Relationality as the Condition of Physical Theory:
An Extrapolation Upon Rovelli's Relational Quantum Mechanics

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Abstract

Every physical theory is constructed from observations performed within a physical frame, and this frame enters the theory at a level antecedent to its equations — in the categorical structure through which observations are organized into a formalism. This is a structural condition on physical theory as such, not a hypothesis about any particular physical phenomenon; its character is analogous to the principle of general covariance, which constrains the form of physical laws without predicting the behavior of any specific system. The condition has a precise formal consequence in the geometric setting: for any non-invariant tensor field under a frame-transformation group, the components specified in any single frame are insufficient to determine the underlying geometric object without explicit specification of the frame. This consequence has been articulated four times in the foundations of physics — in the tensor reformulation of electrodynamics, in the relativity of simultaneity, in the unification of energy and momentum, and in the geometric unification of space and time — each time by identifying a frame-dependence carried implicitly in the prevailing formalism and absorbing it into a geometric object across the class of frames. Rovelli's (1996) relational quantum mechanics is the most explicit contemporary articulation of the structural condition: the frame is the physical system to which a quantum state is referred, and the relational structure is exhibited directly at the level of the measurement interaction. The condition implies that relationality must arise wherever current physics is examined at the level of its foundations — not because relationality is a fundamental feature of the physics under description, but because it is a necessary feature of any theory constructed from observations performed within physical frames, and open foundational problems are most plausibly resolved by making implicit frame-dependences explicit rather than by eliminating them.

1. INTRODUCTION

In 1996 Carlo Rovelli proposed a reinterpretation of quantum mechanics which he called relational. His thesis was that the difficulty of the measurement problem originates in an implicit premise of the standard formulation — the premise that the state of a physical system is an observer-independent quantity — and that the problem dissolves once this premise is replaced by the explicit recognition that state assignments are relations between physical systems. Rovelli modelled his move on Einstein's 1905 treatment of the Lorentz transformations, where Einstein had identified the pre-relativistic premise of observer-independent time as the source of the difficulty in interpreting the transformations and reformulated kinematics on the basis of its removal.

I want to suggest in this paper that Rovelli's move admits a theoretical extrapolation. The relational structure that Rovelli articulated for the specific case of quantum mechanics is not a feature of quantum mechanics. It is a structural condition of physical theory as such. The condition is that every physical theory is constructed on the basis of observations performed from within a physical frame, that this frame constitutes a set of physical and structural constraints on the observations, and that these constraints enter the theory at a level antecedent to its equations — in the categorical structure through which the observations are organized into a formalism. What Rovelli established for quantum states generalizes: a physical theory constructed from observations performed within a frame necessarily carries that frame in its structure, whether or not the formalism acknowledges it.

This is the central thesis of the present paper: frame-dependence is not a contingent artifact of particular formalisms but a structural condition of any physical theory whatsoever, and foundational progress in physics consists, in each of its major episodes, in the explicit articulation of a frame-dependence that the prior formalism had carried implicitly. The paper is organized as follows. Section 2 develops the argument for the thesis as a structural condition of physical theory. Section 3 states one formal consequence of the condition for the case of geometric quantities under frame-transformation groups. Section 4 examines four historical instances in foundational physics where the condition has been articulated. Section 5 presents Rovelli's relational quantum mechanics as the most explicit contemporary articulation of the condition. Section 6 considers what the condition implies for the contemporary foundational situation. Section 7 concludes.

A terminological remark is in order. I use the word "frame" in a sense that generalizes Rovelli's use of "observer." A frame, in this paper, denotes the physical setting from which an observation is performed or a theoretical construction is carried out — including position, state of motion, dimensional embedding, and the formal and mathematical categories available at the time. A frame is therefore not only a coordinate system or a state of motion; it is the full set of physical and structural conditions constraining a particular act of physical observation or theoretical formulation. Where the paper refers to the theoretical agents who carry out reformulations, the word "physicist" is used directly.

2. THE CONDITION

The thesis of this paper is a claim about the necessary structure of physical theory. Before deriving its consequences and exhibiting its historical articulations, I state the claim carefully and argue for it.

2.1. The four-step argument

The argument has four steps.

Step 1. Physical theories are constructed from observations, and every observation is performed by a physical system situated within the larger physical system to which the theory applies. This is an empirical fact about the practice of physics, not a metaphysical posit. Measurements are performed by apparatus which occupy definite positions and states of motion within the laboratory; theoretical formulations are carried out by physicists who occupy definite spatiotemporal and dimensional regimes within the physical world; in every case, the act of observation or theoretical construction is performed by a physical system that is itself part of the physical reality under description. No physical theory has ever been constructed from a vantage external to physical reality, nor is such a construction available in principle.

Step 2. A physical system performing an observation is characterized by a collection of physical and structural parameters: its position, its state of motion, its dimensional embedding within the spacetime manifold, and the mathematical and conceptual categories available to the physicists who formalize the observations into a theory. I call this collection, taken together, the frame from which the observation is performed. The frame includes the spatial and temporal coordinates of the observing system; it includes the dimensional structure of the manifold within which the system is embedded (a system whose world-volume is restricted to a lower-dimensional submanifold of spacetime has access to a different class of observations than one with access to the full manifold); it includes the mathematical formalism, the conceptual distinctions, and the categorical structure available at the time of theoretical construction. The frame is not an addition to the observing system; it is the physical and structural specification of the conditions under which the observation is carried out.

Step 3. Observations performed from within a frame necessarily carry the constraints of the frame, because the classes of observable quantities, the admissible categorical distinctions, and the available formal descriptions are each a function of the frame. No operation internal to the frame verifies the observations against physical reality as it stands independently of any frame, because such a verification would require access to a non-physical vantage, which by Step 1 is unavailable. Any procedure that appears to eliminate frame-dependence is itself a procedure formulated within some frame, and the apparent frame-independence of its output is a property of that frame's categorical structure, not a property of physical reality as such. Frame-dependence is therefore not a contingent artifact of particular formalisms; it is a structural feature of any theory constructed from observations performed within physical frames.

Step 4. The constraints imposed by the frame enter physical theory at a level antecedent to its equations. They appear not only in the numerical values of observed quantities — which is the familiar sense of frame-dependence in special relativity — but in the categorical structure of the theory: in what is identified as a fundamental quantity, in which distinctions are drawn between kinds of physical entity, in what constitutes a complete specification of a physical state. These categorical choices are themselves a function of the frame from which the theory was constructed, and they shape the form of the equations before the equations are written. The equations express relations between quantities specified within the categorical structure of the frame; the categorical structure of the frame is therefore prior to, and not derivable from, the equations of the theory.

To make Step 4 concrete before the historical cases of Section 4 arrive: in Maxwell's pre-relativistic formulation, the distinction between electric and magnetic fields is built into the categorical grammar of the theory as a distinction between independently fundamental quantities. This categorical choice is not derived from the equations; it precedes them, shaping what the equations are equations *of*. The relativistic reformulation reveals that the distinction is a frame-relative decomposition of the Faraday tensor $F^{\mu\nu}$, not a frame-independent categorical fact. The frame in which the distinction appeared categorical — the low-velocity, non-relativistic observational regime — had been present in the formalism all along, not as a numerical parameter but as a structural condition on what counted as a fundamental quantity. This is precisely what Step 4 asserts, and it is what each of the four historical cases of Section 4 exhibits in its specific context.

2.2. The status of the claim

The claim of Step 4 is unfalsifiable in a strong sense. Any proposed counterexample — any physical theory offered as evidence that construction without frame-dependence is possible — would itself be a theory constructed by physicists from within some frame, and would therefore instantiate the claim rather than refute it. There is no empirical test that decides the claim, because the claim concerns the structural conditions under which any empirical test is itself performed.

This unfalsifiability is appropriate to the character of the claim. The claim is not a hypothesis about a particular physical phenomenon; it is a structural statement about the relationship between physical theories and the frames from which they are constructed. Structural statements of this kind are standard in the foundations of physics. The principle of general covariance, in its strongest reading, is a structural statement of analogous character: it does not predict the behavior of any specific physical system but specifies a structural requirement on the form of physical laws. The present claim is similarly structural: it specifies a condition on the relationship between any physical theory and the frame from which its observational basis is obtained.

The analogy with general covariance is worth pressing further. The principle of general covariance is not falsifiable as a structural requirement — no single experiment decides whether physical laws must be expressible in generally covariant form — yet it carries genuine empirical content through its consequences in particular theories. It constrains what theories are admissible, predicts the form that solutions must take, and has guided productive foundational work in gravitational physics for over a century (Norton 1993). The present claim stands in exactly the same relation to its historical articulations: the structural condition is not tested directly but through the productivity of the four-step pattern it predicts. Each instance in which making an implicit frame explicit resolves an interpretive difficulty and reveals a genuine invariant is a confirmation of the pattern, not by falsifying a rival but by extending a research orientation that has repeatedly proved productive.

A further objection deserves direct treatment: that unfalsifiable structural claims are philosophically vacuous, carrying no genuine content beyond what their proponents choose to read into them. The response requires distinguishing two senses of empirical content. The first is direct falsifiability: a claim has empirical content in this sense if a specific experimental outcome would count as evidence against it. The second is indirect or cumulative confirmation: a claim has empirical content in this sense if the research orientation it generates can be assessed as more or less productive, and if specific results could in principle undermine it. The present claim belongs to the second category. Its confirmation is cumulative — each historical articulation of an implicit frame-dependence adds to the evidential base — and the claim would be substantively undermined if foundational progress were shown to proceed systematically by a different pattern, such as the elimination of frame-dependence in favor of genuinely frame-independent descriptions, rather than by its explicit articulation. This would not falsify the structural condition by counterexample but would defeat the research orientation it recommends. The claim is therefore substantive without being directly falsifiable, in the same way that the principle of general covariance is substantive without being directly falsifiable.

It is worth locating the present claim in relation to the structural realist programme in philosophy of science, since the proximity is close enough to require explicit differentiation. Ontic structural realism, as developed by Ladyman (1998) and French and Ladyman (2003), holds that what physics describes are structures — relations and relational properties — rather than intrinsically characterized objects, and that the objects of physical ontology are constituted by the relational structure of the theory. The present claim is not a claim of this kind. It does not assert that physical reality is fundamentally relational in its ontological constitution; it asserts that the *description* of physical reality is necessarily relational to a frame, because every description is constructed from within a physical frame. The distinction matters: structural realism makes a claim about what there is, while the present claim makes a claim about the conditions under which physical theories are constructed. A physicist who rejects structural realism on ontological grounds can accept the present claim in full, since the claim is about the structure of physical description rather than the structure of physical reality. The relationality the present paper identifies is a feature of theory construction, not a feature of the entities theories describe. Where structural realism reads frame-relative quantities as evidence for relational ontology, the present claim reads the same quantities as evidence for a structural condition on the practice of physics.

The empirical content of the claim lies in its consequences in particular cases. For any specific physical theory, the claim implies that the frame from which the theory was constructed will be present in the theory's categorical structure, and that making this presence explicit will be a productive operation in foundational analysis. The four historical cases of Section 4 and the quantum-mechanical case of Section 5 provide the empirical support for this prediction. Whether future theories continue to exhibit the pattern is testable; whether past theories have exhibited it is a matter of the historical record.

2.3. The dimensional generalization

A clarifying point about the scope of the claim. Frame-dependence in physics is often identified with the special-relativistic situation in which numerical components of physical quantities transform under changes of inertial frame. This is one form of frame-dependence. It is not the only one, and the structural condition of this paper is broader than the kinematic case.

The frame, as defined in Step 2, includes the dimensional embedding of the observing system within the manifold under consideration. This introduces a kind of frame-dependence that is categorically distinct from the kind captured by Lie group actions on a fixed manifold. When an observing system's worldvolume is confined to a lower-dimensional submanifold, it does not obtain a lower-dimensional projection of higher-dimensional observations in the way that a Lorentz boost projects a four-vector onto a spatial hyperplane. It obtains, instead, a set of observations whose entire categorical structure is intrinsically lower-dimensional: the admissible observables, the available invariants, and the fundamental distinctions of the resulting theory are all determined by the dimensionality of the submanifold from which the observations are performed. Higher-dimensional invariants are not merely inaccessible in practice; they are not formulable within the categorical apparatus of the lower-dimensional frame.

The Kaluza–Klein construction makes this concrete, and it is worth applying the four-step pattern of Section 4 to it explicitly. Kaluza (1921) showed that five-dimensional general relativity, when the fifth dimension is compactified at a scale below observational resolution, yields a four-dimensional effective theory. The five-dimensional theory contains a single geometric object: the metric $\hat{g}_{AB}$ on the five-dimensional manifold $\hat{M} = M^4 \times S^1$, where $A, B \in \{0, 1, 2, 3, 5\}$. When the fifth dimension is compactified, this metric decomposes under the four-dimensional diffeomorphism group as

$$\hat{g}_{AB} \longrightarrow (g_{\mu\nu},\, A_\mu,\, \phi), \tag{1}$$

where $g_{\mu\nu}$ is the four-dimensional metric of general relativity, A_μ is a gauge field identified with the electromagnetic potential, and ϕ is a scalar field. Applying the four-step pattern: (a) the four-dimensional physicist treats gravity and electromagnetism as categorically distinct physical fields, a classification that is built into the categorical grammar of the four-dimensional theory as a distinction between independently fundamental quantities; (b) the frame from which this classification is made is the four-dimensional compactified regime, in which the fifth dimension is inaccessible and the dimensional embedding of the observational frame is restricted to M^4; (c) the geometric object that carries the same physical content across the class of dimensional frames is $\hat{g}_{AB}$, the five-dimensional metric, which exhibits the gravitational and electromagnetic fields as a single unified structure; (d) the four-dimensional fields $g_{\mu\nu}$ and A_μ are recovered as frame-relative components of $\hat{g}_{AB}$ under the compactification, in exact formal parallel to the recovery of $\vec{E}$ and $\vec{B}$ as frame-relative components of $F^{\mu\nu}$ under a Lorentz boost.

The four-dimensional physicist observing from within the compactified regime does not obtain a lower-dimensional projection of the five-dimensional metric in the way a Lorentz boost projects a four-vector; she obtains a set of observations whose entire categorical structure is intrinsically four-dimensional. The unification of gravity and electromagnetism in the five-dimensional theory is a fact about the geometric object $\hat{g}_{AB}$; the apparent separation into two distinct fields is a fact about the four-dimensional dimensional frame. What the $\vec{E}/\vec{B}$ case exhibits at the level of frame-relative decomposition of a single tensor under a kinematic frame transformation, the Kaluza–Klein case exhibits at the level of frame-relative decomposition under a dimensional frame transformation: in both cases a single geometric object appears, within the frame, as a categorical distinction between independently fundamental quantities.

The dimensional case differs from the kinematic case in one formal respect. The formal consequence stated in Section 3 applies to tensor quantities transforming under Lie group actions on a fixed manifold; a dimensional frame transformation is not an action on a fixed manifold but a change in the dimension of the manifold itself, and equation (1) is not an instance of Proposition 1 but a structurally analogous result at a different level. The dimensional case therefore extends the scope of the structural condition beyond the kinematic setting: it establishes that the condition applies wherever the categorical apparatus of a physical theory reflects the dimensional constraints of the observational frame from which it was constructed, which includes but is not limited to the kinematic frame-dependences of Section 3.

The inscription of the frame into the theory therefore operates at the level of the categorical apparatus, not only at the level of numerical values. What the four historical cases of Section 4 exhibit in the kinematic setting, and what Rovelli's case exhibits in the system-relational setting, the Kaluza–Klein case exhibits at the level of which fields and quantities are available for formulation at all.

3. ONE FORMAL CONSEQUENCE

The structural claim of Section 2 has a precise formal consequence in the geometric setting, which is standard in differential geometry and is cited here as a precisification rather than a new result. Let M be a smooth manifold, G a Lie group acting smoothly on M representing the relevant frame-transformation group, and T a tensor field on M representing some physical quantity. If T is not G-invariant — that is, if there exists $g \in G$ such that $g \cdot T \neq T$ — then the components of T in any single frame are insufficient to recover T as a geometric object without explicit specification of the frame in which those components were read. The frame is therefore a logical parameter of the components, not a passive backdrop against which they are displayed.

This result makes precise the distinction, recurring in each of the four historical cases of Section 4, between an *implicit* formalism — one that displays components T_g for some fixed but unspecified frame g, carrying the frame as a silent parameter — and an *explicit* formalism, one that exhibits the tensor T as a section of the appropriate bundle and recovers components by evaluating T in a specified frame. These two formalisms have identical physical content; what differs is their transparency about the frame-dependence. The contribution of the reformulations reviewed in Section 4 is precisely this move from implicit to explicit. It is also worth noting that genuine invariants — the rest mass m, the spacetime interval ds^2, the Casimir invariants of a representation — become identifiable as such only once the geometric object is exhibited across the class of frames; invariance is a relational property that the implicit formalism obscures.

The quantum-mechanical case of Section 5 requires different formal apparatus: the frame there is not a coordinate choice on a fixed manifold but a physical system, and the passage between frames is not a group action but a change of interaction partner. The present result is therefore one formal consequence of the broader structural condition, not its complete mathematical content.

4. FOUR PRIOR ARTICULATIONS

The structural claim has been articulated, in particular cases, four times in the foundations of physics prior to Rovelli. Each articulation took a theory in which a frame-dependence was carried implicitly and rewrote the theory in terms that made the dependence explicit. The structural pattern common to all four cases can be stated as a four-step methodology: (a) a class of quantities treated as observer-independent is identified as actually frame-dependent; (b) the frame from which the quantities were specified is made explicit; (c) a geometric object is introduced that carries the same physical content across the class of frames; (d) the original quantities are recovered as the frame-relative components of this object. I review the cases with this pattern in view, attending in each to the philosophical literature that bears on the move.

4.1. Electric and magnetic fields

The pre-relativistic formalism treated the electric and magnetic fields as distinct physical quantities. Under a Lorentz boost of velocity v along the x-axis, the transverse components mix:

$$E'_y = \gamma(E_y - vB_z), \tag{2}$$

$$B'_z = \gamma\left(B_z - \tfrac{v}{c^2}E_y\right). \tag{3}$$

The identification of a component as electric or magnetic depends on the frame to which it is referred. The reformulation introduced the antisymmetric tensor

$$F^{\mu\nu} = \begin{pmatrix} 0 & -E_x/c & -E_y/c & -E_z/c \\ E_x/c & 0 & -B_z & B_y \\ E_y/c & B_z & 0 & -B_x \\ E_z/c & -B_y & B_x & 0 \end{pmatrix} \tag{4}$$

on four-dimensional spacetime, and rewrote Maxwell's equations as

$$\partial_\mu F^{\mu\nu} = \mu_0 J^\nu, \quad \partial_{[\alpha} F_{\mu\nu]} = 0. \tag{5}$$

The four equations of the original formulation collapsed to two manifestly covariant equations. The frame in which the $\vec{E}/\vec{B}$ distinction was made was, in the original formulation, carried implicitly. The reformulation made it explicit by exhibiting the geometric object across the class of frames.

The philosophical question this case raises is whether the frame-dependence of the $\vec{E}/\vec{B}$ distinction is a fact about the physics or a fact about the formalism. Earman (1974) argues that covariance results of this kind are not automatically substantive: a formalism can be rendered covariant by the introduction of absolute objects, in which case the covariance is a formal property of the presentation rather than a physical discovery. The present case, however, is not of this kind. The mixing of electric and magnetic components under boosts — equations (2)–(3) — is a physical prediction confirmed by experiment: a charge at rest in one frame produces a purely electric field, while the same charge in motion produces a magnetic field measurable by an independent observer. Jackson (1998, Ch. 11) derives the fields of a moving charge from the Coulomb field by Lorentz transformation, illustrating that the $\vec{E}/\vec{B}$ distinction is not a notational artifact but a frame-relative decomposition of a single physical object. The reformulation articulates this fact rather than merely repackaging it. The frame carried implicitly in Maxwell's original equations is the low-velocity, non-relativistic frame in which the electric and magnetic aspects of the field were first characterized experimentally and in which the absence of relativistic mixing made the distinction appear categorical rather than relational. A related analysis of gauge freedom as irreducible frame-dependence, rather than as surplus structure to be eliminated, is developed in Healey (2007) for the case of Yang–Mills theories; the parallel with the present reading of the $F^{\mu\nu}$ reformulation is direct.

4.2. Simultaneity

Newton's *Principia* took simultaneity as a frame-independent relation between events. The Lorentz transformation falsifies this: for two events simultaneous in frame S at positions x_A and x_B,

$$t'_A - t'_B = -\frac{\gamma v}{c^2}(x_A - x_B), \tag{6}$$

which is nonzero unless the events are spatially coincident or the relative velocity vanishes. The reformulation replaces the frame-independent notion of simultaneity with a relation between events and frames: events are simultaneous-relative-to-a-frame, and the frame-invariant content is specified at the level of the spacetime interval and the causal structure it induces. The frame in which Newton's notion of simultaneity was meaningful — the low-velocity regime in which surfaces of simultaneity differed negligibly between observers — was carried implicitly. The reformulation made it explicit by exhibiting simultaneity as a relation rather than a property.

Friedman (1983, Ch. 4) argues that the content of special relativity cannot be reduced to a mere redefinition of simultaneity, because the geometric structure of Minkowski spacetime is substantively richer than the Newtonian structure it replaces. The structural reading of the present paper is consistent with this: the point is not that simultaneity was merely conventional and the reform was semantic, but that the Newtonian formalism carried the frame of low-velocity observation at the level of its categorical grammar — treating as a frame-independent property what the new theory identifies as a frame-relative relation. The reform is conceptual, not merely notational, precisely in the sense Step 4 of the argument specifies: it occurs at the level of categorical structure, not only at the level of numerical values.

4.3. Energy and momentum

The pre-relativistic formalism treated energy and momentum as independently conserved quantities. Under Lorentz boosts they mix: a particle at rest in one frame has nonzero momentum in any frame in which it moves. The reformulation introduced the four-momentum

$$p^\mu = \left(\frac{E}{c}, \vec{p}\right) \tag{7}$$

as a single geometric object whose components in any frame yield the energy and momentum measured in that frame, and whose Lorentz-invariant magnitude

$$p^\mu p_\mu = -\frac{E^2}{c^2} + |\vec{p}|^2 = -m^2c^2 \tag{8}$$

specifies the rest mass on which all inertial frames agree. The frame in which energy and momentum were specified separately was, in the original formulation, carried implicitly. The reformulation made it explicit by exhibiting the four-vector across the class of frames.

This case illustrates the observation of Section 3 that genuine invariants become identifiable only once the geometric object is exhibited across the class of frames. In the pre-relativistic formalism, both energy and momentum appeared as fundamental, and their separate conservation laws appeared as independent facts. The reformulation reveals that what is genuinely frame-independent is neither energy alone nor momentum alone but the invariant magnitude $p^\mu p_\mu = -m^2c^2$, the rest mass. The separate conservation laws are frame-relative projections of a single covariant conservation law on the energy-momentum tensor. Making the frame explicit — exhibiting p^μ as the underlying geometric object — is what makes the invariant quantity visible as such.

4.4. Space and time

Classical physics took space and time to be distinct categories: space the three-dimensional container of position with a Euclidean metric, time a one-dimensional parameter of change. A Lorentz boost is, geometrically, a hyperbolic rotation of the spacetime coordinates that mixes a spatial direction with the temporal one. The reformulation articulated the decomposition by introducing the four-dimensional spacetime manifold equipped with the Minkowski metric

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2, \tag{9}$$

on which the partition into space and time appears as a frame-relative decomposition rather than as a categorical distinction.

This case is the most general of the four, because what was articulated as frame-relative was not a particular physical quantity but the categorical grammar of classical physics. On the structural reading of the present paper, the Minkowski reformulation is both a reconceptualization of the categorical apparatus and a discovery that the prior categorical apparatus was frame-relative: what classical physics treated as a frame-independent categorical distinction is revealed as a decomposition of the spacetime manifold relative to a choice of timelike direction. The frame which had carried the classical separation was the frame of low-velocity human observation, in which Lorentz contractions and time dilations are negligible and the space/time distinction appears absolute. The Minkowski metric is the geometric object that exhibits this separation as frame-relative, in exact parallel with $F^{\mu\nu}$ exhibiting the $\vec{E}/\vec{B}$ separation and p^μ exhibiting the energy/momentum separation. That the subsequent dispute over the physical content of general covariance was so extended (Norton 1993) is itself evidence that the reform operated at the level of categorical structure rather than merely at the level of numerical values.

4.5. *What the cases exhibit*

The four cases exhibit, each in its specific context, the four-step structural pattern stated at the opening of this section. In each case: (a) a class of quantities treated as observer-independent is identified as frame-dependent ($\vec{E}/\vec{B}$ as separately fundamental; simultaneity as a frame-independent property; energy and momentum as independently conserved; space and time as categorically distinct); (b) the frame from which the quantities were specified is made explicit (the low-velocity, non-relativistic regime of pre-relativistic physics in each instance); (c) a geometric object is introduced that carries the same physical content across the class of frames ($F^{\mu\nu}$, the spacetime interval, p^μ, and the Minkowski metric respectively); (d) the original quantities are recovered as frame-relative components of this object.

In each case the formal result of Section 3 is the substrate of the move: the original formalism displays components T_g without exhibiting the underlying tensor T, and the reformulation exhibits T directly.

The four cases predate Rovelli's reformulation of quantum mechanics by decades. They establish that the structural claim has empirical content as an account of how foundational progress in physics has historically proceeded. Each case is a specific instance of the claim articulated for a specific physical theory; collectively, they exhibit a recurrence that cannot be plausibly attributed to coincidence and that motivates the interpretation of foundational progress as the systematic articulation of frame-dependences carried implicitly in current theory. Rovelli's case instantiates the same pattern, but with a distinction: where the four prior cases embedded the structural move in the resolution of a specific physical problem, Rovelli isolated the move itself as the explicit object of analysis. Section 5 examines this distinction and its significance.

5. ROVELLI'S ARTICULATION IN QUANTUM MECHANICS

Rovelli's 1996 reformulation of quantum mechanics is the most explicit articulation of the structural claim in contemporary physics. The articulation is more direct than the four prior cases because Rovelli isolated the structural move as such, rather than embedding it in the resolution of a specific physical problem. I present his argument here in the detail required to exhibit it as an articulation of the structural condition of Section 2.

5.1. *The Einstein analogy*

Rovelli opens with an explicit parallel to pre-1905 electrodynamics. The Lorentz transformations

$$t' = \gamma\Big(t - \frac{vx}{c^2}\Big), \quad x' = \gamma(x - vt), \qquad (10)$$

had been derived by Lorentz in the late 1890s and were mathematically unambiguous. Their interpretation was not. Under the premise that time is an observer-independent quantity, the transformations are incompatible with any consistent account of electromagnetic phenomena in moving bodies; attempts to reconcile them with absolute time produced the increasingly elaborate auxiliary postulates of late aether theory.

Einstein's 1905 resolution introduced no new mathematics. He identified the premise of observer-independent time as the source of the difficulty, discarded it, and reformulated kinematics under the explicit recognition that time is relational to the frame in which it is measured. Under this reformulation, the Lorentz transformations ceased to present interpretive difficulty.

Rovelli's thesis is that the measurement problem in quantum mechanics occupies a structurally analogous position. The Hilbert-space formalism, the unitary evolution, the Born rule, the projection postulate are not in dispute. What has been in dispute is the status of quantum states in relation to measurement. Rovelli proposes that the difficulty originates in the premise of observer-independent state, that this premise plays the same structural role in the quantum case that observer-independent time played in the pre-relativistic case, and that its removal resolves the difficulty in the same way.

In the framework of the present paper, Rovelli's move is an articulation, for the case of quantum mechanics, of the structural condition stated in Section 2. The frame to which a quantum state is referred — the physical system with which the measurement interaction is established — had been carried implicitly in the standard formulation of quantum mechanics, just as the inertial frame to which the time of an event is referred had been carried implicitly in the Newtonian formulation of mechanics. Rovelli's reformulation makes the frame explicit. Whether it does so on the model of the four prior cases of Section 4, or in a structurally distinct way, is examined in the remainder of this section.

5.2. The two-observer analysis

The central argument of Rovelli's paper is a two-observer analysis that exhibits the frame-dependence of state assignments directly. I reproduce it here, following Rovelli (1996, pp. 1640–1644), because it is the argument on which the present paper builds.

Consider a quantum system S with a two-dimensional Hilbert space spanned by the eigenstates $|1\rangle$ and $|2\rangle$ of an observable q. At an initial time t_0, the system is in the superposition

$$|\psi_S(t_0)\rangle = \alpha|1\rangle + \beta|2\rangle, \tag{11}$$

with $|\alpha|^2 + |\beta|^2 = 1$. Let O be a second physical system — in Rovelli's terminology an observer, understood as any physical system capable of becoming correlated with S through interaction. O has its own Hilbert space with states $|O_{\text{init}}\rangle$, $|O_1\rangle$, and $|O_2\rangle$ corresponding to the pre-interaction configuration and to the configurations in which O has registered the outcomes 1 and 2. At time t_1 the interaction between S and O implements a measurement of q.

Two accounts are now available of what happens between t_0 and a subsequent time t_2.

Account 1 (relative to O). Relative to O, the measurement at t_1 produces a definite outcome. The probability of outcome 1 is $|\alpha|^2$ and the probability of outcome 2 is $|\beta|^2$. After the measurement, the state of S relative to O is the corresponding eigenstate $|1\rangle$ or $|2\rangle$.

Account 2 (relative to a third system P). Let P be a third physical system which does not interact with either S or O during the relevant interval. P describes the composite system $S+O$ by the Schrödinger equation applied to the combined Hilbert space. The interaction Hamiltonian produces, by unitary evolution, the entangled state

$$|\psi_{S+O}(t_2)\rangle = \alpha|1\rangle \otimes |O_1\rangle + \beta|2\rangle \otimes |O_2\rangle. \tag{12}$$

Relative to P, there has been no collapse; neither S nor O alone has a definite state at t_2.

The tension. The two accounts are incompatible under the assumption that the state of S is an observer-independent quantity. Account 1 assigns S a definite eigenstate of q at t_2; Account 2 assigns S no such state, S being entangled with O. If states are observer-independent, only one account can be correct, and the adjudication between them constitutes the measurement problem.

Rovelli's resolution. Rovelli argues that both accounts are fully correct, and that their apparent incompatibility arises from the premise of observer-independent state. Under the replacement of the premise by explicit relationality, both accounts become valid. Account 1 gives the state of S relative to O. Account 2 gives the state of $S + O$ relative to P. These are distinct physical quantities, not rival assignments of a common quantity.

5.3. The articulation read structurally

The two-observer analysis is the articulation, for the quantum-mechanical case, of the structural condition of Section 2. The frame from which a quantum state is assigned is, in this argument, the system O in its physical interaction with S. The state $|\psi_S\rangle$ is not a property of S alone; it is a relation between S and the frame O to which the description is referred. Different frames yield different relations, and the relations are not rival values of a single observer-independent property but distinct physical quantities each valid in its own context. The frame — the physical system to which the state is referred — enters the formalism at a level antecedent to the equations, since the equations of quantum mechanics do not specify, on their face, with respect to which system a state is being assigned.

The standard formulation carries this specification implicitly; Rovelli's reformulation makes it explicit.

The structural pattern is the same as in the four cases of Section 4, but with one important difference that is itself significant. In the four cases, the frame was specified by an inertial state of motion or a coordinate choice on the manifold, and the Lie group of frame transformations was a group of geometric transformations on a fixed manifold. In Rovelli's case, the frame is a physical system, and the "transformation" between frames is not a coordinate change but a passage between distinct physical interactions. The frame-dependence is therefore not captured by the formal result of Section 3; it is a different formal type of frame-dependence, requiring different formal apparatus. This demonstrates that the structural condition of Section 2 admits multiple formal realizations: the geometric realization of the four prior cases, the system-relational realization of Rovelli's case, and the dimensional realization of the Kaluza–Klein case. What unifies them is not a common formalism but a common structural feature: in each case, a class of physical quantities treated as observer-independent is reformulated as relational to the frame from which it is specified.

5.4. The postulates

Rovelli proposes that the relational reformulation admits axiomatization in terms of information-theoretic postulates. He states two main postulates in the 1996 paper (pp. 1655–1657):

Postulate 1. There is a maximum amount of relevant information that can be extracted from a physical system.

Postulate 2. It is always possible to acquire new information about a system.

The two postulates are not inconsistent, Rovelli argues, because the acquisition of new information renders some previously relevant information irrelevant. The first postulate yields the discreteness of quantum theory; the second yields the Heisenberg uncertainty relations. Rovelli argues that a substantial portion of the structure of the Hilbert-space formalism can be recovered from these postulates under the relational premise.

The information-theoretic content of the postulates is not essential to the present paper. What matters is that the postulates are stated in relational terms throughout: the information referred to in both postulates is the information that one physical system possesses about another, not the information about a system in some absolute or observer-independent sense. The frame from which the information is specified is built into the formulation of the postulates themselves. This is the explicit articulation of the structural condition at the level of the foundational axioms of quantum mechanics, rather than only in the interpretive layer.

5.5. Two responses to objections

Two objections to Rovelli's proposal are worth stating, along with his responses, since they anticipate objections to the broader thesis of the present paper.

The first is that relational quantum mechanics collapses into solipsism. If each frame has its own account of the world, and if no observer-independent facts are available, there is no shared reality. Rovelli's response (1996, §5) is that relationality does not preclude shared content. Frames can interact with each other, and under interaction their accounts become correlated in ways constrained by the structure of quantum mechanics. The world described by multiple frames is not a single observer-independent world but a network of frame-relative accounts whose mutual consistency under interaction is the substantive content of the relational theory.

The second is that the notion of "observer" in relational quantum mechanics is too permissive. If any physical system can be a frame, the concept carries no distinctive content. Rovelli's response is that this is the intended result. The term denotes any system with respect to which the state of another system is specified; it carries no commitment to consciousness or apparatus. This is the same usage standard in Galilean and special relativity, where the observer is a reference frame and the physical nature of the frame is irrelevant to its role in the theory.

Both responses extend, with the appropriate modifications, to the broader thesis of the present paper.

5.6. Relational quantum mechanics and the secondary literature

The structural reading of Rovelli's proposal developed in this paper can be sharpened by locating it against two bodies of secondary literature: the literature on the limits of quantum mechanics as a complete theory, and the literature on competing interpretations of the measurement problem.

Bell's later essays, collected in Bell (1987), provide a useful foil. Bell argued persistently that the standard formulation of quantum mechanics is unsatisfactory because it relies on the concept of "measurement" or "observation" without specifying what counts as one — a circularity that renders the theory's own primitive undefined. His preferred remedy was to identify a level of physical description at which definite events occur, whether through hidden variables, explicit collapse dynamics, or some other mechanism that removes the observer from the foundations of the theory. Rovelli's proposal moves in the opposite direction. Rather than eliminating the observer from the foundations, it makes the observer — the physical system to which a state is referred — an explicit and ineliminable parameter of any state assignment. On the structural reading of the present paper, Bell's diagnosis is correct: the standard formulation does carry an implicit frame, and this implicit frame is the source of the interpretive difficulty. But the prescription differs. Bell sought to make quantum mechanics frame-independent by grounding it in frame-independent events; Rovelli makes the frame explicit and treats frame-relativity as the correct description of what quantum mechanics is about. The difference is not a disagreement about the diagnosis but about whether frame-dependence is a defect to be eliminated or a structural feature to be articulated.

The contrast with Everettian interpretations is also instructive. The many-worlds interpretation, in its standard formulation, takes the global wavefunction to be the fundamental observer-independent object, with apparent measurement outcomes arising from decoherence within branches. This is formally a choice of the implicit frame: the global wavefunction is specified with respect to no particular physical system and is in this sense the limit of observer-independence. Weinberg (1995, Ch. 3) discusses the formal apparatus of the Everettian programme in the context of quantum field theory; the difficulty of recovering a preferred basis for the branch decomposition — the preferred basis problem — is, on the structural reading of the present paper, a problem of the same kind as the measurement problem itself: it arises because the frame relative to which the decomposition is performed has not been specified. The relational approach avoids the preferred basis problem precisely because it does not posit a global observer-independent wavefunction; the state is always specified relative to some physical system, and there is no question of which basis is preferred independently of that specification.

Misner, Thorne, and Wheeler (1973, Ch. 44) offer a relevant perspective from the gravitational side. Their discussion of the quantum mechanics of closed systems — systems with no external observer — anticipates the difficulty that Rovelli's two-observer analysis makes precise: if the universe as a whole is the system under description, there is no external frame relative to which its state can be assigned in the standard formulation. Relational quantum mechanics resolves this not by positing a special role for the universe's state but by insisting that state assignments are always inter-systemic: any subsystem of the universe can serve as the frame for another. This dissolves the closed-system problem in the same way that the relational treatment of simultaneity dissolves the problem of absolute time — by identifying the implicit assumption (that there must be a privileged external observer) and removing it.

6. IMPLICATIONS FOR CONTEMPORARY PHYSICS

The structural condition developed in this paper has implications for the foundational situation in contemporary physics. It is worth stating these implications carefully, since the condition makes a claim at a different level than most proposals in the foundations literature, and misreading the level at which it operates leads to both overestimating and underestimating its content.

The condition does not identify a specific mechanism for reconciling general relativity and quantum field theory, nor does it predict any particular feature of a unified theory. Its value is diagnostic rather than constructive: it provides a reading of the foundational situation according to which open problems in contemporary physics are problems in which implicit frame-dependences have become salient and require explicit articulation in the formalism, on the model of the historical cases of Section 4 and the quantum-mechanical case of Section 5. What the condition implies is that wherever contemporary physics is analyzed at the level of its foundations, the four-step pattern of Section 4 — identification of an implicitly carried frame, explicit articulation, introduction of a geometric or relational object across the class of frames, recovery of the original quantities as frame-relative components — should be expected to be productive.

The ADM decomposition of general relativity provides a concrete illustration of the structural condition's diagnostic value — and it is important to note that the ADM case differs from the four historical cases of Section 4 in one significant respect. In the historical cases, the four-step pattern was completed: the implicit frame was identified, articulated, and absorbed into a geometric object, resolving the interpretive difficulty. The ADM case is an instance of the pattern at the stage of diagnosis rather than resolution: the implicit frame has been identified and is well understood, but the appropriate relational object that would carry the physical content across the class of foliations in a fully diffeomorphism-invariant quantum theory of gravity has not yet been found. This is why the case has diagnostic rather than merely retrospective value — it is an open problem of exactly the kind the structural condition predicts. The ADM formalism decomposes the four-dimensional spacetime manifold into a one-parameter family of spacelike hypersurfaces, yielding a Hamiltonian formulation in which the gravitational field evolves on a three-dimensional spatial manifold. Applying the four-step pattern: (a) the implicit frame is the foliation choice itself — a structural selection made at the level of the formalism, not fixed by the physics of general relativity; (b) making it explicit means recognizing that different foliations yield inequivalent Hamiltonian descriptions of the same underlying spacetime, so that any particular ADM application carries a frame-dependent element that the formalism does not name; (c) the geometric object that carries the physical content across foliations is the four-dimensional metric $g_{\mu\nu}$ itself, which is foliation-independent by construction; (d) the coordinate-dependent quantities of any given ADM application are recovered as frame-relative components of $g_{\mu\nu}$ under the specified foliation. This case is formally parallel to the space/time separation of Section 4: in classical physics, the categorical separation of space from time was a frame-relative decomposition of the spacetime manifold carried implicitly by the low-velocity observational frame; in ADM, the foliation plays the same structural role. Wald (1984, Ch. 10) develops the gauge freedom associated with foliation choice; Norton (1993) situates it within the broader dispute over general covariance.

The orientation the structural condition suggests for contemporary foundational work is therefore a reading of the open problems rather than a constructive program. The reading is that the most productive foundational moves available are those that identify implicit frame-dependences in current theories, articulate them explicitly, and introduce the appropriate geometric or relational objects that carry the physical content across the class of frames. This does not determine what those objects will be in any particular case — that is the substantive physical and mathematical work. It indicates where the work is most likely to be necessary, and it provides a template, instantiated four times in the historical record and once in Rovelli's reformulation, for what success in that work looks like.

7. CONCLUDING REMARKS

I have argued in this paper that every physical theory is constructed from observations performed within a physical frame, that this frame constitutes a set of physical and structural constraints on the observations, and that these constraints enter the theory at a level antecedent to its equations — in the categorical structure through which the observations are organized into a formalism. This is the structural condition of physical theory. The condition is unfalsifiable in the empirical sense, since any proposed counterexample is itself a theory constructed from within some frame; it is a structural statement about the relationship between physical theories and the observational frames from which they are built, rather than a hypothesis about any particular physical phenomenon.

The condition has formal consequences in specific settings. For tensor quantities under Lie group transformations of frames, the components specified in any single frame are insufficient to determine the underlying geometric object without explicit specification of the frame. This consequence has been articulated in four previous instances in the foundations of physics: in the tensor reformulation of electrodynamics, in the relativity of simultaneity, in the unification of energy and momentum, and in the geometric unification of space and time. The most explicit recent articulation is Rovelli's 1996 reformulation of quantum mechanics, in which the frame is the physical system to which a state is referred, and the relational structure is exhibited at the level of the measurement interaction.

The thesis of the paper is that what Rovelli articulated for quantum mechanics is one instance of a structural condition that obtains throughout physical theory. The condition implies that relationality must arise as a structural feature wherever contemporary physics is analyzed at the level of its foundations — not because relationality is a fundamental feature of the physics under description, but because it is a necessary feature of any theory constructed from observations performed within physical frames. The implication for contemporary foundational work is a reading of the open problems: as situations in which the relational structure inherent to theory construction becomes salient and requires explicit articulation in the formalism. The resolution of such problems, when obtained, is most plausibly achieved not by the elimination of frame-dependence in favor of a frame-independent formalism but by the explicit articulation, at the level of the categorical structure, of frame-dependences that current theories carry implicitly. The dimensional generalization of the frame concept, developed in Section 2 through the Kaluza–Klein case, shows that this structural condition extends beyond the kinematic and system-relational realizations of Sections 4 and 5 to the level at which the dimensional character of the observational frame determines which quantities are formulable as observables at all — a third formal realization of the structural condition, distinct from both the geometric and the system-relational, and subject to the same four-step pattern of articulation.

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