The undiscovered model driving modern physics' successes

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Abstract

The mathematical formulation of theories is a key driver of modern physics' successes, and reflects a foundational principle. Physicists are guided by this principle, and in doing so are granted all the benefits afforded by a hard science. Herein, I argue that this principle has even more to offer. For physicists to make sense of each other's mathematically formulated theories (MFTs) they must share a universal understanding on how to interpret them. In terms of model theory, there must be a set of (basic but) universally accepted interpretations that relate the language of MFTs to meaningful elements. Because these interpretations apply to all MFTs, a model of (just) these interpretations would be a submodel of all models of MFTs. These universally accepted interpretations were, effectively, the bases for Max Tegmark's mathematical universe hypothesis (MUH). This allowed Tegmark to relate many aspects of quantum and relativistic physics back to his hypothesis. However, Tegmark's goal of accounting for spacetime and quantum phenomena requires a model beyond universally accepted interpretations. I show that as a result, the model described by Tegmark's MUH is not a submodel of all existing models of MFTs. In contrast, I derive a novel model of just these universally accepted interpretations such that all models of all potential MFTs are, effectively, extensions to this novel model. Therefore, this novel model can enhance our understanding of every MFT, and facilitate collaboration and the unification of models across the branches of modern physics.

Keywords: interpretations of modern physics, philosophy of science, formal system, mathematical universe, mathematical structure, interpretations of quantum mechanics

1 Introduction

In terms of model theory (see definitions 1, 2 and 3), Einstein's theory of special relativity[1] is not just a theory. This is because it specifies how to interpret its mathematical symbols. As a theory, it defines relationships among symbols of a formal language[2]. However, interpretations for a formal language's symbols belong to models, not theories[2]. Meaning, the interpretations for the symbols e, m and c in the equation $e = mc^2$ as energy, mass and the speed of light, are not part of the theory aspect of special relativity but would be part of any model of it. These shared interpretations unite all models of special relativity based on a shared understanding.

Definition 1 *A theory is a set of sentences formulated in a formal language that define relationships among the symbols of that language[2].*

Definition 2 *A model is a set of* interpretations *that assigns meanings to symbols of a given* language *within a specified* domain*[2].*

Definition 3 *A submodel is a model that shares the same language and domain as another model but provides a subset of its interpretations[2].*

Herein, a novel submodel is derived, not for models of special relativity but for models of all mathematically formulated theories of modern physics (MFTs). An in-depth understanding of model theory is not required; it is sufficient to understand the above definitions. In §2, the domain and formal language for the novel submodel is identified by identifying those common to all models of MFTs. Then the novel submodel is derived in §3 by identifying the fundamental interpretations that all physicists apply when interpreting a MFT. This novel model is similar to the model described by Max Tegmark's mathematical universe hypothesis (MUH)[3]. However, as discussed in §4, Tegmark's MUH[3] includes an additional interpretation not accepted by all physicists. As a result, the model described by Tegmark's MUH[3] is not a submodel of all models of MFTs.

The ultimate aim of this work is to expose the untapped benefits of discovering a submodel common to all models of MFTs. Such a submodel is derived herein from physicists' shared interpretations that allow them to make sense of each other's MFTs. The practical benefits, I argue, go far beyond enhancing our understanding of how physicists collaborate. The novel submodel implied by these shared interpretations is a basic model of the universe, one that is implicitly accepted by all physicists and inherent in all models of MFTs. In technical terms, all models of a MFT are, effectively, extensions of this novel submodel. Therefore, this novel submodel can be extended to unite any set of compatible models. In this way, this novel submodel can facilitate collaboration and advancement throughout modern physics and across its branches (see §5).

2 Language & domain of models of MFTs

Tegmark's mathematical universe hypothesis[3] (MUH) opens with a reference to Galileo Galilei's famous statement that the universe is a grand book written in the language of mathematics[4]. Whether this is true or not[3, 5–12], Galileo Galilei's statement is reflected in all mathematically formulated theories of modern physics (MFTs)[3, 12]. By definition, the language of all MFTs is the language of mathematics.

Language of MFTs: the language of mathematics.

Following Galileo Galilei's quote, Tegmark[3] refers to Wigner's reflections on the 'unreasonable effectiveness of mathematics in the natural sciences'[5, 6]. This highlights the domain to which MFTs apply, which is the universe[5–8]. As Tegmark[3] details, models of MFTs describe and explain physical properties across space and time, along with the constants (of the universe) and laws of physics that govern them. Therefore, the domain of modern physics (and models of MFTs) includes the following sets:

Domain of models of MFTs: all laws of physics, all constants of the universe, all physical properties, space and time[3, 5, 6].

There is no consensus as to why models of MFTs are so adept at modeling the universe[5, 6, 9, 10, 13] but there is a strong consensus that they are[5–8]. In the next section, a common submodel of these models is derived by identifying a set of universally accepted interpretations.

3 Universal interpretations

The essential claim of Tegmark's mathematical universe hypothesis (MUH)[3] is that the universe is so well modeled by mathematical structures[5–8], because it fundamentally is an eternal mathematical structure (and nothing more)[3]. In terms of the nature of reality, this assertion is not without its critics[14]. However, the focus here is restricted to the universal interpretations behind this essential claim.

The mathematical structures, which Tegmark[3] refers to as modeling the universe so well, are those defined by MFTs. Although MFTs do not all agree on a common mathematical space, they all either define or extend a mathematical space (e.g. spacetime or Hibert space)[1, 3, 11, 15–18]. These mathematical spaces are mathematical structures, which are extended via mathematically formulated laws (of physics), which are defined in terms of the mathematical space[3, 11, 18]. As Tegmark[3, 18] argues, these mathematically formulated laws, effectively, combine with the mathematical space to form an overall mathematical structure (OMS)[3, 18]. Therefore, all MFTs, essentially, define an OMS[3, 11, 18]. It is the remarkable ability of these OMSs to model the universe that inspired Wigner's reflections on the 'unreasonable effectiveness of mathematics in the natural sciences'[5, 6] and Tegmark's[3] essential claim.

Tegmark's[3] eternal mathematical structure spans both space and time and includes all laws of physics. This reflects the fact that theories of modern physics model dynamic systems. Therefore, MFTs include either a space that incorporates time (e.g. spacetime) or formulas (for laws of physics) that are time dependent (e.g. the time-dependent Schrödinger equation[19]). Consequently, every OMS (of a MFT) expresses a topology that includes time[3]. That is, an OMS includes a topological space across space and time, within which mathematically formulated laws of physics are realized[3, 11].

Outside of ontological debates, §4 discusses the main criticism of Tegmark's MUH[3]. However, none of the criticisms[12, 14, 20–25] are directed at the assertion that the OMS defined by a MFT is interpreted as the structure of the universe (including the laws of physics). This reflects the fact that physicists universally interpret MFT's, and more specifically the OMSs they define, as describing the structure of the universe[3, 5, 6, 11, 12, 15–18, 25–27], as expressed by the following.

Universal interpretation 1 *The OMS defined by an MFT is interpreted as describing the structure of the universe, including the topology of space and time along with laws of physics.*

The eternal nature of Tegmark's[3] *eternal* mathematical structure is an expression of the principle of uniformity of nature[28] (principle 1). A valid MFT is one whose OMS is shown to model the universe accurately in different places and at different times[4]. As Hume[28] detailed, this is contingent on the principle of uniformity of nature (principle 1), which asserts that the structure of the universe remains consistent. As this principle is a principle of all scientific theories[4] this assertion applies to all models of MFTs (see Fig. 1).

Principle 1 Uniformity of nature*: The laws of nature are consistent across space and time.*

Beyond their structure, OMSs include constant values and variables. This inclusion of constant values implies a universal interpretation which (again) matches the interpretation given by Tegmark's MUH[3] (see interpretation 2).

Universal interpretation 2 *Mathematical constants are interpreted as eternal values inherent in the universe (see Fig. 1).*

Figure 1 depicts the model of Tegmark's[3] essential claim, apart from the interpretation of variable values. Like constant values, Tegmark's MUH[3] interprets variable values as being included in the eternal mathematical structure (the universe)[3]. Although Tegmark[3] provides a logical account of how these values *could* come from an eternal universe, the interpretation that they do is not universally accepted (see §4). A MFT does not define the values of its variables. Consequently, variable values are

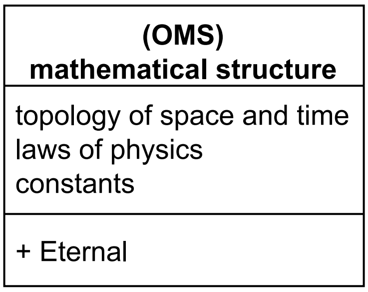

Fig. 1 The overall mathematical structure (OMS), defined by a MFT, is interpreted as representing the universe's constants and eternal structure, where this structure includes the laws of physics and the topology of space and time.

not inherent in a MFT's OMS. Instead, variable values come from observations/measurements conducted during an experiment. That is, physicists universally apply the following interpretation when conducting a scientific experiment.

Universal interpretation 3 *Variable values are interpreted as measurement values (see Fig. 2).*

Although the variable values associated with a MFT are not part of the OMS, they are all related to it via their variables (see Fig. 2).This implies that the same laws of physics and topology of space and time relate to each of these measurements. However, measurement values are presumed to be subject to the laws of physics, rather than defining them. Therefore, although these values vary between experiments, this does not violate the principle of uniformity of nature[28]. Consequently, measurement values are not assumed to be eternal[17, 29].

These universal interpretations cover the fundamental elements of a MFT. Specifically, this includes a MFT's variable values and its OMS, which includes a mathematical space, mathematically formulated laws and constant values. Together with the common domain and language of all MFTs this forms a model I call the minimum mathematical universe model (miniMUM), which is concisely expressed as:

Definition 4 Minimum mathematical universe model (miniMUM)*: The OMS of a MFT is interpreted as the universe's constants and eternal structure, including the laws of physics and the topology of space and time. The values of the OMS's variables are interpreted as measurements.*

There are other universal interpretations inherent in the miniMUM not explicitly expressed by the above definition. This is because any relationships between the mathematical elements discussed would imply relationships between their corresponding elements in the physical domain. For example, when a set of compatible mathematical structures is combined, it forms a larger mathematical structure that includes the original set. Therefore, any set of compatible MFTs could be combined to form an OMS

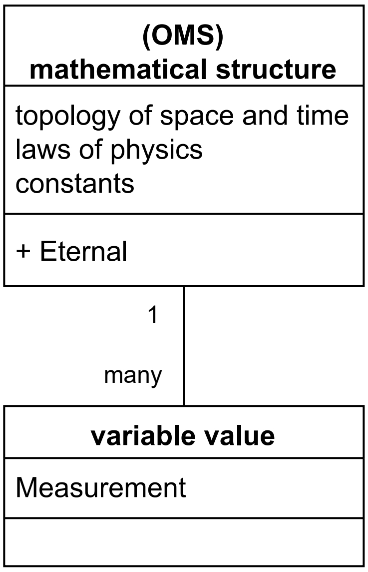

Fig. 2 Variables values are interpreted as being measurements which are all subject to the same eternal laws of physics, constants and topology of space and time.

that included the OMSs of each MFT. This leads to interpretation 4 when considering a set of MFTs that form a theory of everything. Apart from variable values, this interpretation is analogous to Tegmark's[3] claim that the universe is fundamentally an eternal mathematical structure.

Universal interpretation 4 *The OMS for a set of (compatible) MFTs that form a theory of everything would be interpreted as all laws of physics, all constants of the universe and the topology of space and time.*

Another implied interpretation can be derived from the concept of a mathematical structure's state space. This interpretation is also shared by Tegmark's MUH[3] and is closely related to the additional interpretation of Tegmark's MUH[3] discussed in §4. Since the mathematical space of an OMS is interpreted as the topology of space and time, its state space would be interpreted as follows.

Universal interpretation 5 *The state space of an OMS is interpreted as the set of possible states for the universe (see Fig. 2).*

Furthermore, since measurements are taken in the context of a realized state, each measurement is associated with the matching possible state. Therefore, the many-to-one relationship between a measurement and the eternal structure of the universe can be more precisely expressed via these possible states (see figure 3).

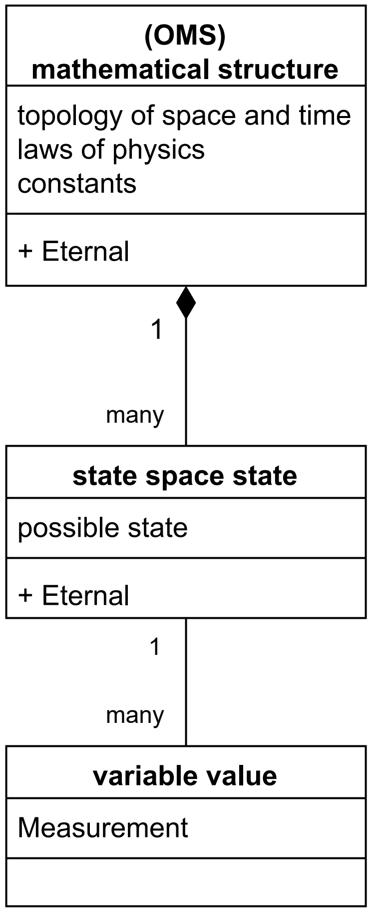

Fig. 3 The state space inherent in a MFT's OMS is interpreted as the set of possible states for the universe. Since each measurement occurs within a realized state, each measurement is associated to one possible state, the possible state that matches the realized state. The line joining the OMS to its state spaces is a UML composition relationship line, to indicate that the state space is part of the OMS. The one-to-many relationship between the OMS and measurements is preserved but expressed more precisely via the OMS's state space.

The miniMUM's domain, language and interpretations are common to all models of MFTs, making the miniMUM a submodel of each of these models. Although Tegmark's MUH[3] shares the same domain, language and interpretations, Tegmark's goal of developing a theory to explain relativistic and quantum phenomena is not satisfied by these interpretations alone. As such, Tegmark incorporated an additional interpretation, which is not universally accepted (see §4).

4 Interpretations of quantum mechanics

The main challenge in modeling both relativistic and quantum phenomena comes down to a fundamental inconsistency between the branches of modern physics[17]. This inconsistency was the focus of the EPR paradox paper[30] and continues to be debated nearly a century later[17, 31]. Mariani[31] describes this challenge as the 'determinacy problem', which is that quantum's indeterminacy, described by assertions 1 and 2, are logically inconsistent with relativity's assertion of determinacy (assertion 3)[31].

Assertion 1 *The wavefunction ψ does not univocally determine the values of all physical properties[31] (p. 5).*

Assertion 2 *ψ encodes complete information about physical systems[31] (p. 5).*

Assertion 3 *Physical properties instantiate determinate values at all times[31] (p. 5).*

As discussed in §3, variable values are universally interpreted as measurements. However, what the above assertions point out is that there is no consensus on an interpretation of variable values outside of a measurement[17]. That is, between measurements there is no consensus on whether variable values reflect determinate values present in the universe (as in assertion 3), or not, as described by ψ (assertion 1 and 2)[17].

The EPR paradox paper[30] challenged assertion 2 claiming that ψ does not encode complete information about physical systems. This position is held by theories of hidden-variables[17]. Such theories represent one of the so-called interpretations of quantum mechanics[17]. Although this interpretation may be, as Tegmark argues[3, 11], only held by a minority of physicists, it is still a valid interpretation to hold[17]. Furthermore, there is not just one other prominent interpretation, but several variants of the Copenhagen interpretation and the many-worlds interpretation[11, 17]. In short, there is no one interpretation that is universally accepted for variable values outside of an observed moment[11, 17, 30, 32, 33].

However, Tegmark's goal for the MUH[3] was not a submodel of all models of MFTs, but a hypothesis that could account for relativistic and quantum phenomena. To this end, Tegmark incorporated the many-worlds interpretation[33], which is based on Everett's relative state formulation of quantum physics (RSF)[32]. Everett's RSF addresses the determinacy problem[31] by challenging assertion 1.

Assertion 1 implies that (between observations) variable values represent something that is indeterminate. Consequently, between observations there would be no well-define state of the universe[17]. Instead, there would only be a set of possible states, where ψ defines the probability for each state to be realized[17].

However, in direct contradiction to assertion 1, Everett's RSF asserts that ψ univocally determines all values of physical properties. Specifically, Everett's RSF asserts that all possible variable values described by ψ for any given moment are realized simultaneously[3, 32, 33]. Meaning, all related possible states are realized and coexist[33]. The many-worlds interpretation[33] argues that the perception that only one of these states exists is due to observer embodiments being well-defined only within a given state[33]. Because a well-defined embodiment does not span states it is only aware of the state in which it is well-defined[33]. This notion is described as observers existing in parallel universes[33], which are universes that exist simultaneously but are causally-independent[3, 11, 33].

Tegmark[3, 11] details several ways causally-independent parallel universes could be subuniverses of our own. Some of these explanations relate the passage of time, such as the expansion of the universe outpacing the speed of light (speed of causation)[3, 11]. However, the passage of time is not interpreted in the traditional way[29] with Tegmark's MUH[3]. Instead, the MUH models the universe as being eternal[34], where all moments past, present and future exist simultaneously without an objective distinction[34]. Tegmark explains how this philosophy is a logical consequence if the structure of the universe is accurately describable by determinate mathematics[3]. This means, however, that Tegmark's MUH requires an explanation for how parallel universes could exist within an *eternal* universe.

To explain this Tegmark[3, 11] offers an extreme form of eternalism, whereby not only are all past and future states realized eternally but all *possible* states are realized simultaneously[3, 11]. In terms of Tegmark's MUH, every state within the state space of the eternal mathematical structure (which is the universe) is realized eternally[3] (see fig. 4). Observer embodiments are included within these eternal states and perceive only their own state[3]. The passage of time is explained as an illusion based on the perception of memories that are present within each state[3]. In the end, Tegmark[3, 11] provides logical explanations for the existence of parallel universes that culminate with the assertion that we live in a complex multiverse[3, 11, 24].

Other than ontological criticisms[14], there have been two main criticisms of Tegmark's MUH[3]. The first is directed at these notions of parallel universes and the resulting multiverse[14, 20–24]. As Liddle[24] put it, these notions go "well beyond accepted viewpoints"[24] (p. 25). These notion are not logical consequences of the interpretations identified in §3, but, as discussed, relate to the many-worlds interpretation of quantum mechanics[33]. The other main criticism has been based on arguments that a mathematical structure is insufficient to account for all aspects of the universe. These arguments relate to both the incompleteness of mathematics[12] and arguments that the physical domain fundamentally cannot account for elements of consciousness (e.g. qualia)[25, 35–41]. However, none of these criticisms related to the interpretations identified in §3, since these interpretations do not imply Tegmark's[3] assertion that the universe is nothing more than an eternal mathematical structure. In general, there have been no criticisms of Tegmark's MUH[3] suggesting that the interpretations identified in §3 are not universally accepted[12, 14, 20–27].

In summary, although Tegmark's MUH[3] is founded on the universal interpretations identified in §3, it includes an additional interpretation not universally accepted. The trade-off of adopting this interpretation, which enabled the MUH to incorporate many aspects of relativistic and quantum physics, is that the MUH is not a submodel of all models of MFTs. The benefits of such a submodel are discussed in the next section.

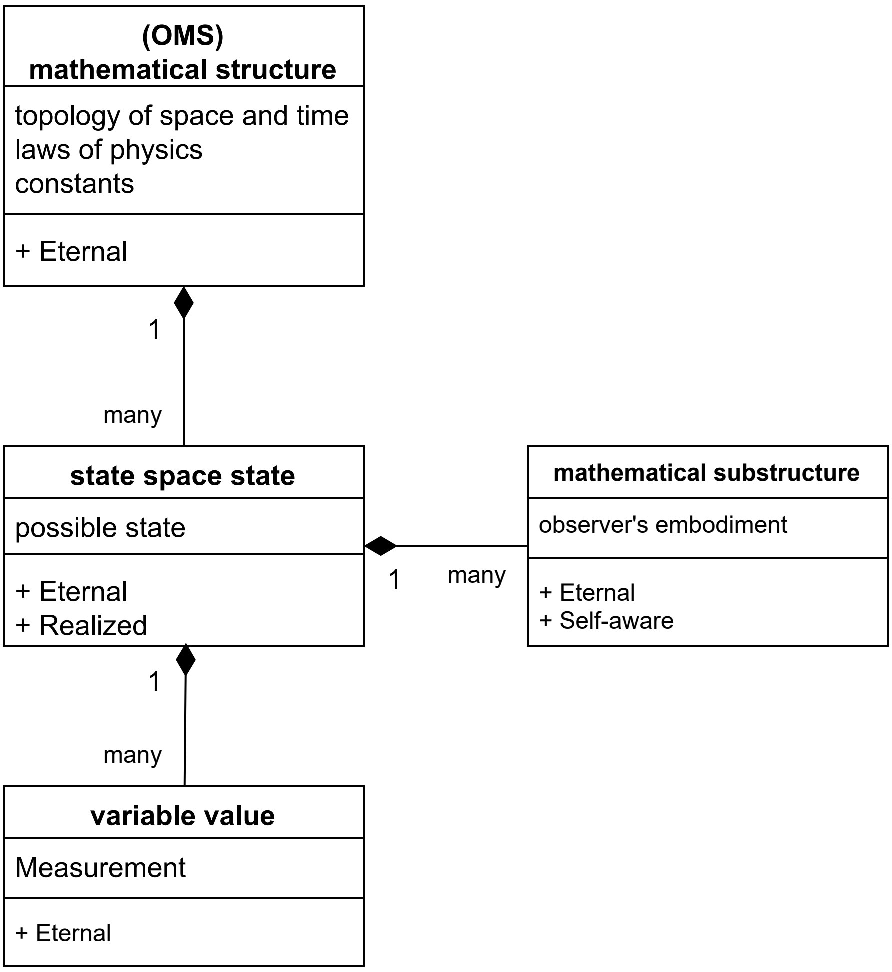

Fig. 4 Here the miniMUM is extended by relating its elements to aspects of Tegmark's[3] multiverse. All lines are UML composition relationship lines to indicate that all components are part of the eternal mathematics structure. Similarly, all components are marked as 'Eternal'. With Tegmark's[3] multiverse all possible states are 'realized' and observer embodiments are 'self-aware' mathematical substructures of a state space state.

5 Discussion

For the MUH to become a submodel of all models of MFTS would require the many-worlds interpretation to be universally accepted[2]. As discussed in §4, this interpretation is related to the determinacy problem described by Mariani[31], which divides the branches of modern physics. Beyond the conceptual issues described by Mariani[31], the determinacy problem reflects a fundamental divide between quantum mechanics and spacetime mathematics[17, 30]. Specifically, while quantum mechanics is fundamentally indeterminate, spacetime mathematics is determinate[17, 30]. This leaves some hope that resolving this mathematical inconsistency could facilitate a resolution of the conceptual inconsistency and result in a theory of everything[42–44].

Recent efforts to unify these mathematical frameworks have largely focused on a correspondence, identified by Maldacena[45]. This correspondence is between two types of spaces, quantum's conformal field theory (CFT) and anti-de Sitter space (AdS) (a special kind of spacetime)[43, 44]. Based on this correspondence, and mathematics from Ryu and Takayanagi[46], van Raamsdonk[47] proposed that spacetime was emergent from quantum phenomena. However, despite supporting research[17, 43, 44, 48–51] and continued progress[52–55], significant challenges remain[43, 56, 57]. For example, the AdS/CFT correspondence relies on the holographic principle[58, 59], which only applies to a universe, unlike our own, that is static and bounded[43, 58, 59]. Furthermore, our universe is a de Sitter space, not an *anti*-de Sitter space[43]. Therefore, a solution based on AdS/CFT correspondence is insufficient to account for the mathematics of spacetime for our universe[43, 56].

If efforts such as these are successful and conclude in a way that establishes the many-worlds interpretation as the only acceptable interpretation of quantum mechanics, then Tegmark's MUH could become a submodel of all models of MFTs. However, Bianchi[60] recently argued that the Copenhagen interpretation is also compatible with these efforts. Meaning, a successful conclusion of these efforts may be insufficient for the many-worlds interpretation to gain unanimous consent. Another way the many-worlds interpretation could gain unanimous consent would be on philosophical grounds. However, debates continue regarding the philosophy of time[29, 34] and whether eternalism is implied by the mathematics of spacetime[61]. Therefore, it seems unlikely that Tegmark's MUH will become a submodel for all models of MFTs any time soon.

However, as Tegmark showed in his popular book[11], the MUH[3] can be used as a submodel when discussing models from both branches of modern physics - as long as these models are compatible with the many-worlds interpretation[24]. In this way, Tegmark's book[11] demonstrates the utility of a common submodel.

The miniMUM is similar to the model described by Tegmark's MUH[3]. However, the miniMUM does not explain any phenomena specific to either relativistic or quantum physics. This is because it is bounded by the commonalities of these branches, specifically the principle of mathematical formulation. As a result, the miniMUM avoids the determinacy problem[31] that divides the branches. Furthermore, this reduces the implied viewpoints. For example, the miniMUM does not share the MUH's[3] viewpoints on parallel universes or a multiverse (see §4). Consequently, it is not subject to the related criticisms[24]. However, as demonstrated in figure 4 the miniMUM can be extended to incorporate such views. This is because, although not mathematically formulated, Tegmark's MUH includes all interpretations included in the miniMUM, including the interpretation of variable values being measurements. Therefore, the miniMUM is a submodel of the model described by Tegmark's MUH.

The real potential of the miniMUM lies in the fact that it is a submodel of all models of MFTs. That is, the miniMUM is a structure that all models of a MFT must adhere to. Consequently, the miniMUM can unite any set of compatible models of MFTs. This is achieved by extending the miniMUM with the models' concepts/interpretations, as was done in §4 to express aspects of Tegmark's[3] multiverse (see fig. 4). Since the miniMUM is a submodel of all models of MFTs, any concept not modelable indicates an incompatibility with the principle of mathematical formulation. Concepts that are incorporated, can be (technically) compared, contrasted and/or combined with other incorporated concepts.

This relating of concepts across models (and branches) could aid research into some of the most fundamental problems of modern physics. In part because such problems often include conceptual aspects[17, 30, 31]. For example, Mariani[31] details several conceptual issues related to the determinacy problem. Furthermore, conceptual relationships can help theoretical physicists identify where mathematical correspondences, between distinct mathematical models/frameworks, are likely to exist. Such correspondences, such as the one identified by Maldacena[45], could be the key to mathematically merging the branches and modern physics to produce a mathematically formulated theory of everything[42–44].

6 Summary

Physicists are only able to interpret each other's MFTs thanks to the set of universal interpretations identified in §3. It is from these general interpretations that a theory's specific interpretations are built. For example, the interpretation of e representing energy in special relativity's $e = mc^2$ equation, is built on the universal interpretation that variable values represent measurements. By incorporating just these universal interpretations, the miniMUM is necessarily a submodel of all models of MFTs. Consequently, the miniMUM is a universal submodel of modern physics such that all models of MFTs are essentially extensions of it. This allows any concept of these models to be expressed in terms of miniMUM. Therefore, the miniMUM offers physicists and philosophers a common model with which to collaborate, gain insights and unite models, across modern physics.

Declarations

The author has no relevant financial or non-financial interests to disclose.

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