Theories of Everything: a Critical Analysis of the Concept as Used by Physicists

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Summary

In this thesis I analyse what a ‘Theory of Everything’ (ToE) entails according to physicists. A ToE should provide a unified theory of all forces of nature, as motivated by parsimony. Ideas about necessity are also present, as many hope a ToE will predict the constants of nature. Topics such as determinism, cosmology and dark matter are omitted from discussions without further motivation. Interestingly, the above characteristics of ToE’s are strongly influenced by its roots in string theory. Finally, ToE’s are often seen as the ultimate unification. Such a definition is too simple, as ideas about necessity and reductionism are also strongly present. In the end, we see that practical, metaphysical and scientific reasoning has influenced the concept.

‘The name ‘Theory of Everything’ instead of ‘Ultimate Law’ or ‘Basic Law’ was a bad commercial.’ (‘t Hooft 1994, 20)

Introduction

Many people with an interest in fundamental physics have likely heard of the term ‘Theory of Everything’ at least in passing. This Theory of Everything (ToE) is often portrayed as a grand idea based on the most fundamental physics we know, a theory that is elusive yet perhaps also within our reach. The discovery of such a theory would be the ultimate victory for physics by providing an all-encompassing framework for the world and the laws of nature. A solid basis all other science could build upon.

It is exactly this rhetoric surrounding ToE’s that causes many physicists to react with a certain ire towards the term. Physicists wonder if it is not overreaching the boundaries of physics and science itself to state that one may find a Theory of Everything that is solely based on physics. In this light, one cannot be surprised that the main criticism concerns the arrogance of the very term ‘ToE’ ('t Hooft et al. 2005; Flam 1992; Wilczek 2021). The criticism is not limited to it being an arrogant term. Notably, the ‘everything’ in ToE is seen as both misleading and insufficient (‘t Hooft 1994, Davies 1994; Polchinski in Hossenfelder 2018; Wilczek 2009). There is even less support for the suggestion that a ToE will be found in the foreseeable future (‘t Hooft 1994; Hossenfelder 2018; 't Hooft et al. 2005).

Given such strong criticism, one wonders why the terminology is still used nowadays. How does such a controversial term survive in a scientific community at all? In fact, the term ‘Theory of Everything’ did not originate as jargon meant to be used among peers. Rather, we will see that the phrase is rooted in popular science. This is reflected in the references that will be used in this thesis. I shall use popular scientific books and articles, interviews with physicists meant for a general audience and conference talks and articles intended for a non-physics scientific audience.

The term’s popular scientific roots combined with the above controversy concerning its legitimacy can explain two things. First, it can explain why ‘Theories of Everything’ never gained traction in academic pieces. Scientists are generally preoccupied with slow and steady progress. One may have a grand goal in mind, but the steps towards this goal as described by academic papers are technical and small. This leaves little room for arrogant but vague terms, negative qualities that 'Theories of Everything' suffer from according to physicists that dislike the term.

Secondly, the surprising longevity of the concept of ToE's also stems from its persistence in popular science. It is obvious that a 'Theory of Everything' has rhetorical power, making it attractive for the interested layperson. Its overambitious nature prevented ToE's from becoming an element of serious scientific discourse in physics, which in turn kept the term ambiguous. This allows authors of popular scientific pieces some leeway when writing about 'Theories of Everything'. It is not quite clear what traits a possible Theory of Everything should possess, and this vagueness makes the term widely applicable. Combine this with the air of mystery and grandness and one can understand how the term persisted in popular scientific writing without resting on a firm scientific basis.

This leaves us with a problem. Here one has this popular and widely used term that is used by physicists, but mainly in non-scientific writings. Due to this, the term has not received rigorous scientific analysis, which the exact definition of a 'Theory of Everything' unclear. Physicists pride themselves on being part of a fundamental and exact science. Being associated with imprecise terms such as a 'Theory of Everything' could throw a spanner in the works. Some physicists have given their opinion on what a ToE should and should not account for, but this discussion is often left to incidental and informal channels, such as interviews and pieces in magazines. So, even though the term is not often used in scientific writings, physicists do frequently use the term in popularising texts. This is the cause of a lack of a clear definition of 'Theory of Everything', which can impede possible discussions about it on the topic of ToE's by causing people to talk past one another. Elucidating what a ToE should and should not include according to physicists, clarifies discussions in the popularasing domain. Finally, further analysis on this topic could allow us to understand what motivations influence the ToE discourse. These motivations can very well point to serious scientific programmes and discussions.

The goal of this thesis ties in with this issue: I want to provide clarity on what a 'Theory of Everything' entails according to these physicists that use the term. To achieve this, I will provide an analysis of the concept of the 'Theory of

Everything' by basing myself on the words of the physicists themselves.[1] It is important to note that I shall not discuss the possible (non-)validity of proposed ToE's. My goal is to find what characteristics members of the physics community ascribe to a ToE. In this discussion, I have chosen to discuss the points of view of physicists that work in branches of physics that are related to the ToE enterprise.[2] The chosen selection of physicists represent a range of views and ideas that together form the main positions regarding ToE's in fundamental physics. This leads us to the question: what is left out of the discussion? The omission of some topics in the context of ToE's will prove worthy of further inquiry. Once I have completed the analysis of the concept 'Theory of Everything', I will give a critical discussion of the concept. This will include a reconstruction of the origin of the concept, an example of the assumptions that physicists make and the implications of the term for physics.

The structure of this thesis will be as follows. In Chapter 1, I shall provide an introduction into some aspects of theoretical physics that are relevant for the discussion of ToE's. Some historical background will be given on the topic to put the nascence of the term into context. Here we shall see that the discourse on ToE's is coloured by its history, which will in turn influence what characteristics are seen as essential to ToE's. Chapter 2 will provide the body of this thesis. Here I shall discuss the core characteristics that a ToE should have to rightfully be called such according to physicists. This discussion includes, but is not limited to, topics of unification, reductionism and simplicity. Even though the term 'ToE' is controversial, we will see that most physicists seem to converge on a relatively similar interpretation of what a ToE should encompass. In Chapter 3, I shall discuss some topics that are rarely mentioned in the ToE discourse, although they are very relevant for physics, namely dark matter, determinism and cosmology. In Chapter 4 I shall critically analyse the concept of ToE's as envisioned by physicists. The discussion in Chapters 2 and 3 allow us to evaluate the origin and usage of the term 'Theory of Everything', which is not without issue. Finally, I argue that one can only account for the definition of ToE's as used by physicists by assuming a comprehensive point of view, including practical, metaphysical

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[1] This is opposed to using popular scientific sources written by non-physicists, as the term 'Theory of Everything' there is often used quite loosely.

[2] These branches include, but are not limited to, particle physics, astrophysics, cosmology and quantum gravity.

and scientific motivation. Multiple philosophers of science have written about the function of unification in physics and I will argue that their notions are not sufficient to explain the conception of a ‘Theory of Everything’ that has all the traits I discuss in this thesis.

Chapter 1: Working towards a Theory of Everything

As mentioned in the introduction, the goal of this thesis is to provide an analysis of what traits a ToE should have, according to physicists. One will need some background, both technical and historical, to have a useful discussion of this topic. The aim of this chapter is to provide that background. First, I shall introduce the concepts that are relevant in contemporary fundamental physics. Fundamental physics is a very broad field with many different research topics, but for our discussion of ToE's it suffices to limit ourselves to particle physics and gravity. Then the role of unification in contemporary physics will be discussed. This will be combined with some historical background on unification in physics. Finally, I shall link these concepts to the emergence of the usage of the 'Theory of Everything' terminology.

The Four Fundamental Forces of Nature

Nowadays, the so-called Standard Model can be seen as the most accurate theory of particle physics. This model describes the fundamental particles and the electromagnetic, weak and strong forces. There are many different particles, seventeen to be exact. Figure 1 shows a schematic overview of these particles. Twelve particles are fermions, the particles of which matter is constituted; these are the blue and grey particles in Figure 1. The particles with an orange colour in Figure 1
are so-called bosons. Bosons are force-carriers, they are the particles that mediate the forces between the matter-particles or fermions. Very crudely put, the fermions do not experience forces by physically 'bumping' into each other, rather, they experience them by exchanging bosons. Finally the last particle is the Higgs boson, which is denoted by the yellow colour in Figure 1.

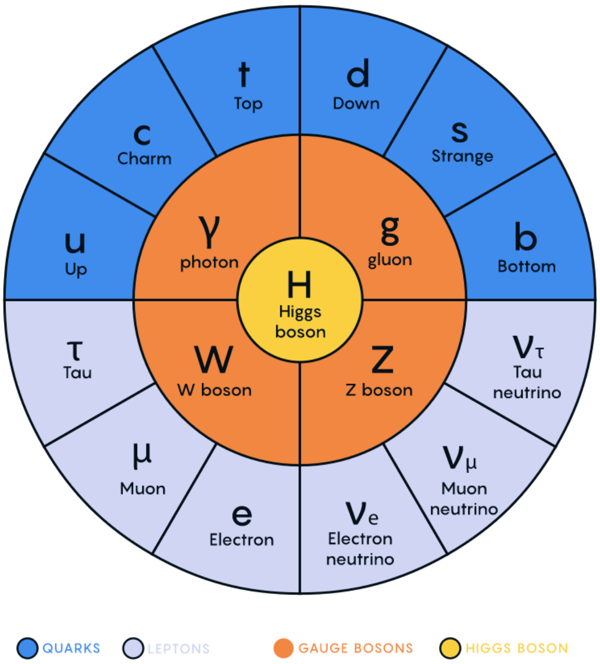

Figure 1. All particles of the Standard Model. (Image by Wolchover, Velasco and Reading-Ikkanda, October 22, 2020, Quanta Magazine, https://www.quantamagazine.org/a-new-map-of-the-standard-model-of-particle-physics-20201022/)

The Higgs particle gives all other particles their mass by interacting with them.[3] Note that empirical confirmation of the Standard Model is relatively recent, some of the four force-carrying bosons were only experimentally discovered in the 1980's. The observation of the Higgs boson completed the experimental verification of the Standard Model in 2012.

Physicists have currently proven the existence of four fundamental forces of nature: the electromagnetic, strong, weak and gravitational forces. These forces all have different strengths and ranges. Three of these, the electromagnetic, strong and weak force, can be described in the mathematical and conceptual framework of the Standard Model. This is the framework of bosons being

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[3] Two remarks can be made here. Firstly, the Higgs boson gives particles a mass through a process involving spontaneous symmetry breaking. The exact details of this process are not relevant for our discussion. Secondly, it is possible that a particle does not interact with the Higgs boson. In this case, the particle would be massless. Photons are an example of such massless particles.

force-carriers between fermions, as mentioned above. Every force is accompanied by specific bosons. To begin with, the boson of electromagnetism is the photon. Electromagnetism concerns the interactions between charged particles, such as electrons. The strong interaction is mediated by gluons. This is the strongest force, as it is responsible for binding fundamental particles together to form 'larger' particles. Finally, the weak force is mediated by the W and Z bosons. This force is, among others, responsible for the decay of particles.

The Standard Model gives us an explanation for three of the four fundamental forces, but this leaves us with an odd one out: gravity. Gravity is the force that causes massive and energetic objects to be attracted towards each other. To our knowledge. gravity does not have a corresponding force-carrying particle, a boson, while the other three forces do act by means of a boson. Gravity is described by the Theory of General Relativity, a theory that is empirically very successful. General Relativity describes gravity in terms of curved spacetime. Figure 2 shows an artistic representation of curved spacetime. The heavier the object, the deeper the well that the object is located in. Thus the distribution of mass causes a curvature in spacetime. An object follows the shortest path in this curved spacetime. The force of gravity then describes how matter and curved spacetime interact.

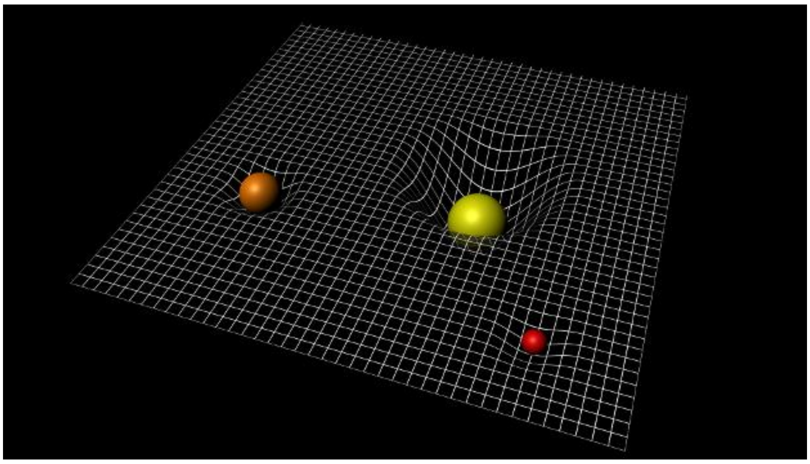

Figure 2. An artistic representation of curved spacetime in two dimensions. (Image by C Carreau, August 30, 2015, European Space Agency, https://sci.esa.int/web/lisa-pathfinder/-/56434-spacetime-curvature)

One can see that the explanatory framework of General Relativity is very different from that of the Standard Model, as gravity is not mediated by bosons. In addition, the mathematical methods used in General Relativity are also different from the ones used in the Standard Model. Due to these differences it is currently impossible to incorporate the Standard Model and General Relativity in the same theoretical model. Even without understanding the exact mathematics, one can already understand from the above discussion that there are large conceptual differences between General Relativity and the Standard Model in their description of forces, which will later prove to be important to understand the concept of a ToE.

Forces and Unification: the Electromagnetic and Electroweak Force

We have just seen that physics currently has two theories, both with a lot of empirical success, that describe the form of forces in vastly different ways. Is this difference a problem? Can it not be that nature has endowed us with these two vastly different mechanisms? This is a perfectly valid position, but we will see that many physicists take a different approach. Physicists, especially those working in theoretical high-energy physics, often invoke unification as a means to make theories simpler and more general. This inclination to invoke ideas of progressive unification in physics is motivated by several historical successes. We shall now examine some examples to gain a better understanding of unifications in physics.

The combination of the electrical and magnetic forces into one electromagnetic force is often mentioned as a very successful achievement of unification in physics. In this unification it was shown that two seemingly independent forces, the electric and magnetic force, could in fact be reduced to a single entity. Electric and magnetic fields were replaced by the so-called electromagnetic field tensor.[4] Treating electricity and magnetism as autonomous forces led to inconsistencies. The introduction of the unified electromagnetic force resolved these issues, allowing us to describe our observations of nature

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[4] The concepts of separate electric and magnetic fields are still used in physics. Even though the electromagnetic field tensor technically gives the ‘correct’ description, it is often sufficient to treat the electric and magnetic fields as distinct. For example in material sciences.

correctly. In the end, the seemingly separate electric and magnetic forces were proven to be faulty relics of flawed human observation. ‘Unification’ refers to ontological unification in this context. Indeed, electromagnetic unification proved that a single force, electromagnetism, lies at the basis of what once seemed to be two distinct forces. (Maudlin 1996, 132-133; Morrison 2018, 385-393)

Another example of such a unification of forces is the unification of the electromagnetic and weak forces. Remember that the weak force is, among others, responsible for the decay of particles. To human perception, these forces appear distinct, but again two forces proved to be two sides of the same coin. The bosons of Standard Model, namely those of the weak force Z and W^+ and W^- and the photon, turned out to be mixtures of gauge bosons of the electroweak force, the B, W_1 ,W_3 and W_3 bosons. The mixture between the electroweak bosons and the Standard Model is expressed in terms of the ‘electroweak mixing angle’, which is an empirical constant. Similarly, the strength of the weak and electromagnetic forces, as expressed by the so-called coupling constant, are also related to each other by this mixing angle. Thus the bosons and coupling constants of the weak and electromagnetic force remain distinctive in the electroweak model. (Morrison 2018, 400-401) It is also notable that one cannot correctly describe the weak force without including the electromagnetic force (Maudlin 1996, 137). This makes unification in this case a necessary component of the theory, as opposed to being a simplification added to the theory as an afterthought.

The type of unification needed to describe the electroweak force is of a different nature than electromagnetic unification. The electroweak unification is based on gauge symmetries. These are mathematical symmetries described by group theory.[5] Applying these symmetries to models of particles gives predictions for specific interactions and traits of particles. This allows one to make empirical predictions. The theory describing the electroweak force is based on a product of two groups, or two symmetries that conserve two different quantities. The first group, the SU(2) group, predicts the existence of three bosons or force-carrying particles, with one of these being neutral. The second group, U(1), predicts the existence of one neutral boson. These mathematically predicted bosons obey the gauge symmetries, which are the mathematical symmetries as defined by the

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[5] See either (Maudlin 1996) or (Morrison 2013) for a more thorough discussion on the role of gauge symmetries in the unification of the electroweak force.

SU(2) or U(1) group in this case. Unfortunately, the electroweak bosons that are written down using these mathematical methods of gauge symmetries, do not match the bosons that are measured empirically.[6] Empirically one measures the Z boson and the photon. As stated above, the Z boson and the photons are mixtures of the electroweak bosons. In the end, the unification of the electromagnetic and weak force is achieved due to gauge group symmetries fixing the behaviour of the electroweak force.

One may wonder what the status of the electroweak unification is, as it is not a straightforward ontological unification such as the electromagnetic unification. The electroweak unification does not fully replace observable quantities in the manner that the electroweak field tensor replaced the electric and magnetic fields. In light of this, various philosophers have evaluated the status of electroweak unification. Philosopher of science Tim Maudlin is of the opinion that the unification of the electroweak force is only a matter of mathematical unification. This mathematical unification is not as good as ontological unification which we saw in the case of the electromagnetic force, because the electroweak force does not fully replace the independent weak and electromagnetic forces. (Maudlin 1996, 136-138) A similar sentiment is expressed by philosopher of science Margaret Morrison, who states that 'the unity achieved was largely structural rather than substantial and as a result does not fit with the ideal of reducing elements of the weak and electromagnetic force to the same basic entity.' (Morrison 2013, 399) Whether one thinks that this is enough to call the electroweak force truly unified is still a matter of discussion. Morrison sees the electroweak force as a 'genuine unity' (402), whereas physicist Howard Georgi does not think it is a full unification (quoted in Maudlin 1996, 138)

Moving Towards Grand Unified Theories and Quantum Gravity

We have now examined earlier cases of unification. Here we have seen that Electromagnetic unification is often regarded as an example of both mathematical and ontological unification. While the status of the unification achieved by the electroweak force is less clear. Further attempts to achieve unification in physics,

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[6] This is due to Higgs symmetry breaking, see (Morrison 2013, 399)

move into empirically uncharted territory. I shall now discuss the emergence of ideas on Grand Unified Theories and Quantum Gravity. Both seek unification of concepts that currently still seem disjoined, although we will see that the motivations behind these two attempts differ.

Grand Unified Theories can superficially be seen as the extrapolation of the electroweak unification. Remember that the Standard Model describes the behaviour of fundamental particles and their relation to the electromagnetic, weak and strong forces. In the previous section, we saw that the weak and electromagnetic forces could be unified into one electroweak force. This unification is essential to be able to consistently write down the theory. One could then wonder whether a similar method could be applied to the strong force. Perhaps the strong force is only seemingly separated from the electroweak force. Our current description of the strong force might prove to be an approximation. If this were the case, a unification of these three forces could be needed so as to arrive at a proper, more fundamental theory than the Standard Model. A theory that could incorporate the strong, weak and electromagnetic force in one simple mathematical description, is called a 'Grand Unified Theory' (GUT).[7] The three forces of the Standard Model would in this case be in some sense reduced to a single force. To the human view, the forces could appear distinct, but if a GUT were to exist, this distinction would only be due to a lack of knowledge of the deeper underlying physics. (Cat 1998, 285-287)

Two things are important to note here. Firstly, even though GUT's extend the path of unification as laid out by the electroweak unification, the type of unification that is required of GUT's is more demanding than the unification achieved by electroweak unification (Maudlin 1996, 139-141). Electroweak unification left us with the product of two groups: SU(2) x U(1), whereas GUT's want to unify the electroweak and strong force into a single, simple group, with 'simple' being a mathematical qualifier here. This directly leads to the second point of interest: the lack of empirical evidence for GUT's. Indeed, at the moment of writing, no experimental proof for a GUT has been found, even though a lot of research in search of GUT's has been performed.

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[7] An example of a GUT is Supersymmetry, often abbreviated as SUSY. Supersymmetry is a broad term, but it generally proposes the existence of new particles. Detection of one of the predicted particles would be empirical verification for supersymmetry.

The lack of empirical proof and the higher demands on unification in a GUT indicate that research on GUT's is based on additional motivation besides empirical verification. This motivation is the one mentioned above: we needed electromagnetism to properly understand the weak force, so perhaps we need further unification to understand the strong force. This line of argumentation is flawed, at least because the type of unification that physicists expect from a GUT is different from the type of unification achieved by the electroweak force (Maudlin 1996, 141). At the same time, we will see that these motives and hopes of unification are incorporated in the ideas on Theories of Everything.

The second topic of this section is that of Quantum Gravity. Recall that gravity is based on a different mathematical and conceptual framework than the Standard Model. I mentioned that gravity is described by spacetime curvature rather than force-carrying particles. Combining the Standard Model or quantum mechanics with gravity has been an issue in physics for quite a while. Quantum mechanics and gravity have a deep incompatibility in the sense that one cannot combine the methods of the two theories without getting into mathematical issues. Yet, the aim to unify gravity and quantum mechanics is motivated by two aspects.

Firstly, a Quantum Gravity description of nature is needed to interpret phenomena that combine strong gravity and quantum effects. Think about black holes or events close to the beginning of the universe (Greene 2000, 4; Smolin 2015). The example of black holes is the most obvious here, as physicists have empirical proof that they exist, yet the current lack of a consistent Quantum Gravity theory prevents them from properly understanding them.[8] A theory of Quantum Gravity is thus needed to properly describe phenomena that we find in nature.

Secondly, the unification of quantum mechanics and gravity aligns with the programme of unification in physics that I referred to above. Some physicists strive to find a theory of Quantum Gravity that merely allows one to describe quantum mechanics and gravity in a consistent way (Rovelli 2011). But often, especially in popularising scientific pieces, Quantum Gravity is depicted as a sort unification. This is due to the dominance of a theory called 'String Theory' in the

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[8] By 'empirical evidence' I refer to the now famous pictures of the black holes Sagittarius A* and M87*.

research field on Quantum Gravity. Later, I shall elaborate on String Theory, but for now it suffices to know that String Theory gives a description of nature that postulates the unification of all four forces. So, String Theory needs a GUT which is then combined with gravity into a single overarching theory that describes all four forces.

Both Grand Unified Theories and Quantum Gravity research are examples of how unification can play a role in fundamental physics. There certainly are fundamental differences between the two research agendas. Grand Unified Theories can be seen as a continuation of the unification of the Standard Model forces, albeit a flawed continuation. Quantum Gravity is instead motivated by the need for a consistent theory to describe certain phenomena we find in nature, such as black holes. Still, both are also motivated by ideas of unification, and these ideas in fact culminate in the conception of a possible 'Theory of Everything', as we will see in the next section.

The Birth of a Term: String Theory as a Theory of Everything

The conception of a Theory of Everything as something that could be realised by particle physics has its origins in the 1980s. Physicist John Ellis claimed to have coined the term in a popularising article on string theory. (Ellis 1986; 2000) The term was actually also used before this article was published in a lecture on Grand Unification (Fritzsch 1977) and a popularising article in Science (Waldrop 1985). The former article mentions a 'Theory of Everything' in the context of GUT's, thus not including gravity, whereas the latter article does not elaborate further on the term. Although the term 'Theory of Everything' was used before Ellis' article was published, Ellis can be seen as the person who first used the term in the context of string theory.

In addition to this, Ellis was also the first to elaborate on what the definition of a 'Theory of Everything' could be. In his 1986 article, Ellis states how string models enthuse physicists, because these models could unite the four forces of nature. He writes:

> 'The cause of all the excitement is the superstring, which many particle theorists are now taking seriously as a candidate 'theory of everything' (TOE) which may unify all

the fundamental interactions-electromagnetism, strong and weak nuclear forces and gravity-and explain the number and couplings of all the elementary particles.' (Ellis 1986, 595)

To understand why Ellis used the term 'theory of everything' in this context, one should understand some developments in string theory. String theory (ST) originally was conceived as a means to understand the strong force, the force that keeps particles such as protons glued together. It soon became clear that another theory, Quantum Chromodynamics (QCD), was better suited to describing the strong force. String theory was not fully discarded however, because physicists noticed something peculiar about the theory: it seemed to provide a quantum description of gravity because ST needs to incorporate gravity to provide a consistent theory. String theory was plagued by anomalies and infinities, but in 1984 John Schwarz and Michael Green provided a solution to these issues. (Waldrop 1985) After solving these technical issues, it became apparent that ST could be more than a quantum gravity theory. By invoking Grand Unified Theories, such as supersymmetry, ST could even provide a theoretical framework to unify all four fundamental forces (Ellis 1986; Flam 1992).

Using ST, one can describe particles in terms of strings. The Standard Model particles we know would then disappear and are replaced by more fundamental entities, namely strings. The different vibrational modes of these strings determine properties such as charge and mass. Vibrating strings then appear to us as particles with specific properties, but the 'deeper reality' of the world is described in terms of strings, according to ST proponents. (Greene, 2000) Due to the unintended nature of these ST traits, it is clear that the ST research program did not come into existence due to a preconceived search for a ToE. Rather than searching for unification and a ToE, one could say that ST accidentally figured out that it agreed with pre-existing ideas and ideals of unification (Rovelli 2014). It is this coincidentally discovered nature of ST that motivated Ellis, and many others after him, to introduce and promote the term 'Theory of Everything'.

We can conclude that searches for unification in physics have a long history. The electromagnetic and electroweak unifications have been proven to give good experimental predictions, although it is possible to debate the degree to which the latter can be seen as a full, ontological unification. Physicists are currently researching the possibilities of further types of unification in physics, for example in the fields that research Grand Unified Theories of Quantum Gravity. In the 1970s, String Theory emerged as a theory that could perhaps achieve the aims of both Grand Unification and Quantum Gravity, as String Theory provided a framework that proposed the unification of all four forces of nature. It is this background that coloured the initial use of the expression 'Theory of Everything' in theoretical particle physics. In the following chapter we will see how the origin of this term has strongly influenced its current meaning.

Chapter 2: Core Concepts of Theories of Everything as Envisioned by Physicists

Now that we have retraced the origin of the term, we will turn to what physicists mean when they use the expression ‘Theory of Everything’ (ToE). I will make a conceptual analysis of the phrase ‘Theory of Everything’ to determine what traits are and are not attributed to it. By ‘conceptual analysis’, I mean that I want to analyse what traits and characteristics a theory should have to be called a ToE by physicists. In addition, this conceptual analysis includes an account of what assumptions are made by physicists when discussing ToE’s, for example assumptions about reductionism and necessity. I shall base myself on the statements physicists make on ToE’s. The physicists whose ideas are discussed, are physicists working on topics such as particle physics, quantum gravity or cosmology. We will see that the opinions on what a ToE should entail differ, although there are also many similarities to be found.

The structure of this chapter will be as follows. First, the role of unification in ToE’s will be elaborated on. Furthermore, some more uncertain characteristics of ToE’s will be discussed. These are characteristics of ToE’s that physicists have discordant ideas on. Think about uniqueness: does a theory only qualify as a ToE if another theory would be logically impossible? I will also touch upon the issue of reductionism. Some physicists are convinced that a ToE would make no useful predictions for larger scale phenomena, whereas others prefer to take a stronger reductionist stance. Finally, the relation between issues such as determinism, dark matter, cosmology and ToE’s will be discussed. The choice of these topics is based on the characteristics that physicists focus on when discussing ToE’s. By basing myself on the words of physicists, I limit myself to their opinions and ideas on ToE’s. If a theme is left out of the discussion here, it is because it is not included in the discourse on ToE’s by physicists.

Unification as the Basis Assumption for Theories of Everything

Unification of Matter and Forces

When discussing the origin of the 'Theory of Everything' as used in the context of theoretical physics, we noted that ToE's and unification are strongly linked. The unification of the four forces of nature, gravity, electromagnetism, the strong and weak force, is the common denominator for practically all mainstream definitions of a ToE. In the context of ToE's, the unification of the four forces of nature in a theory that describes all matter and forces is always mentioned (Barrow 1994; Davies 1994; Davies and Brown 1999; Ellis 1986; Greene 2000; 't Hooft et al. 2005).

The exact definitions that these physicists give can slightly differ. For example, string theorist Brian Greene defines a ToE as 'a quantum mechanical theory that encompasses all forces and all matter' (Greene 2000, 423). Marcelo Gleiser states that when physicists talk about a ToE, they assume that 'what we see as electricity, magnetism, or the weak and strong interactions or even gravity would [...] behave as one single force.' (Paulson et al. 2015, 20) Although their phrasing differs, both Gleiser and Greene refer to the idea that a ToE should be all encompassing, describing all physical substances in terms of one coherent framework.

The concept of unification of matter and forces is essential to achieve the proper framework for a ToE. Physicist John Barrow summarises this idea by stating that a ToE would be produced by 'four-fold unification' of the known forces of nature (Barrow 1994, 42). Barrow expands this statement by noting that 'ToE's as currently conceived are simply attempts to encapsulate laws that govern fundamental forces of nature within a single law of nature derived from the preservation of a single overarching symmetry.' (Barrow 1994, 44) This could be a gauge symmetry, as discussed in the last chapter, for example. So, if all four forces of nature share a specific form of mathematical symmetry, one could describe them as unified in a mathematical framework. The idea that four-fold unification is achieved through mathematical symmetry is common, as it may be seen as a successor of the electroweak unification and Grand Unified Theories programme. Note that Greene and Gleiser do not directly refer to principles of symmetry, although they agree with Barrow on the fact that a ToE should include all forces and matter in a single law of nature.

Even when physicists dislike the term ‘Theory of Everything’, they recognize that the mainstream idea of a ToE invokes unification. Sabine Hossenfelder is an example of this. She disagrees that physicists should aim to find a ToE, as she sees no empirical or logical need for such a theory, making a ToE unnecessary to solve scientific problems. But she is aware of what physicists mean when discussing a ToE: ‘What physicists mean by a theory of everything is then a theory from which all the four fundamental interactions derive.’ (Hossenfelder 2020). We shall see that most physicists demand more from a ToE than unification of forces and matter, although this characteristic will remain the basis of the concept.

We may conclude that there is a consensus over the fact that a ToE would include unification of forces and matter, among both physicists who like and dislike the terminology. If physicists do not believe in unification, they criticise the idea that a ToE can exist rather than giving an alternative, non-unificationary definition of it.

Types of Unification

From what has just been said, we may conclude that a ToE will involve a unification of the four forces and matter. The physicists I mentioned do not fully elucidate what they mean by such a ‘unification’. In our next chapter, a more in-depth analysis of the role of unification in physics will be given. With our current knowledge I may however already identify two aspects of unification that may play a role in a ToE.

Firstly, the aim may be a mathematical unification. Physicist Paul Davies notes that ‘in its most ambitious form, a ToE combines all physical laws and principles into a single, unified mathematical scheme, hopefully captured by a formula that fits onto a shirt.’ (Davies 1994, 226). This echoes the sentiment of Barrow, who notes that mathematical symmetry principles could combine several laws of nature into one underlying law (Barrow 1994). Both Barrow and Davies do not explicitly state that a ToE would indicate that all matter and forces have a common material basis. Rather, they mention that physicists could use the same mathematics to describe the physical phenomena. The significance of this mathematical unification is that it does not necessarily make any ontological assumptions. If one can use the same mathematical technique to combine different laws of nature into one expression, this does not mean that you already presuppose that this formula must correspond to a unity in nature itself.

In addition to mathematical unification, a physicist can postulate ontological unification. A unification of this kind is often proposed by string theorists such as Brian Greene. To clarify, Greene also assumes a mathematical unification, in the mathematical language of string theory. But String theory postulates that a ToE can achieve an ontological unification as well because the 'stuff' of all matter and all forces is the same (Greene 2000, 146). This 'stuff' consists of the so-called strings. Simply put, all particles are strings and all strings are identical, they just vibrate differently.

In the end, the unification of particles and forces takes centre stage in the definition of a ToE. When physicists discuss unification of this type, they do not necessarily indicate an ontological unification, though. When discussing 'unification', physicists often refer to a type of mathematical unification that would allow us to describe all four forces of nature in the same mathematical framework. In addition, a ToE may achieve ontological unification.

The Conceptions of Simplicity in a Theory of Everything

This concept of a ToE as a unification of particles and forces also has strong components of belief in simplicity and symmetry. In this section, I shall argue that assumptions about simplicity form a core belief in the concept of ToE's. To properly account for this, I shall give some additional information regarding philosophical accounts of simplicity in science. We shall then again turn to the words of physicists, and I shall argue that it seems that one can identify three dimensions of simplicity in ToE's: a mathematical, an aesthetic and an ontological dimension. In reality, this distinction cannot be made that easily. In this discussion, it will become clear that ontological parsimony as an aesthetic criterion that is projected onto the mathematics of possible ToE's plays a core role in this story.

First, the idea that one scientific theory displays a higher degree of ‘simplicity’ requires some explanation. Generally a preference for ‘simpler’ theories can be seen as either a type of methodological judgement based on empirical successes or rather a type of personal, aesthetic judgement. The former refers to the idea that theories with a higher degree of simplicity are empirically more successful than their more complex counterparts. The latter position states that a higher degree of simplicity has no connection to empirical success. According to this opinion, simplicity is a personal and often aesthetic judgement of theories. (McAllister 1991, 1-2; 1996, 105-109) Philosopher James McAllister states that this is a false distinction (112). To properly account for the function of simplicity in scientific theories, one needs to distinguish two different parameters: the form and degree of simplicity. The form of simplicity refers to the different manners in which a theory can be simple. For example, a theory may be simple in the sense that it uses simple methods or because it posits few ontological entities. We shall return to this topic later. At any rate, the degree of simplicity describes the extent to which a given form of simplicity is realised in a theory. It is important to note that the different forms of simplicity are not linked, so one form of simplicity may be high in one form and low in another form of simplicity. For example, a theory could postulate the existence of only three entities, making the degree of ‘simplicity of entities’ quite high. The same theory could use very complicated mathematics, so the realised degree of ‘mathematical simplicity’ would be quite low. (112-117)

According to McAllister, the preference for a specific form of simplicity is largely an aesthetic judgement (122) A theory that exhibits the preferred form of simplicity more, will be seen as a beautiful theory. This indicates that a specific form of simplicity can be an aesthetic component of a theory. In turn, aesthetic properties or beauty can be seen as a value that is projected onto an object, rather than a property that is intrinsic to an object. This view is named ‘projectivism’. (McAllister 2005, 15) So in the context of simplicity, an object may exhibit a certain form of simplicity that is valued by personal aesthetic criteria, motivating the observer to find the object to be beautiful. Of course, aesthetic judgements can differ among scientists and this may be one of the causes of all the controversy regarding simplicity and beauty: one person’s beauty is another’s hubris.

The second element of simplicity that McAllister describes, the degree to which a theory is simple, can be seen as an empirical criterion to prefer one theory over another. (McAllister 1996, 122-123). Such an empirical assessment is only possible if the empirical successes of two theories can be compared, though. This is not possible in the context of ToE's, which do not exist yet.[9] Even without empirical comparison, a specific form of simplicity can still be preferred by scientists, but this preference will be based on personal aesthetic motivations, as discussed above.(124)

For our discussion, it is useful to state what forms of simplicity exist. One can broadly divide forms of simplicity into two groups. Firstly, the form of ontological parsimony, which states that no more ontological entities than necessary must be proposed. Secondly, elegance, or syntactic simplicity, refers to the succinctness of postulates needed for a theory and, roughly put, simplicity of the formulation of a theory. (Baker 2022) These two different categories can be divided into further subgroups. Often there is a tradeoff between parsimony and elegance. A more parsimonious theory may need more postulates, whereas introduction of more entities into a theory may increase its syntactic simplicity. (para. 1) This does not deny that theories may express various forms of simplicity. (McAllister 1996, 113) So a theory that is both elegant and parsimonious is not prohibited.

This brief analysis of the role of simplicity in scientific theories can be applied to ToE's. When physicists discuss ToE's, we indeed find that physicists themselves evaluate simplicity in aesthetic terms. Rather than referring to simplicity solely in terms of methodology, simplicity is seen as something beautiful, which makes it worthy of pursuit. For example, 't Hooft states:

> 'All we wish to do is marvel at Nature's beauty and simplicity. We have seen and tasted the beauty, simplicity and universality of our latest theories and models of the fundamental particles and the cosmos. We are now trying to uncover more of that.' ('t Hooft 1994, 37).[10]

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[9] String theory, which is seen as a possible ToE by some of its proponents, does not give proper empirical predictions, so the same issue holds.

[10] 'The latest theories and models' in this context includes the Standard Model, which, according to 't Hooft, is 'elegant and aesthetic, but not elegant and aesthetic enough.'(26).

Similar opinions are voiced by Lisa Randall and Steven Weiberg. Firstly, Randall states that 'The ultimate goal is a simple, elegant, unifying theory' ('t Hooft et al. 2005, 258). For Weinberg, simplicity is one of the aspects that makes a theory beautiful and in turn this sense of beauty could help the physicist guide whether progress towards a ToE is made (Weinberg 1992, chap. VI).[11] These quotes show that physicists declare that the aesthetic component of simplicity cannot be ignored in connection with ToE's.

Physicists indeed have aesthetic motivations when invoking symmetry, which invoke the question: what form of simplicity motivates these aesthetic judgements? Let us return to the distinction between parsimony and elegance. Physicists often indirectly refer to the concept of parsimony when discussing ToE's, revealing the importance of this form of simplicity for a ToE. Simplicity is seen as a trait of nature itself, not just as a characteristic of our theories. For example, the quote of 't Hooft above mentions 'Nature's beauty and simplicity' ('t Hooft 1994, 37), which indicates that the simplicity he finds beautiful is considered an element of nature itself, and it is an ontological trait. Randall states that 'simple principles underlie physical reality' even if this is not immediately apparent in daily life ('t Hooft et al. 2005, 258). Even though Randall refers to 'principles' in this quote, it is clear that she refers to the idea that nature itself is simple, rather than simplicity lying in few postulates on which we base our theory.[12] Finally, Paul Davies admits that 'the search for such a (unified) ToE is to a certain extent an act of faith, motivated by the deep belief that nature ought to be simple.' (Davies and Brown 1988, 6) This statement reflects the idea that a preference for parsimony is motivated by personal aesthetic beliefs, rather than it being motivated on empirical grounds.

Parsimony can exhibit itself in different ways. Remember our discussion on unification. Physicists often strive to combine all laws of nature into one single, overarching law that perhaps would prove that the four forces can be unified into a single force. Here the goal parsimony is realised by reducing the four forces to a single one. We also saw the stronger demand of ontological unification, which states that there exists only one entity, such as strings in string

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[11] Weinberg prefers to call this a 'final theory'.

[12] Again, it is not excluded that ontological simplicity leads to a theory that is also based on few postulates.

theory. Lisa Randall summarises this view by stating that: ‘we want to explain everything in terms of one single force acting on fundamental objects, whether they be particles or strings or membranes.’ (Paulson et al. 2015, 21) This can be seen as the highest degree of parsimony that a ToE could reach, although we saw that a ToE does not need to propose ontological unification.

Another example will be discussed in the next section, namely the simplification of constants of nature. Regarding this, John Barrow explains: ‘More often than not, this simplification occurs because quantities previously regarded as separate constants of Nature are found to be related or are discovered to be composed of combinations of other more basic constants of Nature.’ (Barrow 2007, 111) With a reduction of the number of constants that are needed, a ToE would again increase parsimony. Of course, other types of simplicity are also mentioned by physicists in the context of ToE’s. Steven Weinberg for example recognises the importance of ‘simple and economic principles’. (Weinberg 1992, chap. VI) Parsimony is the more dominant form of simplicity in ToE discussions, though.

The simplicity of nature should be represented in the mathematics of a ToE. Mathematics is the language of contemporary physics and the aesthetic preference of a form of simplicity will be represented in the mathematics used to describe a possible ToE. If an equation exhibits a property that triggers positive aesthetic judgments, it will be seen as beautiful. In the context of ToE’s, equations should somehow reflect the simplicity of nature. Physicists often refer to ‘simple mathematics’ or a ‘simple law’ that should lie at the core of a ToE ('t Hooft 1994, 35; Barrow 1994, 40; 't Hooft et al. 2005, 257) Barrow notes: ‘We have found that the world is curiously adapted to a simple mathematical description’. (Barrow 2007, 2) Preferably, a ToE would be ‘captured by a formula that fits onto a shirt.’ (Davies 1994, 226) The mathematical simplicity that physicists refer to here, probably does not indicate that laymen should be able to understand a ToE easily. So the type of simplicity that is referred to must be of another nature. In the context of simple mathematics, ‘simplicity’ is regularly mentioned in the same breath as ‘unifying’. (Barrow 2007, 18; Davies 1994; 't Hooft et al. 2005, Weinberg 1992, chap. X) This once more points to parsimony, as we discussed above, but reflected in the mathematics that is used by physicists.

We can conclude that simplicity is at the core of the ToE enterprise, especially in the form of parsimony. At first sight it may seem that physicists are referring to different types of simplicity when discussing aesthetic, ontological and mathematical simplicity of ToE's. We have seen that a clear distinction of these three dimensions actually does not exist. Simplicity, especially in the form of parsimony, is seen as an aesthetic trait of theories. In turn parsimony is represented by the formulae that physicists use to describe reality. This type of argumentation may be at risk of being circular, something that we shall later discuss in Chapter 4.

Determining the Constants of Nature with a Theory of Everything

In the previous section, I showed how ideas about unification and simplicity are central to ToE's. However, while unification can be seen as a necessary criterion for a ToE, it is not sufficient. Many physicists are of the opinion that a ToE should be able to determine the values of several constants of nature to be rightfully called a ToE. With 'constants of nature', I refer to the constants that are part of the Standard Model as referred to above. These constants include the masses of elementary particles and the coupling strengths of the strong, weak and electromagnetic forces.[13] When I refer to additional constants of nature, this will be specified.

These constants of the Standard Model are currently experimentally determined. There currently exists no method for deriving them from physical principles using our theories. Many physicists find the contingent nature of these constants quite unsatisfactory, a feeling that is heightened by the seemingly fine-tuned nature of our universe. 'Fine-tuning' refers to the idea that complex phenomena and observations can only be explained in terms of a very specific model. Change the constants and rules of the model a little and very different results will appear. Fine-tuning has a long history, but in the context of physics it

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[13] See ('t Hooft 1994, 24-25) for more details of the known Standard Model particles. While 't Hooft states that there are 19 constants of nature as defined by the Standard Model, newer knowledge shows us that the Standard Model contains 26 free constants, not 19. This is due to the fact that neutrinos have mass, which introduces three extra mass parameters, three mixing angles and one so-called CP-violating phase.

involves the specific values of the constants of nature. If the constants of the Standard Model were slightly different, complexity would not be able to arise as atoms and molecules would not be able to form ultimately. Why is it that we live in a universe that has constants of nature that make the existence of human intelligence possible?

A theory that is simple and unifying may not answer these questions surrounding fine-tuning. For many physicists, a theory will therefore only qualify as a ToE if it can answer at least some of the questions surrounding fine-tuning. Thus additional, metaphysical motivations are invoked when defining a ToE. Which are related to the idea that the world is the way it is due to a certain reason, rather than the universe being a product of coincidence. In the language of physics, this idea of necessity is translated to the idea that a ToE should somehow predict or fix the values of the constants of nature. Note that previous unifications have not achieved a solution for fine-tuning. So some physicists hope that a ToE can achieve what no theory has achieved before by proving that seemingly contingent constants are actually rigidly fixed. This would make a ToE self-explanatory, as it would be able to explain its own principles. Physicists that take such a position want to prove a metaphysical trait with a physical theory, a curious stance which I shall return to in Chapter 4.

For now, I want to focus on the different views among physicists regarding this topic. We will discuss three stances on this subject, ranging from strict to more lenient demands. First, the position that a ToE should exactly fix the constants of the Standard Model will be discussed. This is followed by a discussion on the view that a ToE should predict these constants, in one way or another. Finally, some physicists are of the view that it is favourable, but not necessary, for a ToE to predict the constants of the Standard Model. The physicists belonging to this final group will also accept a theory to be a ToE if it does not fulfil this demand.

Prediction of Constants as a Necessary Demand

The first group that I shall discuss places stringent demands on the determination of constants as a characteristic of a ToE. Firstly, a ToE should determine these constants without a need for experiments, as ‘the ultimate ToE would, ideally, need no recourse to experiment at all'[14] (Davies and Brown 1988, 7). In addition, these constants also need to be determined with exactitude. So, a ToE should not state that a certain constant lies within a range of values, but the ToE should fix the value with, in principle, infinite accuracy. On this score, Leonard Susskind writes:

> 'Theoretical physicists have always hoped that the underlying laws of physics — the laws of particle physics — would be uniquely determined by the internal consistency of some particularly simple mathematical theory. Not only would the theory explain why the proton and neutron are about 1,800 times heavier than the electron, but the theory would also explain itself: no other theory is possible.' (Susskind 2005, 257)

This position regarding a ToE states that physicists hope that, if physicists were to find a ToE, they would also be able to find that a slight change in the ToE would lead to inconsistencies that make the theory useless.

We previously discussed the function of mathematical simplicity. Here I would like to focus on the importance of uniqueness and internal consistency that Susskind refers to. Two proponents of this stance are Gerard 't Hooft and Steven Weinberg. 't Hooft explicitly states that 'a good theory of everything should not contain any freely adjustable constants of nature that take the form of real numbers.' ('t Hooft 1994, 25).[15] Experimentally determined constants always have a small range of uncertainty. So, a ToE based on these experimental constants could be formulated in slightly different forms by taking different values of the constant. This violates 't Hooft's condition that 'there exists no closely resembling alternative theory.' Noticeably, 't Hooft states that a slight change in a ToE would make it 'unlikely or elegant', indicating that other ToE's are not strictly logically impossible according to this position.(20)

For 't Hooft, this demand is prior to the actual existence of any ToE. If we find a theory that unified all four forces and matter without exactly determining the constants of nature, this would not be a ToE for 't Hooft.

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[14] Davies and Brown do not necessarily agree with this, although they recognise the sentiment.

[15] Simply put, 'real numbers' are numbers that can take every arbitrary value, including infinitely many decimals.

Steven Weinberg would also like a ToE to calculate the constants of nature precisely. He supports a view he coined ‘logical isolation’. According to Weinberg, ‘logical isolation’ refers to the fact that we can image different ToE’s, indicating that there is a group of possible ToE’s that all are logically consistent internally. In reality, only one of these ToE’s properly describes our universe. In turn this ToE is ‘rigid’, as we cannot adjust it slightly without ‘the theory leading to logical absurdities’.[16] (Weinberg 1992, chap. X) So a ToE should still be able to Weinberg elaborates on this by stating that:

> ‘In a logically isolated theory every constant of nature could be calculated from first principles; a small change in the value of any constant would destroy the consistency of the theory. [...] In this case, although we may still not know why the final theory is true, we would know on the basis of pure mathematics and logic why the truth is not slightly different. (Weinberg 1992, chap. X)

A logically isolated theory thus contains a high degree of inevitability. Weinberg is of the opinion that there is beauty in the inevitability of a theory (1992, chap. VI). Earlier I showed that Weinberg sees aesthetic judgements as a relevant guide in research on fundamental physics. We notice again that beauty in the shape of inevitability could possibly guide us towards a logically isolated ToE that predicts the constants of nature exactly, according to Weinberg.[17]

Prediction of Constants as a Preferred Characteristic

The second group holds similar hopes regarding the determination of constants by a ToE, but they are less rigorous in their demands. The first example of this position is given by John Barrow, who states that ‘An acid test of any ToE would be the ability to predict the values of constants of nature, mass and charge of particles.’ (Barrow 1994, 53). In this context, the usage of ‘acid test’ indicates that Barrow sees the derivation of constants of nature from a theory as an important element of a ToE. At the same time, he does not expect that these constants can be determined uniquely by a ToE (259). Paul Davies agrees that a ToE should give

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[16] Weinberg does not elucidate how we can imagine alternative ToE’s while simultaneously using ‘pure mathematics and logic’ to to know why a ToE would not be slightly different in his book.

[17] An underlying motivation is that both ‘t Hooft and Weinberg hope to avoid invoking the anthropic principle to determine why the constants of nature are so fine-tuned, although Weinberg is milder on the issue than ‘t Hooft. ('t Hooft 1994, 35; Weinberg 1992 chap. IX)

‘an account of the various masses, coupling constants and other parameters that describe how these particles interact.’ (Davies 1994, 226) From Davies’ usage of ‘an account’ we can infer that his demands are probably not as strict as ‘t Hooft’s or Weinberg’s.

Lee Smolin states that the constants of nature represent a ‘state of ignorance’ and scientists need to search for a theory that is able to produce these constants (Smolin 2021). Smolin’s motivation is not driven by a strong sense of inevitability or beauty, but by a discontent with the current lack of explanations for the values of the constants of nature. Smolin wants to develop falsifiable hypotheses that could provide an answer to this question. Notably, Smolin states that ‘the correlation between unification and reduction in the number of parameters has not worked recently’ (Smolin 2007a, 330), probably referring to string theory. Smolin dislikes the ToE terminology so he has explicitly mentioned the above in the context of nature. Still it is clear that physics, according to Smolin, should provide an answer to the question of why the constants of nature are what they are.

Prediction of Constants as a Possible Characteristic

The final group do not demand that a ToE should determine the constants of nature, although they are not opposed to the idea. Brian Greene, a string theorist, states that a ToE should in the best case be unique and inevitable. Unfortunately for string theory, the hope to find a unique ToE was decimated when physicists realised that string theory yields many, many different theories. As a consequence, string theory is currently not able to give a good prediction for the values of the constants of nature (Smolin 2012; 2019).[18] In turn, string theorists propose the existence of multiverses. Constants of nature take different values in all these different multiverses and the universe we observe with its specific constants is simply one of many universes. The string theorists fit this idea into their conception of what a ToE encompasses. Greene states:

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[18] This issue arises due to the fact that string theory introduces additional dimensions. These dimensions need to shrink and ‘curl’ to be able to correspond to the spatially three dimensional world we observe. This ‘curling’ can occur in vastly different ways, each leading to very different universes and constants of nature.

> ‘We should require that our ultimate theory give a quantum-mechanically consistent description of all forces and all matter [...]. However, if the multiverse picture is correct - a huge if - it *may* be asking too much for our theory to explain, as well, the detailed properties of the particles masses, charges and the force strengths.’ (Greene 2000, 368).[19]

String theorist Edward Witten also doubts whether a ToE can predict the constants of nature: ‘Can a unified field theory be used to compute the dimensionless constants that we observe in nature, or do the values of these constants depend on the choice of a solution of the unified field theory?’ ('t Hooft et al. 2005, 257) From these statements we see that string theorists, driven by a lack of a unique theory, let go of the idea that a ToE should be able to determine the constants of nature. Lisa Randall recognises the issue:

> ‘To derive the properties of the world in which we live, theorists need to make assumptions about various parameters. Originally, string theorists hoped string theory would dictate these parameters. But this is looking increasingly unlikely’ ('t Hooft et al. 2005, 258)

String theory thus encountered a problem that rendered obsolete the ideal of uniqueness and rigidity when determining the constants of nature obsolete. The reaction to this development is quite interesting. Instead of rejecting string theory as a possible ToE, string theorists have changed the demands they place on a theory being a ToE candidate. Compare this to the opinion of ‘t Hooft, who will only accept a theory as a ToE if his exacting demands are met.

We may conclude that many physicists hope that a ToE can predict the values of the constants of nature. There are gradations in the description of this wish. Physicists like ‘t Hooft and Weinberg will only be satisfied with a ToE that leaves little to no room for alternatives and doubt. They want to derive the constants of nature from a ToE and explain why these constants could not have taken another value. This opinion differs from the string theorists, who made their definition of a ToE more lax in light of scientific developments.

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[19] Greene uses the terms ‘theory of everything’ and ‘ultimate theory’ interchangeably.

The Role of Reductionism in Theories of Everything

We now switch to a slightly different aspect that according to its proponents a ToE must adhere to. Namely, its reductionist assumptions. The previous characteristics of a ToE were mainly demands on the traits and predictions of a ToE. The role of reductionism in a ToE is distinct, because it is an assumption that underlies the ToE programme, rather than a characteristic of the formulae and concepts of a ToE itself. To even be able to speak of a ToE as a theory that lies at the base of everything else, physicists must adopt a reductionistic stance. Regarding this, Max Tegmark states: '[R]eductionism, looking at the ultimate Lego-like building blocks, is at a minimum central to the theory of everything.' (Paulson et al. 2015, 20) Without the assumption that a ToE is the basis of all phenomena, the ToE would be 'just another theory' rather than a Theory of Everything.

Further clarifications regarding the meaning of 'reductionism' are useful. When using the word 'reductionism', I refer to the concept of so-called 'interlevel reductionism', the concept that reduction of theories is possible between different levels of complexity. Two further categories are important, namely ontological reductionism and epistemological reductionism. The former represents the idea that all systems consist of smaller scale entities. According to ontological reductionism, a system is only a sum of its parts. When adopting the strongest interpretation of ontological reductionism, one can see the world as a sequence of consecutive levels of complexity, where each level can be reduced to a lower scale level until some kind of base is reached. Epistemological reductionism states that theories of a certain level of complexity can be reduced to theories of a lower level of complexity, for example the reduction of the laws of biology to the laws of chemistry. The key point here is that epistemological reduction declares something about our knowledge and what our theories can describe, whereas ontological reductionism expresses an idea about a property of the world itself. (Andersen 2001, 153-154)

Many physicists adopt a reductionist stance and stress the idea that a possible ToE is seen as the most fundamental theory that science could produce. All higher-level phenomena should somehow agree with the ToE, or at least not conflict with it. The above position is also strongly physicalistic, 'physicalistic' referring to the view that everything in the universe is physical. The stance of ontological reductionism is often combined with physicalism, leading to the notion that all there is can be reduced to a fundamental base layer that is physical. (van Riel 2019, para. 1) A ToE could provide such a base layer: if a ToE is the most fundamental theory to be discovered, all other phenomena are somehow grounded in a physical world.[20] We will see that the concept of a ToE assumes a type of physicalist reductionism in its definition, although the role of reductionism will prove to be more elusive at a second glance.

In this section, I shall highlight two different approaches to this reductionistic stance. The first group adopts a strong ontological reductionist view. These physicists state that all entities in the world could be *in principle* reduced to a ToE, if we were to find it. The second group is of the opinion that strong ontological reductionism is untenable. They see a ToE as a necessary but not sufficient description for the world. At macroscopic and more complex levels, additional information is needed to describe the world. Finally, we shall see that both groups of physicists seem to denounce epistemological reductionism as a useful concept for a ToE.

ToE’s and Strong Ontological Reductionism

First I shall discuss the position of physicists that invoke ontological reductionism when discussing ToE’s. This position states that one could, in principle, reduce all that exists to the lowest level constituents, as described by a ToE.[21] Regarding this, Paul Davies states: ‘Only if one adopts the stance of complete reductionism can an explanation of these sorts of (higher level) phenomena be said to follow, implicit and in principle only, from the physicists’ Theory of Everything.’ (Davies 1994, 227) Davies refers to the fact that physicists who argue that a ToE can also explain more macroscopic phenomena must accept complete reductionism, ‘complete reductionism’ referring to a combination of ontological and epistemological reductionism. Even if one accepts complete reductionism, practical issues prevent one from describing, for example, a cell in terms of a ToE, hence such an explanation is only possible ‘in principle’. But, the ‘complete reductionist’ view states that the only thing that hinders us from completing the

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[20] The idea of a theory being ‘most fundamental’ is also represented in terms such as ‘final theory’ or ‘ultimate theory’, which are sometimes used interchangeably with ‘theory of everything’.

[21] This is a realist stance: the constituents of a ToE, which is a *theory*, refer to something that is realised in nature.

ontological reductionist chain down to the lowest level is a lack of knowledge. Still, even if one were to find a ToE, the exact manner to link it to more complex phenomena may remain unclear. This is caused by a lack of knowledge, rather than fundamental and ontological limitations, though.

Complete reductionism is a very strong view on reductionism, but one that is held by many physicists. George Ellis states that 'Many scientists are strong reductionists who believe that physics alone determines outcomes in the real world', but Ellis does not want to be a strong reductionist (Ellis 2014). A proponent of this strong reductionist approach is Brian Greene. Regarding physical laws of complex systems, he states 'My own feeling is that they do not represent new and independent laws of physics. [...] I see this as a matter of calculational impasse, not an indicator of the need for new physical laws.' (Greene 2000, 17) So the issues with reductionism are epistemological, rather than ontological, according to Greene.

Steven Weiberg is also known for his defence of reductionism. Similarly to Greene, he thinks that the laws of complex systems could ultimately be traced back to more fundamental laws at the level of elementary particles.[22] Weinberg summarises this attitude as follows:

> 'For me, reductionism is not a guideline for research programs, but an attitude toward nature itself. It is nothing more or less than the perception that scientific principles are the way they are because of deeper scientific principles [...] and that all these principles can be traced to one simple connected set of laws.' (Weinberg 1992, chap. III)

Here the 'simple connected set of laws' could be given by a ToE. This is the type of reductionist approach that Ellis refers to. Weinberg does see some issues with epistemological reductionism, which we will discuss later.

Finally, to account for the existence of complex phenomena, a ToE must be able to generate, in principle, arbitrary complexity. A ToE should at least not produce results that conflict with the complexity we observe in the universe. 'T Hooft explicitly states that 'evolution according to these [ToE] laws will give rise

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[22] Weinberg does leave the possibility open that another branch of physics, or even science, could be the 'source' of the most fundamental laws: 'At this moment in the history of science it appears that the best way to approach these laws is through the physics of elementary particles, but that is an incidental aspect of reductionism and may change.' (Weinberg 1992, chap. III)

to nearly infinite complexity' and goes as far as to include life, intelligence and more ('t Hooft 1994, 20). Here we again see the belief that all systems are simply the sum of their parts, with the most fundamental 'parts' and their behaviour being described by a possible ToE.

ToE's and Issues with Strong Ontological Reductionism

The second group of physicists renounce the idea of strong ontological reductionism. According to them, the behaviour of higher level systems cannot simply be reduced to the behaviour of their lowest level constituents. Their issues with the strong reductionism as mentioned above are not based on calculational issues or lacking human intelligence. They do not invoke any non-physical additional entities though, so this is still a physicalist position.

The first example of this position is given by Marcelo Gleiser, who states that 'it is [...] impossible to predict the behaviour of complex biomolecules from a bottom-up approach based on fundamental physical laws.' as we can expect to find unique and different laws of organisations for each level of complexity (Gleiser 2022). Gleiser here states that we cannot reduce higher-level phenomena to, ultimately, particle physics as each level of organisations contains new and irreducible information. In turn, he argues we cannot explain higher-level phenomena with lower-level theories.[23] This criticises epistemological reductionism, which is discussed below.

Secondly, John Barrow writes that only a ToE is not enough to describe all phenomena as 'other factors must enter to complete the scientific description of the Universe.' (Barrow 1994, 39) Barrow does not explain what these 'other factors' should be, but in his view these factors cannot be reduced to lower-level phenomena. Ultimately, Barrow thinks a ToE would be a necessary yet not sufficient way to describe the world. (Barrow 1994, 47; 2007, 246-247). This indicates that for complex phenomena, their behaviour is more than just the sum

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[23] Physicists are often a bit sloppy when discussing reductionism, as they tend to conflate epistemological and ontological reductionism. This is, at least partly, caused by the belief that our theories are a direct mapping of reality. Hence, if a physicist states that it is impossible to predict biology using physics, they generally mean that we cannot make such predictions *because* nature does not work like that.

of their parts. Both Barrow and Gleiser express the view that macroscopic phenomena contain information that is not reducible to smaller parts. For example due to the fact that the organisation of particles gives rise to new phenomena.[24] From this we can conclude that they both disagree with the notion of strong ontological reductionism.

Admittedly, both Gleiser and Barrow do not fully give up ontological reductionism as neither denies the materialist assumption that complex systems only consist out of entities that could be described by a ToE. The 'anti-reductionism' in rather stems from the idea that each level of complexity exhibits new behaviours that are a consequence of the organisation of lower level entities, instead of being a consequence of the traits of these lower level entities. (Barrow 2007, 165; Gleiser 2022) Still, this position differs enough from the 'stronger' ontological reductionism to warrant a mention.

ToE's and Epistemological Reductionism

The previous sections discussed the relevance of ontological reductionism for ToE's. However, even the physicists with the strongest stances on ontological reductionism do not automatically agree that epistemological reductionism is viable, though. There are too many practical issues preventing us from deriving higher-level laws from a possible ToE. Remember the quote of Paul Davies: 'Only if one adopts the stance of complete reductionism can an explanation of these sorts of phenomena be said to follow, implicit and in principle only, from the physicists' Theory of Everything.' (Davies 1994, 227) Even in the case of 'complete' or ontological reductionism, complex phenomena can only be described 'in principle' in an 'indirect' manner. There are simply too many practical issues that would prevent us from applying a ToE to complex phenomena, even if the assumption of ontological reductionism were correct.

These practical issues with epistemological reductionism are not even denied by the staunchest reductionist. Gerard 't Hooft, a believer in a strong ontological type of reductionism ('t Hooft 2001) thinks that 'chaotic behaviour will prevent us from computing just anything we want to know at a very early stage' ('t Hooft 1994, 31). Even if we were to find a ToE, it would tell us nothing about higher level phenomena and it would certainly have no effect on daily life

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[24] This echoes the idea of 'emergence', but this topic is too elaborate to analyse here.

(16). Similarly, a ToE would not render other branches of science useless. Weinberg states: ‘I consider myself a reductionist, but I do not think that the problems of elementary particle physics are the only interesting and profound ones in science, or even in physics.’ (Weinberg 1992, chap. III) Finally, Marcelo Gleiser states a sentiment similar to ‘t Hooft: ‘A TOE has nothing to say about who you are, if you will win the lottery, or how long you will live.’ (Gleiser 2021)

From these statements we can conclude that physicists participating in the discussions surrounding ToE’s often identify problems with epistemological reductionism. Even physicists that believe in a strong type of ontological reductionism, such as Weinberg and ‘t Hooft, mention this issue. Reductionism is indeed at the core of a ToE, but it is specifically ontological reductionism that forms this core. Physicists are quick to admit that the results of a ToE will probably not easily be extended to wider applications, even within physics. In reality, many physicists are working on vastly different topics than those relevant for a ToE, such as condensed matter or neurophysics. A ToE would be largely irrelevant for the results of these branches of physics. Thus the boundaries of the application of a ToE already lie within the very scope of physics, making the successful extrapolation of a possible ToE to other disciplines even less likely.

Chapter 3: Characteristics of Theories of Everything Outside the Main Discourse

We now arrive at a point where we have considered what could be called the ‘mainstream’ elements in the discussion of ToE’s. The reader with an interest in physics may find this limited range of criteria puzzling, because many questions regarding ToE’s are still open at this point. Certainly a ToE should tell us something about the (in)determinism of the world? Or about cosmology and dark matter? In fact, these topics are of marginal importance in the ToE discussion.[25] I have selected these topics as they refer to important questions in physics and because they are mentioned by at least one of the studied physicists. The fact that some important questions are only scarcely mentioned in ToE discourse, takes us to the question: what did physicists say on these topics? And what could warrant the fact that these aspects are rarely discussed?

What does a Theory of Everything tell us about the (in)determinism of the universe?

The first point I shall discuss is the information a ToE could give us about the universe being either deterministic or indeterministic. When I discuss ‘determinism’, I refer to the concept of ‘causal determinism’: the idea that all states in the world are linked to previous states by the laws of nature. Indeterminism is the opposite of causal determinism, as it holds that a causal connection between an antecedent and consequent state does not always hold. In an indeterministic universe, a degree of fundamental chance or uncertainty can exist and one cannot explain all states in terms of preceding states. (Hoefer 2016) Questions regarding determinism have a long history, with physical theories of nature often being invoked to argue that the world is either deterministic or indeterministic. One could expect a ToE to at least touch upon this question.

Surprisingly, the possible (in)deterministic nature of ToE’s is scarcely mentioned in the ToE discourse of physicists. Gerard ‘t Hooft is the only physicist

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[25] Even more topics are not mentioned in ToE discussions at all, for example the matter-antimatter disparity in the universe. I omit such topics as they do not occur in the studied literature at all.

discussed in this thesis that does have a strong opinion regarding the role of determinism in a ToE. He is of the opinion that statistical elements in our scientific theories, and in a possible ToE, are a measure of human ignorance. A precursor to a proper ToE could have statistical elements, but a proper and final ToE should make these elements disappear. ('t Hooft 1994, 33). Regarding the role of indeterminism and statistics in a ToE, ‘t Hooft states: ‘Much more reasonable is the suspicion that the statistical element in our predictions will eventually disappear completely as soon as we know *the complete theory of all forces*, the Theory of Everything.’ (‘t Hooft 1997, 14) Thus, ‘t Hooft reduces statistics and the indeterminism following from it to a human lack of knowledge, a metaphysical position with a long tradition. ‘t Hooft is of the opinion that quantum mechanics is deterministic and a ToE should follow this and possess the same features.[26]

Another position is mentioned by John Barrow, although in an indirect manner. Barrow believes that the universe might have random and indeterministic elements. He never goes as far as to state that a ToE must be of indeterministic nature, but with respect to the predictions that a ToE makes he does state:

> ‘If the Universe possesses intrinsically random elements in its make up, inherited from its quantum origins or from random symmetry-breakings during its early evolution, then we must take our own existence into account when evaluating the correspondence between reality and the cosmological predictions of any Theory of Everything.’ (Barrow 2007, 201)[27]

The first part of this quote is especially relevant for us, as Barrow states the possibility that the universe is ‘intrinsically random’.[28] In another text Barrow

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[26] ‘t Hooft believes in the so-called ‘hidden variables’ interpretation of quantum mechanics. This interpretation states that the indeterminism of quantum mechanics is only apparent. In reality, there should be variables that allows us to deterministically predict quantum behaviour. These variables are currently hidden from us. ‘t Hooft is aware of his preconception with regard to this position, as he states: ‘So I will try not to emphasize my personal belief in some more advanced version of hidden variables, but I won’t hide it either.’ ('t Hooft 1994, 33)

[27] ‘Our own existence’ refers to the anthropic principle here.

[28] The link between quantum mechanics and indeterminism is well known. By contrast, the connection between symmetry breaking and indeterminism is less apparent, though. Symmetry breaking occurs when a system ‘chooses’ one state of a series of degenerate, or ‘equivalent’, states. This process can be interpreted as being both deterministic and indeterministic.

discusses the possibility that the constants of nature are not determined exactly, as quantum fluctuations may influence the values of constants of nature (Barrow 1994, 55). Barrow is not as strict in his assessment of indeterminism as ‘t Hooft is about determinism, as he does not demand a ToE to be deterministic. Rather, he leaves both possibilities open.

One of the reasons that physicists are not very likely to comment on the (in)deterministic nature of ToE's could be the philosophical nature of the issue. It is often assumed that quantum mechanics is an indeterministic theory. In reality, this indeterminism is often seen as stemming from the dominant interpretation of quantum mechanics rather than from its mathematical and theoretical framework. A ToE lies ‘below’ regular quantum mechanics, but the fact that many conceptual issues remain in quantum mechanics will probably infect the interpretation of a ToE. If quantum mechanics itself does not conclusively tell us whether nature is truly (in)deterministic, physicists may assume that a ToE will not either.

In the end, physicists would like nature itself to reveal whether it is indeterministic or deterministic. It is up to nature rather than the physicist, in principle, to determine what metaphysical bagage a ToE should have. Of course, we have seen that enough metaphysical claims regarding unification and simplicity are made with regards to ToE's. These claims are based at least partly on the implementation of gauge symmetries, which we discussed above. For the physicist, the mathematics of gauge symmetries makes the simplicity and unity apparent.[29] Quantum mechanics has no similar type of mathematical rigidity pointing to either indeterminism or determinism. We may assume that this might be the reason that (in)determinism is an obvious absentee in the physicists' discussion on ToE's.

Cosmology and Dark Matter in ToE's

We shall now turn to a different topic, namely the role of cosmology in ToE's. Physicists sometimes point out that the smallest and largest scale phenomena are strongly related to each other. For example, the strength of interactions at the

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[29] Although we previously discussed that one can critique this very specific interpretation of ‘simplicity’ and ‘unification’.

level of Standard Model interactions can influence the possibility that galaxies can exist. Change the interactions strengths a little, and galaxies would fly apart or collapse. So, perhaps knowledge of the smallest scale phenomena as expressed in a ToE could also teach us something about cosmology. It turns out that this link between cosmology and ToE's is indirect at best. I shall focus here on three elements: the cosmological constant, dark matter and initial conditions or boundary conditions of the universe.

The cosmological constant

First, the role of the cosmological constant. Remember that we discussed the possibility of a ToE determining the constants of nature. In the section 'Determining the Constants of Nature with a Theory of Everything' in Chapter 2 we focussed on the constants of nature as given by the Standard Model, such as coupling constants and masses. The so-called 'cosmological constant' was left out of this discussion, but I would like to touch upon it here. The cosmological constant is an element of Einstein's field equations of the theory of general relativity. It is commonly interpreted as being the 'vacuum energy', a type of background energy. Another interpretation is that the cosmological constant refers to 'dark energy', a type of ununderstood energy that is needed to explain our observations of the universe. The most recent measurements show that the cosmological constant has a value of about 10^{-52} m^{-2}. This is an extremely small value, so the cosmological constant is often referred to as being zero, although technically this is not correct. The value of this constant is very fine-tuned, as a slight change could have drastic consequences for the evolution of the universe. If the cosmological constant were one order of magnitude larger, stars and galaxies would never have come to exist. (Barrow 2007, 131)

The cosmological constant can be seen as the 'odd one out', because it is a constant of General Relativity rather than of the Standard Model. This is reflected in the discussion of the cosmological constant in ToE's. For example, remember 't Hooft's stance on ToE's and the constants of nature. He demanded a ToE to give an exact prediction for these constants. Regarding the cosmological constant, he states: 'Strictly speaking there is also the so-called *cosmological constant* which is also incalculable, but it may perhaps be set to be identically zero.' ('t Hooft 1994,

25) In a more recent article he states a slightly different sentiment: ‘I am convinced that this problem [of the cosmological constant], and that of black holes, will require a much more revolutionary approach.’ ('t Hooft et al. 2005, 257) These statements show an evolution in ‘t Hooft’s thinking, but they also display that the role of the cosmological constants in ToE’s is not very clear.

Weinberg gives the cosmological constant a similarly exceptional position: ‘The one constant of nature that may have to be explained by some sort of anthropic principle is the one known as the cosmological constant.’ (Weinberg 1992, chap. IX) All other constants could be fixed by symmetry, whereas the cosmological constant may need the ‘anthropic principle’. Most simply put, this principle states that the universe has the right values for the constants of nature to support the existence of intelligent life. If the values were any different, intelligent life could not exist and would not be there to observe these constants. Weinberg thinks that all other constants could be fixed by symmetry principles, but the cosmological constant could have a peculiar position in a ToE as it may not be determined by a ToE.[30] So it may be possible that a ToE could determine all constants of nature, except for the cosmological constant. Then the anthropic principle would need to be invoked, but it is only used to explain the value of one constant, rather than over twenty constants of nature.

Cosmologist Masataka Fukugita draws an even clearer distinction between the cosmological constant and ToE’s. His opinion summarises the above points:

> ‘The existence of the cosmological constant, or vacuum energy, has fundamental implications for physics. If a theory of everything were to tell us nothing specific about this energy, that would perhaps be the most important result. We would then not need to worry about its arbitrary value (and could appeal to the anthropic principle without hesitation). Or perhaps the theory of everything contains a compromise solution, with a dynamically varying vacuum energy.’ ('t Hooft et al. 2005, 258)

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[30] Weinberg did hope that the cosmological constant may also be explained by theory: ‘I hope that string theory really will provide a basis for a final theory and that this theory will turn out to have enough predictive power to be able to prescribe values for all the constants of nature, including the cosmological constant. We shall see.’ (Weinberg 1992, chap. IX)

This quote shows that the prediction of the cosmological constant by a ToE is not seen as a necessity of the theory. Again, it may very well be that physicists prefer to ‘wait and see’ what a ToE can tell us about the cosmological constant, rather than demanding that a ToE should predict a value of the cosmological constant. This view indeed differs quite a bit from the view on other, Standard Model, constants of nature. Finally, ‘dark energy’ and the cosmological constant are often discussed as elements of cosmology, whereas physicists working on ToE’s are regularly specialised in either quantum gravity or particle physics. So, a more practical reason for the lack of discussion on the cosmological constant may be that it lies slightly outside of the niche that most physicists working on ToE’s focus on.

Dark Matter

In the preceding discussion, the concept of ‘dark matter’ was not touched upon. Unlike dark energy, dark matter is one of the main focuses of research in particle physics. Currently we know that about 85% of the matter constituent of the universe is dark matter, rather than the ‘regular’ matter we observe. All physicists working on topics relevant for ToE’s must be fully aware of the relevance of dark matter. The fact that it is scarcely mentioned when discussing ToE’s can therefore be seen as a strange omission.

The only physicist consulted for this thesis that mentions dark matter explicitly is Marcelo Gleiser: ‘A TOE would combine particles of matter, particles of force, dark matter and dark energy into a single theory describing all four forces as manifestations of a single force.’ (Gleiser 2013) Other physicists make no statements about whether dark matter will be an element of a ToE.

I can see two explanations for this absence. Firstly, it may be that a ToE is not needed to determine the origin of dark matter. Fukugita states: ‘We probably do not need such a theory [a theory of everything] to answer the dark matter problem — we hope that experiments will reveal the nature of this matter directly.’ ('t Hooft et al. 2005, 258) Many models and experiments are focused on the search for dark matter without involving ToE’s. For example, some models propose that ‘dark matter’ may be a new particle and we would need to experimentally measure this particle. So it is indeed possible that dark matter may be measured without needing a ToE. This separates the issue of dark matter from the ToE endeavour. The determination of Standard Model constants is strongly linked to ToE's, as we have seen above.

Secondly, dark matter may be of a very different nature than regular matter. The 'dark' in 'dark matter' stems from both its unknown nature and the fact that it does not absorb or emit light. The goal of finding a unified law of the four forces of nature is difficult enough for regular matter without invoking dark matter. It may be that dark matter is some type of strange matter that does interact through one of the four forces. In another scenario dark matter is not particle-like matter at all. At the moment, physicists simply do not know. Leaving dark matter out of ToE's gives physicists an exemption from postulating how dark matter should fit within a ToE. The nature of dark matter is currently so much of a mystery, that even discussing its role in a ToE could be too much of an assumption of its meaning. This argument is a pragmatic one, though. In Chapter 2, we have seen that some physicists include their ideas of simplistic beauty and necessity in ToE's, which are not necessarily backed up empirically. What is it that makes dark matter too 'unknown' to discuss in the context of ToE's? In this light, we can criticise the idea that a ToE is truly a Theory of *Everything*. For what is 'everything' if 85% of matter is missing?

Cosmological Initial Conditions

If we compare the laws of nature to a game, we can distinguish the rules of the game from the actual game that is being played, the actual match. Take a chess match: if you know the rules of chess, you do not know yet what match is being played. An analogy can be made with the laws of nature. Knowing, for example, the laws of gravity is not enough to predict the trajectory of a ball that is thrown on earth. One would need to know the initial conditions: what is the velocity of the ball after it is thrown? Additional information is needed to apply the laws of nature to this specific scenario. Something similar holds for ToE's. The 'rules' of a ToE need to be combined with information on initial conditions, so we know what 'match' is being played in our universe.[31]

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[31] Of course, this is not a perfect analogy. To fully describe a chess match, one needs to know all the moves. You still need to know every state of the game to fully describe the game. In physics, you need knowledge of a few parameters to 'fix' the subsequent process. This means that you do

A proper ToE should perhaps include such initial conditions as well. The initial conditions of a ToE are often equated to the 'initial conditions of the universe'. That is, the traits and relevant parameters that describe the universe after its starting point. These initial conditions could 'fix' why the universe is the way it is or why we are in this universe rather than in another. In other words: if one saw the laws of nature as a game with specific rules, the initial conditions of the universe could help us to determine *what specific version* of the game we are playing.

It is currently not quite clear what the expression 'initial conditions of the universe' should exactly refer to. Brian Greene states: 'We don't know what the initial conditions of the universe were, or even the ideas, concepts and language that should be used to describe them.' (Greene 2000, 365) Greene's statement indicates that this concept of 'cosmological initial conditions' is currently not well understood. Not only do physicists lack knowledge on the value of 'initial conditions', they currently do not know what they even should measure or calculate to find them.

Still, many physicists have an intuition about what the term means, and it is often used in the context of popular science. For example, John Barrow states that 'some prescription for initial conditions is crucial if we are to understand the observed universe.' (Barrow 2007, 62) These cosmological initial conditions 'play a role in determining the size of the Universe, its shape, its temperature, and its composition.' (66) Hence, even though physicists do not know what these 'initial conditions' exactly encompass, they do feel like a description of the universe is not complete without them.

It makes sense to wonder what a ToE could tell one about the initial conditions of the universe, as these initial conditions influence the development of the universe at later times: 'If there are special initial conditions which start the evolution of the Universe upon the course that leads to the present, what is it that selects those rather than any other starting conditions?' (Barrow 2007, 66). This echoes a similar sentiment of the determination of the constants of nature: theoretical physicists are rarely content with an unexplained variable or law of

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not need to have knowledge on every physical state to make correct predictions. In turn, indeterminism could problematise this concept, but the role of indeterminism in ToE's is unclear, as discussed above.

nature. So, there seems little reason to believe that physicists would accept a set of contingent initial conditions of the universe.

Again, Gerard ‘t Hooft takes a strong stance on the role of initial conditions. For him, a ToE should ‘include a description of the ‘boundary’ of the universe, as well as its initial state.’ ('t Hooft 1994, 20) ‘t Hooft explicitly wants to know what the ‘starting configuration’ of a ToE is (19). According to this view, a ToE must include initial conditions of the universe to be called a ToE. This falls in line with ‘t Hooft’s idea that a ToE should give exact predictions of the constants of nature, which we discussed before. According to this view a ToE should leave nothing unexplained, it should tell us the rules of the game *and* fix what game we are playing.[32]

Such a strong view on the role of initial conditions in a ToE is quite rare, though. Steven Weinberg is far from certain that initial conditions can be derived from a ToE, although he leaves the possibility open (Weinberg 1992, chap. II) John Barrow thinks that it may be impossible to determine the initial conditions of the universe, as we cannot exclude the possibility that we live in a nonrepresentative part of the universe (Barrow 2007, 75).[33] The initial conditions of the universe should hold for the entire universe. We can only see a part of the universe, the ‘visible universe’, thus it would be impossible to derive general initial conditions from what could be a non representative part of the universe. (Barrow 1994, 53)

Still, there exists a hope that a ToE could one day play a role in the determinations of cosmological initial conditions. Regarding string theory as a possible ToE, Greene asks himself ‘whether our candidate “theory of everything” truly lives up to its name and determines its own cosmological initial conditions, thereby elevating them to the status of physical law.’ (Greene 2000, 366) Again we see the hope expressed that a ToE could elucidate why we live in this universe, rather than another universe with different traits. Knowledge of cosmological initial conditions could provide a basis for understanding several traits of our

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[32] Note that ‘t Hooft does not explicitly demand that the initial conditions can be derived from a ToE. It remains vague if this means initial conditions are added ‘by hand’ or follow from some type of calculation.

[33] Barrow motivates this opinion by the idea of ‘Inflation’. See (Barrow 2007, 73-75) for further details.

universe such as temperature and composition, elements that are mentioned by Barrow (Barrow 2007, 66).

Remember the quote on the previous page, where Greene expressed that we still simply do not know what the expression ‘initial conditions’ for the universe refers to. We saw multiple physicists expressing the hope that a ToE could help one to determine these initial conditions of the universe, while simultaneously acknowledging the hypothetical nature of the topic. This hypothetical nature is probably the reason that the topic of initial conditions of the universe is rarely included in discussions of ToE’s. When it is discussed, physicists express the aspiration to find a ToE that would find laws to describe our universe, as well as determine its composition and traits. This is a line of thought that follows the ideas on the determination of the constants of nature.

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Chapter 4: A Critical Examination of Theories of Everything

In the previous chapters, I have closely examined the definitions of a ToE as provided by physicists. Physicists are not philosophers, so their ideas regarding ToE's contain some characteristics that may seem unsophisticated to a philosopher. Because of this, I used philosophical concepts to analyse the words of physicists in the previous chapters. This allowed us to get a better grip on what characteristics a ToE should exhibit.

In this chapter, I will shift my tone from descriptive to more normative, as I believe that the concept of a ToE as described in the previous chapters deserves a critical discussion. I shall inspect the concept in three ways First, I shall briefly discuss the impact of the origin of the term on its current meaning. Secondly, the contents of a possible ToE will be critically analysed. Finally, I want to focus on the implications a ToE may have on science, with a special focus on the function of unification.

ToE's and Their Origin

Near the end of Chapter 1 I wrote that the first coherent definition of the term 'Theory of Everything' occured in the context of string theory. String theory at that time seemed to answer multiple questions in physics, as it seemed to be a theory that could unify the four forces of nature and explain traits of the fundamental particles. This is what triggered Ellis to use the term ToE, as string theory was the first theory that could possibly provide a framework that could solve multiple issues at once.

This initial version of string theory already ran into difficulties thirty years ago (Flam 1992), and yet it is still prominently present in contemporary theoretical physics. But of course, the dominance of string theory is not without controversy (Smolin 2006; Woit 2007). It has several technical problems, but its main flaw is the lack of empirically testable predictions. Many physicists feel that a proper theory should yield empirical predictions, and it is very plausible that string theory will not be empirically testable any time soon.

The status of string theory is relevant to our discussion of ToE's because the concept of a ToE was never quite able to shake off its origins. We have seen that ideas on unification, simplicity and determination of the constants of nature are regarded as core concepts of a ToE. This concept is not very different from the initial statement made by Ellis in 1986. In the end, the ideals of a ToE originate in the characteristics of string theory and its current conception still follows these ideas.

Interestingly, we also saw that string theorists eased the demand that a ToE should be able to give an exact prediction of the constants of nature. Possible ToE's and string theory are often conflated in this context. Rather than stating that string theory is not a ToE candidate, some physicists change their demands for a ToE. 'Marketing' string theory as a ToE is still quite popular, and popular scientific books on the topic are still being published.[34] Often string theory is seen as the 'best' ToE candidate, but it might just as well be the only candidate. Perhaps one could say that the game is rigged if the definition of a ToE is tailored to a specific theory. In other words: it makes sense that string theory is seen as a possible ToE, because the very origin of the term is based on string theory. Stating that string theory is the 'best' candidate for a ToE therefore contains a high degree of circularity. One could argue that this is a cynical view on ToE's, but it should be critically noted that the current conception of ToE's continues to be influenced by its origins in string theory.

The Traits of ToE's

But let us now focus on the traits that are identified in a ToE. First, I would like to begin with the characteristics that are not, or scarcely, mentioned by physicists. Here I identify two issues. Firstly, the lack of discussion on dark matter and dark energy in ToE's. Only about five percent of the energy content of the universe is estimated to be 'ordinary' matter, the matter we describe with our current laws of nature. The vast majority of the energy in the universe is distributed amongst either dark matter or dark energy with respectively 27% and 68%. When discussing ToE's it may be perfectly valid to state that 'everything' refers only to

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[34] For example Kaku (2021). In this book, Kaku does not solely focus on string theory, although he does see string theory as the best ToE candidate that currently exists.

regular matter. And yet, I have never encountered such a distinction in the literature. The concept of dark matter was mentioned by only one physicist, who was moreover trying to criticise ToE's. (Gleiser 2013) As we have seen, ToE's are often discussed in popularising pieces, so it makes sense to leave some of the more esoteric topics of physics out of the discussion. This should not be a problem for the discussion of dark matter though, as it is often discussed in popularising literature, and the basic concepts can be understood without too much technical background. This makes the omission of dark matter in discussions on ToE's at best peculiar and at worst negligent.

Secondly, it was mentioned that physicists rarely mention their stance on the (in)determinism of a ToE. One could argue that it is impossible to determine a priori whether the world is deterministic or not. Withholding judgement regarding the role of determinism in ToE's may indicate that physicists do not want to impose specific traits onto the world. It would be helpful if physicists would clarify why they evaluate determinism differently from other characteristics, as many physicists do impose other characteristics onto the world.

Take the determination of the constants of nature, for example. Many physicists hope that a ToE will somehow fix these constants to solve issues surrounding fine-tuning. The idea that empirical constants can ultimately be fixed by a ToE also imposes a certain worldview on physics. Here we can see a jumbling of physics and metaphysics. If one wants to both derive the constants of nature from a ToE and use a ToE to explain why these constants could not have had another value, one uses a physical theory to prove a metaphysical assumption about necessity.

Similar arguments can be made for the specific forms of unification and simplicity as discussed above. There is no definitive reason to demand that nature should adhere to our ideas of unification and simplicity. Remember our discussion of McAllister regarding simplicity. He stated that judgements on simplicity always contain an aesthetic element. In this line of argumentation, simplicity judgments of scientific theories can never escape a degree of relativism. Again I want to stress that one scientist's idea of simplicity does not need to agree with another scientist's idea of simplicity.

A critical look regarding the role of parsimony in ToE's is also warranted. Remember that simplicity in ToE's is an aesthetic judgement that is expressed in terms of parsimony, as represented by the mathematics used. Such reasoning runs the risk of becoming circular. Electroweak unification can serve as an example here. Remember that electroweak unification provided a mathematical framework for unification. Parsimony, in this case the combination of two forces into one, is represented mathematically in terms of gauge symmetries. The success of gauge symmetries in the Standard Model motivated scientists to evaluate gauge symmetries as an aesthetic property of theories. Ultimately the success of gauge symmetries in electroweak unification prompted physicists to extrapolate the technique to Grand Unified Theories (GUT), in the hope that the gauge mechanism could unify the weak, electromagnetic and strong force.[35] But there is currently no proof yet that GUT's give an accurate description of reality, and the concept has been criticised in the last years (Hossenfelder 2020). While ToE's do not need to invoke gauge symmetries, this example still clarifies what I mean by the risk of circular argumentation.

This line of argumentation based on simplicity judgments could work if one were prepared to update their aesthetic judgements once their empirical limitations are proven (McAllister 1992, 202-208). It possible that we never find a proper correlation between a specific form of simplicity and empirical relevance. Physicists should always reflect on their aesthetic simplicity judgements and change them if they prove to be empirically inadequate. It may thus be possible that parsimony is not a good guide to research, which may make it premature to grant it such an important role in ToE's.

This naturally leads us to the role of unification in ToE's. The interpretation of 'unification' for a ToE takes a specific and limited form by focusing on a unified description of all forces and matter. The term 'unification' is used quite casually by many physicists, almost making one forget that it is a term with a much broader meaning than is implied by the authors who use it. The interpretation that I have discussed here is often seen as being specific for theoretical high-energy physics. Condensed-matter physicists defend a different ideal of unification for example, as they defend methodological unity. This is the

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[35] In the 1990s it was proven that supersymmetry, a specific type of GUT, would unify the coupling strengths of these three forces at a high energy scale. This brought about a revival of research on GUT's.

idea that all branches of physics use similar methods and concepts, allowing different branches to learn from one another. (Cat 1998, 253). Such an interpretation of 'unity' differs strongly from the definition as used in this thesis.

It follows that ideas about unity are influenced by more than empirical reasoning, as scientists in different branches of physics hold different opinions regarding what type of unification should be promoted. Philosopher of science Jordi Cat summarises this by stating that 'reflections on unity belong to an ideological level that extends beyond specific scientific research and yet drives it or is suggested by it.' (254) This point of view coincides with our discussion on ToE's. I have shown that ideas on unification in ToE's are connected to aesthetic simplicity judgments related to parsimony. This ideal of a simple unification is a recurrent topcic in popularising pieces that discuss ToE's. The influence of simple unification ideals is not limited to popularising literature though, as a lot of research in theoretical high-energy physics is focused on string theory, GUT's and quantum gravity. While ToE's might represent an unreachable ideal for most physicists, it cannot be denied that these ideals influence actual research that is being done. Physicists discussing ToE's are not merely telling stories irrelevant for science. They are expressing their hopes for what physics may be able to explain one day, and these hopes can in turn influence and guide research programmes.

Finally, one may wonder if any alternatives to the dominant view of a unified ToE are possible. A few physicists have mentioned such ideas. To begin with, physicists Stephen Hawking and Leonard Mlodinow stated that a ToE may consist of an aggregate of theories that together describe all phenomena. A network of theories may prove to be a ToE (Hawking and Mlodinow 2010). Furthermore, physicist George Ellis has proposed that:

> 'It may be that fundamental physics in the end involves two different intermeshed theories: a Grand Unified Theory (GUT) and unimodular Loop Quantum Gravity, with no hidden dimensions and no string theory landscape. The unification will be in terms of broad approaches underlying physical theories (Lagrangians, variational principles, physical symmetries, etc.) but not necessarily one overriding theory that encompasses all fundamental physics in a unified form.' (Ellis 2014)

Ellis' view of unification is closer to a unification of methodology than ontological unification, and differs strongly from the mainstream ideas on ToE's as discussed here. It may be possible that this view gains traction among physicists, but at the moment the ideas of Ellis, Hawking and Mlodinow on ToE's are not mainstream. Most of the physicists that are positive with regards to ToE's hold the hope that unification of the four forces may be achieved, until proven differently. There is currently no conclusive argumentation pro or contra unification, which is why many physicists are probably hesitant to change their views. If indisputable empirical proof were to show that the unification programme is doomed to fail, this would be very different.

The Implications of ToE's for Physics

Finally, this leads us to the question: what can this definition of a ToE teach us about physics as a scientific discipline? Can it expose something about the nature of physics or about the current status of the field? This discussion should be approached with some care, as I have shown that ideas about ToE's are not often used in scientific literature. I do think ToE's can tell us something about physics as a scientific discipline as many subjects relevant for ToE's are the object of serious research. Think about topics such as string theory, quantum gravity and supersymmetry. Furthermore, the concept of a ToE was based on the words of physicists themselves. Even when physicists do not refer to ToE's in their research papers, their popular scientific pieces reveal what beliefs they hold about nature, and these beliefs can in turn influence what scientific research is performed.

Remember that one of the core concepts of a ToE is the unification of the four forces of nature. This compels us to take a look at what philosophers of science have written about the unification in physics. The following discussion is by no means exhaustive, but it will provide some philosophical basis for us. Before I commence, I want to mention that 'unification' is not a monolithic concept. Unification in physics is often associated with ToE's (Morrison 2013, 381), but it can also appear in very different contexts. For our analysis, the unification of forces is most relevant. But, most philosophers do not explicitly distinguish unification of forces from other types of unification, such as methodological unification. Nevertheless, we can use the pieces mentioned below to sharpen our thinking regarding ToE's.

Let us start with a paper by Molly Kao (2019). She proposes that unification can be seen as a guiding principle in physics research. Rather than using unification as a justification for a theory, Kao states that unification principles may aid in developing new theories which in turn may be experimentally tested (3276). In addition, she states that unificatory principles are used 'to solve problems in different domains without a clear account of how and why it should be able to do so.' (3266) When comparing this to the contents of Chapter 2, we recognize that physicists do use unification as a guiding idea when determining what they would like a ToE to be.

I disagree with two things regarding this assessment. Firstly, we have seen that the emergence of string theory has coloured the ToE discourse. String theory was originally seen as an alternative for strong force theories, and later it was shown that it might provide a unification of the four forces. So, the notion that ToE's are 'guided' by unification is somewhat misleading. Secondly, regarding ToE's, I think many physicists have strong intuitions how unification should occur and why it might work. Indeed, we have seen that some physicists have strong metaphysical intuitions about beauty, simplicity and necessity. In turn one could argue that the 'how and why' of unification is supported by these intuitions: unification is achieved through unification of the four forces, because this would maximise parsimony. This does not answer the question why simplicity should be promoted in theories, of course.

Philosopher Kian Salimkhani in turn disagrees with the notion that metaphysical intuitions are relevant when discussing the role of unification in physics (2021). He challenges both that unification itself is an aim of physics and that research on unification is driven by metaphysical ideas (5861). Instead, he argues that unification in physics is merely a by-product of methodological strategies. Salimkhani notes that 'over time the theories of physics have become more and more unified' (5878). He explains this in terms of methodological strategies, which he calls 'internal explanations'. An example of such strategies is the goal to eliminate inconsistencies in theories. Usage of such methods should lead to higher degrees of unification in physics (5867). Salimkhani notes that this ‘implies a certain sense of necessity’ (5879). I am of the opinion that one cannot discuss ToE’s without invoking metaphysical presuppositions. Physicists often do not hide their presuppositions either, as we have seen. Beauty, simplicity and unification are often strongly linked to one another.

One could retort that our discussion on ToE’s refers to popularising discourse, rather than ‘official’ science. As I have argued, one cannot fully isolate ‘official’ science fully from popular science, especially when scientists themselves write popularising works. Perhaps scientists do not publish papers called “A Theory of Everything”, but serious research is being done on both string theory and Grand Unified Theories. Part of their appeal for scientists is the fact that they could provide unification of forces. Metaphysical ideas about simplicity and in turn unification thus do play a role in physics. The relevance of these ideas may be discussed, but their existence is undeniable.

Philosopher Peter Galison does acknowledge that metaphysical reasoning is relevant when analysing unification in physics (2016). He states that ‘unity talk rarely walks alone’ (26), by which he means that political, scientific and metaphysical reasoning all influence the role of unification in physics. Indeed we have seen that both metaphysical and scientific reasoning play a role in ToE’s. I discussed the metaphysical aspects above, but that does not mean I deny that there are scientific reasons to pursue unification of forces. We have seen that prior unifications of forces have been successful, which would make it logical to try to repeat the step. This sentiment is echoed by philosopher Tim Maudlin, who similarly states that ‘in the final step, the GUT [Grand Unified Theory] will somehow be unified with gravity in a *Theory of Everything* (TOE)’ (Maudlin 1996, 129). Physicists have a long way to go until they might be able to find a ToE that meets their demands, but Maudlin’s statement shows us that their hopes are not solely based on a mirage.

An account of unification is not enough to explain the demands that are placed on a ToE, though. An important aspect of a ToE, which is not discussed in any of the above pieces, is the idea of necessity. In Chapter 2, I discussed that most physicists hope that a ToE might be able to predict the constants of nature. Additionally, a ToE would perhaps even provide a reason why these constants do not assume another value. Maudlin’s statement represents the general idea that a

ToE is ‘simply’ the final unificatory step that physicists hope to achieve, but in this thesis I have shown that ideas of necessity are also important when discussing ToE’s. Unification is a core element of possible ToE’s, but one also needs to account for multiple other factors to fully understand the term. Necessity is one of them, but we have seen that simplicity and the role of reductionism are also relevant.

Finally, let me return to Peter Galison. He noted that political reasoning is often also a part of the unification talk in physics (Galison 2016, 26). This dimension became very apparent at the end of the 20th century, when the construction of a very large particle collider, the ‘super conducting super collider’ (SCC), was cancelled halfway through the development by the US Congress. This was preceded by lively debate within the physicists community regarding the meaning of ‘unification’ in physics. Physicists such as Steven Weinberg strongly defended the ideal of unification of forces and reductionism, but the pleas of particle physicists were not enough to save the SCC. (Cat 1996, Weinberg 1992)

I have not discussed science policy or grant systems in this thesis, but the course of events surrounding the SSC can be seen as one of the signals that particle physics and theoretical physics were losing funding after their heydays in the 20th century. In this context, it is not a leap to recognize that popularising works on ToE’s can help to enthuse and engage a general audience regarding theoretical physics. As funding is dwindling and revolutionary results are becoming rarer and rarer, the discipline needs to show its relevance. The topic of ToE’s are sure to get the attention, which in turn might contribute to both funding and attracting aspiring physicists. I do not mean to imply anything nefarious with this analysis. Few physicists will write lies about physics to sneakily obtain money. But most physicists are aware that they need to set foot in the public arena to keep their field in the public eye, especially as theoretical physics is not a natural interest of most people.

Conclusion

The goal of this thesis was to analyse the concept of a ‘Theory of Everything’. To research this, I based myself on the words of physicists themselves. Together, these physicists represent the different views in the literature on the subject of ToE’s. The term is mainly used in popularising works, which I consulted in the shape of books, magazine articles and interviews.

I researched what aspects are deemed to be important for ToE’s. Central to ToE’s is the concept of the unification of the four forces of nature, the weak, strong, electromagnetic forces and gravity. Unification is motivated by ideas about simplicity, specifically in the form of parsimony or ontological simplicity. We also identified that simplicity is an aesthetic trait of ToE’s that is represented through the mathematics used to construct the theory.

A simple and unified theory is not yet a ToE, though, as most physicists would like to derive the constants of nature as defined by the Standard Model with a ToE. Some of them go as far as to state that a ToE should be able to answer why the constants of nature take specific values. Ideas about necessity are thus also present in ToE’s, which shows that some physicists would like to prove metaphysical traits with a physical theory. Reductionism is also a key element to the ToE enterprise, as a theory cannot be seen as ‘most fundamental’ without accounting for a type of reductionism. Most physicists adopt a stance of ontological reductionism, in varying strengths, although applying a possible ToE to more macroscopic phenomena is not seen as a viable option. Even physicists strongly committed to ontological reductionism acknowledge that epistemological reductionism is thus not feasible.

Still, some key research interests of the fundamental physics community are not or barely present in the ToE discourse. I have identified three categories: indeterminism and determinism, dark matter and cosmological topics. The omission of dark matter is especially strange, as physicists are well aware that regular matter constitutes only a fraction of the matter in the universe. Failing to account for dark matter in a ToE would make the ‘everything’ in its name useless. Another peculiarity is the status of the cosmological constant. Whereas some physicists express the belief that the constants of the Standard Model can be derived from a ToE someday, discussion surrounding cosmological constant is often missing. In some cases, the cosmological constant is given an exceptional position, as it is seen as the one constant that we may not be able to derive from a ToE. Why such a distinction is warranted, remains unclear.

This leads us to the critical examination of the concept of a ToE. Here I identified that the phrase has never shaken off its origins, which are rooted in string theory. The first usage of the term was in the context of string theory as a theory that could unify the forces of nature, as well as explain the constants of the Standard Model. Ever since, the term has been deeply influenced by this definition. We can also critique the characteristics of a ToE. Why are some important issues, for example the previously mentioned topics of dark matter and indeterminism, not discussed? I have no clear answer to this, but perhaps physicists do not want to speculate on the nature of dark matter, or make metaphysical assumptions about the determinism or indeterminism of the universe. The oversight of these topics leaves one unsatisfied at the very least. In any case, it is clear that physicists are not afraid to discuss metaphysical ideas, as the ideals of parsimony and necessity play important roles in ToE's.

Finally, we have taken a look at what the definition of a ToE might imply for physics. I have identified that ToE's involve metaphysical ideas regarding unification, although the concept of unification is not sufficient to explain what a ToE entails. Political and practical reasoning are also of relevance when discussing ToE's: although the term is rarely used in scientific papers, it is very common in popularising pieces. In the light of dwindling funding and less revolutionary results, an idealistic concept such as a ToE may help to keep theoretical physics in the public mind.

In the end, the discussion surrounding ToE's provides a fascinating look into physics on the edge of popular and 'official' science, where metaphysical ideals, practical considerations and scientific reasoning meet. We will probably not find a Theory of Everything in the foreseeable future. And yet, it is a phrase that will remain strongly associated with theoretical physics. Even if it remains loved by some, and hated by others.

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