The universal theory of structure: a fundamental ontology for ontic structural realism

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Abstract: Ontic Structural Realism (OSR) holds that structure is ontologically fundamental, yet it lacks a precise metaphysical account of structure. Returning to the insight that originally motivated structural realism, I develop a new basis for OSR grounded in the metaphysical foundations of mathematics. This approach draws on the principles of *ante rem* structuralism and their formal axiomatizations to define Structure Theory (ST), the view that structures exist *sui generis* and constitute the subject matter of mathematics. ST compels OSR to confront its "collapse problem" of distinguishing physical from mathematical structure. I argue for embracing the collapse by adopting the Mathematical Universe Hypothesis (MUH), which identifies our physical universe as an *ante rem* structure. This yields the Universal Theory of Structure (UTS), providing a fundamental ontology of structures for both mathematical and physical reality. The theory refines OSR's fundamentality thesis from the vague "physical reality is structural" to the metaphysically substantive "physical reality is an *ante rem* structure," thereby strengthening responses to criticisms concerning representation, objecthood, and causation. The UTS also illuminates important foundational problems concerning the applicability of mathematics, the particular form of our universe, and the nature of existence. I conclude that the theory's unifying and explanatory virtues support an inference to the best explanation.

Keywords: Ontic structural realism, *Ante rem* structuralism, Mathematical universe hypothesis, Structure theory, Universal theory of structure

1 Introduction

Ontic structural realism (OSR) holds that structure is ontologically fundamental, yet even its foremost proponents acknowledge that the appropriate characterization of structure remains an ongoing challenge (French & Ladyman, 2010). While structure is typically characterized as giving ontological priority to relations over objects, this remains too vague to secure OSR's realist ambitions. What precise metaphysical account of structure can OSR adopt? Motivated by Worrall's (1989) insight that the mathematical content of physical theories survives theory change, I propose a new basis for OSR by turning to the structuralist foundations of mathematics. Previous inquiries in this direction have focused on unifying foundational frameworks for mathematics, such as set theory, category theory, and univalent foundations. While these unifying frameworks offer valuable representational tools, they do not by themselves specify the required ontology.

I turn instead to the metaphysical foundations of mathematics, specifically to *ante rem* structuralism: the view that structures exist independently of instantiation and that mathematics is the language we use to describe them. I refer to the principles of *ante rem* structuralism and their formal axiomatizations as Structure Theory (ST). Adopting ST compels OSR to confront its "collapse problem" of distinguishing physical from mathematical structure (French, 2014). I argue not to resist the collapse, but to embrace it. If we accept that structures exist, and that physical reality is exactly mathematically describable (what I term the weak MUH), then we have strong reason to identify the physical universe with an *ante rem* structure (the strong MUH). The adoption of the strong MUH should be understood as the *universalization* of ST, because it recognizes that ST's existing ontology accounts for a larger domain. To reflect this, I term the broad ontological package the Universal Theory of Structure (UTS). I conclude that the UTS delivers precisely the metaphysical clarity that OSR needs to secure its realist ambitions.

This approach remedies the shortcomings of prior engagements with *ante rem* structuralism. Some OSR theorists (Busch, 2003; Psillos, 2006; French, 2006) considered the view, but they did not sufficiently explore the identification of our physical universe with an *ante rem* structure, leading to dismissals that warrant reconsideration. My previous defense (Hamlin, 2017) of a universal ontology of *ante rem* structures was based on Shapiro's (1997) specific formalization, whereas the present account remains neutral regarding competing formalizations. I also include a novel evaluation of the ontology's suitability as a foundation for OSR, while arriving at distinct conclusions concerning its epistemic status.

The argument proceeds as follows: Section 2 traces the original impetus for structural realism, arguing that it suggests turning to the metaphysical foundations of mathematics for clarity regarding the central notion of structure. Section 3 establishes that ST provides a fundamental ontology of *ante rem* structures for mathematical discourse. Section 4 deconstructs Tegmark's MUH into three component parts, outlining their mutual entailments before reconstituting them as the UTS. Section 5 shows how the UTS sharpens the notion of structure and thereby strengthens responses to several criticisms of OSR. Section 6 demonstrates how the theory illuminates further foundational problems, providing independent support for the universalization. Section 7 outlines the explanatory benefits that universalization confers upon ST itself. Section 8 addresses conceptual, empirical, and methodological objections to the identification of physical and mathematical structure. Section 9 evaluates the theory according to the classic theoretical virtues of unification, explanatory power, and simplicity, demonstrating how it compares favorably to alternatives.

2 Motivating realism about structure

John Worrall (1989) introduced structural realism by noting that the mathematical content of physical theories survives even radical theory change. He pointed to the equations governing refraction and reflection, which persisted from Fresnel's wave theory of light into Maxwell's electromagnetic theory, and the equations of Newtonian mechanics that can be recovered as a limiting case from the newer relativistic theory. Drawing implicitly on the structuralist philosophy of mathematics then gaining prominence, Worrall held that this mathematical content expressed *structural relations*. He therefore concluded that scientific realists should be structural realists.

This realism about structure was later extended by Ladyman (1998) to the metaphysical thesis that physical reality is fundamentally ontologically structural, a position known as OSR. However, subsequent discussions by OSR theorists have tended to characterize structure autonomously, often in incompatible ways, with little anchoring in the theoretical considerations that motivated realism about structure in the first place. These persistent ambiguities concerning the nature of structure have weakened OSR's claim to be a genuine realism (Arenhart & Bueno, 2015; Bueno, 2019; Muller, 2010).

The problem, I argue, stems from OSR adopting the terminology of the philosophy of mathematics without also considering its metaphysical implications. Chakravartty (2004) rightly emphasizes that securing a metaphysical foundation for structural realism requires moving beyond structure as a mere label for mathematical content and toward a substantive account of what metaphysical realism about structure entails. While McKenzie (2017) highlights that OSR has recently benefited from an increased engagement with a priori metaphysics, I argue for a pivot back to the philosophy of mathematics, the very field that inspired talk of structure in the first place, and where the concept remains most thoroughly developed.

3 The structuralist foundations of mathematics

This section outlines mathematical structuralism and distinguishes unifying foundations from metaphysical foundations. It details the principles of *ante rem* structuralism and their formalizations in various axiomatic theories, collectively referring to them as ST. This theory furnishes a fundamental ontology of *ante rem* structures whose explanatory reach is subsequently shown to extend well beyond mathematics.

3.1 Mathematical structuralism

The prevailing framework in the philosophy of mathematics is structuralism, whose motto is "mathematics is the science of structure." Structures are a novel type of entity, distinct from familiar physical objects and even unique among abstract entities, making them particularly challenging for our intuitions to grasp. Mathematical structuralism posits that the primary subject of mathematics is not individual objects, but the broader relational structures they constitute. For example, mathematics is about the natural number structure, whose individual objects, the numbers, have properties that are determined by their relations to the other numbers. If mathematical structuralism is correct, it seems that Worrall was on solid ground when he referred to the preserved mathematical content of physical theories as "structure." However, key issues remain: what is the ontological status of structures, and what metaphysical conclusions can be drawn from realism about them?

3.2 The inadequacy of unifying foundations

OSR theorists have often turned to set theory (Arenhart & Bueno, 2015), category theory (Bain, 2013; Lam & Wüthrich, 2015), and most recently the univalent foundations program (Chen, 2024) for insight into the nature of structure. While each of these frameworks has been argued to inform a philosophical analysis of mathematical structuralism, they do not, on their own, specify the nature or existence of structures. Shapiro (2004) argues they are best understood as *unifying foundations for mathematics*. These foundations seek to provide a single framework within which all of mathematics can be derived. They do provide tools by which the mathematical structure of physical theories can be represented,[1] but on their own, they do not supply the metaphysical clarity that OSR needs. Noting this gap, Arenhart and Bueno (2015, p. 128) ask: "perhaps the defender of OSR will claim that there is a metaphysical notion of structure underlying every kind of mathematical representation, something that the relevant mathematical tools simply are unable to grasp adequately." This inadequacy is precisely the case for the unifying foundational frameworks, which motivates a shift to the metaphysical foundations project for answers.

3.3 Metaphysical foundations

Shapiro (2004) describes the distinct task of providing a *metaphysical* foundation for mathematics. A central concern guiding this project is defining the relationship between structures and their instantiations in physical or abstract systems. A view called non-eliminativism holds that structures exist as real entities, which cannot be eliminated in favor of their instantiations. Within non-eliminativism, the *ante rem* variant offers a stronger realism: structures exist regardless of whether they are instantiated in physical or abstract systems. *Ante rem* structures exist *sui generis*, in their own right, not reducible to the existence of anything else.[2] Drawing from Shapiro (1997) and Călinoiu (2020), the principles of *ante rem* structuralism can be summarized:

> **Existence**: Structures exist, *sui generis*.
> **Positionalism**: Structures are constituted of positions and relations between them.
> **Restricted Structuralist Thesis (RST)**: Positions have a principled subclass of structural properties.[3]
> **Formality**: The relations of a structure are formal.[4]
> **Freestandingness**: The positions of structures can be instantiated by any other objects.
> **Coherence**: Coherent mathematical theories successfully characterize structures.[5]

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[1] Ladyman and French (2010), Landry (2007), and Proszewska (2022) have rightly advocated a pluralist and pragmatic approach to representing physical structure.

[2] The contrasting *in re* version of non-eliminative structuralism holds that structures depend on their instantiations for their existence, which would result in a vicious regress of structure and instantiation if it were to supply a fundamental ontology.

[3] Shapiro (1997) originally defined the structuralist thesis as the idea that positional objects in structures have *only* structural properties. Burgess (1999) quickly showed this formulation was inconsistent, because having no non-structural properties was itself a non-structural property. The RST states that positional objects have a principled subclass of structural properties, and defining that principled class has guided recent discussions.

[4] Relations are defined using only logical terminology and other objects and relations of the structure.

[5] The method of demonstrating coherence depends on the specific axiomatization of the principles of *ante rem* structuralism. According to Shapiro's and Leitgeb's accounts, coherent theories are those that are both deductively

Semantics: Mathematical discourse is about structures and their positional objects.[6]

These principles have been formalized into several axiomatic theories that precisify and systematize our understanding of *ante rem* structures. A formal axiomatic theory of structure, as opposed to a unifying foundational framework, would specify its own primitives, and use them to express identity and existence conditions for structures and their positions. It would provide an ontology and illuminate how mathematical languages are understood to be about that ontology. Table 1 summarizes the basic features of the currently available formal axiomatic theories of *ante rem* structures:

Table 1: Formal axiomatizations of the principles of ante rem structuralism.[7]

Theory / Proponents	Formal logic / Features	Restricted Structuralist Thesis
Sui generis structure theory by Shapiro (1997, 2008)	Second-order logic; re-axiomatization of model theory. The theory directly describes structures and their positions, using analogues of ZFC axioms to express the richness of mathematics.	Properties definable using the relations of a structure are structural.
Encoding structure theory by Nodelman and Zalta (2014) and amended by Murphy (2021)[8]	Second-order quantified S5 modal logic; abstract object theory + *ante rem* principles. The theory imports a mathematical theory and produces an abstract object (structure) encoding all the truths of that theory.	Encoded properties (a special mode of predication, whose properties are those required to make the defining theory's theorems true) are structural.
Unlabeled graph theory by Leitgeb (2020)[9]	Second-order logic with identity; graph axioms. Takes a theory of graphs, and produces an *ante rem* structure without relying on sets.	Isomorphism-invariant properties are structural.
Fregean abstractionist structure theory by Linnebo and Pettigrew (2014)[10]	First-order logic; Fregean abstraction principles. The theory imports a mathematical model (set-model) and abstracts away all non-structural properties to produce the *ante rem* structure.	Defines instantiation, purity, and uniqueness, showing how the abstraction operator produces an *ante rem* structure satisfying them.

consistent and model-theoretically satisfiable. Abstractionism presupposes coherence because it takes a mathematical model as an input. Murphy (2021) imports a coherence principle into object-theoretic structuralism, requiring that an abstract object (structure) cannot encode contradictory properties.

[6] If a mathematical theory is categorical, it describes a single intended *ante rem* structure. If a mathematical theory is algebraic, it intends to describe a class of *ante rem* structures. Singular terms of mathematical theories refer to positions in structures.

[7] Horsten's (2019) generic structure approach, which imports an arbitrary-object semantics into structuralism, offers an interesting perspective on *ante rem* structures, but does not yet furnish a dedicated formal axiomatization. Călinoiu (2020) provides a useful review of the advantages and objections to the various formalizations of ST.

[8] Murphy (2021) imports the principles of coherence, freestandingness, and formality that characterize *ante rem* structures into the abstract object theory of Nodelman and Zalta (2014). This limits the ontology to *ante rem* structures instead of all abstracta in abstract object theory.

[9] The framework is limited to unlabeled graphs, but Leitgeb argues that the overall approach may be generalizable to the rest of mathematics.

[10] Abstractionist structure theories are sometimes classified as *in re* as opposed to *ante rem*, because the method of defining a structure begins with a model. However, Linnebo and Pettigrew (2014) suggest that abstractionism is compatible with *ante rem* structuralism because once the structure is abstracted, it exists *sui generis*, no longer dependent

I use Structure Theory (ST) as a label for the broad metaphysical package encompassing the informal principles of *ante rem* structuralism and their various axiomatizations. This is novel terminology that requires justification. Some logicians may expect a label like ST to denote a specific formalization, but this need not be the case. Consider the analogous case of set theory, which does not single out a specific theory of sets, but instead serves as an umbrella term for the principles of collection, membership, and iteration that are common to various formalizations such as ZFC, NBG, and NF. I will use ST in the same flexible way.

I maintain neutrality regarding specific axiomatizations because there is no uniquely best formal axiomatization of the principles of *ante rem* structuralism. While it is important that ST *can* be formalized, the universalization of a fundamental ontology of structures depends largely on the informal principles that characterize that ontology. Whereas Muller (2010) and Lam and Wüthrich (2015) suggested that OSR should be based on a formal axiomatic theory of structure, my argument is a forerunner to that project. This should not be read as a retreat from formalization; instead, the approach applies to the entire class of formal theories. I will return to discuss where the specific formalization may matter for the universalization argument.

ST is a leading view in the metaphysical foundations of mathematics that provides a realist ontology of structures for mathematical discourse. Its key advantages over its eliminativist rivals are that it preserves a face-value semantics, and is not hostage to a canonical (physical or abstract) background ontology. ST still faces significant challenges, most notably the epistemological access problem, its handling of non-trivial automorphisms, and concerns about ontological extravagance. I will therefore adopt ST provisionally, and then show that once it is universalized to account for both mathematical and physical reality, it will gain a more powerful physical justification.

4 The universalization of a fundamental ontology of structures

ST can provide a fundamental ontology for OSR once it is universalized to include the physical universe in its domain. I decompose Tegmark's (1998, 2008) MUH into three elements: a weak (descriptive) MUH, a strong (identity) MUH, and a structure-theoretic component (updated to ST). The weak MUH leads directly to OSR's collapse problem, and the strong MUH dissolves the problem by embracing the identification rather than resisting it. This universalizes ST to account for all fundamental ontology, both mathematical and physical.

4.1 The weak (descriptive) MUH

Scientists and philosophers have long marveled at the extraordinary success of the mathematization of physical theory. Let the weak MUH denote the hypothesis that physical reality is exactly and completely describable by mathematics, such that a mathematical description of physical reality can exhaust the role of physics. It holds that mathematical theories can be not just approximate or idealized descriptions of physical systems, but exact ones. The

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on a system that instantiates it. The abstraction is therefore an epistemic route to metaphysically autonomous structures.

weak MUH implies the existence of a "Theory of Everything" (TOE) set of equations, which would, in principle, allow one to predict any physical outcome that can be predicted. The mathematical describability of the dynamical laws also extends to the actual states of reality.

The weak MUH shares with Epistemic Structural Realism (ESR) the assertion that the physical universe is amenable to mathematical description, but it differs in two key respects. Firstly, the weak MUH strengthens the claim of fidelity by asserting that the mathematical description is exact and complete. Secondly, the weak MUH remains neutral on the nature of mathematical ontology, avoiding ESR's commitment that the scientifically knowable part of reality is structural.

There are several motivations for considering the weak MUH. The first is the remarkable success of the mathematization of physical theory. The second is the survival of mathematical content through theory change. Finally, it is supported by Tegmark's (2008) External Reality Hypothesis, which holds that an observer-independent world demands a "baggage-free" language (mathematical) to describe it. These considerations motivate the weak MUH, but they do not strictly entail it. It is conceivable that the idealizations pervasive in physics provide space between the mathematical description and reality itself. However, the view is relatively uncontroversial, and is almost a working assumption in physics. An acceptance of the weak MUH, in the context of mathematical structuralism, leads directly to OSR's collapse problem.

4.2 The collapse problem

The relationship between physical and mathematical reality has been the source of much debate and controversy. Several commentators have pointed out difficulties in determining whether the theoretical terms of our physical theories refer to physical entities or to mathematical constructions (see for example Resnik, 1997). Reflecting on this issue, French and Ladyman (2003a, p. 45) note that OSR "blurs" the boundary between the physical and the mathematical, though they were quick to clarify that "blurring does not imply identity" (French & Ladyman, 2003b, p. 75).[11] This blurring of the mathematical and the physical culminates in what French (2014, p. 195) has called the "collapse problem" for OSR:

> If intrinsic natures are taken out of the picture and a 'purely' (however that is understood) structural description advocated, then it may become hard to discern any difference between the physical world and the mathematical world. Indeed, given the mathematization of science, and physics in particular, the structural description of the physical world may appear to be entirely mathematical… Hence, the concern runs, the structural realist must conclude that the world is a mathematical structure.

[11] Philosophical responses to this ambiguity vary. One strategy is to simply refuse to answer what distinguishes the physical from the mathematical, as Ladyman and Ross (2007) do. Esfeld (2011) and Psillos (2012) both highlight the problems for realism of not sufficiently clarifying the relationship. Cao (2003) argues that OSR is already committed to the identification of the physical with the mathematical, but Saunders (2003, p. 129) responds by taking issue with the commitment that physical structure is "merely" mathematical. French (2014) highlights several potential ways to distinguish physical from mathematical structure, finding causality the most promising, but none of them compelling, several of which I will return to in Section 8.1.

French acknowledges that the most natural way to solve OSR's collapse problem would be to identify the physical and the mathematical. However, he refers to this as "biting the bullet," and warns that it risks "falling prey to Platonism." Rather than viewing this identification as a concession to be feared, I argue that embracing the universal reality of a fundamental ontology of structures results in substantial explanatory and unificatory advantages.

4.3 The strong (identity) MUH

The collapse problem pressures the structural realist to clarify the relationship between mathematical description and physical reality. The strong MUH provides a direct solution by proposing the ontological identification of our physical universe with an *ante rem* structure. Once ST and the weak MUH are accepted, the strong MUH becomes a highly motivated conjecture in multiple ways. First, given that fundamental ontological kinds are scarce, it is rational to utilize the *sui generis* ontology of structures that ST already provides. Additionally, the weak MUH constrains our search to entities that admit of exact mathematical description, and *ante rem* structures uniquely satisfy this condition. Finally, *ante rem* structures are unbounded in complexity and size, so the ontology necessarily contains large, world-like structures consistent with our physical universe.

There are of course other interpretations of the weak MUH that posit that the physical universe is isomorphic to an *ante rem* structure, but possesses additional, non-structural features that make it 'physical.'[12] The inference from ST and the weak MUH to the strong MUH is therefore not a strict logical entailment, but an abductive one. It is now only provisionally adopted and will ultimately be justified by an inference to the best explanation. This will require a detailed consideration of its theoretical virtues, which the subsequent sections will develop. For now, the strong MUH emerges as a highly motivated hypothesis to consider.

4.4 The Universal Theory of Structure (UTS)

The adoption of the strong MUH results in the *universalization* of ST. The strong MUH does not add to the ontology of ST, but instead recognizes the physical universe as an entity already present in the ontology. This universalization expands ST's reach from the ontology of mathematics to include physical reality. This expanded reach comes at no additional complexity cost as the models of ST and the UTS are the same; there is only a difference in philosophical commitment.

Tegmark's MUH implicitly contained several distinct theoretical posits that I make explicit: a weak (descriptive) MUH, a theory of structure, and the strong (identity) MUH.[13] Several

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[12] This would align with ESR, where all we can know about the physical universe is its structure, but that it may also contain unknowable individual objects. This, however, is a complication that does no explanatory work. If the *ante rem* structures already exist and are sufficient to account for physics, why add another unexplained layer? One is welcome to defend the added ideology, but I am not motivated to do so. I will further discuss alternatives that accept the weak MUH but deny the strong MUH in Section 9.4.

[13] The main point of difference between the UTS and Tegmark's account concerns the structure-theoretic component. Notably, Tegmark (1998) did not reference Shapiro's (1997) first formal theory of structure. He clearly expressed an *ante rem* structuralist view of mathematics, but the structure-theoretic was informal and somewhat underdeveloped.

considerations motivate a re-labeling of the main idea. First, the result of combining ST with the strong MUH is no longer a hypothesis; it is better characterized as a theory. Second, the ontology is structural, not mathematical per se. It goes beyond the claim that the physical universe is described by mathematics to the claim that it is an *ante rem* structure. Finally, formulating the weak MUH without a dependence on ST allows it to stand on its own independently of our philosophy of mathematics. For these reasons, I will refer to the overall metaphysical package as the UTS, and reserve the weak/strong MUH labels for the specific hypotheses they denote. A definitional recap may prove helpful:

> **ST:** Structures exist *sui generis*; mathematics is the language that describes them.
> **Weak MUH:** The mathematical description of the physical universe is exact and complete.
> **ST + Weak MUH → Strong MUH:** Our physical universe is an *ante rem* structure.
> **UTS = ST + Strong MUH:** Only *ante rem* structures exist fundamentally; our physical universe is one of them.

The central conjecture can now be summarized. In the context of mathematical structuralism, the weak MUH generates the collapse problem for OSR. If one already accepts a vast ontology of mathematically describable and world-like structures, a direct solution to the collapse problem is to identify the physical universe with one of them. This identification universalizes ST to become the UTS, expanding its reach to account for the fundamental ontology of both mathematical and physical reality. Since each *ante rem* structure is understood as a universe unto itself, I refer to the class of all structures as the *structural multiverse*. Having established the theory, I now demonstrate how it provides a theoretical foundation for OSR.

5 Applying the UTS to the problems of OSR

The UTS sharpens OSR's vague slogan "structure is all there is" into a precise identity thesis that our physical universe is an *ante rem* structure. This allows for improved responses to a number of criticisms of OSR regarding the collapse problem, representation and realism, the status of objects, intrinsic properties, and causality. Ultimately, the UTS helps secure OSR's status as a substantive metaphysical doctrine. While French (2014, p. 207) warned that "the advocate of OSR cannot simply adopt the strategies of mathematical structuralism," I argue that a careful adoption is both possible and beneficial.[14]

5.1 Collapse

His (2008) paper did include formal modelling tools for a large class of finite and computable structures, but in his appendix, he deferred to model theory for precision, which as discussed is not itself a theory of structure. Overall, his account reads more like a descriptive inventory of structures than a metaphysical theory of structure. This motivates our turning to the metaphysical foundations of mathematics, and specifically to formal theories of *ante rem* structures.

[14] Morganti (2011) suggests that applying the strong MUH to solve problems with OSR is "revisionary." However, I argue that blocking its adoption requires extra, unmotivated moves. Furthermore, there are abundant reasons to consider the strong MUH independent of its benefits to OSR; indeed, these benefits were not central to Tegmark's (1998) original proposal, which was conjectured concurrently with OSR (Ladyman, 1998).

The strong MUH dissolves OSR's collapse problem by embracing its conclusion. According to the UTS, the physical universe is what it appears to be, namely an *ante rem* structure. Physicality is no longer understood as an objective property of a structure, but is instead understood as an indexical property of an observer. An *ante rem* structure is physical from the perspective of an observer within it. This allows us to distinguish the physical from the mathematical without recognizing an objective difference, which French (2014) points out may be necessary lest OSR fall on the wrong side of the boundary. This reveals that the collapse problem did not stem from OSR's core tenets, but from unmotivated attempts to distinguish physical and mathematical reality. I will return in Section 8.1 to various attempts to distinguish mathematical from physical reality and thereby avoid the collapse problem. Even if the collapse is embraced, OSR must still clarify the relationship between reality and its mathematical representations.

5.2 Representation and reality

A central challenge for OSR is clarifying what exactly it is realist about. Chakravartty (2007) and Bueno (2019) have both argued that it is insufficient to say we are realists about structure without explaining what structure actually is. Instead of directly characterizing structure in realist terms, OSR theorists often only speak of structure in terms of its mathematical representations. For example, Ladyman and Ross (2007, p. 158) suggest that the "world-structure" simply exists and can be mathematically represented, and Wallace (2022, p. 28) likewise states that fundamental reality can be "exactly and completely" represented by a mathematical structure. These representational claims leave them without a clear realist account of the fundamental ontology. The core problem, as Muller (2010) emphasizes, is that without an actual theory of structure, OSR risks going without a viable account of reference, leaving it unable to say what the physical universe is beyond 'that which is represented.'

Ladyman, Ross, and Wallace complicate the ontological picture by relying on a two-step representational hierarchy, where mathematical models (like set-models) represent structures, which in turn represent physical reality. However, the lesson of the collapse problem is that there is no way to distinguish physical reality from a mathematical structure, implying a relationship of identity, not one of representation. The UTS offers a more direct account by making a crucial distinction: mathematical models do the representing, while *ante rem* structures, including our physical universe, constitute the reality that is represented.[15] This move avoids circularity because *ante rem* structures are independently characterized by ST. Identifying our physical universe with an *ante rem* structure is precisely what allows us to distinguish metaphysical reality from its mathematical representations, thereby strengthening OSR's status as a genuine realism.

The sense in which the UTS supports OSR's claim to be a realism about physical theory can now be stated. A physical TOE (implied by the weak MUH) should be understood as a mathematical model that exemplifies, and thereby represents, the *ante rem* structure that is our

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[15] Mathematical models can represent *ante rem* structures because of the freestandingness of the structures. What is an object from one perspective can be an office from another (Shapiro, 1997). These offices can be occupied by any system of objects that satisfies the relations, including the sets of a mathematical model. The mathematical model therefore represents the structure by providing a system that exemplifies it.

physical universe. According to Wallace's (2022) "math-first" physics, which is a natural companion to the UTS, the relationship between the TOE and physical theories such as the Standard Model of Particle Physics (SM) is one of *instantiation*. This is a mathematical relationship where a substructure of the TOE's models realizes the structure of the models of the SM.[16] According to this account of inter-theoretic relations, the SM succeeds in (approximately) representing our *ante rem* structure. So, the SM is *non-fundamental* in the sense that its representational success is domain restricted and approximate. However, we should be *realists* about the SM in the sense that it successfully represents what is fundamental (our *ante rem* structure), including its unobservable features. The UTS thereby grounds scientific realism about physical theories in a robust realism of the fundamental ontology.

5.3 The status of objects

The status of objects in OSR has long been debated. French (2010) maintains that objects can be eliminated altogether in favor of a purely relational metaphysic, while others like Ladyman and Ross (2007) and Esfeld and Lam (2008) argue that OSR only requires that its objects be "thin" in the sense that all their properties are determined by the relations they take part in. I argue that ST clearly aligns with a non-eliminativism about objects. I then distinguish fundamental positional objects from familiar scientific ontology such as quantum fields, which likely belong to non-fundamental ontology.

According to ST, structures are constituted of positions and relations between them, and positions are treated as bona fide logical objects by each of ST's formalizations. This entails a face-value semantics: when we refer to the number '3,' we are referring to a genuine object, namely the third position in the natural number structure. While van Fraassen (2006) was concerned that eliminativism about objects risked collapsing the mathematics/physics divide, the UTS implies the opposite: that identifying physical and mathematical reality actually secures a non-eliminativism about objects. It is important to clarify that just because structures have objects does not imply that they have metaphysical individuals. Metaphysical individuals are a particular kind of object, one that is self-subsistent and has an intrinsic nature. On the contrary, positional objects such as the numbers are metaphysically "thin" in the sense required by the RST.

Having established the existence of fundamental positional objects, we must address the status of familiar scientific entities like genes or electrons, which likely occupy a non-fundamental ontology. The UTS is strictly a theory of fundamental ontology, and is not committed to any specific account of the non-fundamental. However, mentioning a promising account will help clarify the distinction and the stakes.

It has become popular for OSR theorists to appeal to the concept of a *real pattern* in order to characterize the ontology of scientific theories. Ladyman and Ross (2007) combine their structuralist metaphysics with a real pattern account of scientific ontology, and more recently

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[16] Wallace (2022, p. 16) goes on to clarify: "In the important case of state-space instantiation... the lower-level theory instantiates the higher-level one if (roughly) there is a map from the lower-level state space to the higher-level state space that commutes with the dynamics and leaves invariant any commonly-interpreted structures (for instance, spacetime structure) in the two theories."

Wallace (2022) has done the same in a way that is highly compatible with the UTS.[17] Wallace describes familiar scientific ontology such as particles and fluids as derivative entities that are the result of "predicate precisifications" of mathematized theories. These ontologies are pragmatic constructs used to speak about the theory in the language of the predicate logic, rather than in the native (mathematical) language of the theory. High-level ontologies of the special sciences are understood as real patterns in the behavior of the low-level ontologies of physics, and the entire ontology is unified at the level of the fundamental mathematically represented structure. What makes a real pattern *real* is that it successfully carries compressed information about what is fundamental, namely the lower-level theory, by way of an inter-theoretic instantiation relationship mentioned in Section 5.2. This framework allows us to distinguish between two types of objects:

> **Fundamental objects**: the positions that constitute *ante rem* structures.
> **Non-fundamental objects**: such as real patterns, that exist within and depend on structures.

Consider an application of this distinction. Some OSR theorists treat quantum fields as if they were fundamental positional objects, but this is not necessarily the case, and we have some reasons to suspect they are not fundamental. In the mathematics of, for example, the Wightman axiomatization of Quantum Field Theory (QFT), quantum fields are defined as operator-valued distributions. However, operator-valued distributions are too complex to be positional objects. ST tells us that singular terms of mathematical theories refer to fundamental positional objects, and operator-valued fields are not singular terms in the mathematics of QFT. An alternative understanding of quantum fields is given by Wallace's (2022) account, where quantum fields are understood as derivative entities resulting from predicate precisifications of the more fundamental mathematized theory (QFT). While these considerations do not definitively reject the fundamentality of quantum fields, they are suggestive enough to bear upon the intrinsic property objection to OSR.

5.4 Intrinsic properties

A persistent objection to OSR targets what McKenzie (2016) terms "fundamental kind properties." These properties such as mass, charge, and spin have been argued to be intrinsic properties of objects, violating even a moderate OSR's commitment to "thin" objects. For example, Berghofer (2018) argues that quantum fields have non-relational, intrinsic properties, and therefore that OSR is refuted. The UTS provides new ways to counter this objection by questioning the fundamental status of the objects involved and clarifying the appropriate standard of relationality.

For Berghofer's objection to work in the present context, quantum fields must be understood to be fundamental positional objects. The RST applies strictly to positional objects, requiring them to have a principled subclass of relational properties. While Berghofer (2018) may

[17] Wallace (2022) deploys the real pattern concept originally developed by Dennett (1991), and expanded upon by Ladyman and Ross (2007), Suñé and Martínez (2021), Millhouse (2022), and Wallace (2024).

be justified in his claim that quantum fields are *the most fundamental* objects according to physical theory, that does not mean that they can be equated with fundamental positional objects. As previously discussed, it is far from certain that quantum fields are positional objects.

Even if quantum fields were fundamental positional objects, Berghofer (2018) applies an inappropriate standard of relationality. He cites Langton and Lewis' (1998) "standard" definition of intrinsic properties as those that exist "independent of accompaniment or loneliness," and uses that standard to argue that quantum fields have non-relational properties.[18] Yet this is an example of OSR theorists using an autonomous definition of relationality, unmoored from the relevant theoretical considerations that motivated structural realism in the first place. We are concerned with structural relations because it is the mathematical content of physical theories that survives theory change. This mathematical content, by the core principles of mathematical structuralism, expresses structural relations, as classically evidenced by the fact that mathematics only characterizes its subject matter up to isomorphism.[19] It follows that if a physical theory is mathematical, then the reality it describes must be relational in the relevant sense. If this were not the case, then we would be debating whether *ante rem* structures are sufficiently relational.

When this mathematically definable standard of relationality is applied, Berghofer's (2018, pp. 7, 14) examples cease to be a problem for OSR. While the Higgs field's non-zero vacuum expectation value "is what it is," it is nonetheless a mathematically defined value (246 GeV) within the theory. Similarly, while a field's spin has its value "irrespective of whether there are other fields," it also takes specific well-defined mathematical values (0, ½, 1). Non-relational properties would be those that are not mathematically defined by the relevant physical theories, and since Berghofer's examples are not of that kind, his argument poses no problems for an OSR based on the UTS.

5.5 Causality

The ambiguity of the slogan "structure is all there is" allows for the interpretation that physical reality is composed of a plurality of distinct structures that must be causally related. Since *ante rem* structures are typically understood to be non-causal, this presents a dilemma. For example, Chakravartty (2007, p. 155) claims that OSR supplies no "causal links" between structures, and Psillos (2006, p. 568) argues that OSR has no ability to bind together a world of "free floating structures."

The UTS resolves this dilemma by clarifying the domain of causation. No causal links are required between structures because structures are not the causal relata. Consider that all of physical reality, including all of spacetime, its particles, fields, and initial conditions, are aspects of a single *ante rem* structure. Therefore, the fact that structures are non-causal with respect to each other is not problematic because no one is claiming that our physical universe causally

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[18] Several defenders of OSR such as French and Ladyman (2010) and Esfeld and Lam (2011) have argued that intuitively intrinsic properties can still be understood through various notions of relationality.

[19] Mathematical structuralists have debated the definition of a relational (structural) property, but Langton and Lewis' definition is not viewed as appropriate for this context. Korbmacher and Schiemer (2018) distinguish between two general approaches to defining a structural property of invariance and definability, and conclude that there is no single correct definition. See also Schiemer and Wigglesworth (2019) and Assadian (2025).

interacts with other universes (other *ante rem* structures). The relevant question is how causality operates *within* structures, not *between* them.

The UTS helps neutralize the causality objection to OSR, but it does not itself commit to a positive theory of how causality should be understood. I will mention an interesting proposal by Andersen (2017), who argues that real patterns can serve as causal relata, where causal relationships are informational relationships between real patterns. The informational relationships stem from a "rich causal nexus," which in this case is the relational structure upon which those real patterns depend and carry information about. An advantage of this approach is that the causal relata are decidedly not "free floating," because these non-fundamental real pattern objects depend on and exist within the more fundamental relational web. This aligns with French's (2006) proposed defense of OSR that structural relations themselves yield the causal power.[20]

5.6 The philosophical status of OSR

McKenzie (2024) raises the concern that OSR has struggled to establish itself as a robust metaphysical doctrine. She argues that OSR often characterizes its notions of structure and object in vague, flexible ways that undermine our ability to substantiate its claims. She argues that OSR risks being better viewed as a mere philosophical stance, whereby OSR theorists abide by the general principle that "the language of physics is mathematics." The UTS offers relief by shifting OSR's fundamentality thesis from "physical reality is structural" to the more metaphysically substantive "physical reality is an *ante rem* structure." This gives much needed clarity concerning what is at stake in the metaphysical picture.

The theory also provides a response to McKenzie's (2024) specific challenge that OSR take a position on whether quantum fields are objects or structures. Tegmark (2008, p. 3) points out that despite the unfinished business in axiomatic field theory, one can view the SM as a whole as describing a structure of "operator-valued fields on $\mathbb{R}^4$ obeying certain Lorentz-invariant partial differential equations and commutation relationships, acting on an abstract Hilbert space." It is widely believed that this structure is not isomorphic to our physical universe, but Tegmark argues that this is a case of a simple structure (the SM) providing a good approximation of a more complex structure, namely our physical universe. So, the SM describes an *ante rem* structure, but what of the status of quantum fields?

The UTS implies that quantum fields are not structures, because quantum fields are entities that exist within the structure of the SM itself. This means we can give a definitive answer to McKenzie's challenge: quantum fields must be objects. I have argued that they are more likely to be non-fundamental real pattern objects than fundamental positional objects, but this question is properly addressed by a theory of the non-fundamental. Even without settling this score, OSR

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[20] It is not clear that causality is a necessary desideratum for a metaphysical account of the fundamental ontology. Ladyman and Ross (2007) note that causal notions become less important to science the closer to fundamental physics one gets. Our most fundamental physical theories like the SM do not employ causal notions at all. Ladyman and Ross instead hold that causation is better understood as a notional-world concept that is (potentially indispensably) useful for tracking the entities of the special sciences. On this reading, an account of causality is properly owed by a theory of non-fundamental ontology.

theorists are no longer merely enjoined to take the mathematics of physical theories seriously, but can now provide substantive answers about what structures and their objects are, and are not. This helps secure OSR's standing as a consequential metaphysical doctrine.

6 Addressing foundational problems

Beyond fortifying OSR against criticism, the UTS also offers additional insights into important foundational problems. These include the applicability of mathematics to the empirical sciences, the particular form of our physical universe, and the existential question of why anything exists at all.

6.1 Applicability (or, why math?)

The applicability of mathematics to the empirical sciences has long been marveled at, with Wigner (1960) famously calling it "unreasonably effective." A recent analysis by Baker (2011, p. 255) highlights the "indispensable and explanatory" aspects of applicability that have most resisted satisfactory explanation. The UTS offers the most direct solution:

> **Premise 1:** Mathematical theories describe *ante rem* structures (ST).
> **Premise 2:** Our physical universe is an *ante rem* structure (strong MUH).
> **Conclusion:** Mathematical theories describe our physical universe.

OSR already suggests that because physical reality is structural, and mathematics is the science of structure, mathematics naturally applies to the physical universe. The UTS grounds this partial solution by explaining *why* reality is structural, by identifying the physical universe as a specific *ante rem* structure, no different in kind from those studied in mathematics. Consider also Maudlin's (2014, p. 52) comments on the problem: "The most satisfying possible answer to such a question is: Because the physical world *literally* has a mathematical structure." However, this raises the question of what *has* the structure and why it does. An even more definitive answer is that the physical world literally *is* an *ante rem* structure. From this perspective, the unreasonable effectiveness of mathematics can be put another way: why does our universe appear to be a structure? Answer: because it is one. This explanation for the 'why math' problem naturally leads to the 'why this math' problem.

6.2 Particularity (or, why this math?)

We now understand that there are many different sets of equations that could describe a universe similar to our own. This raises the question, which Tegmark (2008, p. 127) attributes to John Wheeler: "Why these particular equations, and not others?" A second, related problem of particularity concerns why our particular equations appear fine-tuned for the existence of life.

The UTS solves the first particularity problem by pointing out that our physical universe is not the only structure. Other structures exist as well, and they are described by different sets of equations. This means the particularity of the equations that describe our physical reality does not signify anything profound, but is merely our "cosmic address" (Tegmark, 2008). If there are physicists living in other structures, they too are wondering why their laws have the particular forms that they do. Importantly, the structural multiverse is not postulated ad hoc in order to explain particularity; rather, it is a direct consequence of ST, which was adopted in Section 3 for independent reasons. The benefit is a case of explanatory consilience.

The second particularity problem concerns why we live in a structure that is improbably suited for life. Conventional fine-tuning arguments such as those reviewed in Barnes (2012) center on the claim that the constants and initial conditions of our physical laws seem delicately balanced to allow for the emergence of life. Proposals like a physical multiverse[21] offer a partial explanation, but they do not address why the global structure, or what Tegmark (2008, p. 128) calls the "master laws," also appears fine-tuned. In the class of all structures, few support life. Why are we so lucky? The fact that our structure supports life is unproblematic because our existence as observers is effectively paid for by an overwhelming emptiness in the rest of the structural multiverse. An anthropic argument of this kind often stirs controversy over what exactly is being explained. It does not imply that our universe is *typical* of life-supporting ones. That is a stronger assertion, and one whose validity I will contest in Section 7.2. It also does not on its own explain the existence of the relevant multiverse; that is the subject of the next subsection. This explanation simply acknowledges the weak anthropic principle: within a vast structural multiverse, the existence of a life-supporting structure, however rare, is unsurprising.

If particularity is explained by the existence of *other* structures, then the improbability of life is explained by the existence of *many others*. This response leads to the question of the existence of the structural multiverse, which I address in the following section.

6.3 Existence (or, why any math?)

The existential problem is often dismissed as meaningless or claimed to be beyond the scope of reason. Leibniz took the problem seriously, arguing there must be *some* reason for its existence, and Heidegger understood it to be the central problem for metaphysics. The UTS allows for a reframing of the problem that eases the explanatory burden while opening up promising explanatory avenues.

The UTS proposes a unified fundamental ontology where everything that exists is, or depends upon, a structure. The 'why anything' existential problem is therefore recast as a 'why do structures exist' problem. This is an easier problem, because we only have to explain why one fundamental kind exists. This already represents progress on the existential problem compared to dualist (or worse) fundamental ontologies. Furthermore, of all the theoretical kinds that one might claim to exist, structures are perhaps the least difficult to accept. Shapiro (1997) notes that almost all mathematicians are "working realists," in that they act and talk as if structures exist, regardless of whether they claim to be philosophical realists; and there are also plenty of those as well.

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[21] The physical multiverse exists within the single *ante rem* structure we call our universe. It includes observer bubbles, quantum worlds, and inflationary pockets. The structural multiverse refers to the class of completely disconnected *ante rem* structures.

Part of the reason that structures are easier to accept into one's ontology is that a structural metaphysic reduces the existential burden. While a materialist metaphysic can be said to be constituted of metaphysical individuals (not reducible to relations) together with relations, a structuralist metaphysic rejects the individuals, requiring only relations and "thin" positional objects that connect them. While structuralism is criticized for its lack of individuals, it has a clear existential benefit: there is simply less to account for ontologically, and self-subsistent individuals were the more difficult part, given their independent and irreducible nature. Explaining the existence of a structure of relations is easier than explaining the existence of a world of material individuals.

This deflates the existential problem, but does not yet offer a positive account as to *why* structures exist. One possible line of argument appeals to the necessity of their existence. The logicists Hale and Wright (2001) and Hale (2013) have put forward arguments that structures exist necessarily because of certain logical properties that themselves exist of necessity. More recently, Leitgeb et al. (2025) have suggested that structures exist necessarily because the truths that organize their elements and relations can be reduced to logic and analytic truths alone.[22] Shapiro (1997, p. 82) has also argued that the existence of mathematical structures is necessary, because to deny the existence of a structure is effectively to deny the existence of its coherent description. Reflecting on the necessary existence of mathematical truth, Rickles (2009) argues that the existence of the physical universe is best explained by its identification with a mathematical structure. This is only a sketch of a plausible account, but it does support the idea that *ante rem* structures are more amenable to existential explanation.[23]

The three foundational problems of applicability, particularity, and existence should not be dismissed as intractable "pseudo-problems." Instead, they should serve as crucial standards for evaluating any candidate metaphysical theory. The challenges faced by empirical science and philosophy in addressing these problems should not diminish their importance; nor should they dissuade us from pursuing new modes of explanation that can better address them.

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[22] Jannes (2009) objects to the strong MUH on the grounds that mathematical truth may not be objective. Yet one wonders what is objective if not mathematics, and Shapiro (2007) argues that mathematical truth meets a broad range of criteria for objectivity.

[23] Further arguments for the existence of *ante rem* structures appeal to the objective coherence of mathematical truth. Shapiro (1997) distinguishes between two forms of mathematical realism: realism in truth-value and realism in ontology. Interestingly, one can hold that mathematical statements are objectively true without committing to the independent existence of the entities those truths are supposedly about. This foregrounds the significance of the objectivity of mathematical truth, which Penrose (2004) suggests is the very essence of mathematical reality: "Platonic existence… is really just the objectivity of mathematical truth". This implies that mathematical truth itself has a metaphysical quality, a perspective echoed by Nodelman and Zalta (2014): "While traditional understandings of structuralism focus on mathematical entities, our view is that a structure is composed of the truths that organize its elements and relations". This focus on mathematical truth lends support to a coherentist framework, where what makes mathematical truths *true* is not a correspondence to a separate prior existing reality, but instead their coherence within self-contained structures of truths. Some structures of truths simply are objectively coherent, while others are not. This perspective has a key advantage: it is easier to accept the necessary existence of a structure of truth than it is to accept the necessary existence of a corresponding abstract entity. The dictum of the prominent coherence theorist Bradley (1907) seems prescient from this perspective: "Our one hope lies in taking courage to embrace the result that reality is not outside truth". The UTS points to a conception of reality that is not outside truth, but instead to one that identifies reality with the very structure *of* truth.

7 The benefits of universalization for ST

Having established how the UTS provides explanatory benefits for problems concerning the physical universe, I now turn to how the universalization of ST also helps to address problems internal to ST itself. These concern motivating the *ante rem* existence of structures and responding to the epistemological challenge to mathematical realism.

7.1 Motivating *ante rem* existence

The indispensability of mathematics to the empirical sciences has long been a central argument for mathematical realism. However, the indispensability argument does not specifically support *ante rem* realism over its *in re* counterpart. Consequently, proponents of *ante rem* structuralism have looked to the philosophy of mathematics, rather than physics, for further support.

The strongest argument in favor of *ante rem* realism emphasized by Shapiro (1997) centers on its semantic advantages. He argues that *ante rem* structuralism allows us to treat positions within structures as bona fide objects referred to by singular terms. This avoids the vacuity problem faced by *in re* structuralism. However, Assadian (2018) argues that the semantic argument faces significant challenges of its own, and concludes that proposed solutions to the problem of singular reference fail to privilege *ante rem* structuralism over its eliminativist rivals, undercutting the view's primary motivation.

The UTS shifts the argument for *ante rem* realism from semantic grounds to physical ones. On the one hand, we know the physical universe exists, though we struggle to explain why it does. On the other, we are not sure whether *ante rem* structures exist, though we would not be surprised if they did. By identifying our physical universe with an *ante rem* structure, we exploit this asymmetry to gain a unique explanatory benefit: the certain existence of our physical universe confirms the existence of at least one *ante rem* structure. This specifically supports an *ante rem* realism, and offers a physically motivated argument, and indeed requirement, for the existence of structures beyond the contested semantic considerations.

7.2 Epistemological access

The epistemological access challenge has long been a central challenge for any realist ontology for mathematics, and the UTS offers new resources to address it. Shapiro (1997, 2011) argues that mathematical structuralism provides significant epistemological advantages over standard Platonist ontologies. He describes a three-component epistemology for *ante rem* structures. It begins with pattern recognition, where a subject observes systems of physical objects arranged in various ways and abstracts a structure from the systems, yielding knowledge of small, finite structures. The second component is a faculty of projection, where the subject notices that finite structures themselves exhibit a pattern, and they project beyond their experience, eventually yielding knowledge of infinite structures like the natural numbers. The most powerful technique is implicit definition, where a subject grasps large or complex structures through implicit definitions, which successfully characterizes a structure if the description is coherent. MacBride (2008) acknowledges that Shapiro gives a largely adequate descriptive account of mathematical epistemology, but argues that Shapiro fails to account for our warranted belief in that knowledge. MacBride (2008, p. 156) highlights the unexplained challenge being that mathematicians are said to be producing knowledge about a causally disconnected realm: "it appears that mathematicians must do the impossible: they must transcend their own concrete natures to pass over to the abstract domain."

Shapiro (2011) responds by pointing out that *ante rem* structures are not located *elsewhere*, because they are not located *anywhere*. The UTS strengthens the argument against the need for a causal (or otherwise) interaction with a separate abstract realm. The theory holds that we literally live inside an *ante rem* structure, allowing us to know at least our own structure through direct empirical methods. While living within an *ante rem* structure does not guarantee knowledge of it, it does make the acquisition of that knowledge far less mysterious. No 'transcendence' is required, because physical observation is already the receipt of signals from the domain in question. Our beliefs are warranted because the source of our knowledge (the physical universe) is identical to the object of our knowledge (*ante rem* structures).[24] Consequently, the access problem is solved not by bridging a metaphysical gap, but is dissolved by the recognition that no such gap exists. This demonstrates that no clear separation exists between the ontology *or* epistemology of mathematics and the empirical sciences.

8 Responding to objections

The strong MUH often faces summary dismissal due to conceptual, empirical, and methodological objections; this section addresses them.[25]

8.1 Conceptual objections

There are several ways used to distinguish physical reality from mathematical reality and thereby avoid the conclusion of the collapse problem. This section responds to the proposed distinctions of abstractness, instantiation, interpretation, surplus, and suitability.

8.1.1 Abstractness

Abstract entities are typically defined in contrast to concrete entities by negation; specifically, by their lack of spatiotemporal and causal properties. Abstract entities are 'nowhere,' 'nowhen,' and they 'do nothing.' I argue that the lack of concrete properties is exactly what qualifies *ante rem*

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[24] Beni (2019) argues that the epistemological challenge extends to OSR, contending that the causal separation between mathematical structures and physical reality precludes an "intelligible account" of their relation, rendering their correspondence a "massive coincidence". The UTS dissolves this problem by identifying the physical universe with the *ante rem* structure, thereby eliminating the causal gap.

[25] A formal objection that does not fit into these categories is that Gödel's incompleteness theorems might pose a problem for the strong MUH (see Hut, Alford and Tegmark, 2006). However, Gödel's theorems are about the limitations of formal systems; they are not about the existence or coherence of structures. The various formalizations of ST have no qualms with Gödel incomplete structures. Furthermore, Gödel himself viewed his theorems as suggestive of realism, because they showed there is more to truth than provability. In that sense, we have more evidence for the existence of structures defined by incomplete theories, not less.

structures to be identified with our physical universe, and that the intuitive rejection of abstractness is the result of conflating two distinct perspectives on structures.

In terms of causality, when Busch (2003) and Pooley (2005) discuss Shapiro's formal theory of structure as a potential basis for OSR, they reject it because the non-causal nature of *ante rem* structures supposedly disqualifies them from accounting for a physical world full of causation. French and Ladyman (2003b) and Esfeld (2009) each explore the possibility that physical structure has causal properties over and above its mathematically defined ones. However, this additional causal ideology is not necessary, because as argued in Section 5.5, causality is best understood to occur within structures, not between them. Until an argument is presented that establishes that causality cannot happen within an *ante rem* structure, causality cannot be used to leverage a distinction in kind between the physical universe and *ante rem* structures.

The second feature used to distinguish the abstract from the concrete is spatiotemporality. Markosian (2000) defines physical objects as those that possess a spatial location, distinguishing them from abstract objects that do not. However, if physical objects must exist in spacetime, then spacetime itself, which is undeniably physical, would not count as physical, since spacetime cannot exist 'within' itself. The UTS resolves this tension by clarifying that our *ante rem* structure does not exist in spacetime, but instead that spacetime exists within our *ante rem* structure. This entails a commitment to what has been called the adynamical model of reality, the block interpretation of time, or simply the B-theory. The core idea of this adynamical model is that structures do not change; instead, they *contain* change. On this reading, spatiotemporality is a property applicable to objects within our physical universe, but not to the universe as a whole. Consequently, it also cannot serve to distinguish our physical universe from *ante rem* structures.

Critics who demand that *ante rem* structures possess spatiotemporal or causal properties should be careful what they wish for. If *ante rem* structures were located in our spacetime, or if they did occasionally bump into us, they would cease to be viable candidates to identify with our physical universe because they would instead be objects within our universe. The fact that *ante rem* structures are 'nowhere,' 'nowhen' and they 'do nothing' is precisely what qualifies them to constitute the fundamental ontology. To explain the persistent intuition that there is a disqualifying distinction, Tegmark (2008) distinguishes two perspectives on structures:

> **The external, adynamical, "Bird's-eye" perspective:** The perspective of a mathematician studying the *ante rem* structure from the outside. The structure is a static, immutable, unchanging entity, with the entire history of the universe existing within it. Observers are understood as complex information processing patterns in the structure. From this perspective, structures are characterized as abstract.
>
> **The internal, dynamical, "Frog's-eye" perspective:** This is the perspective of an observer living within the *ante rem* structure. The observer experiences themselves as a time-traveler, flowing from one moment to the next in a constantly changing state of reality. From the perspective of such an observer, their own structure will feel uniquely concrete.[26]

[26] In a classical reality, what would appear as point-mass particles moving about in $\mathbb{R}3$ according to Newton's laws in the dynamical model would appear as coupled curves in $\mathbb{R}4$ in the adynamical model. More generally, the continuous

Our physical universe *feels* concrete to us simply because we are frog-eyed observers embedded within its structure. We are bound to our structure, inseparable from it, and caught up in its relational web. We call our structure concrete because it is more consequential to us than other structures are. Concreteness is revealed to be perspectival, applicable to entities within one's own structure but not to structures themselves, and is therefore unable to mark an objective physical/mathematical distinction.

8.1.2 Interpretation

Some have claimed that what distinguishes physical structure from mathematical structure is the presence of a suitable interpretation. As French and Bueno (2018) put it, physical content enters when we relate abstract structures to observation, experiment and measurement. However, the ability to interpret an *ante rem* structure in a testable manner is an epistemic, not an ontological requirement. Tegmark (2008) acknowledges that physicists are not satisfied knowing the structure alone; they also seek an interpretation connecting it to observables. For example, if someone did produce a mathematical model that was claimed to be isomorphic to our physical reality, physicists would be unable to evaluate it without an additional set of coordination rules. However, there still would be a fact of the matter as to whether that model was isomorphic to our physical universe. The interpretation allows us to *do* physics and test the structure, but it is not an ontic feature of the structure itself. Reality is surely indifferent to our quest to understand it.

Physics might even be able to proceed without an external interpretation. Tegmark proposed a method of using the automorphism group of a structure, which encodes the structure's internal symmetries, to compute the dynamical laws of the structure.[27] This method highlights where the specific formalization of ST may prove physically significant, because the various formal theories handle non-trivial automorphisms in starkly different ways. Some may be incompatible with Tegmark's method, while others might explain the symmetries with different ontological commitments. The UTS therefore brings new physical urgency to this problem, while also offering a potential physical constraint to evaluate the formal theories of structure.

8.1.3 Instantiation

A common objection, raised by Psillos (2006) and Cao (2003), is that *ante rem* structures are not instantiated and so cannot be identified with our instantiated physical universe. This objection relies on an *in re* conception of structure that holds that structures exist but not *sui generis*. However, the whole point of *ante rem* structuralism, and the formal theories of structure that express its principles, is that structures exist independent of instantiation. For *ante rem* structures, instantiation is also an epistemic rather than an ontological requirement. Instantiation is analogous to representation or modeling. When we instantiate an *ante rem* structure, we model it

global symmetries of the adynamical action correspond, via Noether's first theorem, to conservation laws in the dynamical picture.

[27] See Bernal, Sánchez, and Soler Gil (2008) for work in this direction.

as a physical or abstract system that we can manipulate and study. For example, we might model a finite number structure with a collection of physical objects, or we might model the entire natural number structure as a set-model of Zermelo ordinals. Likewise, physicists instantiate aspects of our physical universe in their mathematical models. In both cases, the instantiation serves as a way to represent and study the *ante rem* structure, not as a means to bring it into existence. *Ante rem* structures exist *sui generis*, in their own right, whether or not we have constructed models of them. This is precisely what makes them suitable candidates for a fundamental ontology.

8.1.4 Surplus structure

Another conceptual distinction between physical and mathematical reality concerns an apparent mismatch in scope. French and Ladyman (2003b) suggest that the realm of mathematics appears far broader than what is required to describe physical reality. There are two readings of this surplus structure objection to consider - representational and ontological - and neither one proves problematic for the UTS. On the contrary, I argue that they help illustrate an important distinction between the mathematical descriptions and the metaphysical reality.

The first reading of surplus structure concerns features like classic gauge redundancies. French and Ladyman (2003b) cite Redhead's (1975) notion of surplus structure, which highlights that many gauge-variant features of a theory do not result in observable differences. However, these features are widely viewed, including by Redhead himself, as representational redundancies. Rickles (2017) extends the analysis of representational surplus to "dual theories" involving non-trivial mappings. Rickles argues that dualities are effectively gauge symmetries of a deeper theory, and that we must quotient out these differences just like we quotient out gauge redundancy. The actual reality is the structure shared by the dual theories, determined by the invariants under the duality map.

Rickles uses dual theories to emphasize an important distinction between the mathematical description and the structural reality it describes, warning against a literal reading of the mathematical theory. This is a salient point in the present context, because despite its name, the MUH does not identify physical reality with a specific mathematical description. This point addresses the concerns of Butterfield (2014), who criticizes the strong MUH on the basis that mathematics is merely a descriptive tool. While true, what mathematics describes are structures, one of which can be identified with our physical universe. To clarify the dispute: reality is perfectly described by mathematics (weak MUH), but is metaphysically structural (strong MUH). The existence of multiple equivalent descriptions for a single structure does not undermine the claim that we inhabit that structure; it simply requires we distinguish the description from the described.

Turning to an ontological reading of surplus, French and Ladyman (2003b, p. 75) point to the sheer volume of mathematical structures that have no bearing on physical reality: "there is more mathematics than we know what to (physically) do with." However, this objection fails in the context of the strong MUH, where each structure is understood as a universe unto itself. The abundance of structures that have no bearing on our physical reality is a simple result of our universe being one particular structure in a vast disjoint ensemble. The UTS is therefore entirely consistent with the fact that most mathematics does not describe our physical universe, a point that also speaks to the suitability objection.

8.1.5 Suitable structure

A related concern, expressed by Bueno (2019), holds that mathematical possibility is too permissive a guide to physical possibility. He points to the Banach-Tarski theorem, which tells us, among other things, that in some structures a sphere can be decomposed and reassembled into a larger one. He argues that this is mathematically possible but physically impossible. However, Bueno implicitly equates "physical possibility" with what is possible in our structure, which is governed by specific symmetries and conservation laws that preclude Banach-Tarski-like operations. What counts as "physically possible" is not universally fixed, but varies from one structure to another. It is only required that at least one *ante rem* structure be compatible with observed physical possibility, not all of them.

8.2 Empirical objections

Beyond conceptual distinctions, critics have also attempted to reject the identification of physical and mathematical reality on empirical grounds. This subsection rebuts 'typical observer' based predictions by showing that the requisite probability measure is undefined, and will likely remain so due to the open-endedness of mathematics. The UTS survives falsification by these arguments, but at the cost of being presently non-predictive.

The most discussed method for generating novel predictions from a multiverse theory such as the UTS involves calculating what a typical observer should experience. Deutsch (2011) argues that if the strong MUH were correct, then the vast majority of universes containing observers would be chaotic outside a typical observer's own brain, leading to a prediction of instant death. He argues that because life goes on as usual, the strong MUH must be false. Vilenkin (2007) similarly argues that because mathematical structures can be arbitrarily complex, a typical observer should predict that they live in a universe with "horrendously complex" physical laws. He suggests this is in conflict with the simplicity of our laws of physics. However, neither prediction is well-defined, as both attempt to quantify and compare infinite classes of observers. This is known as the measure problem: without a well-defined and principled method to compare the infinities, we cannot compute probabilities about what we should expect to observe. The challenge is common to all theories that posit an infinite ensemble, because any conclusion about typicality depends entirely on the chosen method for comparing the infinite sets.[28]

Several approaches to taming these infinities have been proposed, with each so far proving inadequate. Tegmark's (2008) idea to restrict the structural multiverse to computable or finite structures is ad hoc and revisionary to both physics and mathematics. Similarly, applying a complexity weight (Schmidhuber, 2000; Tegmark, 2008) lacks a principled motivation relative

[28] While typicality reasoning may not be valid across the structural multiverse, it does seem to be valid *within* our structure, otherwise physics would have trouble predicting anything, quantum or otherwise. How to ensure metaphysical consistency of these two facts remains to be better understood.

to other weightings.[29] Finally, I previously (Hamlin, 2017) appealed to Bostrom's (2002) Self-Indication Assumption (SIA) to weight structures by observer count, but the SIA is highly contested and, as Adelstein (2024) notes, cannot on its own yield a defined probability measure.

A potential reason to doubt even the future possibility of solving the measure problem arises from the Principle of Indefinite Extendibility.[30] This principle implies that no formal theory can encompass the entirety of structural reality. In Hellman's (2003, p. 19) words, "There is an open-endedness, incompleteability, or indefinite extendibility that is an essential aspect of mathematics." One can always add axioms to a formal theory of structure to describe structures not previously recognized. This poses a serious challenge for the measure problem, because it is unclear how we could possibly form a measure on a quantity not only larger than a set, but larger than any formal theory can express.[31]

The measure problem remains the most significant barrier preventing novel, testable predictions. Read and Le Bihan (2021) nonetheless argue that philosophical multiverses like those implied by the strong MUH may be amenable to empirical testing and falsification. They distinguish between two notions of predictivity. They acknowledge that while the strong MUH is not "decision-theoretically" predictive due to the measure problem,[32] it may still be falsifiable in a weaker sense of being subject to a future empirical inadequacy. One possibility of the latter kind is raised by Tegmark (2008), who argues that the strong MUH makes a mathematical regularity prediction. This holds that we should continue to discover more mathematical regularities in nature, which effectively amounts to the claim that the weak MUH will continue to be confirmed. However, Hossenfelder (2022) points out that it is not clear what we would have to observe in order to demonstrate the empirical inadequacy, because an inability to incorporate empirical data may simply mean we have not yet considered the correct theoretical structure.[33] For now, the strong MUH remains non-predictive *tout court*, although not necessarily so in principle.[34] Even if it is not rejected for failing predictions, the strong MUH has been ignored altogether on methodological grounds.

8.3 Methodological objections

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[29] Schmidhuber's (2000) "Speed Prior" complexity weighting could be motivated in principle, but it requires additional problematic assumptions about the existence of a "Great Programmer" who is trying to optimize the efficiency of simulating universes.

[30] For a detailed discussion, see Rayo and Uzquiano (2006) and Hellman and Shapiro (2018).

[31] Whereas Gödel's theorems discovered the limits to formalization of truths about individual structures, indefinite extendibility concerns the limits to formalization of truths about the entire structural multiverse. The principle implies that all formal theories of structure will necessarily have to balance incompleteness with universality.

[32] Decision-theoretic predictions require a well-defined measure on the space of solutions to quantify one likelihood against alternatives.

[33] The difficulty of imagining empirical data that cannot be fitted into a mathematical model suggests the weak MUH is on solid ground.

[34] Read and Le Bihan (2021) define predictivity *tout court* essentially as empirical adequacy, namely that a theory has "at least one solution compatible with the empirical data gathered thus far." I read their definition as one of *successful* prediction *tout court*, whereas predictivity *tout court* itself should be understood as the possibility that the theory might one day encounter empirical data for which it does *not* have a compatible solution (model).

A common objection to the strong MUH is that it is not even worth considering in the first place. These methodological objections fall into two main categories. First, critics argue it fails the standards of empirical science due to its lack of novel predictions. Second, some naturalistic metaphysicians argue that it violates constraints on appropriate metaphysical inquiry. However, I argue that both criticisms apply inappropriate standards to a metaphysical proposal of this scope.

8.3.1 Empirical relevance

Ellis and Silk (2014) criticize multiverse theories for failing to make novel predictions, claiming that without them we have no reliable way of assessing their epistemic status. Hossenfelder (2022) contends that the absence of novel predictions relegates the strong MUH to the realm of 'opinion or aesthetic preference.' It may be that predictivity is a good demarcation criterion for science, and that on this basis the UTS should not be classified as a scientific theory. However, to say that non-predictive theories are empirically and therefore epistemically idle is to inappropriately project the normative evidential standards within physics to the broader quest for knowledge. We might not be able to falsify a theory with predictions, but we can criticize it on other empirical grounds, and the theoretical virtues that Ellis and Silk deride are essential to doing so. Deutsch (1998) points out that most scientific theories are rejected not for failing predictions, but for lacking the theoretical virtues that make them worth testing in the first place. Our knowledge, even our scientific and physical knowledge, could not possibly grow without acknowledging these virtues.[35]

The UTS is currently non-predictive, but that does not make it empirically vacuous. The UTS is already empirically adequate, not only in the weak sense of being compatible with all our current observations, but also in a strong sense of actually having models in which all results of physics can be embedded. It is also inconsistent with some physical theories (or interpretations thereof) involving irreducible randomness that have otherwise been taken seriously, such as collapse quantum theories (GRW/CSL).[36] The foundational problems can also be construed as being about observations that the theory is motivated to explain: we observe that our universe is described by mathematics, that it has its specific form, and that it exists in the first place. These observations are not empirical in the sense of being measurements of contingent magnitudes that are characteristic of the physical sciences, but that does not make them any less important to explain. The UTS is motivated by empirical content in multiple ways; just not by novel

[35] While novel predictions provide the most potent means of falsification, they are not the only criteria for evaluation. Eddington would not have organized an expedition to test General Relativity without independent grounds for valuing the theory. Mere testability was not the primary appeal, as testable hypotheses are trivially easy to construct. Rather, General Relativity commanded attention because it unified and explained known phenomena, virtues that are rare to achieve and which justify the effort of empirical testing.

[36] The UTS is consistent with apparent randomness in state histories, just not with fundamental and irreducible randomness in the metaphysics. It might be true that we live in a structure composed of many states that are not related by unitary dynamics. In this case it would be quite the coincidence that the dynamical laws relating the states obeyed the probabilities of quantum mechanics as opposed to any other random progression. By contrast, the metaphysical picture given by Everettian quantum theory is straightforwardly consistent with the UTS.

predictions. The charge of empirical vacuity might apply to ST itself, but certainly not to its universalization.

There are two notable consequences of the lack of novel predictions. The first is that it limits the degree to which the UTS can be corroborated. While this does not preclude confidence in the truth of the theory, it does place the UTS at a major epistemic disadvantage relative to any hypothetical rival capable of equivalent explanatory power that is predictive. However, the current absence of such rivals mitigates this limitation. The second significance is that the theory will likely evolve slowly, because we cannot subject it to repeated rounds of variation and empirical testing. We can only evaluate it as an explanation of what we already observe, and we are short on foundational problems that it has not already solved. This is all the more reason to be careful in our assessment of the available evidence.

The lack of novel predictions leads critics like Stoeger et al. (2004) to argue that the strong MUH should be understood as a part of metaphysics. While I agree that it is indeed a piece of metaphysics, it is not for *that* reason. Metaphysics is not untestable physics. The theory is a part of metaphysics because of the types of problems it is concerned with. It does not ask about the particular form of our physical reality, but instead speaks to more fundamental questions about its nature. If a metaphysical theory did make a testable prediction, that would not make it a part of physics; it would instead be understood as predictively constrained (scientific) metaphysics. For now, the UTS is properly classified as a non-predictive metaphysical theory. Before assessing the theory by its theoretical virtues, we must address a final methodological objection regarding the appropriate standards for metaphysical inquiry.

8.3.2 Naturalistic metaphysics?

Some commentators refuse to consider the strong MUH because it does not meet scientific standards, while others refuse to consider such hypotheses because they are claimed to not even meet appropriate *metaphysical* standards. Ladyman and Ross (2007) argue that metaphysical claims should be motivated by their ability to show how multiple scientific hypotheses, including at least one drawn from fundamental physics, can jointly offer greater explanatory power than they would individually. They call this the Principle of Naturalistic Closure (PNC), which effectively limits metaphysics and tasks it with developing consilience relations among the empirical sciences. It is on this basis that Ladyman and Ross (2007, p. 158) advocate silence concerning the relationship between the mathematical and the physical: "In our view, there is nothing more to be said about this that doesn't amount to empty words and venture beyond what the PNC allows."

Ladyman and Ross (2007) argue that the PNC is a good normative heuristic because it efficiently indicates whether any given metaphysical hypothesis stands a chance of contributing to objective knowledge. These efficiency gains, however, are necessarily paid for by a loss in accuracy. Their normative heuristic limits metaphysics to the task of unifying empirical science, highlighting the epistemic reliability of hypotheses that attempt to explain and unify the "web of empirical knowledge." However, this definition problematically excludes mathematics from the target domain of unification. While I agree that mathematics is not an empirical science, Ladyman and Ross acknowledge it "indispensably and irreducibly" figures in the empirical sciences, and enjoys a similar epistemic reliability. It is fine for Ladyman and Ross to argue that mathematics is not a part of the natural world, but it would be premature to restrict metaphysics with a normative heuristic based on that belief.[37] Recent decades have seen a resurgence of naturalism in the philosophy of mathematics, with Baker (2009) arguing that any consistent naturalism must include mathematics in its scope. Indeed, mathematics and physics are so intimately bound that it would be a difficult surgery to try to separate them, and metaphysics should not attempt, much less enforce, such revisions.

To better account for the indispensability of mathematics for explaining the natural world, we might propose an amendment to the PNC, one that expands its scope to explicitly allow for, though not require, the unification of mathematics with the empirical sciences.[38] Given that the principle is a normative heuristic, the question becomes whether including mathematics in the domain of unification provides a more accurate and efficient filter. I contend that it does, as it would still block vast swaths of "neo-scholastic metaphysics," but it would do so without imposing a painful separation between empirical science and the mathematics it indispensably relies on. This revised PNC would also highly motivate rather than block the UTS, a point that itself suggests that excluding mathematics results in a loss of heuristic accuracy.

The rejection on methodological grounds is premature. Demands for novel predictions mischaracterize the role of a metaphysical theory, and normative heuristics are not strong enough to force a dismissal. The charge of 'empty words' seems unfitting, given that empty words are precisely those that fail to explain or unify, and the UTS does both at a remarkable level. The argument will now turn to the theory's virtues, as they are the ideal standards of evaluation.

9 Theoretical virtues

The UTS is assessed according to the classic theoretical virtues of explanatory power, unification, and simplicity. The goal is to support an inference to the best explanation. I will conclude with a brief comparison with alternatives.

9.1 Explanatory power

Good explanations typically give you back more understanding than you ask for, and the UTS is no exception. While ST was originally motivated by the work it did in providing a metaphysical foundation for mathematics, a striking fact is that once universalized, this same theory provides powerful insights into diverse and important problems that have long been a challenge for both science and philosophy. The theory offers broad explanatory benefits: it improves responses to several objections to OSR, it addresses three foundational metaphysical problems, and it even fortifies ST itself. This is a case of consilience: it shows that we have not merely fit the theory to

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[37] Ladyman and Ross (2007, p. 33) admit that their principle has the status of a "normative heuristic" and is not the result of a "logical analysis," and therefore cannot be "applied algorithmically." Taking lessons from the failures of logical positivism, they recognize that the boundaries will not always be sharp, and allow for some permissiveness in the principle's application.

[38] Their original principle might be more suitably named the Principle of Empirical Closure (PEC).

explain one set of problems, but that we tapped into a deeper explanatory structure. Explanatory power is the most important theoretical virtue and is also the greatest strength of the UTS.

9.2 Unification

Many advancements in our understanding of reality have resulted from unifications of previously disparate domains. The UTS continues this trend, which results in the unification of the ontology of mathematics and the physical sciences. We have long divided our best theories into two categories: physical theories that actually describe reality, and mathematical theories that are merely useful in describing reality. This treats mathematics instrumentally and then struggles to account for its applicability. Instead, the UTS reveals that both mathematical and physical theories are about a common domain of *ante rem* structures, just different parts of it and using different methods. Mathematicians operate at a level external to any particular structure they study. They typically consider structures as completed wholes, with perfect axiomatic information about them, and therefore have access to deductive methods. Physicists on the other hand exist within as integral parts of the structure they are studying. They only have incomplete information about their structure, gathered by observation and experimentation. They use this information to establish relationships among observable phenomena, creating empirical substructures that are used to whittle down the set of structures they may inhabit into a class that is empirically adequate. According to the UTS, the key difference between mathematics and physics lies not in subject matter (they both study structures), but in perspective and methodology. It reveals that mathematicians are mapping the structural multiverse and physicists are determining our location within it. This unification is significant, extending beyond traditional unifications within or even between empirical science domains, and is another major virtue of the theory.

9.3 Simplicity

Multiverse theories have often been criticized for being ontologically extravagant, but I argue that considerations of simplicity strongly support the UTS. Baker (2022) characterizes simplicity as a complex theoretical virtue, distinguishing between syntactic simplicity (elegance) and ontological parsimony (number and kinds of entities). In terms of syntactic simplicity, the UTS is clearly theoretically elegant: ST provides a vast ontology using minimal principles, and universalizing it via the strong MUH adds no new primitives. The theory does not require additional ideology to unify the physical with the mathematical; it simply takes an existing formalism and expands its reach.

While syntactic simplicity is naturally viewed as a pragmatic virtue because elegant theories are easier to use, ontological parsimony is more often considered an epistemic virtue. Ontological parsimony can be further analyzed in terms of quantitative parsimony (the number of individual entities) and qualitative parsimony (the number of kinds of entities). French (2014) appeals to considerations of quantitative parsimony to characterize the strong MUH as "ontologically inflationary," because it holds that a vast number of structures exist. However, such an objection actually targets ST itself rather than its universalization, and one is free to argue that there are fewer structures than mathematicians suppose there are. The ontology of ST is large, but not too large; it is just the right size, by design, to provide an ontology for mathematics.[39] We certainly should not hold the fact that the UTS is universal over all fundamental ontology *against* the theory.

The UTS scores even better on qualitative parsimony, because it holds that only one fundamental kind of entity exists, namely *ante rem* structures. This is advantageous because we only need a single existential explanation for that fundamental kind, not a separate one for each entity of that kind. This is especially significant because existential explanations have proven hard to come by. From this perspective, a unified fundamental ontology of structures is absolutely *minimally* inflationary.[40] The charge of ontological extravagance appears to be exactly backwards; the UTS is instead shown to be syntactically elegant, quantitatively commensurate, and qualitatively optimal.

This analysis suggests a further re-evaluation of the MUH's reputation, which has often been characterized as radical, even by Tegmark himself. While the strong MUH may be radical in its implications, it is conservative in its ontological load. The real ontological heavy lifting is done by ST. The strong MUH is conservative in other respects as well. It makes no problematic distinctions between mathematical and physical structure, and is, after all, the result of 'accepting the conclusion' of the collapse problem. Doing so allows for a uniform and non-revisionary semantics for both mathematical and physical theories. It also recognizes only one fundamental ontological kind (structures), and a minimalist metaphysic (relations without irreducible individuals). If the strong MUH is considered radical, then one wonders how its alternatives fare.

9.4 Alternatives

An inference to the best explanation requires a consideration of competitors. While a comprehensive survey is infeasible, we can evaluate how the UTS compares to several general classes of alternatives, using the theoretical virtues of explanatory power, unification, and simplicity as evaluative criteria. I start with nominalism and dualism, which reject the unification of mathematical and physical reality, and then consider two variants that accept unification but restrict or expand the size of the fundamental ontology.

9.4.1 Nominalism

The first option is to reject ST altogether by adopting anti-realism toward mathematics, alongside some form of structural realism about physical reality (French & Ladyman, 2003b; Arenhart & Bueno, 2015). This approach could be summarized by the motto: *reality is structural; there are no (ante rem) structures.* This combination surpasses the UTS in terms of ontological simplicity, because it recognizes only a single instance of a single fundamental ontological kind. However,

[39] Shapiro (1997) argues against efforts to trade away quantitative parsimony for added (modal) ideology.

[40] This trend toward accepting vast ensembles of a single kind is also supported by the historical progression of science. Again and again, we have learned that what we once took to be unique turns out to be one member of a far larger class. Berenstain (2020) draws from this trend the conclusion that there is no prior reason to assume that our universe is the only one.

this simplicity betrays more significant explanatory challenges concerning the foundational problems. It cannot explain the particularity of the single ontological instance (our physical universe), and it also denies the physical universe the existential explanation available to *ante rem* structures. The problem of applicability is especially acute, because it holds that mathematics is not about real entities, except in the unexplained case of the physical universe. While the collapse problem can be responded to with "representation-as" claims, these are question begging, and they threaten structural realism's status as a genuine realism. These challenges are in addition to the classical vacuity problem with nominalist mathematics. While scoring well on simplicity, this view suffers from more significant explanatory and unificatory deficits.[41]

9.4.2 Dualism

If the rejection of mathematical realism is deemed too costly, one might instead propose a dualism where we accept ST but deny the strong MUH (for example, Deutsch, 1998; Linsky & Zalta, 1995). This position would accept the existence of the structural multiverse, with one *ante rem* structure being scientifically indistinguishable from our physical universe, but it would deny the identification. The primary challenge to this approach is captured by the collapse problem: what distinguishes the physical world from its structurally identical (and already existing) mathematical counterpart. The applicability problem benefits from mathematical realism, but the solution remains incomplete, as it must still explain the correspondence between the physical and mathematical reality. The problems of particularity also remain completely unaddressed. Another significant challenge with this approach is that its dualist fundamental ontology requires two existential explanations. This is perhaps the most difficult position to maintain; once ST is accepted, its universalization becomes difficult to deny.[42]

9.4.3 Restricted structural multiverses

Given the significant explanatory and unificatory costs of rejecting the identification of physical and mathematical reality, a promising alternative is likely a variant of the UTS. One might hold that the structural multiverse is smaller than mathematical practice would suggest it is. The Finite Universe Hypothesis (Tegmark, 2008) restricts structures to those with finite positions, and the Computable Universe Hypothesis (Tegmark, 2008; Schmidhuber, 2000) restricts structures to those with computable relations. Both succeed in addressing the foundational problems in a similar way. A restricted structural multiverse has the potential advantage of taming the infinities that result in the measure problem; however, this itself is not evidence for the restriction, as reality is certainly indifferent to our ability to test it. The approach also introduces new difficulties. It fails to account for the entirety of mathematics as it is actually practiced, which goes against the

[41] A related view does not reject the existence of structures altogether, but instead views their existence as dependent upon physical systems that instantiate them. This is *in re* mathematical structuralism, and is often associated with the Aristotelian realism of Franklin (2011). It similarly struggles to account for physical particularity and existence. It does accommodate applicability, though it does not fully explain it.
[42] This is further evidenced by the rarity of philosophers who accept both OSR and *ante rem* structuralism, as this combination is highly tenuous without also adopting the strong MUH.

faithfulness principle that guides the philosophy of mathematics. It also faces difficulties with our most successful physical theories, such as General Relativity, because the theory's reliance on the continuum makes it consistent with an infinite and non-computable class of structures. While potentially testable, restricting the structural multiverse faces serious challenges to its consistency with existing knowledge.

9.4.4 Expansive ontologies

One might instead argue that ST does not recognize a big enough ontology. David Lewis's (1986) modal realism posits the reality of all logical possibilities, which is a looser constraint than mathematical coherence. Likewise, Nodelman and Zalta's (2014) object-theoretic approach admits a broader ontology of abstracta, some of which are not purely structural, including inconsistent, informal, and fictional objects. However, we have better reasons to believe in the existence of *ante rem* structures than we do for these other more general forms of abstracta. Such broader ontologies are not necessary to account for mathematics or the empirical sciences, and as such they are not PNC-motivated even in our revised sense.[43] The extra abstracta also do not contribute to solving any of the foundational problems already addressed by a pure structural ontology, nor do they support a realism about physical structure. The broader ontology is also incompatible with the proposed existential solution, to the extent that it appeals to the objective coherence of mathematical truth. Ultimately, we must draw the line somewhere, and faithfulness to mathematical practice offers the least problematic boundary to draw.

The various alternatives considered appear to incur significant trade-offs in explanatory power, unification, or simplicity. Some uncertainty remains regarding the exact size of the structural multiverse; yet, what matters for the universalization argument is not the structural multiverse's exact cardinality, but the more defensible claim that it exists and is extraordinarily vast.

10 Conclusion

The UTS is offered not as a radical departure, but as a natural homecoming for OSR. Structural realism originated with the insight that the mathematical content of physical theories survives theory change. While it successfully adopted the structuralist terminology from the philosophy of mathematics, it subsequently took a detour by attempting to characterize structure autonomously, leading to much confusion and disagreement about what structure actually is. The present work adjusts this course, returning to the metaphysical foundations of mathematics to secure the precise ontological basis that OSR has long required.

The principles of *ante rem* structuralism and their formalizations into axiomatic theories of structure were collectively recognized as ST, which provides a vast ontology of *ante rem* structures. These structures exist *sui generis* and are exactly mathematically describable, and some of them are suggestively world-like. In this context the identification of the physical universe with

[43] This is a point that demonstrates that our revised PNC is not toothless. It is also why I recognized Murphy's (2021) modification of abstract object theory that limits the comprehension axiom to *ante rem* structures alone (they are motivated by the revised PNC).

one such *ante rem* structure is highly motivated. This identification results in the *universalization* of ST, because the theory expands its reach to account for all fundamental ontology, both mathematical and physical.

This universalization offers deep and diverse explanatory advantages. It sharpens OSR's fundamentality thesis from the vague "physical reality is structural" to the substantive claim that "physical reality is an *ante rem* structure." This precision enables improved responses to several criticisms of OSR, offers powerful insights into foundational metaphysical problems, and simultaneously addresses difficulties internal to ST itself. These benefits are delivered by reframing the relationship between mathematics and the empirical sciences, rationalizing their indispensable relationship by revealing them as complementary methods of exploring a unified fundamental reality of structures. This is achieved with remarkable simplicity, by merely recognizing the full universality of ST's existing ontology. While the theory does not currently yield novel predictions, its theoretical virtues jointly support an inference to the best explanation. This inference to the UTS then provides new, physical justification for the original adoption of ST, completing a bootstrapping argument that vindicates the theory's own ontological foundation.

The UTS offers a fundamental ontology, which is only one component of a comprehensive metaphysical system, and open questions abound. While I argued that the universalization of ST proceeds largely independently of its formalization, further analysis of specific formal theories of structure in the context of the strong MUH is a logical next step. A focal point for these investigations will likely be how the various formalisms treat non-trivial automorphisms and their compatibility with Tegmark's proposal for computing dynamics from pure structural descriptions. Another important task is forging a stronger bridge between the UTS and empirical science. This will require supplementing the fundamental ontology of structures with an account of non-fundamental ontology, most promisingly with a theory of real patterns. Addressing these issues will require significant interdisciplinary collaboration, but is essential for the pursuit of a truly naturalistic metaphysics.

The UTS is inspired by the idea that the physical universe appears to be a structure for the simple reason that it *is* a structure. Seen in this light, the theory sheds its radical reputation to reveal a conservative core, offering a natural standard against which more complex alternatives can be compared. Ultimately, this ontological identification dissolves the perceived gulf between our best methods of understanding reality, pointing toward a renewed unity in the family of objective inquiry.

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