Relationalism about Space and Time: Revisiting an Unfinished Revolution

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Abstract

This essay revisits the Leibnizian/Machian tradition of relationalism in light of recent developments in physics and metaphysics. While historically dismissed as conceptually elegant but technically deficient, relationalism has re-emerged as a viable foundation for fundamental physics through the advent of pure shape dynamics and the metaphysics of self-subsisting structures. These approaches address longstanding philosophical and physical challenges concerning empirical adequacy, the reconstruction of physical magnitudes, and the grounding of dynamical laws. By re-examining the trajectory of relationalist thought and clarifying how recent proposals fulfill its core ambitions, the essay presents a case for the renewed relevance of relationalism in foundational research.

Keywords*: Relationalism; pure shape dynamics; self-subsisting structures.*

1. Introduction

Few debates in natural philosophy have been as enduring as the one between relational and substantival conceptions of space and time. From Leibniz's early articulation of a relational view to Mach's critique of Newtonian mechanics, relationalism has repeatedly returned as an attempt to understand spatiotemporal structure as emergent from matter and its configurations. Yet for much of the history of physics, this view remained more of a philosophical aspiration than a physical framework.

The perceived failure of relationalism was codified with clarity and historical nuance by John Earman in Earman (1989), where he argued that the relationalist program had consistently fallen short: lacking precise formulation, failing to reproduce observed phenomena, and offering no serious rival to the explanatory power of frameworks such as Newtonian mechanics or general relativity, which rely on spatiotemporal structures that are external to material systems. Relationalism, in Earman's reading, amounted to a metaphysical aspiration in search of a viable physical theory. Furthermore, philosophers such as Shamik Dasgupta have argued that the traditional framing of the debate—cast in terms of modality or representation—should be replaced with a more fine-grained account in terms of metaphysical grounding (Dasgupta, 2011). On this view, the central question is whether spatial facts are explained by or grounded in the distribution of matter and its relations, or vice versa. Similarly, Hartry Field has challenged relationalists to account for the full quantitative structure of space and time—the very geometry and metrical content of physics—without positing a substantivalist manifold (Field, 1984). These critiques sharpen the stakes: a viable relationalism must not only eliminate surplus structure, but do so in a way that preserves explanatory and descriptive adequacy.

In the last few decades, a series of developments under the umbrella of shape dynamics (Mercati, 2018) and pure shape dynamics (Koslowski et al., 2022) have dramatically altered the landscape. Championed by the work of Julian Barbour and Bruno Bertotti (Barbour and Bertotti, 1977, 1982), these frameworks propose a fundamentally relational formulation of dynamics based on reduced configuration spaces, i.e., *shape spaces*, that eliminate any notion of absolute position, orientation, and scale. This reduction is achieved both formally and metaphysically: it corresponds to a commitment to ontological parsimony, where only those features that track physical differences among possible worlds are retained. Moreover, the pure shape dynamics framework has been embedded within a broader metaphysical picture, most notably, the notion of *self-subsisting structures* developed in Vassallo et al. (2022, 2024). These are relational configurations that exist independently of any embedding space or external time, offering a candidate ontology that is both minimalist and dynamically rich. The combined framework of pure shape dynamics and self-subsisting structures introduces new strategies for recovering physical quantities from purely relational information, thus responding in a principled way to concerns about explanatory adequacy and ontological clarity.

This essay examines how these developments represent a genuine step forward for the relationalist program. Section 2 traces the classical roots of relationalism and the conceptual tensions that persisted between its early philosophical ambitions and the structure of physical theories. Section 3 identifies and consolidates the main philosophical challenges that relationalism has faced in modern discourse. Section 4 introduces the frameworks of shape dynamics and pure shape dynamics, with emphasis on the latter’s formal and conceptual distinctiveness. Section 5 develops the metaphysical articulation of pure shape dynamics via the theory of self-subsisting structures, including its treatment of time. Section 6 addresses quantum extensions of the framework, highlighting the importance of adapting relationalist principles to quantum theory if relationalism is to offer a comprehensive foundation for modern physics. Section 7 offers a historiographical perspective on the marginalization of relationalism and its recent revival. Finally, Section 8 reflects on the unfinished aspects of the framework and outlines what remains to be done to fulfill the promise of a truly relational foundation for physics.

The discussion aims to provide a clear and self-contained account of how relationalism, long dismissed as a philosophical dead end, has re-emerged as a viable research program in both physics and metaphysics. Reassessed through this modern lens, it becomes plausible that what we can call an “unfinished revolution” remained so because it awaited the right conceptual tools. Those tools, this essay contends, are now available.

2. The Classical Tradition

While a reliance on relational motion can be traced back to Cartesian physics, relationalism begins its full-fledged philosophical development in the writings of Gottfried Wilhelm Leibniz, who argued that space and time are not substances or independent entities but abstractions from the order of coexisting and successive material things. In his correspondence with Clarke (Ariew, 2000), Leibniz maintained that to speak of space as something in which objects are located is to mistake a system of relations for an entity in its own right. He supported this view with two central principles: the Identity of Indiscernibles and the Principle of Sufficient Reason. According to these principles, if two possible worlds differ only in the overall location or orientation of all matter in space, but are otherwise indiscernible in their internal relational content, then they must be metaphysically identical. Any surplus structure beyond relational facts is metaphysically idle.

However, Leibniz's foundational insight lacked a dynamical counterpart. Indeed, Leibniz provided no mechanism for how motion or inertia could be explained purely in terms of relations, leaving the explanatory advantage to Newton, because he could invoke explanatorily powerful notions such as absolute acceleration relative to a fixed background. This asymmetry between the metaphysical elegance of relationalism and the empirical success of substantivalist mechanics set the tone for the debate for over two centuries.

After Leibniz, other thinkers, including Berkeley and Huygens, questioned aspects of Newtonian dynamics and explored relationalist ideas. However, they too did not propose a complete alternative framework. An especially interesting proposal came from Carl Neumann in the nineteenth century (cf. Barbour, 2001, §12.2), who introduced the notion of *Body Alpha*: a hypothetical reference body meant to account for inertial effects without positing absolute space. This idea anticipated the suggestion that inertial structure might be determined by the distribution of mass-energy in the universe, rather than by any fixed background.

It is with Ernst Mach that relationalism returns to prominence with renewed critical force. In his Science of Mechanics (Mach, 1883), Mach famously analyzed Newton's bucket experiment, in which the concavity of water in a rotating bucket is taken to reveal absolute rotation. Mach questioned whether such acceleration is genuinely absolute, proposing instead that inertial effects arise from the body's relation to the rest of the matter in the universe. This relational view, which came to be known as "Mach's principle" (cf. Barbour and Pfister, 1995, for a comprehensive discussion of this principle) draws on the idea that what we call inertial motion is defined relative to the "fixed stars," that is, the bulk matter content of the cosmos. Though Mach's proposal lacked formal equations, it marked an important shift: a move from accepting inertial structure as given to seeking its explanation within a fully relational ontology. Einstein drew inspiration from this vision in developing general relativity, though the final formulation of the theory reintroduced substantival elements through the manifold and metric structure of spacetime.

Thus, from Leibniz to Mach, relationalism remained largely a philosophical critique rather than a concrete alternative to existing physical theories. Besides lacking a worked-out mathematical formalism, relationalism was unable also to provide a systematic account of how observable quantities like distance, duration, and acceleration could be recovered from relational configurations. The conceptual continuity from Neumann's Body Alpha to Mach's fixed stars illustrates the recurring aspiration to anchor inertial structure in the matter distribution of the universe, but the explanatory mechanisms remained elusive.

Henri Poincaré brought this difficulty into sharp focus. In a famous thought experiment (Poincaré, 2017, chapter 7), he imagined a community of astronomers confined to a solar system much like ours, unaware of the broader universe. These scientists, he argued, would eventually find it convenient—perhaps even inevitable—to introduce absolute notions such as the orientation or rotation of space in order to make sense of inertial effects. They might, in fact, hypothesize an invisible reference body like Neumann's Body Alpha, but Poincaré warned that such a postulate would function more like a placeholder than an explanation, i.e., a conceptual artifice introduced to preserve empirical adequacy in the absence of a fully relational account. The true challenge is to avoid artifices like this without sacrificing descriptive power.

3. Challenges to Relationalism

Before turning to recent relationalist proposals, it is useful to recall the main philosophical objections that have historically cast doubt on relationalism's viability as a physical theory. These objections, articulated most prominently by Earman, Field, and Dasgupta, center on the concern that relationalism cannot match the empirical precision, explanatory scope, and metaphysical clarity of substantivalist frameworks. At the same time, they help to sharpen the standards that any contemporary version of relationalism, faithful to the legacy of Leibniz and Mach, must aspire to meet.

John Earman's historical and philosophical assessment of relationalism in Earman (1989) offers a particularly influential critique. Drawing on the Leibniz–Clarke correspondence, Earman argues that relationalism, while philosophically attractive, consistently fails to offer the formal resources needed to match the empirical and explanatory achievements of its substantivalist rivals. In Newtonian mechanics, for instance, inertial motion and absolute acceleration are defined relative to a fixed background structure: a spatial frame with absolute positions and a temporal parameter with absolute durations. Earman notes that without comparable resources, relationalism is unable to reconstruct key dynamical features, such as inertial frames or the empirical significance of acceleration.

Take the case of two equal-mass material globes tied together by an inextensible rope and uniformly rotating around their center of mass in an otherwise empty universe. Because of the centrifugal forces acting on this system, the rope will exhibit a tension. The substantivalist has a clear explanation of this empirically observable effect: in the rotating frame of reference tied to the system, the centrifugal forces arise because of the acceleration, which is due to the change of direction with respect to absolute space. So the facts about the forces acting on the system and the subsequent tension of the rope are accounted for and thoroughly explained by the fact that the system rotates with respect to the absolute inertial reference frame represented by absolute space. This scenario also prompts a plausible prediction: if the system stopped rotating, the rope's tension would go to zero because, at that point, the reference frame tied to the system would overlap with the absolute inertial frame (i.e., the system would be at absolute rest). Note how this entire story can also be given a precise mathematical formulation, which can indeed be found in most elementary physics textbooks.

Can the Leibnizian/Machian relationalist provide an equally powerful account of the system without invoking any external spatial background? The answer is simply *no*, because the vocabulary of the relationalist is too meager to reconstruct the situation. Indeed, the relationalist can only talk about instantaneous spatial distances between the two globes, but these never change throughout the dynamical evolution. Also, there are no "fixed stars" in this universe to which a change of direction can be referred. Therefore, there is no way the relationalist can account for the rope's tension (or lack thereof). Of course, the relationalist may retort that the whole thought experiment is misguided, given that we have no way to ascertain how the system would really behave in an empty universe. However, this would amount to avoiding the challenge rather than answering to it. Clearly, this issue highlights a deep concern about whether empirical phenomena can be described at all without implicitly reinstating the very structures that relationalism aims to avoid. As long as relationalists remain unable to offer principled, systematic methods for defining inertial motion without reference to an absolute background, Earman concludes, they fall short of the standards set by successful physical theories.

This critique dovetails with Hartry Field's influential argument in Field (1984). Field accepts the attraction of eliminating unobservable structure but warns that doing so demands the recovery of a great deal of sophisticated geometry. A relationalist theory must be able to reconstruct distances, durations, angles, and curvature purely from the relations among material entities. In effect, Field challenges the relationalist to derive the entire metric and affine structure of spacetime from a base of purely relational facts. Without this, he argues, any talk of eliminating space and time risks collapsing into mere slogan. Importantly, Field's critique is forward-looking: he imagines that if such a relationalist reconstruction could be supplied, it would indeed undermine the need for substantival spacetime. But until then, the epistemic and ontological advantages of relationalism remain speculative.

Shamik Dasgupta's challenge is of a more explicitly metaphysical nature. In Dasgupta (2011), he reframes the relational–substantival debate in terms of metaphysical grounding. Rather than focusing on modal or representational equivalence, he asks what grounds the spatiotemporal facts we observe. He maintains that the grounding relation is asymmetric: if relationalism is to succeed, then the facts about geometry and motion must be grounded in purely relational facts about matter. But this is precisely what seems to be missing in standard relationalist theories. As Dasgupta emphasizes, traditional relationalism lacks the tools to show how the quantitative content of geometry—facts about length, angle, acceleration, and duration—could be metaphysically grounded in configurations of matter alone. A convincing relationalist ontology must therefore do more than eliminate substantival structures; it must show how the spatiotemporal features of the world arise from, or at least are determined by, relational configurations.

The picture that emerges from these objections is one of deep structural dependence: the successes of physical theories appear to rest on elements that relationalism seeks to reject. The tasks of describing inertial motion, recovering metrical relations, and grounding the geometry of space and time seem to require more than relational configurations have traditionally been able to supply. If relationalism is to move beyond philosophical appeal and provide a robust foundation for physics, it must find a way to meet these interconnected demands on its own terms.

Here comes the turning point in this entire story. As it will be argued in the following sections, some modern attempts at articulating a Leibnizian/Machian framework for physics have now come very close to meeting these demands—much closer, in fact, than any other attempt made in the past.

4. A New Chance for Relationalism

A significant breakthrough in the development of a modern relationalist framework came with Shape Dynamics (SD). Originally developed by Julian Barbour and collaborators, SD aims to reformulate classical mechanics and general relativity in a way that captures the core relationalist insights of Leibniz and Mach (see Mercati, 2018, for a comprehensive textbook on the subject, and Gomes et al., 2011, for the original paper proposing the core insights of SD as a theory of gravity "dual" to general relativity). Its key innovation lies in eliminating the reliance on an external spacetime structure and describing dynamics instead within a reduced configuration space that retains only the physically meaningful relational degrees of freedom.

This reduction begins with the insight that many aspects of a system's configuration—such as its overall position, orientation, and scale—are surplus structure, unobservable and dynamically irrelevant. These are factored out by quotienting the full configuration space by the symmetry group of translations, rotations, and dilations, a procedure that captures the very spirit of the Leibnizian critique of absolute space as a redundant structure. The result is shape space, i.e., a space of configurations defined purely by the internal relations among constituents. Importantly, this operation singles out conformal structure as fundamental, that is, the physical content of a configuration lies in the ratios of distances as encoded in the internal angles, which correspond to empirically observable quantities. Measurements, thus, amount to comparisons between different parts of a configuration, one acting as a unit against which the other is gauged. Importantly, this procedure makes sense only for closed systems, ideally the universe as a whole—a global perspective that echoes Mach's take on physics.

Once absolute structure is eliminated, dynamics can no longer be defined in terms of motion through space or evolution in time. Instead, SD constructs dynamics using a timeless action principle defined on shape space. The central tool here is *best-matching*, which is a variational method to define an intrinsic derivative between configurations by optimally aligning them through the allowed symmetry transformations. This alignment defines a notion of *equilocality*—how parts of one configuration correspond to parts of another—and thereby underwrites a relational definition of change. Geodesic paths on shape space, defined by this intrinsic derivative, represent dynamical evolution without any reference to an external clock or coordinate frame. Most importantly, the dynamics obeys the constraints that the total linear, angular, and dilational momenta of the material content of the universe must be zero—an automatic consequence of declaring *ab initio* that total translations, rotations, and scaling transformations are physically vacuous. This construction, among other things, immediately explains why relationalists should regard scenarios like the rotating globes thought experiment as unphysical: their very setup involves a violation of the global relational constraints (e.g., in a universe inhabited by just two material globes, it makes no sense to define rotational motion with respect to their center of mass).

To describe geodesic motions over shape space, however, SD still requires a monotonically increasing parameter along each dynamical trajectory. While this parameter is formally arbitrary, it is not dynamically inert: it *must* be specified to compute evolution, yet lies outside the relational data. This residual dependence on an external "time-like" parameter reveals a limitation in SD's formulation. It motivates the transition to Pure Shape Dynamics (PSD), a refinement of the framework that removes the need for parametrization altogether (cf. Koslowski et al., 2022, for a technical introduction to the framework).

PSD's key innovation is to define a system's evolution through a set of geometric degrees of freedom internal to each curve in shape space. These degrees of freedom function analogously to state variables in thermodynamics: they determine how the system evolves, but are themselves part of the system rather than external to it. In thermodynamics, state variables are large-scale properties that provide a macroscopic description of a system—global characteristics, in this analogy, that summarize the overall state of the relational configuration. As such, the equations of motion in PSD resemble equations of state, describing how a system changes as a function of its internal geometric characteristics. This formulation renders PSD remarkably versatile. The framework is general enough to in principle describe a wide range of physical systems—from N-body classical models to general relativistic systems and even quantum systems—by enriching the intrinsic structure of its dynamical curves as needed.

A central concept in PSD is that of *complexity*: a measure of the degree of clustering or structure in a configuration (see Barbour et al., 2014, for the first articulation of this notion). In an N-particle system, for example, configurations where all particles are equidistant exhibit low complexity, while configurations with highly localized clusters have high complexity. Complexity provides a natural "time stamp" on configurations, allowing one to define a meaningful, intrinsic ordering of configurations without appealing to an external parameter. As complexity increases (or decreases), one can track the system's evolution entirely from within.

Moreover, PSD explains how effective spatial and temporal measurements—rods and clocks—can emerge locally from the global relational dynamics. Stable subsystems, such as Kepler pairs in an N-body system, act as dynamically generated standards. A Kepler pair consists of two particles that become gravitationally bound and trace regular, typically elliptical orbits around their shared center of mass. Because these motions are dynamically stable and repetitive, they provide a reliable reference for assigning spatial distances and time intervals. Crucially, all Kepler pairs that form throughout the evolution of the system will agree on these standards, since they emerge from the same global dynamical mechanism. In this way, robust local spatiotemporal notions arise consistently and coherently across configurations, all within a theory that is globally spacetimeless —reinforcing the Machian view that the universe as a whole determines local physical content. This feature also speaks to a key epistemological virtue of the framework: it shows how observer-accessible data—such as durations and distances—can be recovered from within a theory that posits no fundamental temporal or spatial background. Instead of assuming rods and clocks as primitive, the framework explains how these emerge dynamically and relationally from the system itself. By accounting for how its own users, as physical subsystems, can access and interpret observable quantities, the theory thus exhibits a remarkable epistemic transparency.

Yet the formal framework of PSD, while powerful, remains incomplete without a metaphysical account of what its structures represent. The theory shows how dynamics can unfold in a purely relational configuration space, but it does not by itself answer the deeper question of what grounds the physical reality of these configurations. To address this, the formalism must be paired with a metaphysical interpretation. That interpretation is provided by the theory of self-subsisting structures.

5. Self-Subsisting Structures and the Grounding of Relational Dynamics

The theory of self-subsisting structures offers a metaphysical framework that complements PSD, allowing it to meet the philosophical demands outlined in Section 3. Developed primarily in Vassallo et al. (2022, 2024), this framework provides a rigorous ontology for a world fundamentally described by relational configurations, without reference to external spacetime or absolute physical magnitudes.

At the core of this approach lies a strong ontological thesis: the fundamental constituents of reality are not particles, fields, or spacetime points, but entire configurations of matter in relational terms. These configurations are self-subsisting in the sense that they do not exist “in” anything else—they are not embedded in space or evolving in time. Rather, they are complete, self-contained structures defined entirely by the internal relations that underlie a conformal structure—that is, relations specifying the intrinsic ratios of spatial configurations, such as relative angles, which remain invariant under changes of absolute scale. This conception draws from the metaphysical stance known as *ontic structural realism*, which holds that structure—not individual objects—is ontologically primary (see Ladyman, 1998, for one of the first modern proposals in this direction). The self-subsisting structures framework provides a concrete physical realization of this thesis, portraying these relational configurations as the true ontological units of the universe. This shift from individual objects to holistic configurations is tied directly to the formal structure of PSD, where each point in shape space represents a configuration stripped of absolute structure. The self-subsisting structures framework interprets these points as ontologically robust entities. A self-subsisting structure is, in this sense, a possible state of the universe: a complete and autonomous node in the global mosaic of reality. The dynamics of such structures unfolds through intrinsic ordering relations among configurations. The ordering can be grounded in features such as increasing complexity, which functions as a kind of “internal clock.” Crucially, this relational evolution arises from lawful relations between structures, encoded in the intrinsic geometry of shape space.

One of the principal advantages of this framework is its explanatory strength. It allows relationalists to answer a version of the grounding challenge posed by Dasgupta: if spatial and temporal facts are derivative, what grounds them? In this framework, such facts supervene on the pattern of configurations and their interrelations. This move builds on the Humean strategy, initially articulated by David Lewis, according to which all facts about laws, causation, and modality supervene on the total distribution of local qualities across spacetime—the so-called *Humean mosaic* (see Lewis, 1986, pp. viii-xi, for a brief characterization of this stance). On this view, the laws of nature do not determine the physical happenings, but rather emerge from the best systematization of the mosaic: the set of regularities that balance simplicity and strength in describing the world. More recently, Super-Humeanism has extended this picture by eliminating even local qualities as fundamental, treating only the distribution of matter as ontologically basic, and deriving everything else, including geometry and dynamical structure, from this sparse base (Esfeld et al., 2018).

The self-subsisting structures framework pushes this line of thought further. Instead of presupposing a spacetime manifold with localized elements, it takes entire relational configurations as primitive. The mosaic here is not a pattern of local instantiations in space and time, but a sequence of self-subsisting, unembedded structures, each defined solely by internal relational features. Geometry and temporality are recovered as systematizations over this sequence. For instance, distances and durations are grounded in the recurrence and regularity of certain structural motifs—such as Kepler pairs and clustering patterns—while temporal ordering arises from intrinsic complexity gradients between configurations (cf. Vassallo and Naranjo, 2025, for the full articulation of such a construction). Thus, spatial and temporal facts are not strictly speaking eliminated, but grounded:

they are higher-level constructs that emerge from the intrinsic relations among the self-subsisting structures themselves.

This perspective also offers a response to Field's challenge: how to recover the quantitative structure of physics from a relational ontology. In the self-subsisting structures framework, material patterns license the reconstruction of inertial frames, durations, and metrical structures as systematizations over the relational data. Moreover, dynamical quantities such as accelerations, angular momentum, and other motion-related properties can be similarly reconstructed for subsystems of the universe. This is achieved without compromising the core relationalist commitment, since the global constraints embedded in the theory ensure that the total linear, angular, and dilational momenta of the universe remain exactly zero by construction. In this way, self-subsisting structures enable a consistent and explanatory recovery of dynamical content from a purely relational base.

The framework also resolves a deep tension in the relationalist project, namely, the need for descriptive adequacy without ontological inflation. Because self-subsisting structures are holistic and dynamically interrelated, they can account for physical phenomena without invoking unobservable background entities. Their evolution is tracked by reference to their intrinsic features, rather than an external time. The resulting picture is one in which the laws of physics are patterns across a space of possible relational configurations, rather than prescriptions for how things change in time.

In this sense, this modern relational framework substantially delivers on the original Leibnizian and Machian promise. It provides a formulation of dynamics free of external spatiotemporal structure, but with the metaphysical resources to ground the geometry and temporality that such standard dynamics presupposes. Relational facts are not explained by embedding them into space and time; instead, space and time are emergent aspects of the structure and order among relational facts. The payoff is remarkable: a coherent and physically informed relational ontology that can underwrite the descriptive and explanatory practices of physics without lapsing into substantivalist assumptions.

6. Quantum Extensions

Any claim to offer a fundamental theory of physics must confront the quantum domain. The empirical success of quantum mechanics, particularly in exhibiting non-local correlations that defy classical expectations (as experimentally proven in the seminal work of Aspect et al., 1981, 1982), compels any metaphysical framework to either accommodate quantum phenomena or risk irrelevance. In this light, the development of a quantum counterpart to the relational framework sketched so far is a clear necessity. Here, however, the conceptual terrain grows more difficult. Quantum mechanics is already philosophically fraught, and its standard formulation is deeply wedded to abstract configuration spaces and wave functions, entities that appear to resist a straightforward relationalist interpretation (or any interpretation, for that matter). To put it in Tim Maudlin's words (Maudlin, 2019, p.77, emphasis in the original): "What the quantum recipe does not resolve, what it does not even purport to address, is *what the physical world is like such that the quantum recipe works so well*."

Against this backdrop, it is plausible to assume that a viable quantum extension of PSD should draw from any theoretical approach to quantum physics that clearly specifies the physical nature of quantum systems—i.e., what they are “made of” from an ontological viewpoint—and the underlying dynamical mechanisms that shape them. In this sense, a promising route lies in the de Broglie–Bohm theory (dBB; see, e.g., Bohm, 1952a,b, for one of the first fully-fledged attempts at articulating this theory). In its standard formulation, the theory posits N material particles having definite positions at all times; in this picture, the particles’ trajectories are determined by the wave function, whose evolution is described by the Schrödinger equation. The way the wave function determines such trajectories is encoded in a mathematical expression suggestively called “guidance” equation. Importantly, this guidance is holistic: the velocity of each particle depends on the wave function, which, in turn, depends on the position of all the particles at a given time. Thus, dBB naturally assumes a global viewpoint, describing the dynamical evolution of a universal configuration of N particles. In doing so, it offers a dynamical account of quantum non-locality that is rooted in the structure of the whole system: all particles instantaneously “feel” each other at any given moment, irrespective of how distant in space they are.

This global perspective makes dBB an ideal candidate for the quantum extension of PSD. Indeed, Vassallo (2015) argues that dBB, although formulated over a spatiotemporal background, is amenable to the quotienting out procedure that leads to a totally relational description of the universe. Furthermore, Farokhi et al. (2024) show that, when the dBB dynamics is formulated within the PSD framework, a striking result emerges: the guiding equation breaks down at the universal level. This means that the universe as a whole is not “quantum” in a dBB sense. Instead, quantum dynamics arises only at the level of subsystems, which elegantly ties with the notion of the *effective* wave function, a construct that encodes how a given subsystem evolves relative to the configuration of the rest of the universe (cf. Dürr et al., 1992, for a technical introduction to this notion in standard dBB theory). In this way, quantum behavior becomes an emergent, context-dependent feature of relational subsystems, rather than a fundamental aspect of universal dynamics. In this sense, the PSD approach to dBB theory not only recovers the standard account of how quantum subsystems interact (e.g., during measurements in the lab), but it does so by implementing a core tenet of relationalism, namely, that the dynamical description of the full system requires no external reference structure—a universal guiding wave, in this case.

This shift also bears metaphysical significance. When combined with the framework of self-subsisting structures, the PSD approach to dBB theory supports a view in which quantum dynamics is not grounded in a primitive, universal wave function because it instead supervenes on the sequence of self-subsisting configurations and their internal relations. In this setting, the wave function represents a codification of patterns in the sequence of relational structures. It emerges from the best systematization of the evolution of relational facts, echoing the Super-Humean strategy discussed in the previous section. Interestingly enough, this perspective seems to go in the direction of recent conjectures in high-energy physics—such as the ER=EPR proposal (Van Raamsdonk, 2010)—that suggest a deep connection between quantum entanglement and spacetime geometry. On this view, entanglement may be the fabric from which spatial structure arises. In the self-subsisting structures framework, this relation is made precise: the internal relational structure of configurations grounds both spatial geometry and quantum correlations, that is, space and entanglement are different aspects of the same underlying relational reality (a full philosophical defense of this view can be found in Vassallo et al., 2024, §5).

Moreover, although dBB theory serves as a natural vehicle for developing quantum relationalism, it is by no means the only one. As pointed out earlier, the essential feature required is not determinism or particle trajectories, but rather a clear ontology—some specification of what exists and how it behaves. Any interpretation of quantum theory that provides such a specification—be it an Everettian model, a GRW-type collapse theory, or related approaches—can, in principle, be reformulated in relational terms: what matters is the commitment to relational degrees of freedom as fundamental.[1] In this light, the quantum extension of PSD and self-subsisting structures opens a pathway toward addressing the problem of quantum gravity. By showing that both quantum and classical dynamics can emerge from the same underlying relational base, this framework suggests a route toward unifying these domains. While a full theory of quantum gravity remains elusive, the approach discussed here points in a promising direction: rather than quantizing spacetime, we may understand spacetime and quantum correlations alike as emerging from a deeper, more primitive relational order.

These developments mark a significant departure from the long-standing view that relationalism lacks the resources to confront modern physics. Rather than trailing behind the dominant paradigms, relational frameworks such as PSD—especially when augmented by the metaphysics of self-subsisting structures—have begun to anticipate and recast some of the most pressing questions at the foundations of physics. Yet, despite these conceptual and technical advances, relationalism has remained at the margins of mainstream discourse. Understanding how and why this happened requires taking a step back.

7. The Relationalist Program in Retrospective

Despite its deep philosophical pedigree, relationalism has long occupied a marginal position in the history of modern physics. From Newton's decisive formulation of absolute space and time, through the geometrization of gravitation in general relativity, the dominant frameworks of physical theory have consistently relied on an external spatiotemporal structure—be it a fixed background or a dynamical field-like construct. Even where relational ideas were entertained by figures like Leibniz, Mach, and Poincaré, they typically appeared as speculative counterpoints to more mathematically tractable, empirically fruitful substantivalist models.

Several factors contributed to this marginalization. One is conceptual inertia: once embedded in the mathematical formalism, external spatiotemporal structures acquired a default legitimacy, and the burden of proof shifted to the relationalist to explain how their absence would not cripple explanation or predictive power. Another factor is technical: until quite recently, relationalism had no framework on par with Newtonian mechanics or general relativity in terms of quantitative precision and empirical applicability. Even attempts like the original Barbour–Bertotti model (Barbour and Bertotti, 1982), despite their elegance, remained largely confined to idealized systems and lacked the metaphysical articulation needed to be taken seriously beyond niche circles. Moreover, the philosophical discourse surrounding relationalism often suffered from a disconnect between metaphysical ambition and physical feasibility. Many relationalist arguments remained at

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[1] An alternative extension of the Barbour–Bertotti framework to the quantum domain has been also developed by Gryb and Thébault (see, e.g., Gryb and Thébault, 2012, 2016). Their program, known as *relational quantization*, treats time-reparametrization symmetry as physically meaningful and recovers a Schrödinger-type evolution for the whole universe. In contrast to the PSD/self-subsisting structures framework, which embraces timelessness at the fundamental level and derives temporal ordering from internal structural features such as complexity, the Gryb–Thébault approach preserves a fundamental quantum dynamics driven by an emergent temporal parameter. While both frameworks aim to implement relationalism, they clearly differ significantly in their treatment of time and the metaphysical commitments this entails.

the level of principle or intuition, failing to produce a viable, working alternative to mainstream physical theories. Critics like Earman and Field were right to insist that mere conceptual coherence is not enough: a relationalist theory must do real explanatory work if it is to be more than a metaphysical gloss.

Yet in light of the developments surveyed in this essay, this verdict now seems increasingly premature. The combined framework of PSD and self-subsisting structures offers a version of relationalism that is both formally robust and philosophically mature. It provides a concrete formalism in which external spatiotemporal structures are dispensed with, not by fiat, but through principled constraints. Indeed, the framework shows how such structures can emerge from an underlying network of relations. Furthermore, it delivers a technically informed approach to quantum physics that is in line with both empirical data and cutting-edge ideas in foundational physics. In this light, the long marginalization of relationalism may be understood as the natural consequence of its premature articulation. Lacking the formal and conceptual tools to express itself rigorously, relationalism was bound to remain a philosophical undercurrent rather than a scientific contender. What has changed is not the aspiration but the machinery. Today, that machinery, shaped by the joint efforts of physicists and philosophers, has begun to catch up. Relationalism may thus seriously aspire to represent the next stage in our understanding of physical reality.

8. Conclusion

This essay has argued that the Leibnizian/Machian vision of a relationalist foundation for physics has in recent years gained new traction through the synthesis of PSD and the metaphysics of self-subsisting structures. This framework overcomes many of the classical objections to relationalism and offers a fertile perspective on time, geometry, and the emergence of quantum behavior. Yet, despite these advances, the picture remains incomplete. Several key issues, both physical and metaphysical, must be addressed for the relationalist program to reach full maturity.

From a physical standpoint, the most pressing loose end concerns the precise conditions under which quantum behavior emerges within the PSD-based dBB model. While the absence of a universal guiding equation is conceptually appealing, the theory currently lacks a detailed account of what triggers the emergence of the guidance equation at the level of subsystems. Without such a specification, the framework cannot fully explain what renders the world we observe “quantum.” This gap points to the need for a richer characterization of the pre-quantum regime: a domain where PSD functions as an autonomous theory, not merely as a “rewriting” of quantum or classical mechanics in relational terms. In this primordial regime, where spatiotemporal and quantum behavior is entirely absent, PSD must define its own observables, kinematical principles, and predictive resources. A related challenge concerns the generalization of the framework to encompass the degrees of freedom found in realistic field-theoretic contexts. Although some preliminary efforts have been made to provide a treatment of dynamical geometry (Farokhi et al., 2025), the current PSD formalism does not yet fully account for internal symmetries, gauge structure, or matter fields. A mature relational theory must articulate how such features arise from its intrinsic variables, lest it fall short of describing the full content of modern physics.

These physical gaps lead naturally into more deeply metaphysical ones. Chief among them is the question of what metaphysically binds self-subsisting structures together. As discussed, these structures are conceived as ontologically autonomous relational configurations, each encoding a conformal geometry via internal angles. But the metaphysical basis for their connectedness—what makes them integrated wholes of coexisting relata—remains elusive. Simply postulating relations like spatial proximity or entanglement between them would amount to little more than placing placeholders where a deeper explanation should be. One promising avenue involves reading off a more fundamental dependence relation from fundamental physics, like the dynamical structure of general relativity. Early results suggest that such a relation may capture the co-dependence between matter and geometry that characterizes general relativistic physics, offering a potential blueprint for a pre-spatiotemporal "glue" (Vassallo, 2020; Vassallo and Hoefer, 2020).

Another underdeveloped aspect concerns the articulation of the primitive ideology of the framework. In other words, what are the basic representational resources PSD and self-subsisting structures rely on? Are internal angles and ratios sufficient to describe the full range of relational facts? What logical operations or modal notions are required to speak meaningfully about lawful transitions from one self-subsisting structure to another? These questions press for a more formally rigorous and philosophically perspicuous articulation of the framework's representational foundations. Likewise, further work is needed to clarify whether the framework is best understood as providing metaphysical grounding, scientific reduction, or both. Earman and Field, as we have seen, challenge the relationalist to account for the quantitative structure of physics in a way that preserves its descriptive and explanatory power. The relationalist approach discussed in this essay seems concretely capable of meeting this challenge, but a clearer characterization of its reconstruction methodology and its metaphysical significance would enhance its dialectical strength. Lastly, the question of temporal ordering and agency remains somewhat obscured in the current formulation. While scalar parameters such as complexity provide a basis for ordering configurations, the framework at the moment lacks a robust account of how we get to perceive time. Given that one of the ultimate goals to secure philosophical dignity for the framework is for it to recover the experience of temporal passage, further metaphysical elaboration will certainly be needed.

These are not fatal flaws but open problems—and the existence of such problems should be expected in any research program that aspires to rethink the foundations of physics. That the PSD and self-subsisting structures framework brings us this far is already a remarkable achievement. However, the recurring caveat of this essay is that, if relationalism is to become a fully mature alternative to substantivalist metaphysics, it must reject the scaffolding of absolute space and time and also supply a coherent and complete account of the structure that remains. As we have seen, such an account really seems within reach: the task ahead is to fully grasp it and to see how far it can take us.

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