UNDERDETERMINATION AND THEORY SUCCESSION FROM THE PERSPECTIVE OF STRING THEORY

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This article investigates the implications of string theory for the conception of scientific theory confirmation. The classical understanding of theory confirmation is based on the assumption that scientific theory building is underdetermined by the available empirical data. Several arguments are presented, which suggest a devaluation of this 'principle of scientific underdetermination' in the context of string theory. An altered conception of scientific progress emerges, that is not based on the notion of theory succession.

1: The case for a philosophy of string theory

String theory is an attempt to provide a unified description of all known physical forces. It replaces the point-like elementary particles of traditional particle physics by extended objects, the so-called strings. This replacement opens an escape route from the problems of non-renormalizability, which have marred all prior attempts to unify quantum field theory with gravitation. The seemingly innocent step from point particles to strings triggers a complex web of mathematical implications, the investigation of which has driven the dynamic evolution of string theory during the three decades since its invention.[1]

Despite its prominent role in contemporary particle physics, string theory to date has not attracted much attention in philosophy of science.[2] This fact can be partly explained by the theory's high mathematical complexity, which renders it rather inaccessible to the non-specialist. Beyond that pragmatic point, however, two arguments seem to suggest a wait-and-see attitude towards the theory's scientific relevance in the eyes of many philosophers of science.

First, the fact that string theory has not been corroborated by any direct empirical evidence thus far seems to render it a mere theoretical speculation. This judgement is apparently supported by the existence of alternative approaches within the field of quantum gravity, which investigate the reconciliation of quantum physics and gravity without relying on the string theoretical approach. (See e.g. [Rovelli 1998].)

Second, string theory at present is a highly incomplete theory. Many of its central aspects have not yet been fully understood. String theoretical research up to now has not reached the phase of specific quantitative calculations of phenomenological predictions, but is still concerned with elementary investigations into the theory's structural foundations.

The conjunction of both arguments may be taken to imply that it is at present too early for a meaningful philosophical analysis of string theory. For a number of reasons, however, this conclusion is unsatisfactory.

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[1] I have offered a slightly more extensive sketch of string theory in [Dawid 2003]. Standard textbooks on the subject are [Polchinski 1998] and [Green, Schwarz & Witten 1987]. A popular introduction is [Greene 1999].

[2] Some of the rare examples of philosophical reflections on string theory are [Weingard 1989], [Butterfield & Isham 2001] and [Hedrich 2002].

Doubts about a philosophical wait-and-see attitude towards string theory first arise from the strong position the theory holds in contemporary theoretical physics. Since 1984, when an important theoretical breakthrough placed string physics within the mainstream of physical research [Green & Schwarz 1984], it can be called the most dynamic field of particle physics. For many years now, the string community has been one of the largest communities in all of theoretical physics and has produced the majority of the field's top-cited papers. Moreover, string theory exerts a strong influence on adjacent fields. Contemporary elementary particle physics model building is dominated by concepts which are either directly inspired by string theory, like the concept of large extra dimensions, or, like supersymmetry, gain authority from the claim that they are implied by string theory. Many recent cosmological models are also based on string theoretical ideas. The fact that an entirely unconfirmed speculative idea can assume such a prominent position in a mature scientific field is quite astonishing.

The current status of string theory looks even more remarkable when one considers the theory's future prospects: today, about 30 years after its creation, string theory still lacks any realistic prospect of becoming experimentally testable. The characteristic experimental signatures of string theory would become observable at the scale of the string length, which, according to standard conceptions, lies many orders of magnitude beyond the reach of all experiments imaginable today.[3] String theorists might easily spend their next 30 years without any experimental support as well. On a purely theoretical level, the situation is not much different. The theoretical difficulties that stand between the string theorists and a full understanding of their theory are too great to even estimate their size. No one can reasonably predict whether these difficulties will be overcome in the foreseeable future to make string theory a mature and fully calculable theory. On the other hand, however, there are no indications that the sequence of limited theoretical steps forward which has characterised the research process in string theory up to now will be unable to sustain the dynamics of string theoretical evolution in the future. The philosopher of science who suggests postponing a philosophical analysis of string theory until it has become a mature and experimentally tested theory therefore takes the risk of neglecting a dynamic and highly influential field of science for many decades to come.

Finally, it is interesting to note how string physicists themselves judge their theory's status. Though they certainly acknowledge theoretical incompleteness and the lack of empirical evidence as deplorable obstacles, the majority of string physicists believe that the purely theoretical arguments found within string theory justify the claim that the theory constitutes an important step towards a deeper understanding of nature. Like many other theories, string theory underwent a first phase during which it was considered a mere speculation, before it acquired the status of a well-established research field. Remarkably, however, this change of status was not brought about by experimental confirmation, but by the solution of some crucial theoretical problems.

A peculiar situation emerges. While string theory must be called an unconfirmed speculation in terms of the traditional criteria of scientific theory appraisal, it has been treated as a well-established and authoritative theory for quite some time by the community of string theorists and by physicists in related fields. No aspect of this constellation is likely to change in the foreseeable future. The philosopher of science has two options as to how to respond to this situation. Either she takes the current prominence of string theory as an anomalous deviation from the solid scientific path and denies it further significance, or she concludes that scientific progress has led to a sustainable shift of the scientific paradigm at the remote frontiers of fundamental physical research. The size and duration of the 'string-phenomenon'

[3] Things might change only if the speculations about large extra dimensions (e.g. [Antoniadis et al. 1998]) turn out to be correct. The coception of large extra dimensions takes the compactified extra dimensions of string theory to be quite large (up to a millimetre) but accessible only to gravitation. This scenario would allow the string scale to be sufficiently low for being testable by future collider experiments.

render the first option rather implausible. The present work will demonstrate that several characteristic properties of string theory enhance the plausibility of the alternative conclusion.

The paper is divided into five sections. After the presentation of the crucial concept of scientific underdetermination in section 2, sections 3 and 4 give arguments for a devaluation of scientific underdetermination in the context of string theory. A modified understanding of theory confirmation and theory succession follows from these considerations and eventually offers a new perspective on the present status of string theory. Section 5 concludes by putting the suggested philosophical shift into a wider perspective.

2: Scientific Underdetermination

The string theorist's self-confidence distinguishes her notably from the exponents of other speculations in modern physics. Empirically uncorroborated models have always played an important role in physics. Particle physics today deals with a number of speculations such as grand unified theories, dynamical electroweak symmetry breaking or large extra dimensions. Cosmology also comprises a wide range of speculative models. In all those cases, scientists develop educated guesses about the likelihood of the concept's future success by assessing the amount of indirect empirical support,[4] available alternatives, the concept's inner coherence and potential theoretical power, its simplicity, aesthetic attractiveness, etc. Based on these arguments, some speculations are considered instructive but unlikely; others are given a good chance to be relevant for the description of nature. In none of the mentioned cases, however, would philosophers of science have fundamental problems in agreeing with the respective specialists on the trustworthiness of the corresponding theory. The specialists' judgements remain based on the time-honoured principle of the pre-eminence of direct experimental evidence for scientific theory confirmation: as long as a scientific theory is not supported by direct empirical evidence, it cannot acquire the status of a well established and well confirmed theory.

String theorists deviate markedly from this path. Based on entirely theoretical arguments, they have developed a degree of trust in the viability of their approach and its crucial importance for a deeper understanding of nature that goes far beyond what a philosopher of science who bases her conception of theory evaluation on an analysis of more traditional scientific theories would consider justifiable without direct empirical confirmation[5]. This puts string theoretical self-esteem at variance not only with the standards of philosophy of science but also with the judgement of physicists in more traditional fields. Physicists who are used to thinking within the standard scientific categories of empirical confirmation and have not been exposed to the internal theoretical argumentation of string physics often cannot follow the string community in their assessment of string theory's status. Anyone in a position to witness the internal view on string theory from within the string

[4] The notion "indirect empirical support for a theory" denotes empirical data that does not represent causal effects of microphysical objects or structures which are distinctively predicted by that theory, but rather finds a better or more consistent explanation in that theory than in available alternative theories. The fact that the renormalisation group running of the measured gauge couplings provides one unified coupling at a certain scale if calculated in the framework of a supersymmetric gauge theory would be a typical example of indirect empirical support for supersymmetric grand unified theories. The observed values for the gauge couplings do not require the posit of supersymmetry or grand unification to be theoretically reproduced. Supersymmetric grand unification, however, would provide a convincing explanation of a quantitative aspect of the gauge coupling values that remains otherwise unexplained. To get direct empirical evidence for supersymmetry or grand unification, one would have to find characteristic signatures (causal effects) of the particles predicted by these theories.

[5] This naturally also applies to those concepts which are necessarily implied by string theory, e. g. supersymmetry.

community as well as the external view of physicists from unrelated fields will find the difference striking.

An analysis of the motivations for string theorists' self confidence without experimental backing requires a closer look at the traditional scientific understanding of theory confirmation. Why do scientists focus on direct empirical theory confirmation?

If a scientist constructs a theory that a) fits the available data and b) predicts new phenomena which have not yet been observed, her trust in the actual existence of the newly predicted phenomena is restrained by one crucial consideration: Other, so far unknown scientific theories may exist, which fit the present data equally well but predict different new phenomena. In other words, scientific theory building must be expected to be significantly underdetermined by the currently available empirical data.

The 'scientific underdetermination principle', as I will call the principle behind this expectation, has to be distinguished from two types of the underdetermination principle which figure most prominently in philosophical discourse. Underdetermination as understood by [Quine 1970] refers to all possible empirical evidence and asserts the existence of logically incompatible, but empirically equivalent theories.[6] Humean underdetermination, on the other hand, refers to the current empirical status quo and asserts that theories about future observations are underdetermined by the presently available data. Scientific underdetermination falls into the second category but has a far more specific agenda than its Humean counterpart.

Hume establishes the underdetermination of theory by experiment at the level of logical possibility without any additional assumptions. The scientist, however, takes induction for granted and presupposes the viability of the scientific method. Based on these assumptions, she feels confident in relying on the predictions of well-established scientific theories in spite of Hume's argument. Arbitrarily chosen exemplifications of Humean underdetermination which are based on a violation of induction and assume ad hoc lapses or changes of natural laws or the accidental character of significant empirical regularities are not considered to be serious scientific alternatives.[7] They do not bother the scientist who assesses the viability of some theoretical prediction.

Scientific underdetermination addresses the freedom of theory choice within the limits of scientific thinking. The claim of scientific underdetermination in a certain field at a given time asserts that it would be possible to build several or many distinct theories which qualify as scientific and fit the empirical data available in that field at the given time. Since these alternative theories are merely required to coincide with respect to the presently available data, they may well offer different predictions of future empirical data which can be tested by future experiments. It is scientific underdetermination due to the existence of such empirically distinguishable theories which will be of primary interest in the following analysis.

The assumption of scientific underdetermination constitutes a pivotal element of the modern conception of scientific progress. If science proceeds, as emphasised e.g. by [Kuhn 1962] or [Laudan 1981], via a succession of conceptually different theories, all future theories in that sequence must be alternative theories which fit the present data and therefore

[6] Much recent philosophical thinking about underdetermination falls into this category. Besides [Quine 1970] and his critics (e.g. [Laudan & Leplin 1991]), examples for such a use of underdetermination are [van Fraassen 1980] or [Sklar 2000].

[7] An example of a theory which fails that test would be the claim that the new billard ball will penetrate the cushion because it does not obey conventional natural laws. Goodman's 'grue-hypothesis', though based on an induction principle itself, would be another example of a theory that would not be accepted as scientific without specific supporting arguments. Precise criteria which distinguish between scientific theories and unscientific schemes are notoriously difficult to define and may change with time.

exemplify scientific underdetermination[8]. Theoretical progress without scientific underdetermination, to the contrary, would have to be entirely accumulative.[9]

Based on scientific underdetermination, two types of theories can be roughly distinguished. Well-established scientific theories are those whose distinctive predictions[10] have been experimentally well tested and confirmed in a certain regime. The general viability of the theory's predictions in that regime is considered a matter of inductive inference.[11] Speculative theories, on the other hand, are those whose distinctive predictions have not yet been experimentally confirmed. Even if a speculative theory fits the currently available experimental data, its distinctive predictions might well be false due to the scientific underdetermination principle.

Following these definitions, string theory clearly falls into the category of speculations. Actually, string theory looks even more speculative than the examples mentioned at the beginning of this section, since it has not proved its ability to reproduce the currently available particle physics data. The fact that string theory is nevertheless treated like a well-established theory by its exponents seems to suggest an implicit devaluation of the principle of scientific underdetermination. The validity of this assessment can only be substantiated by a philosophical analysis of the theory itself and of the scientific arguments which have led to its construction. The latter are of crucial importance for the string physicists' trust in their theory and shall be considered first.

3: Contextual Reasons for String Theorists' Self-Confidence

The three reasons for string theorists' trust in their theory which will be presented in this section are based on general characteristics of the research process that leads towards string theory and do not rely on any specific properties of the theory itself.[12] All three reasons have precursors in earlier scientific theories but arguably appear in string theory in a particularly strong form. In the end it will become evident that all three points are closely related to the question of scientific underdetermination.

a) The plain argument of no choice: String theorists tend to believe that their theory is the only viable option for constructing a unified theory of elementary particle interactions and gravity. The various forms of canonical quantum gravity[13], which do not refer to string theory, try to reconcile gravitation with the elementary principles of quantum mechanics and

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[8] It should be emphasised that the last statement would lack distinctive meaning if based on the most radical reading of Kuhn's incommensurability thesis. The statement relies on the assumption that adherents of the successive theories referred to can find a consensus with respect to the scientific characterisation of the collected empirical data. In the context of particle physics, which shall be analysed in the present work, this assumption clearly seems justified as adherents of all existing particle physical theories share the same understanding of the implications of specific particle experiments for theory building.

[9] The scientific underdetermination principle is closely related to the pessimistic meta-induction of [Putnam 1978] and [Laudan 1981] but does not share the latter's anti-realist claims. It reflects an ontologically neutral assessment of the status of scientific theories that is fairly uncontroversial in recent science and philosophy of science.

[10] I.e. predictions, whose experimental confirmation would be direct empirical support for the novel theoretical claims of the theory.

[11] A scientist's formulation of the notion of well-established theories can be found for example in [Weinberg 2001].

[12] The given arguments are an attempt to give a structured account of what is 'common lore' among string physicists. It is difficult to pinpoint a 'locus classicus' for each argument. One can find a combination of all three arguments in chapter 1 of [Polchinski 1998] and in [Polchinski 1999]. Arguments a) and c) appear in [Greene 1999] (see e.g. chapter 1).

[13] The currently most influential example is loop quantum gravity ([Rovelli & Smolin 1990], [Rovelli 1998].

therefore discuss the question of unification at an entirely different level than string theory. The latter stands in the tradition of the standard model of particle physics that was developed in the 1960s and 70s as a theory of all microscopic interactions and is based on pivotal concepts such as non-abelian gauge theory, spontaneous symmetry breaking, and renormalizability. String theory's goal is to reconcile gravity with these advanced and successful concepts of contemporary particle physics and therefore to provide a truly unified description of all natural forces. In this endeavour, the traditional investigations of canonical quantum gravity do not constitute alternatives, which leaves string theory as the only available way to go.[14] That is not to deny the relevance of the investigations of canonical quantum gravity. String theorists would just argue that, once the viable results of canonical quantum gravity are put into the context of contemporary particle physics, they will blend into the string theory research program.

The crucial problem for a unification of point-particle physics and gravity is the non-renormalizability of quantum gravity within the traditional field-theoretical framework. As long as this obstacle remains, quantum gravity cannot be considered viable at the Planck scale, the scale where the gravitational coupling becomes strong. Early attempts to solve this problem applied the traditional methods of gauge field theory and tried to deploy symmetries to cancel the dangerous infinities. For some time the concept of supergravity that utilizes supersymmetry looked like a promising candidate to carry out this task, but eventually the appeal to symmetry principles was understood to be insufficient. As it turns out, the remaining theoretical options are quite limited. One might venture into giving up some of the most fundamental pillars of today's physics like locality, causality, unitarity, or continuity. Ideas in these directions have been considered, but did not lead to any convincing theoretical schemes. If one wants to retain these most fundamental principles, then, according to a wide consensus, there remains only one way to go: to drop the idea of point particles, which univocally leads to string theory. (see e.g. [Polchinski 1998] and [Polchinski 1999]). It may thus be said that string theory is the only option for finding a unification of all interactions within the framework of the long standing fundamental principles of physics.

Naturally, this claim of 'no choice' will not remain uncontested: who can rule out that one of the most fundamental principles of physics indeed has to be jettisoned at this stage to describe nature correctly and that string theory is nothing more than a delusive 'easy' way out that just does not accord with nature? An immediate 'soft' answer to this question is provided by an argument that plays an important background role for the string theorists' self-confidence.[15]

b) The example of the particle physics standard model: Most string theorists, at least those of the first generation, are mainly educated within traditional particle physics and their scientific perspective is based on the tremendous success of the standard model. The latter

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[14] There also exists a tradition of thought that questions the necessity of quantizing gravity in a theory that gives a coherent description of quantum physics and gravitation. (Recent works are [Wüthrich 2004] and [Mattingly 2005].) Though some ideas concerning quantum theories of gravitation without quantized gravity have been put forward, as yet none of them has been formulated in any detail, however. Like canonical quantum gravity, those considerations at the present point address the reconciliation of gravity with basic quantum physics but do not offer concepts for a coherent integration of gravity and advanced particle physics.

[15] The history of science contains earlier claims of univocal inference from observation to the theoretical scheme. Newton's 'deduction from the phenomena' has been taken up in [Norton 1993 & 1994], while [Worrall 2000] has emphasized that deduction's dependence on prior assumptions. Newton's claim is based on the assertion of an immediate and intuitively comprehensible connection between observation and theoretical explanation. Compared to the Newton, the situation in string theory has decidedly shifted towards the assertion of a radical limitedness of options for mathematically consistent theory construction while the intuitive aspect of Newton's argument has been dropped. Whether this shift, in itself, enhances the authority of the string theoretical claim of no choice may be a matter of dispute. The following sections, however, will demonstrate that the string theoretical claim can be embedded in an entirely new and more powerful argumentative framework.

was created based on entirely theoretical arguments in order to solve a technical problem (how to make nuclear interactions renormalizable) and it predicted a whole new world of new particle phenomena without any initial direct empirical confirmation. In this respect the standard model is a direct precursor of string theory and string theorists view their endeavour as a natural continuation of the successful particle physics research program. The fact that purely theoretical initial arguments led to the highly ambitious standard model theory that eventually was so impressively confirmed by experiment conveys a specific message to particle physicists: if you knock on all doors you can think of and precisely one of them opens, the chances are good that you are on the right track. Scientists working on quantum gravity have thought about all currently conceivable options, including those which drop fundamental physical principles. The fact that exactly one approach has gained momentum suggests that the principles of theory selection which have been successfully applied during the development of the standard model are still working.

Now, in further analogy with the standard model case, it is important to note that the theoretical success of string theory by no means implies the eternal survival of today's most basic physical postulates. The standard model's success did not exclude (and its creators did not intend to exclude) that more fundamental modifications of physical theory might also be able to cure the problem of the renormalizability of nuclear interactions. For example, instead of relying on gauge symmetries, one could have ventured already in the 1960s to make the step towards extended elementary particles, a step that was later successfully realised by string theory. To believe in the standard model in the early 1970s merely meant assuming that any more far-reaching change of physical postulates, in as much as it would be successful, would itself imply the standard model predictions. This assumption has been vindicated by the subsequent development of physics. Extended elementary particles have emerged as a (potential) next scientific step but it turned out that their introduction, if consistently done, implies gauge theory as well.[16]

In the same vein, the string theorist expects that more fundamental changes of physical principles, if they are required, would be consistent only in a string theoretical context. A body of explicit analysis supports this expectation and may be exemplified by an argument in [Polchinski 1999]. Polchinski starts with an innocent looking posit of a position-position uncertainty relation instead of the posit of extended elementary objects and he shows that the efforts to make that idea work eventually imply the very string theory he had set out to circumvent.

While the example of the highly successful standard model can strengthen confidence in the validity of string theory, it can hardly exclude string theory's failure. The next argument will indicate that such failure would at any rate leave a lot to be explained.

c) Internal coherence: It is widely held that a truly convincing confirmation of a scientific theory must be based on those of the theory's achievements which had not been foreseen at the time of its construction. Normally, this refers to phenomenological predictions which are later confirmed by experiment. However, there is an alternative: Sometimes, the introduction of a new theoretical principle surprisingly provides a more coherent theoretical picture after the principle's theoretical implications have been more fully understood. This kind of theoretical corroboration plays an important role in the case of string theory. Once the basic postulate has been stated, one observes a long sequence of unexpected deeper explanations of seemingly unconnected facts or theoretical concepts.

String theory posits nothing more than the extendedness of elementary particles. Its initial motivation was to cure the infinity problems of quantum field theories that include

[16] String theory can only be consistently formulated in a way that makes its low energy effective theory a gauge theory. (See e.g. [Polchinski 1998], chapter 12.)

gravity.[17] Remarkably, string theory does not just provide a promising framework for quantum gravity but actually implies the existence of gravitation. The gravitational field necessarily emerges as an oscillation mode of the string. String theory also implies that its low energy effective theory must be a Yang Mills gauge theory, and it provides the basis for possible explanations of the unification of gauge couplings at the GUT-scale. The posit that was introduced as a means of joining two distinct and fairly complex theories, which had themselves been introduced due to specific empirical evidence, thus turns out not just to join them but to imply them.

String theory also puts into a coherent perspective the concept of supersymmetry, a symmetry between particles of different spin based on an intertwining of the inner symmetries so crucial in gauge theories and the Lorentz symmetries. Initially, interest in this concept was motivated primarily by the abstract mathematical question whether any generalisation of the classical symmetry groups was possible. As it turns out, supersymmetry is the maximal consistent solution in this respect. Soon after the construction of the first supersymmetric toy-model, it became clear that a formulation of supersymmetry as a gauge-symmetry (=local supersymmetry or supergravity) had the potential to provide a fuller understanding of the particle character of gravity. (The particle corresponding to the gravitational force in a field-theoretical formulation of gravitation, the so-called graviton, turned out to be the superpartner of the gauge particle of supersymmetry.) In the context of string theory, on the other hand, it had been realised early on that a string theory that involves fermions must necessarily be locally supersymmetric.[18] The question of the maximal symmetry group, the quest to integrate the graviton naturally into the field theoretical particle structure, and the attempts to formulate a consistent theory of extended elementary objects thus miraculously blend into one coherent whole.

A problem that arises when general relativity goes quantum is black hole entropy. The necessity to attribute an entropy proportional to the area of its event horizon to the black hole in order to preserve the global viability of the laws of thermodynamics was already understood in the 1970s. The area law of black hole entropy was merely an *ad hoc* posit, however, lacking any deeper structural understanding. In the 1990s it turned out that some special cases of supersymmetric black holes allow for a string theoretical description where the black hole entropy can be understood in terms of the number of degrees of freedom of the string theoretical system. [Strominger & Vafa 1996] Thus, string physics provides a structural understanding of black hole entropy.

All of these explanations represent the extendedness of particles as a feature that seems intricately linked with the phenomenon of gravity and much more adequate than the idea of point-particles for a coherent overall understanding of the interface between gravity and microscopic interactions. The subtle coherence of the implications of the extendedness of elementary objects could not have been foreseen at the time when the principle was first suggested. It would look like a miracle if all these instances of delicate coherence arose in the context of a principle that was entirely misguided.[19]

[17] To be precise, this was the initial motivation to deploy string theory as a theory of all physical interactions. String theory actually had been invented in 1968 as a candidate for a description of strong interactions [Veneziano 1968]. Only after it had turned out to fail in that context, did it find its ‘true purpose’ as a universal theory in 1974 [Scherk & Schwarz 1974].

[18] World sheet supersymmetry of a string that includes fermions was discovered by [Gervais & Sarita 1971]. A string theory that shows local target space supersymmetry was finally formulated by [Green & Schwarz 1984].

[19] There do exist cases in the history of science where the inference from a concept’s success to its viability was invalidated by the fact that just one aspect of the concept was responsible for the success while important parts of the concept were misguided. A prominent example would be the ether theories whose success was based on the viability of the wave equation. In the case of string theory it is difficult to imagine anything of that kind, since the concept is based on one simple and entirely structural posit which would seem impossible to reduce without taking it back altogether.

It is difficult to assess at this stage to what extent it is justified to base serious confidence in the viability of string theory's phenomenological predictions on the presented type of no miracles argument. The problem is that one cannot rely on past experience. Though exemplifications of a theory's unexpected power to provide theoretical coherence do exist in earlier scientific research, arguably they have never been so strong while experimental confirmation remained entirely absent. A thorough comparison of the argument of internal coherence in string theory with similar lines of arguments in other fields would be helpful for getting a better grasp of the situation, but lies beyond the scope of the present article.

Each one of the three presented reasons for string theorists' self confidence can be interpreted in terms of a devaluation of the scientific underdetermination principle. The argument of 'no choice' suggests that the existence of alternative scientifically satisfactory theories is a less natural assumption in the case of string theory than in prior physical contexts. It therefore works directly against the viability of the scientific underdetermination principle. The other two arguments do not directly affect the principle's viability, but question its importance for theory evaluation. The success of the particle physics research program shows that consistency arguments in particle physics can lead reliably towards correct empirical predictions despite the underdetermination argument. String theory's tendency to create unexpected internal coherence provides a specific argument for the theory's viability that circumvents considerations about scientific underdetermination.

While the arguments discussed so far have been based on characteristics of the research process that leads towards string theory, the following section will show that arguments based on specific properties of string theory work in a very similar way against the principle of scientific underdetermination. These arguments naturally rely on the precondition that string theory is a valid theory and thus are circular if used in an isolated way. Taken in conjunction with the previous considerations, however, which strengthen the status of purely theoretical arguments for string theory's viability, they can make the overall case stronger and more coherent.

4: Specific String Theoretical Arguments

The following question can be asked: if string theory turned out to be valid and successful according to present scientific criteria, would this carry any implications for the validity of the underdetermination principle? Two properties of string theory are crucial for answering this question: string theory a) is 'structurally unique' and b) gives reason to be understood as a final theory.

a) Structural uniqueness: String theory's basic postulates uniquely determine the theory's structure. All prior physical theories have free parameters which can be tuned in order to fit the quantitative specifics of the empirical evidence. Special relativity does not specify the velocity of light, neither Newtonian mechanics nor general relativity specify the size of the gravitational constant, and Maxwell's electromagnetism and quantum electrodynamics do not fix the size of the elementary charge and the fine structure constant, respectively.[20] The

[20] For the sake of precision, this series of statements needs some specification. Some of the abovementioned parameters are dimensionful parameters. Within the respective theories, these parameters' specification thus can be understood as a matter of definition. However, the embedding of the respective theories within our observed world requires a comparison of the theories' fundamental constants with the scales of the everyday world. It is in the context of this comparison that free dimensionless parameters arise whose determination cannot be understood as a matter of definition. Complex theories like quantum theories or general relativity with a cosmological constant relate different length scales or different interactions and thus contain dimensionless free

standard model of particle physics, the current joint description of all nuclear interactions, involves more than 20 free parameters such as mass terms, coupling constants, and mixing angles which have to be determined experimentally. String theory is the first physical theory that does not contain or allow any free parameters. (See e.g. [Polchinski 1998], chapter 1.) According to string theory, all quantitative characteristics of the world stem from purely structural characteristics of the string and are a result of string theory's complex dynamics.

A similar statement can be made concerning the spectrum of possible models of the theory, which are defined by various discrete characteristics such as symmetry structure, number of particle generations, number of spacetime dimensions, etc.[21] Under very basic conditions such as the existence of fermions and more than one spatial dimension, string theory seems to allow only one model. Until the early 1990s it was believed that five different consistent superstring models[22] existed which differed by symmetry structure. The discovery of the important role of string dualities[23], however, led to the well-founded conjecture that these five models merely constituted different formulations of the same theoretical structure [Witten 1995, Witten & Horava 1996][24]. Today it is generally assumed that there is exactly one way to build a superstring theory. This situation once again distinguishes string theory from most traditional theories which allow a considerable amount of structural choice within their fundamental theoretical framework. To take the example of a theory that, like string theory, provides the basis for the description of a large number of different phenomena: gauge field theory is highly flexible in accommodating all those microscopic phenomena which happen to show up in an experiment. Theoretical arguments do not predetermine the gauge symmetry structure and the number of particle generations and therefore allow a nearly unlimited number of models with different interaction structure and particle content.

I will refer to the fact that string theory knows neither free parameters, nor a variety of models, with the term 'structural uniqueness'. The structural uniqueness of the fundamental theory has to be clearly distinguished from the question of the string theory ground state. Consistency arguments imply that superstring theory must live in ten space-time dimensions. All dimensions except the four visible ones are thought to be 'compactified', i.e. each of them runs back into itself after a minimal distance like a tiny cylinder surface. The compactification of the six extra dimensions is a matter of the theory's dynamics and its outcome constitutes the ground state of the theory. If the physical equations allowed several or many energetically equivalent ground states, the choice of the actual ground state would be a matter of the statistical quantum dynamics of the early string-universe and could not be theoretically

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parameters within their own theoretical framework. A theory like string theory that gives a joint description of all fundamental phenomena by nature does not require an embedding of its characteristic scales into some 'rest' of the world that is not covered by the theory. In its case the question of free parameters therefore is reduced to the intra-theoretical situation.

[21] The term 'model' is deployed in various ways in physics and philosophy of science. In this article, the term is used in the way it appears in particle physics in notions like 'standard model' or 'model building'. It refers to the specific theoretical constructions which are possible within some theoretical framework, i.e. a fundamental set of physical postulates. The various models of a theory are not ontologically equivalent and have different empirical implications. The distinction between 'theory' and 'model' emphasizes the important difference between the fundamental conceptive framework of a theory and the specific choices made when selecting the theory's precise form. (My use of the term 'model', though prevalent in particle physics in general, does not quite match string theoretical terminology. String theorists speak of the various string theories - models in my terminology - as well as of string theory as the overall scheme behind these models. Such equivocal use of the term 'theory', however, would have added unnecessary confusion to the present discussion.)

[22] Superstring models are string-theoretical models which include fermions. Such models must be supersymmetric, i.e. they must obey a specific symmetry between fermions and bosons to be consistent, which leads to the name 'superstring'.

[23] String dualites play a very important role in string physics. If a model is dual to another model, this means that it represents a description of the very same physical situation as the other model with some inverted characteristic parameter, e.g. the string coupling constant or the compactification radius of a closed dimension. It was understood in the mid 1990s that all superstring models are connected by a web of dualities.

[24] For a popular account, see [Greene 1999].

predicted. Since there are enormous numbers of mathematically imaginable compactification patterns for the six extra dimensions, string theory would require some physical vacuum selection mechanism that reduces the number of physically possible ground states to a relatively small number or one in order to retain the theory's low energy predictive power.

It has always been a natural goal of string theoretical research to establish the theory's predictive power at low energies. However, the dynamics of string theory is far too little understood today to allow any reliable judgement whether a vacuum selection mechanism exists in the theory, and if so, what it would look like. Current assessments of the situation range from (i) the traditional stance that one can expect enough so-far unexplored structure to be confident that a vacuum selection mechanism will show up, through (ii) attempts to deal with the status quo statistically without anticipating any final answer to the question [Douglas 2003], to (iii) suggestions to drop the idea of a vacuum selection mechanism altogether [Susskind 2003]. The following analysis will address the philosophical implications of string theory's more favourable prospective scenario (i).

Let us imagine that a highly predictive[25] structurally unique theory is phenomenologically viable at some stage. How would structural uniqueness affect the status of the scientific underdetermination principle? The principle of scientific underdetermination acquires its plausibility based on a specific understanding of the scientific process. According to this understanding, the scientist builds theoretical structures, which reflect the regularities observed in nature up to some precision, and tunes the structures' free parameters to fit the quantitative details of observation. The successful construction of a suitable theory for a significant and repeatedly observable regularity that characterises the world is assumed to be just a matter of the scientist's creativity and diligence. If it is always possible to find one suitable scientific theory however, it seems natural to assume that there can be others as well. There may always exist different choices of theoretical structure that have coinciding empirical implications up to some precision in the observed regime if their respective free parameters are fixed accordingly. The principle of underdetermination follows from this.

If one considers only the class of highly predictive structurally unique theories, the situation is entirely different. Compared to the general case of all possible scientific theories, the chances for being able to describe a specific empirical data set with a highly predictive structurally unique theory are strongly reduced for two reasons. First, a highly predictive theory that does not allow any freedom of choosing parameter values or modifying qualitative characteristics in order to fit the empirical data, is compatible with far less sets of empirical data than a conventional theory. Second, the difficulties to come up with structurally unique theories suggest that there are far less structurally unique theories than conventional ones. Actually, the only structurally unique theory known in science today is string theory.

Considering both the generality of the principles which define a theory like string theory and the vast range of possible phenomenological regularities and parameter values, it is most natural to assume that highly predictive structurally unique theories, if found at all, can only be found for a very small subset of points within the huge space of all possible regularities. Since there is no reason for expecting that different structurally unique theories, each of them based on a different set of fundamental physical principles, have a tendency to give similar empirical predictions, the notion that several highly predictive structurally unique theories have empirical implications which are nearly, but not precisely, equal must then be considered highly improbable. The principle of scientific underdetermination, which looks convincing if applied to the set of all scientific theories, therefore lacks plausibility if applied to the set of highly predictive structurally unique theories.

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[25] 'Highly predictive' in this context means roughly that the number of physically possible ground states of the theory is lower than the number of possible values of some observable that can, within reasonable boundaries, be distinguished by a precision measurement.

According to the previous paragraphs, it is plausible to expect that none of the alternatives which might arise to an empirically confirmed highly predictive and structurally unique theory would be structurally unique and highly predictive itself. Such alternatives then could be of two different kinds. First, an alternative theory could be structurally unique with respect to all parameters and theoretical features relevant for the description of the phenomena which had been accounted for by the predecessor theory while introducing a free parameter that is relevant only for phenomena unknown to the predecessor theory. Since such a free parameter would not enhance its theory's chances of being coherent with the empirical data that was accounted for by the predecessor theory, however, the occurrence of an empirically viable theory of that kind cannot be considered more likely than the occurrence of an alternative highly predictive structurally unique theory. This scenario therefore leads back to the assessment of the likelihood of scientific underdetermination among structurally unique theories.

Second, alternative theories could lack structural uniqueness or high predictiveness with respect to phenomena correctly accounted for by a highly predictive structurally unique theory. The probability of the empirical success of alternative theories of that kind is not constrained by the considerations of the previous paragraphs. However, a different kind of argument can be raised against the assumption that such alternatives could be scientifically successful: If a structurally unique and highly predictive theory were able to reproduce the available empirical data at some stage, it would be implausible to expect that theory to be replaced later on by a theory that is not structurally unique or not highly predictive in the same regime. The fact that a highly predictive structurally unique theory had been successful at all would turn into a miracle if such a replacement occurred. Why should a highly predictive theory be able to reproduce the empirical data without any tuning of parameters at some stage if it eventually has to give way to a theory that either requires the tuning of parameters or lacks comparable predictive force for other reasons?[26] The question of the existence of alternative theories that are not structurally unique thus loses its crucial importance for the understanding of theory succession.

Summing up the previous arguments, a highly predictive structurally unique theory that fits the empirical data at some stage can neither be expected to be replaced by another structurally unique theory nor by a theory that does not belong to that class. This suggests the termination of the progressing sequence of scientific theories. It must be expected that a highly predictive structurally unique theory that fits the present experimental data should describe all future experiments correctly as well. The pessimistic meta-induction thus fails and one must feel compelled to call any empirically successful structurally unique theory a serious candidate for a final theory.[27]

This conclusion has an interesting further implication. If a highly predictive structurally unique theory were able to reproduce the empirical data at any energy scale, this could be taken as a strong confirmation of that theory's characteristic predictions, even if those predictions had not been tested themselves and the available data could also be reproduced by other theories. In the case of conventional theories, the inference from a

[26] The basic argument applied here is not specific to theories without free parameters. If some theory explains the quantitative relation between two of its parameters, any viable successor theory must be expected to be able to explain that relation as well. Otherwise, the principle that a theory should be able to explain its predecessor's success would be violated. In the case of a structurally unique theory, all quantitative relations between its parameters are fixed. This means that a successor theory which has a free parameter that is relevant for the structuring of phenomena described by the predecessor theory necessarily runs into the stated problem.

[27] Note that the refutation of the pessimistic meta-induction is NOT based on a proof that no successor theory can be found. The argument rather works at the same level as the pessimistic meta-induction itself: According to the pessimistic meta-induction it must be reasonably expected that our present theories will be superseded, even though that cannot be proved now. If an empirically confirmed structurally unique theory existed, this situation would be inverted. The reasonable expectation would be that the structurally unique theory represented a final theory, even though that could not be proved.

theory's empirical adequacy at one scale to its viability at another scale was prevented by the scientific underdetermination principle. But in the context of highly predictive structural uniqueness, that principle looses its pivotal role and the inference becomes viable as a statement about the most reasonable expectation. String theory might some day show the significance of this consideration: if it turned out that string theory delivered specific low energy predictions which fit all presently known phenomenological data in particle physics within the given experimental limits of accuracy (just like the particle physics standard model does today), this would obviously not constitute experimental confirmation of strings at their own characteristic scale. Nevertheless, even the staunchest supporter of the predominance of experimental confirmation would be obliged to attribute a very high probability to the validity of string theory's high energy predictions.

b) The final theory claim: The property of structural uniqueness suggests that string theory, if valid and predictive at low energies, should be taken as a 'final theory' that will not be superseded by a more accurate or more far-reaching physical theory later on. Interestingly, similar 'final theory claims' occur in two other contexts in string theory without having to rely on the theory's low energy predictive power. To begin with, there is a simple historical point. String theory is the first physical theory that seriously claims to provide a fully unified description of all known elementary physical phenomena.[28] Therefore it is the first theory that allows a final theory claim if full unification of all fundamental phenomena is taken to be a goal of science.[29] In this light, it looks natural that a structurally unique theory arises precisely at the stage when the entire range of observed phenomena is being covered by one theory.

A more powerful final theory claim is related to an interesting implication of string dualities. The string world shows a remarkable tendency to link seemingly different string scenarios by so-called duality relations. Two dual theories (models) are exactly equivalent concerning their observational signatures, though they are constructed quite differently and may involve different types of elementary objects and different topological scenarios. The kind of duality relation relevant in our present context is T-duality. String theory, as has been mentioned above, suggests the existence of compactified dimensions. Closed strings can be wrapped around compactified dimensions like a closed rubber band around a cylinder and they can move along compactified dimensions. Due to the basic principles of quantum mechanics, momenta along closed dimensions can only assume certain discrete quantized eigenvalues. Thus, two basic discrete numbers exist which characterise the state of a closed string in a compactified dimension: the number of times the string is wrapped around this dimension, and the eigenvalue of its momentum state in that very same dimension.[30] Now, T-duality asserts that a model where a string with characteristic length[31] l is wrapped n times around a dimension with radius R and has momentum eigenvalue m is dual to a model where a string is wrapped m times around a dimension with radius l^2/R and has momentum eigenvalue n. The two descriptions give identical physics.

This fact can be generalised and eventually implies that all tests of distances smaller than the string length can be understood as tests of correspondingly larger distances as well. Duality thus translates all information below the string length into information above the

[28] The term ‚fully unified description' is used in the sense that all elementary physical phenomena can be deduced from one integrated set of physical principles or assumptions. Classical mechanics and electrodynamics, being based on different physical principles, do not form a fully unified theory in this sense. The standard model, while being an entirely coherent description of all nuclear forces, is no fully unified description of nuclear forces since it introduces distinct gauge groups for strong and electroweak interaction. This lack of unification is viewed by particle physicists as one important reason to venture beyond the standard model (e.g. towards grand unified theories) despite the lack of empirical evidence.

[29] Final theory claims which did not rely on full unification were raised in the past, notably in classical physics at the end of the 19th century.

[30] The two numbers are called 'winding number' and 'Kaluza-Klein level', respectively.

[31] The characteristic string length denotes its length when no energy is being invested to stretch it.

string length, rendering the former fully redundant. An absolute limit is set on attaining new physical information below a certain scale and so formally puts an end to the continuous physical search for new phenomena at ever smaller distance scales (see e.g. [Witten 1996]). String theory implies that one cannot go beyond it by looking closer at nature. The internal structure of the theory thus contains a final theory claim.

The string-theoretical posit of a minimum length must be clearly distinguished from weaker finality assertions which appear in earlier physical theories without justifying a final theory claim. Thus the posit of elementary particles in microphysics generally does not exclude independent new phenomena which require additional theory building; and the absolute speed limit introduced by special relativity does not translate into a finite kinetic energy per particle - any experiment carried out at a finite energy scale therefore leaves room for new physics beyond that scale. String theory is the first theory where a universal limit in microphysics is established and where physics up to that limit could in principle be tested by experiment.

In a traditional scientific context a final theory claim that is based on a specific scientific theory must remain questionable due to the scientific underdetermination principle. The devaluation of scientific underdetermination described in previous sections therefore constitutes a necessary precondition for a truly powerful final theory claim, which, in turn, further weakens underdetermination. Thus the termination of the process of theory succession and the limit to new empirical evidence form a coherent whole.

c) A new conception of scientific progress: Claims of a final theory smack suspiciously of a declaration of the end of science. The current condition of string theory, however, suggests a quite different conclusion. The standard conception of scientific progress takes for granted a significant disparity between experimental search and theoretical fit with respect to their respective time horizon. While the ongoing discovery of new physical phenomena is elevated to an eternally valid principle of scientific research that puts a final empirical inventory (and consequently a final physical theory) forever beyond the grasp of human inquiry, the completion of the specific scientific theories which fit a certain set of phenomenological data is considered a finite and predictable enterprise. The scientists who take on the challenge to create a theory about some phenomena based on some set of principles and assumptions are expected to be able to complete that theory as a coherent and calculable structure (modulo some minor unsolved aspects, perhaps) within a reasonable amount of time. The distinction between the infinite duration of the quest for new physics and the limited creational period of single theories clearly mirrors the reality of traditional scientific research. In the case of string theory, it blocks the appreciation of the genuine novelty of the situation.

As described above, string theory provides a concrete notion of a final theory. Thus, if valid, it reduces the time until we reach a final description of nature to the time we need to complete string theory itself. This step, however, goes along with a vastly extended time horizon for the completion of this one theoretical scheme. It may be helpful at this point to remember the situation four centuries ago, when philosophers like Francis Bacon and René Descartes laid the foundations of the scientific world-view. Bacon as well as Descartes considered the creation of the scientific method itself to be the main achievement on the way towards a correct understanding of the world. The scientific details in their understanding could then be filled in within a lifetime. History has confirmed the immense fertility of the scientific method, but it has also disappointed the early expectations of imminent full enlightenment. The scientific method turned out to be a starting point for many generations of ever deepening research, which, despite its success, did not reach the elusive endpoint of a full description of nature.

The situation in string theory today might bear some resemblance to the old history of science. String theory, by establishing the notion of a final theory, might well prove to be of great significance for our understanding of nature, but might nevertheless disappoint hopes to provide a specific time frame for the fulfilment of its ultimate promise. We are in no position today to assess whether - and, if so, when - a full formulation of string theory will be found, and we have no reason to assume that it will happen anytime soon. The arguments by analogy derived from the examples of earlier theoretical schemes fail because of the significantly different level of complexity of string theory and its nature as a final theory. One might well compare the seemingly never-ending sequence of theoretical problems arising on the way towards a complete understanding of string theory with the sequence of new physical phenomena that characterises traditional physical research. In the same way as the perspective has emerged in the traditional scientific setting that science will always face new phenomena and, therefore, will never reach a final theory, one could now be led to suspect that string theory will always face new theoretical problems and will therefore never become fully mature. String theory thus should not be taken to announce an end of science but rather to represent a new phase of scientific progress. In this new phase, progress in fundamental physics is no longer carried by a sequence of limited, internally fully developed theories, but rather by the discovery of new aspects of one overall theoretical scheme whose general characteristics identify it as a candidate for a final theory, yet whose enormous complexity bars hope of a full understanding in the foreseeable future.

5: Conclusion

A web of coherent arguments has emerged which suggest a reassessment of the classical notion of theory confirmation. A significant devaluation of the principle of scientific underdetermination implies a considerable increase of authority for purely theoretical theory confirmation.[32] At the same time, final theory claims introduce the new conception of a scientific process that is characterized by intra-theoretical progress instead of theory succession. These developments neither imply that we should abandon the quest for empirical confirmation, nor that it is justified to equate the authority of theoretical and empirical confirmation. The status of a merely theoretically confirmed theory will always differ from the status of an empirically well-tested one. However, in the light of the arguments presented, this difference in status should not be seen as a wide rigid chasm, but rather as a gap of variable and reducible width depending on the quality of the web of theoretical arguments.[33]

It is interesting to note that the rapprochement between theoretical and empirical confirmation becomes more pronounced if scientific theory is interpreted realistically. A realist view of scientific theories faces the well known problem that the theoretical evolution and the prospect of theory replacement threaten the long term survival of ontological posits. Thus empirical evidence can never guarantee the viability of a specific realist scenario. Given the arguments against underdetermination derived from string physics, there is no clear reason why a well-founded theoretical confirmation of a theory could not have similar authority for the trustworthiness of some corresponding realist picture as empirical confirmation. New theoretical conceptions (be they based on new observations or new analysis) equally threaten the realist picture in both cases. In addition, it must be taken into account that string theory's claims to be a final theory counter the pessimistic meta-induction and therefore enhance the plausibility of the assumption that some realist interpretation can survive in the long run. In this light, it can be argued that a realist physical scenario developed in the context of string

[32] This, of course, includes indirect empirical support, i.e. those observations which have led to the prior set of theories from which the theoretical scheme in question has been construed.

[33] One might liken the situation to a comparison between first person and third person observation. While the difference in status is indissoluble, a coherent web of information about some observation by others can make me believe in that observation nearly as strongly as if I had made it with my own eyes.

theory based on entirely theoretical arguments might have better prospects than any realist picture based on empirical evidence had at an earlier stage of science.[34]

Clearly, the arguments presented in this paper do not come up to a logical refutation of the traditional appraisal of theory confirmation. A philosopher of science could interpret the analysed characteristics of string theory's structure and evolution in terms of the traditional scientific paradigm without facing any clear contradictions or inconsistencies. The point to be appreciated is the following, however: the construction of the scientific paradigm is itself not a matter of logical deduction, but a matter of plausibility, coherence and success; the assumption of scientific underdetermination and the concept of scientific theory succession are based on the most plausible interpretation of the scientific process witnessed in traditional science. A change of the conception of scientific progress thus does not have to be based on strict logical deduction either. It may well rely – and arguably it should be expected to rely - on a shift of plausibility at the same level of argumentation that implemented the scientific paradigm in the first place. It is the claim of this article that such arguments in fact abound in the context of string theory. Those arguments are based on probability considerations and plausibility assessments but gain force due to their multitude and joint message. Jointly, they suggest that an altered perspective on the conceptions of theory confirmation and theory succession allows a more convincing and more coherent overall understanding of the status of string physics than the traditional picture of the scientific process.

The asserted shifts of the scientific paradigm and philosophical conceptions like structural uniqueness or finality cannot be generalised straightforwardly to other scientific fields; rather, they highlight the widening gap between the characteristics of the vast majority of scientific fields and those of the most fundamental physical theories. The increase of this gap makes it necessary to develop specific philosophical tools to deal with fundamental physics. The emergence of a new philosophical understanding of science at its most fundamental level, however, should put the mechanisms of applied science into a new perspective as well.

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[34] The quest for a realist interpretation of string theory faces some further unusual properties of string physics (see [Dawid 2003]).

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