Philosophy of String Theory

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Abstract

1 Introduction

The basic idea of string theory goes back to the late 1960s. (For textbooks on string theory, see Polchinski 1999, Zwiebach 2007, Becker, Becker and Schwarz 2007. For a collection of texts on early string theory, see Cappelli, Castellani, Colomo, Di Vecchia 2012. A philosophy-minded history of string theory is Rickles 2013.) After its foundations had been laid from 1968 onwards as a candidate theory for describing strong interaction (Veneziano 1968), string theory was proposed as a universal theory of all interactions in 1974 (Scherk and Schwarz 1974) and became popular after the formulation of the action of a quantized superstring (Green and Schwarz 1984). Since then, string theory has played the role of the leading approach to a unified theory of all interactions.

String theory's history as a subject of philosophical investigation is much shorter. Apart from Weingard (1989), which introduced string theory to philosophers, not a single philosophical paper on string theory was written in the 20th century. After a second philosophical "suggestion" to look at the theory at turn of the 21st century in Butterfield and Isham (2001), the theory became a subject of more extensive philosophical inquiry about a decade ago. Increasing activity in recent years may indicate the emergence of a fully fledged philosophical field of research.

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2 The Role of String Theory

A consistent theory of quantum gravity is a main desideratum of contemporary fundamental physics. Observed phenomena in high energy physics at this point can be very well accounted for by the standard model of particle physics. Observed gravitational phenomena are covered in a satisfactory way by general relativity. However, neither of those two theories on its own can provide a satisfactory description of the very early and dense states of the universe. What is needed is a consistent theoretical scheme that accounts for both types of phenomena, nuclear interactions and gravity.

There are two and a half ways to search for such a theory. The half-option would be to retain the theories of general relativity and quantum field theory and just try to make them consistent with each other so that they can work in conjunction to describe regimes where both types of interaction are relevant.[1] No promising headway has been made in that direction and there are reasons to doubt that this is a viable way to go. The other two options start from one of the existing conceptual frameworks and build a theory from that starting point that can cover the other side as well. Canonical quantum gravity, loop quantum gravity, and related approaches start from gravity and aim at developing a quantized theory of gravity. String theory starts from the perspective of particle physics and aims to generalize it to include gravity.

In the eyes of string theorists, two general observations speaks in favor of the latter approach. First, the principles of gauge field theory, on which the standard model of particle physics is based, put strong constraints on theory building. The requirement that the theory of quantum gravity should enforce that its low energy effective theory is a gauge field theory therefore is a powerful guideline for theory building. Second, the approach seems to work in principle, which is by no means a trivial observation. An extension of the gauge principle to supersymmetry leads to a graviton, which suggests that quantum gravity is a natural extension of gauge field theory.

String theory started from a perturbative perspective, keeping the format of calculating Feynman diagrams but replacing the pointlike particles of quantum field theory by small one-dimensional objects, the strings. This modification is assumed to generate a finite theory, thereby offering a solution to the problem of the non-renormalizability of quantum field theories of gravity. Moreover, the fact that a quantized string necessarily contains a graviton as one of its oscillation modes renders the approach a natural framework for describing quantum gravity. The posit of extended elementary objects also seems consistent with the high energy behaviour one is led to expect from

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[1] for a philosophical perspective on that strategy, see Wüthrich (2004).

a theory of quantum gravity. The generation of black holes in particle collisions at the Planck scale enforces an upper limit to testing energy scales that fits well with the intrinsic fundamental length scale of the string. This vague initial argument was later fleshed out based on the minimal length scale imposed by string theory's duality structure (see below).

The seemingly innocent step towards extended fundamental objects carries huge conceptual implications. A quantized string theory that describes both fermions and bosons must be supersymmetric (that is, show a symmetry under transformations between fermionic and bosonic degrees of freedom). The quantization of this superstring only works in a consistent way in 10 spatiotemporal dimensions. The 6 extra dimensions remain invisible at low energies. They are understood to run back into themselves like cylinder surfaces, thereby generating a topologically complex spactime structure (a Calabi-Yau space).

Moving beyond a strictly perturbative perspective reveals that string theory contains higher-dimensional objects of various dimensions called branes (Polchinski 1995). Branes play a crucial role in one of the most remarkable features of string theory. In a number of cases, specific realizations of string theory that differ with respect to the kinds of symmetries they have, the radii of their compact dimensions, their spacetime topologies, the dimensionality of their higher dimensional objects and other characteristics are dual to each other: they are empirically fully equivalent and the features of one formulation are related to features of its dual by a duality transformation. Duality relations connect all five types of superstring theory.(Witten 1995) Another duality relation connects string theory on AdS space (a space with constant negative curvature that corresponds to the solution of the Einstein equations for empty space with a negative cosmological constant) to a conformal string theory on the boundary (Maldacena 1998), thereby revealing a deep connection between string theory and gauge field theory.

String theory in many respects is a very different kind of conceptual scheme than any other physical theory we know. In the following, I will give a brief survey of some of the most important novel characteristics of string theory that deserve serious philosophical attention. A number of them have by now been addressed extensively in a philosophical context. Others still lack the philosophical attention they deserve.

3 Specific Physical Characteristics of String Theory

3.1 The central role of the concept of duality

As already emphasized in the introduction, dualities play a pivotal role in string theory. They have also been at the center of the theory's philosophical analysis.

Dawid (2007, 2013), Matsubara (2013) and Rickles (2011, 2017) identified string dualities as a serious problem for scientific realism. The extent to which dual theories differ from each other with respect to their fundamental ontologies is incompatible with ontological scientific realism (Dawid 2007). For a number of reasons, dual formulations of string theory should be treated as different perspectives on one theory rather than as distinct theories: string theorists clearly treat them as one theory (Matsubara 2013); only the entire web of dual formulations allows an adequate understanding of string physics (Dawid 2013); dual theories can be transformed into each other by duality transformations (Rickles 2017). As pointed out by Castellani (2009), viewing duals as different perspectives on the same theory goes counter to the classical view that links theory individuation to a theory's ontological import.[2]

Dawid (2007, 2013) and Matsubara (2103) argue that structural realism is in a better position than ontological realism to account for dualities but faces problems of its own. Dawid (2007) suggests that string theory might support a specific form of structural realism (consistent structure realism) that relies on the fact that string theory at a fundamental level is fully determined by consistency arguments. (It has no free parameters and no freedom of model choice.) Rickles (2017) also favors a structuralist approach. He emphasises that duality transformations, in revealing physically irrelevant transformational degrees of freedom, are comparable to gauge transformations (see also de Haro, Teh, Butterfield 2017). This analogy suggests that anything that can be changed under duality transformations is unphysical and no candidate for the theory's real content. Only characteristics invariant under duality transformations, such as the global symmetry group, should thus be acknowledged as real. Rickles argues that this leaves sufficient room for a structural realist take on string theory.

An interesting specific context for analysing the anti-realist import of dualities is provided by S-duality. S-duality transforms a theory into a dual with inverse coupling constant. In string theory, S-duality arises as one of the pivotal duality relations that connect all five types of superstring theo-

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[2] See e.g. Coffey (2014) for a recent exposition of the latter view.

ries. The fundamental strings of one theory show up as solitonic solutions (nonperturbative effects characterised by a topological charge) in its S-dual theory (Harvey and Strominger 1995). The fundamental objects of one theory thus emerge as complex composite objects of its dual. String physicists Sen (1999) and Susskind (2013) have taken this characteristic of string theory to indicate that the theory does not allow for a reductionist understanding of the world. Objects don't stand in an unequivocal constituent-compound relations to each other. Sen's and Susskind's arguments support the incompatibility of string theory with ontological scientific realism.

McKenzie (2017) outlines a strategy for avoiding this conclusion in the (non-string theoretical) context of Montonen-Olive duality, a duality relation that holds in N=4 supersymmetric conformal field theories: for a given coupling strength, one of the dual formulations can look more natural. This may justify the selection of a preferred fundamentality order in a world that is characterised by that specific coupling strength.

As emphasised by Susskind (2013), this defence of a preferred fundamentality ordering does not work with respect to string theory, however. The string coupling constant is no fundamental parameter that can be set to a certain value but corresponds to the value of a quantum field (the dilaton). Selecting the value of the string coupling therefore is a matter of the theory's dynamics. The value of the dilaton field can vary in space-time, thereby creating a situation where one of the dual descriptions is simplest at one point in spacetime and the other description is preferable at another point.

Castellani (2017) raises a different issue. Understanding the solitonic objects in terms of composite states may seem plausible when viewing them from a perturbative starting point but is much less natural when analysing them in terms of Noether charges and topological charges. The latter point of view would conceive of solitonic solutions as distinct elements of the particle spectrum without establishing a constituent-compound relation. Whether or not solitons are construed as compounds thus seems itself a matter of choice. In this light, reductionism may be taken to fail in the presence of any nonperturbative effects in quantum field theory irrespectively of the question as to whether or not duality relations arise.

Huggett (2017) addresses the issue of specifying the physical essence of dual theories by focussing on another duality relation. T-duality relates a theory with a given radius of a compact spatial dimension to a theory with inverse radius (measured in units of the string length). The duality transformation thereby transforms winding numbers of strings around that dimension into transverval momentum and vice versa. Based on the understanding (established above) that dual formulations don't amount to different theories but give the same physical description, Huggett distinguishes two possible ways to interpret this statement. According to the first interpretation, dual theories offer a translation manual. Moving from one description to its dual thus amounts to a transmutation of terms. This would allow attributing reality to a certain radius of a compact dimension since the duality transformation to a small radius would be compensated for by a transmutation of terms. The second interpretation holds that terms have the same meaning in both of the dual formulations. In that case, the real physical content of the theory has to be reduced to what remains invariant und duality transformations. The radius of a compact dimension would be indeterminate. Huggett rejects the first option because it offers no satisfactory way of viewing a different world with inverted radius based on the initial meaning of terms.

A different perspective on dualities is chosen by Dawid (2017). Dawid compares dualities to the traditional take on empirical equivalence in physics. Empirical equivalence, Dawid argues, was understood in the 20th century in terms of the flexibility of theory building due to the deployment of advanced mathematical and conceptual tools. Once those tools have been developed, making use of them them allows for various conceptual representations of the same empirical data set. Dualities tell a very different story. In their case, new conceptual tools are deployed not to develop new theories but to demonstrate the empirical equivalence of existing theories that had previously been understood to substantially differ from each other. What is revealed by duality relations thus is a more constrained rather than a wider spectrum of theories. Dawid (2017) argues that this constitutes a significant shift with respect to the role of new conceptual tools in physics.

A technical analysis of gauge/gravity duality is carried out in de Haro, Teh, Butterfield (2017)and de Haro (2016)[3]. Global symmetries are invariant under duality transformations but often have a different physical interpretation in the dual theory. Gauge transformations, to the contrary, do not survive duality transformations, which reflects the fact that they deal with unphysical degrees of freedom of a given formulation. The way in which global symmetries and gauge symmetries play out in gauge/gravity duality involves a number of subtle issues that are addressed in the papers.

3.2 The emergence of spacetime

The issue of duality leads up to another important philosophical discussion: the emergence of spacetime in a string-theoretical context. AdS/CFT duality relates a string theory on a specific background space to a conformal field theory at the boundary of this space. While there is strong support for the

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[3] For a survey of gauge gravity duality see also de Haro Mayerson, Butterfield (2016)

understanding that this relation has the status of an exact duality, it is an open question whether the duality can be generalized to a relation between any string theory and a gauge theory dual. Though some general arguments would suggest as much (see e.g. 't Hooft 1993, Strominger 2001), no manual for a general gauge/gravity duality has yet been found.

Some string physicists (see e.g. Seiberg 2007, Horowitz and Polchinski 2009), have expressed their understanding that gauge/gravity duality could be understood in terms of emergent spacetime. A number of philosophical papers have tried to square claims of emergence made by string theorists with the philosophical use of the concept of emergence. The core problem is the following. While emergence has a directedness, an exact duality relation is symmetric. The translation manual leads both ways without singling out one of the dual theories as more fundamental. There is no way to interpret one of the dual theories as a low energy effective theory of the other.

Dieks, van Dongen and de Haro (2015) reject the applicabity of the concept of emergence to exact duality relations for that reason. They suggest that, among the current discussions of dualities in the context of quantum gravity, only Verlinde's (2011) entropy approach to gravitation, which does not posit an exact duality but merely a duality relation at the level of effective descriptions, qualifies as a suggestion of emergent gravity. Rickles (2013) expresses similar doubts about viewing gauge/gravity duality as a basis for the emergence of spacetime. He argues that indications of an emergent character of spacetime in the context of string theory are in line with more general reasoning in the context of quantum gravity and don't substantially rely on the issue of duality.[4] Teh (2017) widens the analysis by asking whether it is possible to identify directedness in duality relations by other means despite their formally symmetric character. He suggests that the most promising strategy to that end would focus on an explanatory advantage of one of the two duals. He comes to the conclusion that, while specific explanations work better in one framework, there is no consistent pattern of favoring one of the duals over the other. This does not exclude, though, that a different formulation of the theory could be found one day, that has a clear overall explanatory advantage that justifies the understanding that other perspectives emerge from it.

Horowitz and Polchinski (2009) argue that, in the case of gauge/gravity duality, the symmetry between the duals may be less clear than in other cases. At the present point, one knows an exact description of the gauge theory

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[4] For a philosophical view on the way the Einstein equations for background space in string theory can be extracted from consistency requirements on the propagation of individual quantum strings, see also Huggett and Vistarini (2015)).

while the exact formulation of the string theory is unknown. This fact would not amount to a fundamental difference between the two theories if it merely indicated a deficit in the present understanding of the string theory side. The asymmetry might be fundamental, however, if it were indeed impossible to reach a full formulation of string theory in any other way than by going to the gauge theoretical dual. In that case, string theory proper would be conceptually dependent on the gauge theory in an non-reciprocal way and therefore could justify the application of the concept of emergence.

3.3 Black hole physics and information loss

Closely related to the last point is the issue of information loss in black holes. It has been a longstanding problem for black hole physics to understand what happens once a black hole evaporates due to Hawking radiation. A conventional understanding of quantum physics would suggest that Hawking radiation cannot contain the information stored in objects that have fallen through the black hole horizon. On the other hand, thermodynamical principles would suggest that no information should have been lost once the black hole has vanished. String theory gives a clear answer based on AdS/CFT duality: since there is no information loss in the dual conformal field theory description, information must also be preserved in the gravitational system. While suggestions regarding the actual process of information conservation on the string theory side have been put forward (see e.g. Almheiri el at. 2013) no full understanding has been achieved so far. Black hole information is one of the most intensely investigated issues in string theory today. The substantial philosophical significance of those investigations has not yet been addressed in the philosophy of science.

3.4 The lack of free parameters and the string theory landscape

At a fundamental level, string theory does not have any free parameters. Due to the web of dualities that connects all five types of string theory, this implies that, at a fundamental level, there is only one realization of a string theory that includes fermions and lives in more than two spacetime dimensions. This fact is one of the most remarkable features of the theory. Dawid (2007) has argued that this property of "theoretical uniqueness" is one specific reason for trust in string theory based on non-empirical theory assessment (see Section 4.2) and can provide the basis for a specifically string theoretical take on scientific realism (see Section 3.1).

For a while, string theory's uniqueness and lack of free parameters raised hopes that the theory might uniquely predict all parameter values of low energy physics. An improved understanding of string vacua (Kachru et al. 2003) then established that one must expect a discrete but huge spectrum of vacua of the theory, represented by what is called the string theory landscape. This substantially reduced the expectations regarding string theory's predictive power and resulted in a more complex picture: the uniqueness at the fundamental level is compounded by a lot of flexibility at the level of the theory's ground states. String theorists have been struggling with understanding the theory's predictive status under these circumstances (see e.g. Douglas 2003). This situation raises a number of important philosophical questions. What is the significance of a theory's uniqueness at a fundamental level given the existence of a landscape? How should one understand the concept of empirical prediction under those circumstances? How should a continuous free parameter be compared to a large but discrete set of allowed parameter values? These and other questions still await analysis from a philosophy of science perspective.

3.5 The multiverse and anthropic reasoning

One very important strand of philosophical analysis related to the string theory landscape is concerned with the multiverse and anthropic reasoning. While the multiverse is rooted in the cosmological concept of eternal inflation (Vilenkin 1983), the string landscape is necessary for providing a physical basis for allowing different values of the cosmological constant and other parameters in each universe of the multiverse. String theory thus plays a crucial role in the setup that eventually leads to anthropic reasoning (Susskind 2010). The philosophical issues that arise in this context are of fundamental importance but lie beyond the scope of this article.

4 The Meta-level issues of String Theory

String theory's philosophical relevance reaches beyond the theory's specific physical import. In a number of ways, string theory raises philosophical questions regarding the research process associated with the theory and, more generally, the role of theory in science.

4.1 The incompleteness of string theory

Nearly half a century of intense work on string theory has not resulted in anything close to a complete theory. As described above, the theory's formulation started from a perturbative perspective and then transcended that approach based on the discovery of duality relations. The most surprising result in this respect was the discovery of AdS/CFT correspondence, which indicated that a string theory could be empirically equivalent to a theory that was no string theory at all. Based on this insight, it is not clear anymore how central strings are to string theory. The insufficient grasp as to what string theory actually stands for raises the question whether one should call it a theory at all at the present stage. A variety of views on this issue have been expressed by string physicists. Historians of science Camilleri and Ritson (2015, 2015a) have emphasised this wide spectrum as a core characteristic of the internal dispute on the theory's status. Roughly, the spectrum of positions can be viewed in terms of two conflicting considerations.

The first consideration emphasises that string theorists so far have failed to grasp even the core principles of string physics in a conclusive way. This may be taken to suggest that what physicists have developed up to this point is less than an actual theory. David Gross (2015) has, in this vein, characterized string theory as a framework: a set of principles that determines the way theory building proceeds but does not fully specify empirical implications. Still, a framework in Gross' sense does constrain the spectrum of empirical data that can be modelled and therefore can be rejected or confirmed on an empirical basis.

The second consideration emphasises the fact that the theory's development at a fundamental level seems driven entirely by consistency arguments without leaving room for conceptual choices on the way. This fact may be taken to indicate that, even though the most fundamental principles of the theory have not yet been found, the conceptual posits that characterize the theory today are sufficient for uniquely determining the theory: string theory is whatever the consistent full set of implications of the posits that define string theory today amounts to. This perspective that treats string theory as a well defined but ill-understood theory is suggested in Witten's (1996) spelling out of string theory's final theory claim or Polchinski's (2019) characterization of the theory's current status.

A more general philosophical analysis of what it takes to be a theory in fundamental physics at the time of string theory is a desideratum in the philosophy of science.

4.2 The theory's strong status despite the lack of empirical confirmation and completeness

The second main meta-level issue that has been raised with respect to string theory is the high degree of trust in the theory's viability many of its peers have developed during the last three decades. This degree of trust is remarkable, given the theory's highly incomplete state (see previous section) and the fact that it has not found any empirical confirmation up to this point. The physicist Lee Smolin (2006), the mathematician Peter Woit (2006) and philosophers Erik Curiel (2001)[5], Reiner Hedrich (2007a, 2007b), Roman Frigg and Nancy Cartwright (2007) argue that this confidence is unfounded and indicates a problematic detachment of fundamental physics from empirical evidence. String theorists Joseph Polchinski (2007, 2019) and Mike Duff (2013) reject that criticism, pointing at inaccuracies of critical presentations of string theory, and argue for the reasonability of trust in string theory.

Dawid (2006, 2009, 2013) puts forward the idea that the trust in string theory and a number of other physical concepts can be best understood by widening the concept of theory confirmation. Theory confirmation is hereby understood in a Bayesian sense as an increase of a theory's probability of being viable. The proposed wider concept of confirmation includes evidence that lies outside the theory's intended domain (i.e. it is not of the type that can be predicted by the theory in question) but nevertheless provides information about the outside world rather than merely about the theory's characteristics. A crucial role in the approach is played by the concept of scientific underdetermination (akin to what Lawrence Sklar (1975) and Kyle Stanford (2006) call transient underdetermination.) Observations about the research process can indicate that scientific underdetermination (which corresponds to the number of empirically distinguishable scientific theories that can buildt based on the available empirical data) is severely limited. Strong limitations to scientific underdetermination can in turn increase the probability that the theory one has developed is viable. If that is the case, such observations about the research process amount to theory confirmation. Confirmation based on such observations is called non-empirical because it is not based on empirical tests of the confirmed theory. Dawid (2006, 2013) proposes three main strategies of non-empirical confirmation. Dawid, Hartmann and Sprenger (2015) and Dawid (2016) formalize this line of reasoning based on Bayesian confirmation theory.

While there is mostly agreement on the fact that physicists do use strate-

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[5] Curiel's paper does not focus on string theory but addresses quantum gravity in general.

gies of non-empirical confirmation, a number of aspects of the approach have been questioned and criticised. Smolin (2014) argues that non-empirical confirmation is too flexible for being reliable and further bolsters dominant research programs in an unwarranted way. Ellis and Silk (2014) argue that that a widening of the concept of confirmation amounts to giving up core pillars of scientific checks and balances. Rovelli (2017) argues that the mismatch between the Bayesian notion of confirmation and the way the term confirmation is used in theoretical physics renders the message of non-empirical confirmation misleading from a physics perspective. Dawid (2019) responds to some of those criticisms. The role of non-empirical theory confirmation is also analysed in Dardashti (2019) and Oriti (2019).

Rickles (2013) argues for some degree of trust in string theory's viability without endorsing non-empirical confirmation. He suggests that the viability of string theory becomes more plausible due to the fertility of the mathematical concepts developed in its context. Matsubara and Johannsson (2013) aim at striking a middle ground in their assessment of string theory. They suggest, following Frigg and Cartwright (2007), that string theory does not constitute a progressive research program in a Lakatossian sense at this point. Still, they argue that the string theorists' way of dealing with their theory looks reasonable from a Lakatossian perspective since, in the absence of a clearly progressive research program, focussing on the strategy that looks most promising is perfectly legitimate for the individual scientist.

4.3 The theory's universality and its final theory claim

The third important peculiarity of string theory pertains to its position within the overall fabric of physics. Theory building in physics may be viewed as a process of successful unification that leads from Newton's unified description of the movements of earthly and heavenly bodies to the conceptually unified relativistic description of all nuclear forces in the standard model of particle physics. The unification of nuclear forces and gravity, which is the aim of string theory, might be the final step in this series of unifications. Moreover, string theory conceptually does not allow for any form of amendment by additional theory. String theory therefore is a fully universal theory not only in virtue of the known set of phenomena that need to be accounted for but in virtue of its conceptual nature. Interestingly, string theory adds to this inherent universality claim an internal final theory claim that is based on a different line of reasoning. T- duality, one of the core string dualities, implies that the theory's own characteristic scale amounts to a minimal length scale. Any statements about a phenomenon at a smaller length scale can be understood as a statement about a phenomenon at a larger length scale by moving to the T-dual description. (See e.g. Witten 1996.)

The universal character of string theory and its final theory claim raise at least three deeply philosophical questions.

First, the question arises whether a theory's finality can be meaningfully supported by arguments that rely on that very theory. Relying on a theory in an argument for that very theory's viability looks viciously circular. Dawid (2007, 2013a) acknowledges that this circularity devalidates a final theory argument when viewed in isolation. He argues, however, that a final theory claim can acquire some force in the context of a broader argument regarding the structure of limitations to scientific underdetermination. In such an argument, the lack of possible alternatives to a given theory is first established in a certain empirical context (for example at a certain energy scale) by conventional arguments of non-empirical theory assessment and then extended beyond that context based on a final theory argument.

Second, the question arises whether and in which way a theory's universal character or its prospects of being a final theory create a different overall understanding of the theory's scientific role and the mechanisms of scientific evolution. Dawid (2007, 2013) relates string theory's final theory claim to its long term incompleteness (see Section 4.1). The canonical understanding of the physical process assumes a finite - usually reasonably brief - time for the completion of a theory but projects an infinite series of theories superseeding each other due to an influx of empirical anomalies. String theory's final theory claim suggests that no further sequence of superseeding theories will be forthcoming. The incompleteness of the theory without indications of full redemption in the foreseeable future may be taken to suggest, however, that the time horizon for completing the (final) theory at hand has shifted towards infinity. In conjunction, those two shifts imply that, while theory development should now be understood in terms of inner-theoretical conceptual evolution rather than theory succession, the prospects for an imminent completion of fundamental physics have barely improved.

Finally, the question arises as to whether and if so how string theory's incompleteness is compatible with a meaningful final theory claim. A number of string theorists have come to doubt this, which arguably has led to a reduced emphasis on string theory's final theory claims in recent years. A substantial analysis of this issue from a wider philosophy of science perspective is still missing.

4.4 The remarkable relevance of string theory as a tool in plasma physics

A further meta-level issue of significant philosophical interest is string theory's remarkable role as a tool for carrying out quantitative calculations of the strongly coupled quark gluon plasma. Those calculations are based on performing a gauge/gravity duality transformation on the strongly coupled gauge theoretical description of the system and then carry out calculations in the resulting gravitational theory, where they are much easier to do. As noted in Section 3.1, gauge gravity duality has only been established for a very specific class of gauge theories, conformal field theories. QCD, the theory describing the quark gluon plasma is no conformal field theory, which means that no actual gravity dual has been identified. Quark gluon plasma calculations based on a duality transformation therefore can only be understood as a fairly rough approximation, which is in line with the fairly rough agreement of such calculations with actual data.

The method's success provides an interesting example of a theory that is taken to be a viable fundamental theory in one context and is utilized as a mere calculational tool in a different context. From a historical/sociological perspective, it is of interest how string theory's utility in that other context has widened the spectrum of physicists that know and deploy string theory in their work. Many of them do so without endorsing the theory as a fundamental theory of all interactions. In a more philosophical vein, one may raise the question whether the theory's success in plasma physics can be of any significance for understanding the theory's prospects as a fundamental theory. None of those issues has been addressed from a philosophy of science viewpoint so far.

5 Conclusion

String theory is a very different kind of conceptual scheme than any earlier physical theory. It is the first serious contender for a universal final theory. It is a theory for which previous expectations regarding the time horizon for completion are entirely inapplicable. It is a theory that generates a high degree of trust among its exponents for reasons that remain, at the present stage, entirely decoupled from empirical confirmation. Conceptually, the theory provides substantially new perspectives on the role of space and time, on the relation betwee a theory and its classical limits, on the uniqueness and the contingencies of a theory and its empirical implications, on the nature of black holes and on many other core issues of physical theory.

All of the described shifts have a profound philosophical dimension. Some of them are specifically bound to string theory. The significance one attributes to those shifts thus may depend on one's assessment of the theory's prospects of being viable. But, at a general level, most of the shifts in perspective associated with string theory raise questions that transcend string theory proper by exemplifying the substantial changes that are forced upon scientists by fundamental physics today. Theory building in an environment of scarce empirical data, the overwhelming conceptual difficulties associated with developing a theory of quantum gravity, the conceptual issues that render the canonical view of theory succession questionable once one reaches the the Planck scale, the emergence of space and time from more fundamental concepts, the seemingly holographic character of quantum gravity, the deep problems related to information in black hole physics: those are all issues faced by contemporary fundamental physics irrespectively of the fate of string theory.

String theory, in the eyes of many of its exponents, offers a number of reasons for assuming its viability as a theory or framework for addressing those issues. But even to those who doubt the theory's viability, it can serve as a case study for the ways in which core issues of contemporary physics transcend our traditional understanding both of what we should expect from a physical theory and how physics works as a discipline.

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