THE THEORY OF EVERYTHING: A DISTANT FANTASY OR AN IMMINENT REALITY?

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ABSTRACT

A Theory of Everything (ToE) aims to reconcile four fundamental forces. These forces are currently described by two incompatible frameworks. The first of these frameworks is the Standard Model of Particle Physics, which accurately describes three of the forces and governs behaviour on microscopic scales. In contrast, gravity, the fourth fundamental force, is described on a macroscopic level using Einstein's theory of general relativity, the second framework. Over the past 100 years, scientists have endeavoured to reconcile these two frameworks into a ToE; however, no resolution has yet been identified. The successful development of a ToE would enable scientists to probe the early universe, an area of physics unaccounted for by current models.

To assess the likelihood that a valid ToE will be discovered, this literature review analyses three approaches: two historic attempts that sparked significant debate and a contemporary (2025) approach that may mark a pivotal change in ToE research. To determine the factors influencing the validity of a ToE, these case studies are evaluated against the criteria of mathematical verifiability, alignment with established knowledge, and experimental accessibility. However, it does not suffice for a theory to be proven true, it must also gain majority acceptance within the scientific community. This review, therefore, also discusses the challenges involved in achieving such acceptance and uses the fluctuating popularity of string theory to evidence this.

INTRODUCTION

The field of physics was built on the ambition to fully understand the world around us. This pursuit is epitomised by the ongoing search for a Theory of Everything (ToE), a single framework capable of describing every interaction in the universe. A valid ToE would be formed by successfully describing all four fundamental forces under one framework. This would allow scientists to probe the early universe, particularly as its dense and hot conditions would facilitate the unification of all fundamental forces into a single interaction (Kolb and Turner, 2018). However, current physical models cannot explain how this unification occurs. A valid ToE would allow this to be better understood.

Current understanding of the universe is described by four fundamental forces:

- **Gravity:** the attractive force acting between all masses, responsible for planetary motion and holding us on the ground.
- **Electromagnetism:** the force governing interactions between charged particles.
- **Strong nuclear:** the force binding atoms together.
- **Weak nuclear:** the force responsible for radioactive decay.

These forces are described by two incompatible frameworks: the Standard Model of Particle Physics (Kolb and Turner, 2018) and Einstein's (1915) theory of general relativity. The Standard Model combines the mechanisms for electromagnetism with the strong and weak nuclear forces and forms a complete framework describing the fundamental particles on a microscopic scale. Standard Model interactions are described using bosons: a special kind of particle, associated with each force, that acts as an intermediary or force carrier (Partanen and Tulkki, 2025).

Gravity, however, does not have an associated force carrier and has not yet been reconciled with the other forces. It is described by Einstein's (1915) theory of general relativity, which proposes that masses distort spacetime. By analogy, spacetime can be visualised as a flat stretched sheet. When a heavy object, like a bowling ball, is placed into the centre, the sheet will stretch and bend around it. Einstein's (1915) theory states that this curvature of the sheet represents gravity. General relativity accurately describes the largest objects in the universe, but is incompatible with the quantum phenomena that describe the microscopic world.

The ongoing aim of ToE research is to unify gravity with the Standard Model, producing a single framework capable of describing every particle, every force, and every interaction (Weinberg, 1993). Unfortunately, despite significant research and several promising approaches, no theory has successfully achieved this. This paper discusses three criteria for evaluating the validity of a ToE and examines how each applies to three proposed theories.

The first criterion concerns the experimental accessibility of a theory. This is arguably the leading method used to accept scientific theories because hypotheses must match the observations of our universe, so it is important that a theory's predictions do not contradict observation. Moreover, Giere (1983) argues that even a theoretical hypothesis has a strong intrinsic link to empirical observation, and hence the ability to conform with experimental results and be experimentally proven is an important characteristic of a potential theory. The second criterion evaluates how rigorously the theory can be proven mathematically, an important basis for all scientific proofs. Since ToEs explore new physics, it is likely that proposed theories reformulate mathematical principles in revolutionary ways. This may mean that rigorous mathematical proofs are not easy to define and will require significant effort and time to be confirmed. Thirdly, a successful theory must gain scientific support, which, as Cushing (1990) notes, can depend on contingent and contextual factors. This makes the acceptance of a theory hard to predict. Whilst some proposed theories build on current scientific models, others create new foundations, which can initially seem unintuitive. The acceptance of a theory is tied to its perceived reasonability. Therefore, as intuitive or preconceived ideas are more likely to be deemed reasonable, the third criterion measures the alignment with pre-established knowledge.

EARLY APPROACHES FOLLOWING GENERAL RELATIVITY: KALUZA-KLEIN

In 1921, physics research focused predominantly on developing the formalisms for electromagnetism and general relativity (this precedes the conception of the strong and weak forces in the 1930s, meaning the only known fundamental forces were gravity and electromagnetism). Whilst this research was mostly distinct, Kaluza aimed to prove that these theories stemmed from the same foundations by adapting the geometry underlying general relativity (Kaluza, [1921], 2018; Kolb and Turner, 2018). He argued that the unification of these theories was only possible if there was greater variability and proposed an additional curled-up fifth dimension. This was revolutionary thinking, as all current experimental observations indicate a four-dimensional universe: the three spatial dimensions (for example, x, y, and z) and a temporal dimension. Hence, no evidence suggests that there may be a higher number of dimensions. By extension, the additional dimension remains out of reach of experimental testing, and so, a large proportion of his theory is experimentally unprovable. This posed a major barrier to gaining scientific acceptance and exemplifies a common problem with ToEs. Despite this, Kaluza's ([1921], 2018) theory gained scientific recognition and continued to be improved upon.

For mathematical solvability, Klein (1926) then imposed geometric conditions on the fifth dimension, namely its infinitesimally small size and cylindricity (it would look like a ring). These approximations led the theory to break down, particularly when applied to particle physics, as it was unable to reproduce experimental observations of particle masses and the value of the cosmological constant.

For many years, these fundamental problems were viewed as the result of improper compactification of the fifth dimension (where compactification is the process of 'curling-up' the additional dimension so that the theory matches the four-dimensional view that we have of our universe). To combat this, some proposed solutions adjusted the structure of the fifth dimension by adding more gauge fields (Wesson, 1999) or adapting the geometry itself (Baptista, 2024). Whilst these techniques showed some merit and resolved the compactification problem, their approaches did not achieve the unification described by Kaluza. Today, some research continues to further Kaluza's ambition (Horoto and Scholtz, 2024), though the support for his approach has been in steady decline, and these research strands are not currently well accepted. Initially, Kaluza's methods were overshadowed by progress in other areas of physics, limiting the progression of his approach. However, the adaptation of Kaluza-Klein's theory paved the way for modern string theory and continues to be studied by a small but diligent group of the scientific community (Wesson, 1999).

APPROACHES IN THE 60S AND 70S: STRING THEORY

Of all the potential ToEs, string theory is often regarded as the most promising and is the eminent frontrunner in popular science (Kolb and Turner, 2018). At its core, string theory reinterprets the Standard Model particles as one-dimensional strings. These strings oscillate at given frequencies that correspond to different elementary particles. Thus, string theory reduces the complexity of the Standard Model from dozens of particles down to a single string (Duff, 1985).

The first string theories stemmed from the expansion of the Kaluza-Klein theories to include the strong and weak nuclear forces. Similar to the argument Kaluza made, the number of dimensions was increased to allow sufficient variation, and as with the Kaluza-Klein theories, the compactification of these additional dimensions caused mathematical challenges. Today, the presence of additional dimensions continues to be a contentious issue. String theories depend on them, yet no experimental evidence has ever indicated that there may be more than four dimensions (Gannon, 2009). The lack of experimental evidence of higher dimensions is often quoted to discredit string theory, but this problem was also seen with the Kaluza-Klein theories, leading some scientists to argue that this method of discreditation is unfair (Gannon, 2009).

From 1960 to 1995, string theory went through many evolutions. These can be categorised by four major periods, each fuelled by the resolution of a fundamental flaw of the previous version (Rickles, 2014). During these periods, the scientific interest in string theory surged, motivated by the possibility of great fame and scientific immortalisation (Smolin, 2006). By 2006, this influence was reflected in academia: twenty of the twenty-two tenured professors at the United States of America's top physics departments were prominent string theorists (Smolin, 2006). There was hence pressure to pursue string theory despite no evidence proving that string theory was the correct approach. This dominance reflects the nature of scientific research, as grants are given to areas of greatest interest and perceived progress (van Leeuwen and Moed, 2012). As a result, string theories constitute a large proportion of the scientific research produced over the past 50 years, evolving string theories from a recognisable extension of Kaluza-Klein to a set of thousands of possible conjectures and ideas (Rickles, 2014).

Most modern string theory developments study M-theory, a branch of string theory, which argues that the thousands of models are different manifestations of one underlying theory (Rickles, 2014). This implies that string theory possesses a level of practical flexibility: its many models can depart from the underlying theory whilst retaining strong empirical fit. Consequently, empirical fit alone cannot confirm the theory because there is no basis for selecting between fits (Cushing, 1990). This flexibility complicates string theory, as every model must be independently verified or refuted. Many critics observe the multi-frontal and diverging approaches to string theory and the difficulty in selecting between them as string theory's largest problem.

Overall, ToE literature provides a polarised view of string theory. Whilst some argue the mathematical beauty automatically lends itself to a ToE (Schwarz, 2009), others see the ever-evolving challenges of applying string theory to gravity and conclude that further developments are unlikely (Rickles, 2020). This distinction in opinion makes it hard to predict the likely success of string theory and the polarity is similarly reflected in popular science, with staunch supporters (Green et al., 2012) and critics (Smolin, 2006) in equal number. In his popular science book critiquing string theory, Smolin (2006) argues that it is the boldness of string theory that has enamoured the world and less so its scientific credibility. Smolin's (2006) argument highlights a larger problem in theoretical physics in that the conceptual elegance of a theory can outshine the need for experimental confirmation. He also argues that string theory's cycles of boom and bust make the prediction of success impossible, an assertion also shared by others (Cushing, 1990; Gannon, 2009). Today, the state of string theory lies unstably between boom and bust, with little work progressing its historical challenges, but new conjectures constantly emerging.

Despite the polarised support, work on string theory unequivocally progressed ToE research and visibility and remains a leading front-runner. However, its many divergent paths weakened public and scientific perception of the theory, highlighting the barriers facing the acceptance of a ToE and the continued complexity and controversiality of string theory.

MODERN APPROACHES: PARTANEN AND TULKKI

In the decades since the major developments in string theory, efforts to unify gravity with the other fundamental forces have generally slowed. However, a recent resurgence of scientific interest has revolved around the work of Partanen and Tulkki (2025). In May 2025, they proposed a new method of quantising gravity which avoids the unphysical infinities that have appeared in historical approaches. If gravity is successfully quantised, then it would be easier to unify with the other Standard Model forces (Oppenheim, 2023). Partanen and Tulkki's (2025) proposal replaces general relativity's notion of curved spacetime to treat gravity as a force mediated by a force carrier, the graviton. The graviton is analogous to the force carriers of the other three fundamental forces, and although it has never been experimentally confirmed, it has been marked as a provisional addition to the set of Standard Model particles since the 1960s (Partanen and Tulkki, 2025).

Their most recent work builds on a previous paper (Partanen and Tulkki, 2024) in which they reformulated Quantum Electrodynamics (the quantum theory of electromagnetism) using a framework that more closely resembles that of the gravitational interaction. This work laid the foundations for reformulating gravity in line with the Standard Model, which they have now extended. If Partanen and Tulkki's (2025) theory is proven true, then it marks significant progress towards quantising gravity and unifying it with the Standard Model. Importantly, their work reproduces the fundamental equations and relations of general relativity; a feat previously missed in other discussions of quantum gravity (Zych and Brukner, 2018; Das et al., 2023).

Partanen and Tulkki (2025) approach the quantisation of gravity using the well-established mathematical technique of renormalisation (redefining fundamental parameters to absorb unphysical infinities). It is argued that this approach marks a move to simpler methodologies, built on current physical models and avoiding the paradigm shifts that polarised, for instance, string theory (Partanen and Tulkki, 2025). Additionally, they avoid the mathematical and conceptual complications of including higher dimensions, as experienced by string theory and the Kaluza-Klein models.

As their paper was only released in May 2025, determining the scale of the scientific response is challenging; however, it has already received significant media attention. This highlights the relevance of the search for a ToE as well as the suitability of their methodology. Many popular science websites and magazines have already published articles heralding their work as a decisive step towards the unification of the fundamental forces (Brigham, 2025; Feldman, 2025). But some reviews are more hesitant to accept the theory until it can be rigorously proven mathematically. In their paper, Partanen and Tulkki (2025) offered the first level of mathematical proof, but higher levels will require more time to achieve. This acts as a reminder that large advances in science require time and work to be fully accepted. Ultimately, it is unclear what impact this paper will have in 25 years, whether it marks a decisive step forward towards a ToE or whether it will become one of thousands of abandoned approaches. It does, however, mark a return to simpler theories that build on pre-existing mathematical frameworks in physics.

CRITERIA FOR ASSESSING A THEORY OF EVERYTHING

At the start of this review, three criteria for evaluating the validity of a ToE were proposed. This section draws from the historical examples studied to analyse the usefulness of experimental confirmation, mathematical rigour, and scientific acceptance for defining a valid ToE.

Although experimental evidence ordinarily constitutes a useful metric for determining the validity of a theory, ToEs extend beyond current understanding of the universe and so struggle to be directly experimentally verified. In the cases of Kaluza-

Klein and string theories, the extension into higher dimensions removed the ability for direct experimental verification because there is no infrastructure for measuring higher-dimensional quantities (Smolin, 2006). Contrastingly, Partanen and Tulkki's (2025) theory was designed around simplicity, yet they offer no form of direct experimental verification either. This indicates a trend that ToEs struggle to gain direct experimental verification.

If the possibility of complete experimental verification is unlikely, then other forms of verification become more important. As such, the rigour with which a theoretical proposition can be proven mathematically is paramount to its success. In the case of Kaluza-Klein, the challenges linked with the mathematical compactification of the higher dimension slowed progress and ultimately led to its limited acceptance. Similarly, string theory faced mathematical barriers as its complexity increased. The diverging approaches led to a set of thousands of theories with no ability to select one over another. As a result, no single theory can be proven mathematically without disproving all the others, a challenge that is ongoing. This highlights the time and commitment needed to mathematically prove a ToE, a problem that Partanen and Tulkki's (2025) theory is currently facing. This delay slows the progression of a theory and prevents its expansion and acceptance. This is particularly apparent for string theory, where this delay had a large effect on the interest in and support for the approach, leading to its current in-between state. Therefore, mathematical verification has been shown to be vital to the acceptance or rejection of a ToE, and complications linked to rigorous mathematical proof significantly affect the perception of a ToE and can contribute to its abandonment.

The positive perception of a ToE is vital for its acceptance and progression. The final criterion aimed to consider how acceptance by a scientific majority impacts the success of a ToE and whether accordance with current physics models influences this. In the case of string theory, its boldness and description of exotic phenomena added both to its allure and its criticism. Kaluza-Klein aligned better with existing models and proposed a variation to general relativity, yet it was largely overshadowed by other progress in physics at the time and only gained large recognition later. By contrast, Partanen and Tulkki's (2025) work explicitly avoided novel approaches, such as higher dimensions, arguing that their methodology purely reformulates existing models. This may suggest that an alignment with current understanding is deemed important by the scientific community. Perhaps the successful acceptance of a ToE lies in its ability to be both revolutionary and palatable, bold enough to redefine understanding without disrupting the foundations of established science.

CONCLUSION

In conclusion, it is not possible to determine the likely acceptance of a valid ToE, though scientists remain optimistic that a suitable theory will be proposed (Cushing, 1990; Gannon, 2009; Partanen and Tulkki, 2025). Many approaches to unification have been offered, all aiming to reconcile gravity with the Standard Model, from additional spatial dimensions in Kaluza-Klein and string theories to simpler mathematical reformulations in Partanen and Tulkki's (2025) approach. However, none of these methods appear to have fully resolved the problem, hindered by untestable assumptions, increasing theoretical complexity or time.

Analysis against the proposed criteria highlights the incompatibility of direct experimental verification for a ToE. This increases the dependency on scientific perception and strong mathematical proofs for defining a theory as valid and reasonable. It was noted that the polarised response to string theory was strongly correlated to its perceived strangeness, and thus the acceptance of future approaches may depend on balancing revolutionary insight and having theoretical consistency. Ultimately, the search for a ToE has majorly progressed scientific understanding in the last 100 years and continues to inspire novel approaches to explain our universe at the most fundamental levels.

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