Persistent Structural Tensions in Contemporary Physics and the Operational Requirements for Their Resolution

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Contemporary physics achieves extraordinary empirical success across disparate regimes, yet relies on a growing set of effective structures whose physical status remains ambiguous. These include nonlocal energy bookkeeping in general relativity, environment-induced decoherence in quantum theory, horizon thermodynamics, and causal propagation without explicit carriers in cosmology. These features do not represent inconsistencies or failures of prediction, but rather persistent structural tensions between formal ontology and operational practice. In this work, we systematically catalogue these tensions and show that they share a common set of implicit assumptions characteristic of response theory: finite propagation, relaxation, dissipation, and boundary dynamics. We formulate a minimal set of operational requirements that any framework capable of resolving these tensions must satisfy, independent of interpretation. As an existence proof, we note that emergent-response frameworks can satisfy these requirements while reproducing all tested limits of established theories. Even if no specific realization is ultimately correct, the requirements identified here remain unavoidable consequences of existing empirical practice.

I. INTRODUCTION

Modern physics rests on two extraordinarily successful pillars: general relativity (GR) and quantum field theory (QFT). Each has been validated to remarkable precision within its domain. Yet despite this success, their coexistence has long been accompanied by conceptual unease. This unease is often framed as a search for "quantum gravity" or as a problem of unification, but many of the most persistent difficulties arise well before such extremes.

In practice, contemporary physics routinely employs effective structures that are not fundamental elements of its formal ontology. These include horizon entropy and temperature, nonlocal energy accounting, decoherence-induced classicality, and causal response without explicit mediators. Such structures are indispensable for calculation and interpretation, yet are often described as auxiliary, emergent, or merely mathematical.

The purpose of this paper is not to propose a new theory, nor to argue that existing frameworks are incorrect. Rather, we aim to clarify what current practice already assumes. We identify a set of persistent structural tensions: places where successful descriptions rely on response-like behavior while declining to assign it physical status. By cataloguing these tensions and extracting their common operational content, we derive a set of requirements that any framework resolving them must satisfy.

II. WHAT IS MEANT BY "TENSION"

By "tension" we do not mean contradiction, inconsistency, or empirical failure. All phenomena discussed here are successfully described by existing theories. Instead, a tension arises when:

- A framework reproduces observations only by introducing effective structures,
- Those structures exhibit dynamics characteristic of physical response,
- Yet the framework denies or obscures the physical status of those dynamics.

Such tensions are not pathologies; they are signals. Historically, similar signals preceded the recognition of thermodynamics, fields, and quantum mechanics themselves. The question is not whether these tensions exist, but what they collectively imply.

III. CATALOGUE OF PERSISTENT STRUCTURAL TENSIONS

A. Energy Localization in General Relativity

General relativity replaces gravitational force with spacetime geometry. While elegant, this move renders gravitational energy fundamentally nonlocal: there is no covariant local energy density for the gravitational field [1]. Nevertheless, phenomena such as binary mergers radiate vast amounts of energy in the form of gravitational waves.

Operationally, energy is conserved globally and radiated causally, yet no local carrier exists. The geometry itself is said to "carry" energy, a statement that functions computationally but lacks a physical mechanism. The theory succeeds, but only by deferring the question of where energy resides during dynamical evolution.

B. Quantum Measurement and Classical Outcomes

Quantum theory prescribes unitary, deterministic evolution, yet measurements yield definite outcomes. The modern resolution appeals to decoherence: entanglement with an environment suppresses phase information and yields classical statistics [2, 3].

Decoherence is experimentally verified and operationally essential. However, it relies on finite response, information flow, and effectively irreversible relaxation. These are features of open systems and response theory, not of closed, fundamental dynamics. The tension lies not in prediction, but in ontology.

C. Horizons and Thermodynamics

Black hole horizons possess temperature and entropy proportional to area [4–6]. These are not optional interpretations; they are required for consistency with quantum field theory and thermodynamics.

Yet horizons are not material objects. The assignment of entropy, viscosity, and conductivity—as in the membrane paradigm—is often described as a calculational tool. Nevertheless, the success of these descriptions depends on treating boundaries as thermodynamically active interfaces.

D. Cosmological Propagation and Horizons

Cosmology describes causal horizons, redshift, and structure growth over vast distances. Light propagates with finite speed, information is limited by horizons, and perturbations relax over time. These behaviors resemble transport in a medium, yet are attributed entirely to geometry and expansion [7, 8].

Once again, the theory works. The tension arises because causal response, damping, and saturation appear without explicit carriers or relaxation channels.

IV. THE HIDDEN COMMON STRUCTURE

Across these domains, a striking pattern emerges. Successful descriptions rely on:

- Finite propagation speeds,
- Relaxation and equilibration times,
- Dissipation or coarse-graining,
- Boundary and interface dynamics,
- Global conservation without local carriers.

These are not generic features of geometry or kinematics. They are the defining characteristics of response theory. Importantly, invoking this structure does not require committing to any specific microscopic model. It merely recognizes what current practice already assumes operationally.

V. OPERATIONAL REQUIREMENTS FOR RESOLUTION

From the tensions identified above, we extract a minimal set of requirements that any framework resolving them must satisfy:

1. Recover all empirically validated limits of GR and QFT,
2. Admit finite propagation and causal horizons,
3. Allow energy transfer without local carriers,
4. Support boundary thermodynamics and dissipation,
5. Reduce to purely geometric or kinematic descriptions in appropriate limits.

These requirements are not speculative. They are imposed by existing observations and calculational success. Any framework lacking them cannot account for current practice.

VI. AN EXISTENCE PROOF

Frameworks based on emergent or response-driven dynamics provide explicit realizations of the above requirements. In such approaches, geometry, locality, and unitary dynamics arise as effective descriptions when response is linear and coherence is maintained, while deviations occur only in regimes of extreme gradients or long propagation.

As one example, the Emergent Condensate Superfluid Medium (ECSM) framework satisfies these operational requirements while reproducing standard limits in all tested regimes. The details of any specific realization are secondary to the broader point: frameworks satisfying the requirements exist.

VII. WHY THE REQUIREMENTS PERSIST

Crucially, even if all existing emergent frameworks were shown to be incorrect in detail, the operational requirements identified here would remain. They are not artifacts of a particular model, but consequences of how contemporary physics already functions.

Thus, the resolution of these tensions cannot lie in abandoning response-like behavior. It can only lie in making explicit what is currently implicit.

VIII. CONCLUSIONS

The most persistent conceptual tensions in contemporary physics do not arise from failed predictions, but from the quiet reliance on effective response structures whose physical status remains undefined. By cataloguing these tensions and extracting their shared operational content, we have identified a set of unavoidable requirements that any resolving framework must satisfy.

Whether interpreted geometrically, statistically, or as evidence of deeper structure, these requirements are already embedded in successful practice. Recognizing them explicitly clarifies the landscape of viable theoretical development and reframes the question of unification as one of response, rather than replacement.

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