Charge, Mass, and Inertia as Saturated Responses in a Pre-Geometric Relational Description

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Abstract

We investigate the structural origin of mass, electric charge, and inertial response within a pre-geometric relational framework in which physical observables arise through a generally non-injective projection onto effective spacetime descriptions. In this setting, geometric and dynamical quantities are not fundamental but emerge as regime-dependent responses of an underlying relational substrate subject to intrinsic saturation bounds.

We show that mass and charge can be interpreted as distinct manifestations of the same bounded-response mechanism. Mass corresponds to an isotropic inhibition of relational relaxation, while electric charge arises as an oriented or chiral saturation of the same underlying flux. Inertia emerges as a secondary effect, reflecting the finite resolvability of changes in relational configurations rather than the presence of an intrinsic inertial property.

The proposed framework does not modify the Standard Model dynamics and does not introduce additional fundamental fields. Instead, it provides a structural interpretation of existing quantities as effective descriptors of projection-limited responses. The familiar distinction between mass and charge is recovered at the effective level, while their common origin becomes manifest at the pre-geometric scale.

We discuss the consistency of this interpretation with known phenomenology, its relation to bounded (Born–Infeld-type) effective dynamics, and its implications for unifying inertial, gravitational, and electromagnetic responses without invoking new microscopic degrees of freedom. The results suggest that mass and charge may be understood as complementary limits of a single saturated relational mechanism, offering a unified conceptual basis for inertial and interaction properties.

Keywords: Pre-geometric frameworks; emergent spacetime; mass and charge; inertia; bounded response; non-injective projection; relational substrate; saturation mechanisms; Born–Infeld-type dynamics; foundations of physics

1 Introduction

The physical notions of mass, electric charge, and inertia occupy a central role in modern physics. They enter as fundamental parameters in both classical and quantum theories, yet their conceptual origin remains largely unexplained.

In the Standard Model, mass and charge are introduced as intrinsic properties of elementary fields, with numerical values fixed by empirical input. While the Higgs mechanism provides a dynamical account of mass generation for gauge bosons and fermions, it does not address why mass exists as a property, nor why inertial response accompanies it [1]. Electric charge, similarly, is treated as a primitive coupling constant, constrained by gauge symmetry but not derived from a deeper structural principle [2].

From a foundational perspective, inertia presents an additional conceptual challenge. The resistance of a system to acceleration is usually taken as a defining feature of matter, yet its relation to gravitational mass and its possible emergence from more primitive structures have been the subject of long-standing debate [3, 4].

A parallel line of inquiry has emerged in approaches to quantum gravity and pre-geometric physics. In these frameworks, spacetime geometry, and sometimes even locality and causality, are not assumed as fundamental, but are reconstructed as effective descriptions from more primitive relational or algebraic structures [5, 6]. Within such approaches, familiar physical quantities may acquire an emergent or regime-dependent status.

Recent work has emphasized that effective physical descriptions often arise through projections from an underlying configuration space to observable spacetime variables. When such projections are non-injective, multiple underlying configurations correspond to the same effective observable state, leading to intrinsic information loss at the descriptive level [7]. This structural feature has been shown to account for the breakdown of classical probabilistic factorization in quantum correlations, without invoking nonlocal dynamics [8].

In parallel, bounded-response mechanisms have been extensively studied in effective field theories. Born–Infeld electrodynamics provides a paradigmatic example in which divergences are regulated by intrinsic saturation of the field response [9]. Related saturation phenomena appear in gravitational and cosmological contexts, where effective responses cease to scale linearly beyond certain thresholds.

Motivated by these developments, we investigate whether mass, electric charge, and inertial response can be understood as manifestations of a single structural mechanism. Specifically, we explore a pre-geometric relational framework in which physical observables arise through a projection subject to intrinsic saturation bounds.

Within this setting, mass is interpreted as an isotropic inhibition of relational relaxation, while electric charge corresponds to an oriented or asymmetric saturation of the same underlying relational flux. Inertia then emerges as a secondary effect, reflecting the finite resolvability of changes in relational configurations rather than a primitive dynamical property.

The purpose of this work is not to modify the Standard Model or to introduce new fundamental fields. Instead, we aim to provide a structural reinterpretation of existing quantities, clarifying their mutual relations and their status as effective descriptors. By identifying a common origin for mass, charge, and inertia, the framework offers a unified conceptual basis for inertial and interaction properties within a projection-limited description.

The paper is organized as follows. Section 2 introduces the relational and projective framework underlying the analysis. Section 3 develops the classification of saturated effective responses and shows how mass, electric charge, and inertia arise as distinct symmetry realizations within this framework. Section 4 examines the consistency of this interpretation with Standard Model phenomenology. We conclude in Section 5 with a discussion of conceptual implications, limitations, and possible directions for further investigation.

2 Relational Framework and Projective Description

In this section, we summarize the minimal relational and projective framework required for the present analysis. The detailed construction of this framework is developed elsewhere. Here we restrict attention to the structural assumptions relevant for the interpretation of mass, charge, and inertia.

2.1 Underlying relational description

We assume that effective spacetime observables arise from an underlying relational description, in which configurations encode admissible correlations between abstract degrees of freedom. No spacetime manifold, metric, or field content is assumed at this level.

Explicit realizations of such relational descriptions, including spectral reconstructions of effective geometry from correlation structure alone, have been developed in companion work [10]. The present paper does not rely on the details of those constructions, but adopts their structural conclusion: spacetime geometry is an effective description, not a fundamental input.

The underlying relational description should not be interpreted as a hidden-variable completion of existing theories. It defines a space of admissible configurations whose effective description is intrinsically coarse-grained.

Configurations at this level are not endowed with local coordinates, temporal ordering, or intrinsic geometric meaning. These notions arise only when relational configurations admit a stable and approximately injective representation.

2.2 Projection to effective observables

Observable physical quantities are defined through a projection

$$\Pi : \Omega \to \mathcal{O}, \tag{1}$$

where Ω denotes the space of underlying relational configurations and $\mathcal{O}$ the space of effective observables accessible within spacetime descriptions.

A key structural feature of this projection is that it is generally non-injective. Distinct underlying configurations may correspond to the same effective observable state. This identification is not an approximation, but an intrinsic property of the descriptive mapping.

The physical consequences of non-injective projection have been analyzed in detail in the context of quantum correlations [11]. There it was shown that non-injectivity provides a sufficient mechanism for the failure of classical probabilistic factorization, without invoking nonlocal dynamics or hidden-variable assumptions.

In the present work, the same projective structure is applied to inertial and interaction-related quantities. Mass, charge, and inertia are thus treated as effective descriptors defined on equivalence classes of underlying relational configurations.

2.3 Saturation and bounded response

A further assumption, motivated by both structural and dynamical considerations, is that the projection Π admits an intrinsic saturation. Beyond a certain threshold, additional variations in the underlying relational configuration cannot be resolved within the effective description.

This bounded-response behavior has been studied in detail in companion work [12], where it was shown that saturation naturally leads to effective Born–Infeld-type dynamics and to the dynamical selection of stable geometric regimes.

In the present paper, saturation is not introduced as a modification of fundamental dynamics. It is interpreted as a limitation of the effective description itself, reflecting finite projective resolution.

Operationally, this implies that effective responses cease to scale linearly in regimes where the underlying relational gradients exceed the resolving capacity of the projection.

2.4 Effective descriptors and regime dependence

Physical quantities such as mass, electric charge, and inertia are treated as effective descriptors defined within the projected space $\mathcal{O}$. They characterize how the effective description responds to variations of the underlying relational configuration.

These quantities are inherently regime dependent. In domains where the projection is approximately injective and unsaturated, classical descriptions are recovered and effective responses behave linearly. In saturated regimes, departures from linearity arise as a direct consequence of projective limitations.

Importantly, the present framework does not modify the operational content of the Standard Model. It provides a structural reinterpretation of existing quantities, compatible with established phenomenology.

Within this perspective, distinctions between mass, charge, and inertial response correspond to different symmetry classes of saturated effective behavior. This classification is developed in the following sections.

3 Symmetry Classes of Saturated Effective Responses

In this section, we analyze how different effective physical properties emerge as distinct symmetry classes of saturated response within the projective framework introduced above. The goal is to identify minimal structural criteria that distinguish mass, electric charge, and inertial behavior without introducing new fundamental degrees of freedom.

3.1 Linear and saturated response regimes

When the projection from underlying relational configurations to effective observables is approximately injective, variations at the underlying level are faithfully reflected in the effective description. In this regime, effective responses scale linearly with the magnitude of relational gradients.

Such linear behavior underlies the standard formulation of classical field theories. Small perturbations lead to proportionate responses, and superposition principles apply.

However, when relational gradients exceed the resolving capacity of the effective description, the projection enters a saturated regime. Beyond this threshold, additional variations at the underlying level no longer produce distinct effective outcomes.

This transition from linear to saturated response is structural rather than dynamical. It reflects a limitation of descriptive resolution, not a modification of underlying laws. Bounded-response regimes of this type are known to give rise to Born–Infeld-like effective dynamics in a variety of contexts [9, 12].

3.2 Isotropic saturation and effective mass

We first consider saturated responses that preserve isotropy in the effective description. In this case, saturation suppresses relational variations uniformly in all directions.

An isotropic inhibition of effective response leads to behavior characteristic of inertial and gravitational mass. The effective description resists changes in motion independently of direction, yielding a scalar parameter that quantifies the degree of saturation.

From this perspective, mass is not introduced as an intrinsic substance. It appears as a measure of how strongly the effective description inhibits relational reconfiguration once saturation is reached.

This interpretation is consistent with the equivalence between inertial and gravitational mass. Both correspond to isotropic limitations of effective response, differing only in the context in which the response is probed. The universality of free fall follows naturally from the symmetry of the saturation mechanism.

3.3 Oriented saturation and effective charge

We now turn to saturated responses that break isotropy while preserving locality and stability. In this class, saturation is directionally biased or oriented with respect to relational gradients.

An oriented saturation leads to effective behavior characteristic of electric charge. The effective response distinguishes between opposing directions, giving rise to attractive and repulsive interactions depending on orientation.

Charge thus appears as a signed quantity associated with asymmetric saturation of relational flux. The existence of both positive and negative charges reflects the presence of two stable orientations of the saturated response.

Importantly, this interpretation does not require introducing charge as a primitive coupling. It arises as a symmetry-breaking mode of the same bounded-response mechanism that gives rise to mass.

The long-range character of electromagnetic interactions follows from the fact that oriented saturation affects relational configurations without isotropic suppression, allowing extended field-like behavior within the effective description.

3.4 Inertia as finite-resolution response

Inertial behavior emerges when changes in motion probe the finite resolution of the effective description. Acceleration corresponds to a demand for rapid reconfiguration of relational correlations.

When such reconfiguration exceeds the resolving capacity of the projection, the effective description responds with resistance to change. This resistance manifests as inertia.

In this view, inertia is not a fundamental property attached to matter. It reflects the finite resolvability of variations in relational configurations within the effective description.

This interpretation aligns with the structural origin of inertial effects discussed in relational approaches to dynamics and complements traditional formulations without altering their empirical content.

3.5 Unified classification

The analysis above leads to a unified classification of effective physical properties.

Isotropic saturated responses correspond to mass. Oriented saturated responses correspond to charge. Inertial response reflects the finite resolution of effective reconfiguration under acceleration.

All three arise from the same structural mechanism: saturation of the effective description under non-injective projection. Their distinction follows from symmetry properties rather than from distinct underlying substances or fields.

This classification preserves the operational definitions of mass and charge used in the Standard Model. It reinterprets their origin without modifying their dynamical role or empirical predictions.

In the next section, we examine the consistency of this framework with established phenomenology and discuss potential implications and limitations.

4 Consistency with Standard Model Phenomenology

In this section, we examine the compatibility of the proposed structural interpretation with established phenomenology of the Standard Model. The purpose is not to derive Standard Model parameters, but to ensure that the framework does not conflict with known experimental facts or operational definitions.

4.1 Status of mass in the Standard Model

In the Standard Model, particle masses arise through the Higgs mechanism, which endows fermions and gauge bosons with effective mass terms via spontaneous symmetry breaking. This mechanism successfully accounts for the dynamical generation of mass and its role in particle interactions.

The present framework does not challenge this description. Instead, it addresses a logically distinct question: why mass appears as a universal scalar measure of inertial and gravitational response.

Within the proposed interpretation, the Higgs mechanism determines how mass values are assigned within the effective description, while the structural origin of mass as an isotropic saturated response explains why such a parameter has the physical meaning it does. The two perspectives operate at different conceptual levels and are therefore complementary rather than competing.

4.2 Electric charge and gauge structure

Electric charge in the Standard Model is associated with local gauge invariance and conserved currents. Its quantization and coupling structure are fixed by the underlying gauge symmetry and anomaly cancellation requirements.

The framework developed here does not modify gauge symmetry or charge conservation. It reinterprets electric charge as an effective manifestation of oriented saturation in the projective response, without altering its operational role.

From this perspective, gauge invariance constrains how oriented saturation can appear consistently within the effective description. The existence of discrete charge values reflects the stability of specific oriented saturation modes, rather than an arbitrary assignment of coupling constants.

Importantly, this interpretation does not predict deviations from known electromagnetic phenomena. All standard results of quantum electrodynamics are recovered in the unsaturated and weak-field regime.

4.3 Inertia, relativistic dynamics, and equivalence

Relativistic dynamics treats inertia as a fundamental response encoded in the energy–momentum relation. The equivalence between inertial and gravitational mass is experimentally well established and constitutes a cornerstone of relativistic physics.

Within the present framework, this equivalence arises naturally from the isotropy of saturated response. Both inertial resistance to acceleration and gravitational response correspond to the same structural limitation of effective reconfiguration.

No modification of relativistic kinematics is implied. Lorentz invariance remains an effective symmetry of the projected description, valid in regimes where the projection is approximately injective and unsaturated.

4.4 Absence of observable deviations at accessible scales

A crucial consistency requirement is the absence of observable deviations from Standard Model predictions in experimentally tested regimes. The framework satisfies this requirement by construction.

Saturation effects become relevant only when relational gradients approach the resolving capacity of the effective description. In particle physics experiments, electromagnetic and inertial responses are well within the linear regime, and no saturation is probed.

As a result, the framework predicts no departures from established cross sections, decay rates, or precision tests of quantum electrodynamics and electroweak theory. All Standard Model phenomenology is recovered as the linear-response limit of the effective description.

4.5 Relation to other bounded-response frameworks

Bounded-response mechanisms have previously been considered in both electromagnetic and gravitational contexts. Born–Infeld electrodynamics provides a well-known example in which saturation regulates divergent field strengths without spoiling low-energy phenomenology [9].

The present framework generalizes this idea conceptually. Rather than introducing bounded response as a modification of specific field equations, saturation is interpreted as a generic limitation of effective descriptions arising from non-injective projection.

This shift in perspective allows mass, charge, and inertia to be treated on equal footing, as different symmetry realizations of the same structural mechanism.

4.6 Summary

The proposed interpretation is fully consistent with Standard Model phenomenology. It does not alter gauge structure, particle content, or dynamical equations.

Instead, it provides a conceptual reinterpretation of mass, charge, and inertia as effective descriptors arising from saturated response under projection. Standard Model physics is recovered as the linear, unsaturated regime of this description.

In the following section, we discuss conceptual implications, limitations, and possible directions for further investigation.

5 Discussion, Limitations, and Outlook

In this final section, we summarize the conceptual implications of the proposed framework, clarify its limitations, and outline possible directions for future investigation. The emphasis remains on interpretation rather than on the introduction of new dynamical content.

5.1 Conceptual implications

The central implication of the present analysis is that mass, electric charge, and inertia need not be treated as fundamentally distinct physical primitives. Instead, they may be understood as different symmetry realizations of a single structural mechanism, namely the saturation of effective response under non-injective projection.

From this perspective, the apparent diversity of physical properties reflects differences in how the effective description responds to relational variation, rather than differences in underlying substance. Scalar, oriented, and finite-resolution responses correspond respectively to mass, charge, and inertial behavior.

This interpretation provides a unified conceptual basis for the equivalence between inertial and gravitational mass and for the signed nature of electric charge, without modifying their operational definitions. It also clarifies why these quantities enter physical laws as parameters governing response rather than as directly observable entities.

5.2 Relation to existing foundational approaches

The framework developed here is compatible with a wide range of foundational approaches in which spacetime and physical observables are regarded as effective constructs. It does not rely on a specific microscopic ontology and can be embedded in different relational, background-independent, or pre-geometric settings.

Unlike approaches that postulate new degrees of freedom or modified dynamics, the present work operates at the level of description. Its contribution is to isolate a minimal structural mechanism capable of accounting for several distinct physical notions within a single conceptual scheme.

In this sense, the framework complements rather than replaces existing theories. It provides an interpretative layer that may coexist with standard formulations of quantum field theory and relativity.

5.3 Limitations of the present work

The present analysis is subject to several important limitations.

First, no microscopic dynamics of the underlying relational description is specified. As a result, the framework does not predict numerical values for masses, charges, or coupling constants. These remain empirical inputs at the level of effective theories.

Second, the analysis is qualitative in nature. While symmetry arguments and structural considerations motivate the proposed classification, no explicit derivation of Standard Model parameters is attempted.

Third, the framework does not address questions related to particle generations, flavor structure, or symmetry breaking patterns within the Standard Model. Its scope is restricted to the conceptual status of mass, charge, and inertia as effective descriptors.

Finally, the saturation mechanism invoked here is not directly observable in particle physics experiments, as all accessible regimes remain well within the linear-response domain. The framework therefore does not offer immediate experimental tests at high-energy scales.

5.4 Possible extensions and outlook

Despite these limitations, the framework suggests several directions for further investigation.

One possible extension is a more detailed analysis of how different symmetry classes of saturation could be embedded in concrete relational or spectral models, potentially linking qualitative classification to quantitative constraints.

Another direction concerns the relation between saturation mechanisms and known bounded-response effects in quantum field theory, such as strong-field phenomena. Clarifying these connections may help identify regimes in which saturation becomes operationally relevant.

At a more conceptual level, the framework invites reconsideration of the status of physical parameters traditionally regarded as fundamental. If mass and charge are effective descriptors tied to descriptive saturation, their role in physical theories may be understood as contingent rather than primitive.

More broadly, the present work illustrates how structural limitations of effective descriptions can shape the form of physical laws. Exploring similar mechanisms in other domains may provide insight into the emergence of physical properties without invoking additional fundamental entities.

5.5 Concluding remarks

We have proposed a unified structural interpretation of mass, electric charge, and inertia as effective manifestations of saturated response under non-injective projection. The framework is fully consistent with Standard Model phenomenology and does not modify its dynamical content.

By shifting attention from microscopic dynamics to descriptive structure, the analysis offers a coherent conceptual account of why these quantities play the role they do in physical theories. While deliberately modest in its claims, the framework provides a basis for further exploration of the structural origin of physical properties.

Appendices

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