or exotic fields but as manifestations of spacetime's structural response dynamics.

This suggests a new research direction in which cosmology becomes the study of spacetime entity dynamics rather than merely the evolution of matter within a passive geometric arena.

8.5 Design, coherence, and physical intelligibility

Finally, the structural coherence of physical constants and laws revealed by this framework raises deep philosophical questions about the intelligibility and apparent design of the universe. The fact that electromagnetic, gravitational, inertial, and quantum phenomena all converge on a common structural foundation suggests an underlying architectural unity rather than a collection of independent coincidences.

While this work remains firmly within the domain of physical theory, it invites broader reflection on why the universe exhibits such remarkable internal coherence and mathematical order—a question that has motivated scientific inquiry since antiquity.

9 Conceptual Diagrams: A Structural Comparison

9.1 Newtonian absolute space

In Newtonian physics, space and time are independent and absolute. Space is a static container, and time flows uniformly everywhere. There is no intrinsic speed limit, and velocities are relative to absolute space.

9.2 Einsteinian geometric spacetime

In relativity, space and time are unified into a four-dimensional spacetime manifold with invariant causal structure. The speed of light c appears as a geometric slope in spacetime diagrams, defining the light cone and causal ordering.

9.3 Entity-based spacetime with structural strength

In Spacetime Entity Theory, spacetime is a physically structured entity with intrinsic constitutive strength C_s^2. The maximal linear response speed C_s defines the causal cone, while electromagnetic and gravitational waves represent excitations of spacetime's structural degrees of freedom.

This interpretation emphasizes that the present framework does not reject relativity but rather deepens it by providing a physical ontology underlying its geometric structure.

10 Conclusions

We have argued that the speed of light in vacuum is not the ultimate speed limit of nature but rather a representative manifestation of a deeper spacetime structural bound determined by the intrinsic constitutive strength of spacetime, denoted C_s^2. The maximal linear response speed $C_s = \sqrt{C_s^2}$ constrains all physical propagation, and the photon speed c saturates this bound in vacuum due to the unique coupling between electromagnetism and spacetime structure.

This reinterpretation resolves longstanding conceptual ambiguities surrounding the origin and meaning of the speed of light, the invariance of causal structure, and the physical significance of electromagnetic vacuum constants. It further unifies electromagnetism, gravitation, inertia, and Planck-scale physics as coordinated manifestations of spacetime's constitutive response architecture.

By shifting the foundation of physics from abstract geometric postulates to physically grounded spacetime ontology, this framework opens a path toward deeper unification and conceptual clarity across fundamental physics. It suggests that constants historically treated as arbitrary inputs are in fact structural parameters of spacetime itself, and that many outstanding puzzles—from mass-energy equivalence to Planck scales and cosmological structure—may find resolution within this unified structural paradigm.

This work constitutes the first in a series developing Spacetime Entity Theory. Subsequent papers will explore universal constitutive response laws across gravitational and cosmological regimes, the structural origin of inertia and mass, and the role of spacetime entity dynamics in black holes, galactic systems, and dark matter phenomena [18].

Author Contributions

Hugang Cui conceived the theory, developed the mathematical and conceptual framework, and wrote the manuscript.

Funding

No external funding was received for this research.

Conflicts of Interest

The author declares no conflict of interest.

Data Availability

All data supporting the findings of this study are contained within the manuscript. Additional derivations and figures are available upon request.

Ethics Statement

This research did not involve human or animal subjects.

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