What Are the Contexts of Complementarities?

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Abstract

The explanatory structure of quantum mechanics and quantum gravity is marked by complementarity: the existence of distinct, mutually incompatible descriptions that are nonetheless each empirically valid in specific observational settings. In recent work, Ryoo (2025) proposed a context-dependent mapping framework (f_c) as an epistemic tool to capture this phenomenon. This framework maps each physically defined "context" to a set of laws that yield coherent and predictive explanations within that context. In this paper, I formally define the notion of "context" underlying the f_c mapping, offer a general structural typology, and present case studies from quantum gravity and entanglement wedge reconstruction to illustrate how explanatory fragmentation is grounded in physical theory rather than epistemic limitation.

Keywords: Complementarity, Context, Philosophy of explanation, Philosophy of science, Quantum mechanics

1. Introduction

Scientific theories are expected to offer coherent explanations of physical phenomena.[1] Yet in contemporary physics, this expectation is repeatedly challenged by cases in which multiple, mutually incompatible descriptions are required to account for the same underlying system. Nowhere is this more evident than within quantum mechanics in which complementarity, the principle that certain descriptions cannot be simultaneously applied, has long resisted assimilation into traditional explanatory frameworks.

[1] By "coherent," I refer to both logical consistency and the compatibility of explanatory principles within a given theoretical framework or observation. This includes the absence of contradictions among applied laws, the preservation of symmetries or constraints, and the capacity to support reliable predictions.

This tension is amplified in domains like quantum gravity, where observer-dependent formulations suggest that distinct, context-bound perspectives are necessary features of physical theory.[2]

These developments raise an urgent philosophical question: What determines the boundaries of a scientific explanation?[3] If incompatible accounts are required to explain a system from different observational standpoints, how should we characterize the contexts under which each account is valid? And what kind of explanatory structure allows us to reconcile this fragmentation without falling into contradiction?[4]

By *(explanatory) fragmentation*, I mean the division of scientific explanation into multiple, mutually incompatible accounts that are each valid only within specific, physically defined contexts. On a related note, it is also imperative to distinguish notions of structural contextuality from epistemic contextuality. The former refers to constraints imposed by the formal architecture of the theory itself. These are in-principle features of how different experimental contexts activate different lawful subspaces. By contrast, epistemic contextuality arises from coarse-graining, limited resolution, or incomplete information. For example, the impossibility of simultaneously measuring position and momentum with arbitrary precision is structural. It stems from quantum theory's mathematical structure and cannot be overcome by better instruments. In contrast, our current inability to detect individual photons in cosmic microwave background radiation is epistemic. Better detectors could in principle resolve this limitation. This paper is primarily concerned with explanations of the former: structural contextuality that reflects the explanatory architecture of the theory itself, though such cases are often intertwined with observational limitations in practice.

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[2] Throughout this paper, “observer” refers to a physically localized measurement configuration.

[3] I use “explanation” in a broad sense to refer to an account that renders phenomena intelligible by appealing to laws, principles, or structures that are compatible and predictively successful within a given framework. I do not commit to a specific account of scientific explanation, but this usage is compatible with structural, causal, and unificationist traditions (Woodward 2003; Strevens 2008; Kitcher 1981).

[4] Throughout this paper, “structure” refers to patterns of relations among laws, observables, and contexts that constrain and enable inference. The notion draws pragmatically from structural realism (Worrall 1989; Ladyman 1998), but is not a metaphysical commitment - only a formal constraint on explanatory organization.

In response to these challenges, Ryoo (2025) proposed a context-dependent mapping (denoted f_c) as an epistemic tool to formally account for the structural fragmentation of explanation in physics. The central insight of this framework is that scientific explanation must be localized to physically defined observational contexts, each constrained by features such as causal access, entanglement structure, and boundary conditions. Rather than assuming that all valid explanations must converge into a single globally consistent theory, f_c tracks how a shared microphysical base gives rise to distinct yet internally consistent explanatory subspaces that are valid only within particular domains.[5] Such a structure is echoed in philosophical accounts of dualities such as AdS/CFT, where distinct models yield equivalent predictions in different explanatory frames (Rickles 2013). Indeed, the AdS/CFT correspondence is a duality between a gravitational theory in anti-de Sitter (AdS) spacetime and a conformal field theory (CFT) on its boundary: two formally equivalent but structurally distinct descriptions.

This paper serves a dual purpose. Firstly, it clarifies the notion of context that underlies frameworks like f_c by addressing a crucial but underdeveloped element: the nature of context itself. Secondly, it establishes a general formal definition of *context* in the presence of scientific complementarities, independently of any particular mapping or interpretation of modern physics. While philosophers have offered various epistemic, perspectival, or pragmatic accounts of context, the explanatory needs of complementarities demand a more precise, physically grounded formalism.[6] I introduce a structural definition of observational context as a quadruple (a 4-tuple) encompassing causal accessibility, entanglement reach, boundary and frame conditions, and operational configuration. I show support that these components capture constraints under which an explanatory description becomes valid.

[5] I use "consistency" to mean that two laws do not jointly yield paradoxes. A theory is consistent if all its laws cohere. "Global" refers to cross-theoretical scope, i.e., all laws in the theory are mutually non-contradictory.
[6] For epistemic and perspectival accounts of context, see Giere (2006), Massimi (2012), Rueger (2005), and van Fraassen (1980). These approaches often treat context as agent-relative or model-driven, without formal physical constraints.

The remainder of this paper proceeds as follows. Section 2 motivates the need for a structural account of context through examples from quantum mechanics and quantum gravity. Section 3 formally defines the context structure - used in the f_c mapping or other kinds of mappings - and distinguishes it from more traditional epistemic accounts. Section 4 demonstrates the framework's application in physically significant cases, including black hole complementarity and entanglement wedge reconstruction.

2. Why Contexts?

Broadly speaking, the philosophy of science often aims for explanations within which laws do not contradict. The goal is to find a single, unified model that applies across all situations. But in modern physics, this goal fails. Quantum mechanics shows that different observers may need different descriptions of the same system. These descriptions can be incompatible, yet each is valid in its own setting.

Bohr introduced this idea through the principle of complementarity in discussions of the wavefunction in quantum mechanics. He claims that the very conditions which define the possible types of measurement entail the exclusion of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments (Bohr 1928). Historically, the motivation was from superposition of quantum states and in particular the wave-particle duality: measurement outcomes depend on the setup and some properties cannot be measured together. Such conflicts in general are often referred to as *quantum contextuality* and a central theoretical result in the foundations of physics to capture this is the Kochen-Specker theorem (Budroni et al 2023).

However, modern attempts to intertwine quantum mechanics with spacetime theories often lead to greater incompatibilities of distinct observations, beyond the features of the wavefunction. They often involve causal patches, which are local spacetime regions that restrain the possible observations. General complementarities involving those patches are deemed *patch complementarities* (Ilgin et al. 2014). To this day, modern developments in quantum gravity and complementarities rely on arguments regarding spacetime locality and quantum states (Concepcion et al. 2024). In both notions of complementarity, each distinct setup gives rise to its own explanatory regime; what determines this manifestation is rooted in various factors including the observer's location, relevant boundary conditions, nonlocal contributions, and experimental intervention.

Strevens (2008), in his *Kairetic account,* expresses the importance of identifying difference-making causes and examining unificationary power. Accordingly, he suggests that to explain something is simply to cite causes that made a difference (Strevens 2008, 155). As argued in earlier work, Strevens assumes a globally consistent core of explanation, and this assumption fails in quantum settings (Ryoo 2025). In complementarities, different observers can access only partial descriptions of the full system.[7] These descriptions may be mutually exclusive, yet coherent and predictive on their own. To explain such phenomena is to map not only causal structure, but also the limits on what can be said about it in a given context.

Context, then, determines what can be said, explained, or predicted. It sets the boundaries of theory. In section 3, I construct such a context as a 4-tuple. Indeed, it treats contexts as formal structures defined by four features: causal access, entanglement reach, boundary conditions, and operational configuration. Each context maps to a consistent subset of laws through the context-dependent mapping. In domains like black hole complementarity or AdS/CFT, such mappings are necessary since global unification is 1) unavailable and 2) blocked by the theory's own structure through the simultaneous nature of quantum mechanics.

3. Formal Contexts

[7] This idea mirrors Galison and Stump's (1996) conception of scientific disunity, where fragmentation is a reflection of the multiple epistemic practices needed to navigate complex phenomena.

If explanation in physics depends on the observer's location, access, and setup, then "context" must be formally defined. This section proposes a structured view of context to track explanatory fragmentation across modern physics.[8] I seek to generally establish the case for the elements of context starting from two assumptions, and leave empirical coverage to the case studies of complementarities in section 4.

<u>3.1: The Minimal Tools</u>

If scientific explanation requires observers embedded within physical theory, what could be a minimal condition for coherent explanatory contexts? To answer this, I begin with two foundational premises widely valued in both physics and philosophy of science.

Premise 1 (Spatiotemporal Embedding): Any physical observer occupies a specific region of spacetime. This region has finite extent: beyond certain boundaries, no information can be accessed or transmitted through classical channels.

Premise 2 (Theoretical Reconstruction): Observers reconstruct physical observables using the principles and mathematical tools provided by available theory. This reconstruction process is subject to fundamental limitations imposed by the theory's structure.

Premise 1 reflects the fundamental locality constraints imposed by special and general relativity. No observer can receive information from spacelike-separated events or from regions beyond their causal horizon. This is both a classically practical limitation and a theoretical constraint built into our modern theories of cosmology. Any weaker assumption would fail to capture the locality constraints that generate complementarity phenomena. Premise 2 acknowledges that explanation requires active theoretical reconstruction of physical quantities. Without this, we have no bridge from context to explanatory content. The observer must use theoretical principles to extract meaningful information from available data, and this process is constrained by what the theory permits.

[8] I do not aim to reestablish the philosophical foundations of context or structural mapping here. I point toward the preliminary development of the context-dependent mapping framework (Ryoo 2025).

I conclude that these two premises capture a minimal set of assumptions in the sense that weaker versions of either may sacrifice explanatory coverage. For instance, a weaker version of Premise 1 that ignored causal horizons would fail to distinguish between observers inside and outside black hole event horizons, eliminating the very structure that generates complementarity. Similarly, a weaker version of Premise 2 that treated explanation as passive observation would provide no mechanism for connecting theoretical principles to observational constraints.

At first glance, it appears that we are on a track to capture complementarities. The premises encompass the possible geometry for general relativity, specifically local spacetime, as well as the nonlocality of quantum mechanical reconstruction. From these premises, we can derive some conditions for explanatory contexts through the following considerations:

Step 1: Given spatiotemporal embedding, any observer's explanatory capacity is bounded by their causal accessibility: the spacetime region from which they can receive or transmit information. This defines what information is in principle available for explanation.

Step 2: Quantum entanglement enables correlations between spacelike-separated regions that cannot be explained by classical causal connections. An observer may therefore reconstruct information about distant quantum systems through these correlations, even when no classical signal could travel between the regions. This “spooky action at a distance” defines a second dimension of observational access beyond what spacetime geometry alone permits. An observer's access to quantum correlations determines which degrees of freedom can be reconstructed nonlocally, independent of direct causal contact within a single region of spacetime.

Step 3: Given that physical theories involve background structures and approximation schemes, the observer's explanatory framework depends on boundary and frame conditions—the geometric, topological, gauge, and asymptotic assumptions that define which effective theory applies and which symmetries are available.

Step 4: Given that reconstruction requires physical implementation, explanatory capacity is constrained by operational limitations. These may consist in the precision, energy scales, and measurement protocols actually available to the observer.

From our empirically motivated steps, it follows that any explanatory context in modern physics must include these four elements:

1) where the observer is located within spacetime;
2) what the observer can access nonlocally beyond spacetime bounds;
3) what kinds of structural or geometric bounds constrain the observer's location;
4) what kinds of interventions and observational bounds constrain the precision, scope, and operational realizability of the reconstruction.

These four jointly define the explanatory arena available to any physical observer and constitute a minimal structure required to map theory to explanation in a physically coherent way.

3.2: The 4-Tuple Context

As mentioned earlier, I propose that the context for quantum mechanics and complementarities is a quadruple:

$$c = (C, E, B, O)$$

Where each element plays a distinct role in delimiting what can be explained. I stress that each element corresponds to each of the four elements numbered above. In section 4, I present examples of these elements.

Causal Accessibility (C)

This specifies the causal region from which the observer can receive or transmit information. It defines the light cone or causal patch in spacetime in which reconstruction is possible. For example, the external observer of a black hole cannot access information inside the event horizon. Contexts with different causal reach yield different operator algebras that shape observed phenomena (Wall 2012; Almheiri et al. 2013).

Any attempt to characterize observational context without reference to causal structure fails to distinguish between physically equivalent and inequivalent observational situations. Two observers might share identical entanglement access, boundary conditions, and operational capabilities, yet if one is causally disconnected from relevant spacetime regions (as in black hole scenarios), their explanatory capacities differ fundamentally. The purely geometric constraint of causal accessibility cannot be reduced to other contextual features, and is hence an integral part of the tuple.

Entanglement Reach (E)

Entanglement Reach captures nonlocal informational access within quantum theory. In contexts where the system's degrees of freedom are distributed across spatial regions or Hilbert space sectors, the observer's entanglement access determines reconstructibility (Dong et al. 2016). As I discuss in section 4, this directly aligns with the use of various tools, such as modular Hamiltonians and entanglement wedges in AdS/CFT (Jafferis et al. 2016; Harlow 2017), and with operationally accessible subspaces in quantum information theory (Nielsen and Chuang 2010). The entanglement structure thus defines both correlation and explanatory relevance within a quantum context.

Another edge case in quantum information theory is the GHZ (Greenberger–Horne–Zeilinger) state. Each pairwise marginal appears classically mixed, but global entanglement produces strong nonlocal effects (Mermin 1990). If one relies solely on causal patch or boundary conditions, the global explanatory power is lost; local measurements appear random, but global entanglement structure enables nonlocal explanatory patterns invisible to any purely classical contextual analysis. This underscores that entanglement reach constitutes a distinct dimension of contextual structure.

Boundary/Frame Conditions (B)

Boundary Conditions specify constraints on the model class, including asymptotic structure (e.g., AdS boundary), gauge fixing, and background geometry. These conditions shape which field equations and symmetries are available to an observer and are essential in effective field theory domains (Weinberg 1996; Donoghue 1994). They define which effective theory applies to a system with an observer. In topological quantum field theory, the boundary conditions determine how local operators are glued together, thereby defining the structure of the modular functor and influencing the category of observables (Baez & Dolan 1995; Freed 2012). These boundary data are essential to the definition of the theory itself, often encoding physical or geometrical information about the system's global structure.

Gauge theory provides subtler illustrations. In the electric Aharonov–Bohm effect, electrons exhibit phase shifts even when traveling through regions of zero electric field, due to the global structure of the gauge potential. This effect hinges on boundary conditions imposed on the gauge field (Peshkin and Tonomura 1989). If such boundary frames are left unspecified or assumed invariant across contexts, one risks attributing physical effects to incorrect dynamical causes. In general relativity, different gauge fixings and slicing conditions lead to different constraint equations and physical interpretations, again reinforcing the explanatory relevance of frame assumptions (Gourgoulhon 2007).

Attempts to specify observational contexts without reference to background theoretical assumptions systematically misidentify the scope of valid explanations. Even in classical mechanics, the choice of coordinate systems, gauge fixings, and asymptotic conditions determines which symmetries and conservation laws are manifest.

Operational Configuration (O)

Theoretical descriptions alone cannot determine explanatory validity; what can be measured depends on implementational constraints. Operational configuration includes experimental setup and sequences. What can be measured, to what degree, depends on these parameters. While operational limitations in practice can be epistemic (e.g. detector resolution), the cases examined here focus on structural operational constraints.

A vivid case appears in quantum non-demolition (QND) measurement protocols. These are engineered procedures in quantum optics and control theory that enable repeated measurement of an observable without disturbing its future evolution. This is achieved only when the measured observable commutes with both the system's Hamiltonian and the measurement interaction, effectively isolating a commutative subalgebra of the full noncommutative theory (Tsang and Caves 2012).[9] QND protocols thus define a subspace of observables that are dynamically coherent and operationally stable. These are the observables that can be accessed repeatedly without collapse or destructive back-action. The emergence of classicality via decoherence is sensitive to choices of coarse-graining and resolution thresholds, both of which are operationally defined.

An observer embedded in an operational regime defined by QND instrumentation does not have access to the full algebra of observables, but only to a restricted, consistent subset. Importantly, this restriction arises from physical limits on what can be repeatedly measured without corrupting the system. Operational configurations physically enforce explanatory fragmentation by selecting only those observables that can be meaningfully tracked and predicted. The broader point is that explanatory reach is constrained by causal or geometric limits as well as the techniques of measurement itself. The operational configuration (O) in QND represents Structural contextuality, because it reflects objective, theory-imposed limitations on which observables can be accessed and retained across time without destroying coherence. Similarly, in quantum gravity, the operational configuration O captures constraints

[9] In the context of (algebraic) quantum theory, a *subalgebra* is a subset of the full *algebra* of observables that can be used to describe a quantum system. Physically, these correspond to the set of quantities that can be jointly tracked under some experimental setup.

like the impossibility of simultaneously measuring complementary variables with arbitrary precision, or the fundamental trade-offs between spatial and temporal resolution imposed by the uncertainty principle.

3.3: Motivations of Independence

I examine the prospects of each component contributing uniquely to explanatory structure. One can see that none can be derived from the others:

C ≠ B: Two observers may share the same causal patch but adopt different boundary conditions. For instance, two observers outside a black hole may both remain causally excluded from the interior (C_{same}) but model the background as either (i) asymptotically flat or (ii) asymptotically AdS. These yield different sets of reconstructible observables due to differences in effective theory, boundary terms, and symmetry algebra. This demonstrates that boundary conditions cannot be derived from causal structure alone.

E ≠ C: Consider a GHZ state shared among three parties in spacelike-separated labs. Each party's causal access, and location in spacetime is locally restricted, but entanglement correlations exist across global Hilbert sectors. Observers may have the same causal patch (C) but differ in their access to global entanglement structure (E), affecting reconstructability (e.g., two parties can reveal nonlocal correlations only when jointly considered). Indeed, sharing a quantum state like a GHZ state often provides different observations regardless of whether a location is shared or not.

B ≠ O: Fix boundary conditions in a system (e.g., impose Dirichlet boundary on a scalar field in AdS). An observer's choice of measurement sequence can render certain predictions infeasible even if the boundary geometry permits them. This operational component (O) governs what can actually be detected and verified, independently of B.

O ≠ E: Entanglement reach refers to the observer's access to quantum correlations; operational configuration refers to measurement precision and apparatus configuration. Even with full entanglement access, a poorly-selected sequence of measurements may prevent precise extraction of information from entangled subsystems, showing the need for O as a separate component.

Hence I assert that there are empirical motivations to consider each component as a unique and non-derivable constraint on explanation in the scenarios considered. Any reduction risks conflate fundamentally distinct physical limitations.

3.4: Application to f_c and Structural Mapping

As mentioned in the introduction, this 4-tuple schema has its motivations partly in f_c, a context-dependent map for explanation. It assigns each physically defined context to a *similarity subspace* (S_i): a subset of physical laws that yield consistent predictions within a particular set of conditions.[10] In the original construction, such laws are assigned based on previous iterations of similar observations (Ryoo 2025). If we know that a double slit creates wave-like patterns, then a triple slit with the same experimental configuration will also generate wave-like interference. More precisely, contexts are deemed similar when they share the same 4-tuple structure, ensuring that the same theoretical constraints and physical limitations apply. Specific prescriptions for assigning similarity subspaces are found in Ryoo's (2025) development. This mapping assumes that not all laws can be applied globally. Instead, laws become explanatory only when bound to a specific physical context. The mapping itself takes the following form:

$$f_c : c_i \rightarrow S_i.$$

Section 4 will show this mapping in action through two relevant case studies. The mapping effectively inputs the context 4-tuple of a particular complementary feature and outputs the set of laws which apply.

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[10] Strevens (2008) introduces a similarity space as a set of laws grouped by a metric of shared underlying principles. A "similarity subspace," while inspired by this, departs from his counterfactual-causal framework by grounding similarity in structural constraints and complementarities imposed by physical theory.

Ultimately, this formal structure builds on the idea that physical theories are not globally valid but must be applied in parts. This aligns with the patchwork view of science (Dupré 1993; Cartwright 1999), though rather than asserting that different domains need different models, f_c provides a rule-based method for assigning coherent laws to specific contexts. It is also worth noting that the similarity subspaces that result from f_c are not arbitrary. They are constrained by the internal structure of the theory, including its symmetries, causal order, and entanglement features. This mapping, applied to the 4-tuple context, identifies the specific subspace of physical laws that remain valid within that context, thereby structuring explanation according to the theory's own internal constraints.

3.5: On the Interpretation-ladenness

An argument could be made that quantum mechanics under particular interpretations brings about a sense of consistency amongst the outcomes, hidden variables, branches, etc., of the wavefunction. This may render the mapping to be interpretation-laden. However, our current interpretations of quantum mechanics do not account for complementarities that arise across causal patches - relative to different observers' local spacetimes. I contend that the 4-tuple framework maintains neutrality by focusing on operationally accessible features that remain invariant across major interpretational divides.

Causal Accessibility (C) remains well-defined across interpretations because it depends only on spacetime geometry and the light cone structure, which are interpretation-independent features of relativistic physics. Whether one adopts Copenhagen, Many-Worlds, or hidden variable theories, the causal patch accessible to an observer is determined by the metric structure of spacetime. This is invariant under the stance that spacetime may be emergent.

Entanglement Reach (E) presents a more subtle case. Of course, interpretations differ on the ontological status of entanglement. Whether it represents genuine nonlocal correlations (Copenhagen), branching correlations across many-worlds, or statistical correlations over hidden variables (Bohmian mechanics), they agree on the operational consequences. By this I mean that all interpretations predict the same correlation patterns in EPR-type experiments and agree on which observables can reveal nonlocal effects. The 4-tuple captures this operational structure without committing to any particular ontological account of what entanglement "really is."

Boundary Conditions (B) and Operational Configuration (O) are similarly interpretation-neutral. Boundary conditions concern the geometric and gauge-theoretic assumptions required to define a well-posed physical problem: features that remain constant across interpretational frameworks. Operational configuration captures measurement protocols and their fundamental limitations, which manifest identically regardless of whether one thinks measurements cause collapse, reveal pre-existing values, or select branches.

The key insight is that complementarities manifest at the level of operational predictions rather than the metaphysical commitments of interpretations. In black hole complementarity, both Copenhagen and Many-Worlds interpretations agree that external and infalling observers cannot operationally access each other's descriptions simultaneously. They differ on whether this reflects fundamental incompatibility (Copenhagen) or correlations across different branches, but they make identical predictions about what each observer can measure and verify.

This operational focus allows the framework to remain neutral while still capturing the structural features that generate explanatory fragmentation. The 4-tuple identifies the physical constraints that determine explanatory boundaries without taking a stance on the underlying metaphysics of quantum mechanics.

4. Instantiations of C

In this section, I claim that the 4-tuple structure of context, that came from our two assumptions, matches the explanatory constraints seen in real physical theories. To make this case, I apply the f_c framework to two central cases: black hole complementarity and entanglement wedge reconstruction. Recall that modern approaches to quantum gravity involve structural contextuality. Both cases show that explanation fragments not because of incomplete knowledge, but because the theory restricts what can be said in different physical contexts. Following our previous discussion regarding wavefunction interpretation-laden contexts, I demonstrate the utility of the 4-tuple in complementarities regarding local spacetimes.

4.1 Black Hole Complementarity

Black hole complementarity was proposed to resolve the black hole information paradox, which arises when unitarity in quantum mechanics clashes with the classical nature of Hawking radiation. From the perspective of an external observer, information appears to be irretrievably lost as the black hole evaporates. Meanwhile, an infalling observer experiences a smooth passage through the horizon, consistent with general relativity. Both views appear valid, but they cannot be globally reconciled with a single global description - hence forming a complementarity (Susskind et al. 1993; Almheiri et al. 2013).

The f_c framework captures this conflict as a case of incompatible contexts. The external observer's context includes late-time access to Hawking radiation, semiclassical spacetime near the horizon, and long-duration measurement of correlations. We can examine the elements of the 4-tuple as so:

Causal Accessibility (C):
For the external observer, causal accessibility is limited to the region outside the event horizon. Signals from the interior cannot reach this observer, so explanations must be constructed from data available at or beyond the horizon. This restricts the observer to semiclassical analysis of outgoing Hawking radiation. In contrast, the infalling observer maintains causal access to regions inside the horizon up to the singularity. This access defines a different causal patch and yields different explanatory constraints.

Entanglement Reach (E):

The external observer analyzes long-range entanglement across the radiation field. This includes correlations between early and late Hawking quanta, which support the idea of unitary information recovery. The infalling observer, however, accesses near-horizon entanglements between local modes. These do not capture the global pattern of information flow and are limited by the short proper time before reaching the singularity.

Boundary Conditions (B):

Each observer relies on a different background assumption. The external observer models the spacetime as asymptotically flat and treats the horizon as a semiclassical surface. The infalling observer assumes a smooth local geometry governed by general relativity. These boundary conditions yield different effective field theories and shape what kinds of regularity or anomalies are expected.

Operational Configuration (O):

Operational configuration captures the structural constraints on what kinds of measurements can be defined, implemented, and sustained within a given physical regime. For black hole complementarity, this includes the finite proper time available to infalling observers before reaching the singularity, the impossibility of sustaining long-duration measurements behind the horizon, and the incompatibility between local quantum field interactions and nonlocal entanglement extraction protocols. For the external observer, meaningful measurements require semiclassical detectors operating very far away, which are incapable of probing Planck-scale curvature or interior geometry (Dey et al. 2019).

Putting this formally, the external context is:

$$c_{ext} = (C_{ext}, E_{ext}, B_{ext}, O_{ext}).$$

It maps to a similarity subspace

$$f_c(c_{ext}) = S_{qft},$$

defined by quantum field theory on curved spacetime. This subspace explains information recovery through long-range entanglement. On the other hand, the infalling observer's context is

$$c_{infall} = (C_{infall}, E_{infall}, B_{infall}, O_{infall}).$$

It includes local access near the horizon, smooth general relativistic geometry, and finite-duration detectors. This maps to

$$f_c(c_{infall}) = S_{gr},$$

a subspace defined by the equivalence principle and the local vacuum structure. The two subspaces cannot be jointly applied, due to the aforementioned inconsistency of the two theories.[11]

4.2 Entanglement Wedge Reconstruction

In AdS/CFT, the boundary conformal field theory encodes information about a higher-dimensional spacetime, referred to as a *bulk* spacetime. But the encoding is not uniform. Accordingly, different regions of the boundary reconstruct different regions of the bulk. The key object is the entanglement wedge: Dong, Harlow, and Wall (2016) proved that an observer with access to a boundary region A can reconstruct operators in the corresponding bulk region E(A), but not beyond it. This reconstruction depends on causal access and entanglement structure. We can examine the components of the tuple as so:

Causal Accessibility (C):

An observer with access to a boundary subregion A can manipulate and measure only operators localized within that region. The causal structure of the boundary restricts their ability to influence or reconstruct

[11] Another example of incompatibility is the firewall paradox from accepting both quantum and relativistic principles at the black hole horizon (Almheiri et al. 2013). The result is a predicted high-energy "firewall" of radiation at the horizon that contradicts the smooth infall expected by general relativity.

operators outside A. This causal limitation defines which bulk operators can be accessed through entanglement wedge reconstruction.

Entanglement Reach (E):

The observer's entanglement reach is determined by the subregion they control. According to the Ryu–Takayanagi prescription and its extensions, access to region A enables reconstruction of the bulk entanglement wedge E(A). As one would expect, operators outside this wedge cannot be reconstructed without access to a larger boundary region. It is easy to see that explanatory power depends on how much of the boundary is entangled with the relevant bulk degrees of freedom.

Boundary Conditions (B):

The background geometry is fixed by the AdS spacetime and the conformal symmetry of the boundary theory. These conditions ensure that the mapping between bulk and boundary observables is well-defined. Changes in boundary geometry or symmetry assumptions would change the reconstruction map and the set of valid explanations.

Operational Configuration (O):

Measurements depend on the control of the boundary theory. An observer in region A can only access a subset of the full operator algebra. Their operational setup constrains what they can reconstruct and verify. These limitations follow from the structure of the theory and the distributed nature of the encoding.

Formally, the observer's context is

$$c_A = (R_A, A_A, B_A, O_A),$$

defined by the boundary region A, the accessible operator algebra A_A, the boundary conditions B_A (e.g. AdS spacetime), and the operational configuration O_A. The f_c mapping sends this context to a similarity subspace

$$f_c(c_A) = S_A,$$

which contains only those bulk observables reconstructible from A. If two observers access disjoint regions A and B, their contexts

$$c_A \text{ and } c_B = (R_B, A_B, B_B, O_B)$$

will map to different subspaces

$$f_c(c_A) = S_A \text{ and } f_c(c_B) = S_B.$$

These may be incompatible. Neither observer can reconstruct the full bulk. Only the union A ∪ B may give access to the interior region E(A ∪ B).

As Harlow (2017) affirms, bulk locality is preserved only within the entanglement wedge associated with the accessible boundary region. Explanation, in this case, is tied to reconstruction capacity, and the f_c framework models this directly. Each observer's context maps to a subset of explanatory content allowed by the structure of the theory. Global descriptions are unavailable because the encoding is redundant and distributed (Pastawski et al. 2015).

This matches the context-dependence seen in black hole complementarity. In both cases, explanation is limited by causal and entanglement structure. f_c makes this limitation formal. It treats explanation as valid only within structurally defined boundaries that follow from the physical theory, beyond modeling choice or observer ignorance.

4.3: A Discussion of Minimality and Extensibility

Within our 4-tuple schema, these four components appear capable of capturing the contexts relevant to complementarity in contemporary physics.[12] The case studies in black hole physics and holographic duality suggest that contexts differing in any of these dimensions yield different explanatory subspaces, while contexts agreeing on all four dimensions yield consistent explanations.

Thus far, I have argued in support of the following aspects of the 4-tuple through these considerations:

1) Each component follows necessarily from spatiotemporal embedding + theoretical reconstruction.
2) They are independent of each other, or at least not easily derivable from each other.
3) Case studies show comprehensive coverage of complementarity phenomena.

The next natural concern is: Could additional components be necessary? Potentially, but the burden of proof lies on critics to identify specific cases where the 4-tuple structure fails to capture relevant contextual differences. The framework is designed to be extensible. Indeed, additional components could be added if empirical cases demand them. Future developments may require additional components depending on the theoretical structure. For instance, spontaneous symmetry breaking (central in cosmological inflation and electroweak theory) introduces context-sensitive vacuum selection, which might demand a fifth axis representing dynamically emergent background structures. Likewise, in quantum information theory, explanatory contexts may depend on computational resource bounds: what can be reconstructed or simulated depends on access to entanglement distillation, error correction, or algorithmic feasibility. These cases suggest that the tuple may be nested within or extended to a higher-dimensional space of explanatory parameters, should empirical or theoretical pressure warrant it. Until these cases are formalized, the current 4-tuple stands as a minimally and empirically grounded structure for explanation. I leave such explorations for future work.

4.4. Relation to Philosophical Theories of Explanation

[12] Since I did not provide an exhaustive list of complementarities, dualities, contexts, etc., I hold the narrower claim that I have shown minimality of the 4-tuple in the scenarios that I have described in this section.

As developed, the f_c mapping is intended to extend primarily the Kairetic and Deductive Nomological accounts of explanation when consistency breaks down. As Ryoo (2025) describes, the subspaces of laws obtained in the scenarios described above can be utilized within such accounts as premises of a deductive model.

On the other hand, in causal regimes, the subspaces may support localized causal modeling (e.g., à la Woodward 2003), though the framework does not assume the global applicability of interventionist structures. Instead, it clarifies when causal relations are definable within a given context. One might suggest that f_c identifies the contextual boundaries within which Woodwardian causal relations are well-defined, while Woodward's framework provides the causal structure internal to each context. However, this integration faces serious conceptual tensions: Woodward assumes that causal relations are objective features of the world, independent of observational standpoint, whereas f_c implies that causal structure is context-dependent. Naturally, this raises the question of whether causal claims are discoveries about the world or constructions constrained by the observer's location within it. In cases like black hole complementarity or AdS/CFT duality, causal relations may be well-defined within a given context but fail to extend across contexts. The obvious example is that causal claims relating infalling matter to outgoing Hawking radiation involve variables accessible to different observers, undermining the global coherence of interventionist causation.

Moreover, Woodward's framework requires that interventions be possible in principle, yet many relevant quantities in quantum gravity are not physically manipulable (e.g. spacetime geometry and entanglement structure). It may even be that the basic features like transitivity become problematic: causal chains spanning multiple contexts do not necessarily yield valid global claims. While one could respond by relativizing causation to context or restricting causal talk to locally manipulable variables, either strategy may require significant revision of Woodward's commitments. Any successful integration of f_c and interventionism may require more careful integrations or modifications.

Similarly, while unificationist accounts treat explanation as the compression of phenomena into general patterns, most prominently in Kitcher's model of minimizing the number of argument schemata required to derive our beliefs (Kitcher 1981). f_c localizes explanatory patterns to physically defined contexts. One might initially interpret f_c as extending unificationism by systematizing explanation within bounded observational regimes. However, Kitcher's framework prizes breadth of scope, minimal pattern diversity, and high stringency; yet f_c implies that different contexts often require fundamentally distinct explanatory schemata that cannot be unified without contradiction. Going back to black hole complementarity, these patterns are internally coherent but mutually incompatible and cannot be integrated into a single unifying argument without violating the structural assumptions of at least one explanatory regime. This raises several philosophical tensions. Does fragmentation across contexts signify the failure of unificationist ideals, or does it reveal the inapplicability of global unification in domains where the theory itself prohibits consistent overlap? Moreover, if explanation is modular, should each context-bound argument pattern be counted separately, undermining Kitcher's pattern minimization criterion?

Kitcher affirms the requirement that explanatory derivations be deductively strong and epistemically constrained, calling it "*stringency.*" There is a need to examine whether this condition can be preserved when explanatory structure is localized. One may adopt a form of hierarchical or meta-level unification. While object-level patterns may fragment, the mapping itself could serve as a higher-order schema for systematizing which laws apply where. This would entail a structured framework for explanatory organization without enforcing global coherence. Alternatively, one might reconceive stringency and pattern scope as context-relative rather than absolute, preserving unificationist motivations in a pluralist framework. These possibilities suggest that f_c can be thought of as both an extension of the unificationist tradition, as well as a modification of it, that aims to preserve its core virtues of systematicity and explanatory economy. Simultaneously, it is important to note that it might relax the assumption of global applicability. A credible integration may therefore require reconceptualizing unification itself: from global compression to context-sensitive systematization, and from universal argument patterns to a structured mapping of local explanatory regimes. This reconfiguration retains the philosophical ambitions of unificationism while adapting them to the physical and structural constraints revealed by contemporary physics.

I conclude that the f_c framework as a context-sensitive epistemic tool may intuitively be compatible with and extending familiar causal, unificatory, and structural (contextuality) ideals into settings where explanation must be localized. It may be worthwhile to aim for a fuller development of its philosophical implications in the future.

5. Conclusion and Future Directions

Contemporary physics increasingly confronts us with explanatory fragmentation. In domains such as black hole thermodynamics and AdS/CFT duality, distinct observers or theoretical regimes yield mutually incompatible yet internally consistent descriptions. These are structural features imposed by the physics itself. Traditional explanatory ideals, such as global unification or invariant causal models, fail to accommodate these constraints.

In this paper, I proposed a general structural account of explanatory context, grounded in the physical features that constrain what can be said or known in any given regime. This account formalizes context as a 4-tuple: Causal Accessibility (C), Entanglement Reach (E), Boundary/Frame Conditions (B), and Operational Configuration (O). Together, alongside our assumption of an observer being in a four dimensional spacetime and having access to the theories of physics, these define the minimal physical arena. Unlike perspectival or pragmatic notions of context, this framework is structurally grounded in physical theory—especially in quantum settings where the boundaries of explanation are imposed by entanglement structure, causal disconnection, or measurement limits.

This conception of context is not tied to any single explanatory framework. However, it provides a minimal foundation for epistemic tools such as the f_c mapping developed in earlier work, which assigns to each context a similarity subspace of laws valid within that regime. As shown in Sections 4.1 and 4.2, these contexts play a central role in structuring explanation in black hole complementarity and entanglement wedge reconstruction, where global coherence gives way to localized explanatory validity.

The broader philosophical contribution is twofold. First, it shows that explanatory pluralism in physics is structurally grounded, not solely epistemic. Second, it provides a minimal yet extensible template for formalizing how physical theories generate valid but incomplete accounts of reality across distinct domains. Future work may explore whether additional parameters, such as computational resources or symmetry-breaking conditions, are needed to extend this tuple to new explanatory settings, such as cosmological models, quantum computing, or emergent spacetime frameworks.

In short, the 4-tuple context structure offers a philosophically robust and physically grounded foundation for analyzing scientific explanation under complementarity. It provides the formal tools needed to preserve explanatory coherence in a world where fragmentation is not failure, but a structural necessity.

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References

Almheiri, Ahmed, Donald Marolf, Joseph Polchinski, and James Sully. 2013. “Black Holes: Complementarity or Firewalls?” *Journal of High Energy Physics* 2013 (2): 62. https://doi.org/10.1007/JHEP02(2013)062.

Baez, J. C., & Dolan, J. (1995). *Higher-dimensional algebra and topological quantum field theory*. *Journal of Mathematical Physics, 36*(11), 6073–6105. https://doi.org/10.1063/1.531236

Bohr, Niels. 1928. “The Quantum Postulate and the Recent Development of Atomic Theory.” *Nature* 121 (3050): 580–590. https://doi.org/10.1038/121580a0.

Budroni, Costantino, et al. (2022). "Kochen-specker contextuality." Reviews of Modern Physics 94.4 (2022): 045007.

Cartwright, Nancy. 1999. *The Dappled World: A Study of the Boundaries of Science.* Cambridge: Cambridge University Press.

Concepcion, Benjamin, et al. 2024 "Complementarity for a dynamical black hole." Physical Review D 110.8 (2024): 086002.

Dey, Ramit, et al. 2019. "Black hole quantum atmosphere for freely falling observers." Physics Letters B 797 (2019): 134828.

Dong, Xi, Daniel Harlow, and Aron C. Wall. 2016. “Reconstruction of Bulk Operators within the Entanglement Wedge.” *Physical Review Letters* 117 (2): 021601. https://doi.org/10.1103/PhysRevLett.117.021601.

Donoghue, John F. *"General Relativity as an Effective Field Theory: The Leading Quantum Corrections."* Phys. Rev. D 50, 3874 (1994).

Dupré, John. 1993. *The Disorder of Things: Metaphysical Foundations of the Disunity of Science.* Cambridge, MA: Harvard University Press.

Freed, D. S. (2012). *The cobordism hypothesis*. *Bulletin of the American Mathematical Society, 50*(1), 57–92. https://doi.org/10.1090/S0273-0979-2012-01391-5

Galison, Peter, and David J. Stump, eds. 1996. *The Disunity of Science: Boundaries, Contexts, and Power.* Stanford, CA: Stanford University Press.

Giere, Ronald N. 2006. *Scientific Perspectivism.* Chicago: University of Chicago Press.

Gourgoulhon, Eric. *3+1 Formalism in General Relativity: Bases of Numerical Relativity*. Lecture notes (arXiv:gr-qc/0703035).

Harlow, Daniel. 2017. “The Ryu–Takayanagi Formula from Quantum Error Correction.” *Communications in Mathematical Physics* 354 (2): 865–912. https://doi.org/10.1007/s00220-017-2904-z.

Ilgin, Irfan, and I-Sheng Yang. 2014. "Causal patch complementarity: the inside story for old black holes." Physical Review D 89.4 (2014): 044007.

Jafferis, Daniel L., Aitor Lewkowycz, Joseph Maldacena, and S. Joseph Weinberg. 2016. “Relative Entropy Equals Bulk Relative Entropy.” *Journal of High Energy Physics* 2016 (6): 004. https://doi.org/10.1007/JHEP06(2016)004.

Kitcher, Philip. 1981. “Explanatory Unification.” *Philosophy of Science* 48 (4): 507–531. https://doi.org/10.1086/289005.

Ladyman, James. 1998. “What Is Structural Realism?” *Studies in History and Philosophy of Science Part A* 29 (3): 409–424. https://doi.org/10.1016/S0039-3681(98)80129-5.

Maldacena, Juan. 1999. "The Large N Limit of Superconformal Field Theories and Supergravity." *International Journal of Theoretical Physics*, 38(4), 1113–1133.

Massimi, Michela. 2012. “Scientific Perspectivism and Its Foes.” *Philosophica* 84 (2): 1–19.

Mermin, N. David. 1990. “Quantum Mysteries Revisited.” *American Journal of Physics* 58 (8): 731–734. https://doi.org/10.1119/1.16395.

Nielsen, Michael A., and Isaac L. Chuang. 2010. *Quantum Computation and Quantum Information*. 10th Anniversary Edition. Cambridge: Cambridge University Press.

Pastawski, Fernando, Beni Yoshida, Daniel Harlow, and John Preskill. 2015. “Holographic Quantum Error-Correcting Codes: Toy Models for the Bulk/Boundary Correspondence.” *Journal of High Energy Physics* 2015 (6): 149. https://doi.org/10.1007/JHEP06(2015)149.

Peshkin, Michael, and Akira Tonomura. 1989. *The Aharonov-Bohm Effect*. Lecture Notes in Physics Monographs, vol. 340. Berlin: Springer-Verlag. https://doi.org/10.1007/978-3-642-88294-2.

Rickles, Dean. 2013. “AdS/CFT Duality and the Emergence of Spacetime.” *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 44 (3): 312–320. https://doi.org/10.1016/j.shpsb.2013.03.003.

Rueger, Alexander. 2005. “Perspectival Models and Theory Unification.” *The British Journal for the Philosophy of Science* 56 (3): 579–594. https://doi.org/10.1093/bjps/axi130.

Ryoo, Hong Joo. 2025. “Towards an Account of Complementarities and Context-Dependence.” *Stance: An International Undergraduate Philosophy Journal* 18: 44–59.

Strevens, Michael. 2008. *Depth: An Account of Scientific Explanation.* Cambridge, MA: Harvard University Press.

Suárez, Mauricio. 2003. “Scientific Representation: Against Similarity and Isomorphism.” *International Studies in the Philosophy of Science* 17 (3): 225–244. https://doi.org/10.1080/0269859032000168908.

Susskind, Leonard, Lárus Thorlacius, and John Uglum. 1993. "The Stretched Horizon and Black Hole Complementarity." *Physical Review D* 48 (8): 3743–3761. https://doi.org/10.1103/PhysRevD.48.3743.

Tsang, Mankei, and Carlton M. Caves. 2012. "Evading Quantum Mechanics: Engineering a Classical Subsystem within a Quantum Environment." *Physical Review X* 2 (3): 031016. https://doi.org/10.1103/PhysRevX.2.031016.

van Fraassen, Bas C. 1980. *The Scientific Image.* Oxford: Oxford University Press.

Wall, Aron C. 2012. "Maximin Surfaces, and the Strong Subadditivity of the Covariant Holographic Entanglement Entropy." *Classical and Quantum Gravity* 31 (22): 225007. https://doi.org/10.1088/0264-9381/31/22/225007.

Weisberg, Michael. 2013. *Simulation and Similarity: Using Models to Understand the World.* Oxford: Oxford University Press.

Woodward, James. 2003. *Making Things Happen: A Theory of Causal Explanation.* Oxford: Oxford University Press.

Worrall, John. 1989. "Structural Realism: The Best of Both Worlds?" *Dialectica* 43 (1–2): 99–124. https://doi.org/10.1111/j.1746-8361.1989.tb00933.x.