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Article

Scientific Realism in the Age of String Theory

Richard Dawid
(Institute for Philosophy and Institute Vienna Circle, University of Vienna, Universtitätscampus 2–4, Hof 1, A-1090 Wien, Austria, email: richard.dawid@univie.ac.at)

Abstract: String theory currently is the only viable candidate for a unified description of all known natural forces. This article tries to demonstrate that the fundamental structural and methodological differences that set string theory apart from other physical theories have important philosophical consequences. Focusing on implications for the realism debate in philosophy of science, it is argued that both poles of that debate face new problems in the context of string theory. On the one hand, the claim of underdetermination of scientific theory by the available empirical data, which is a pivotal element of empiricism, loses much of its plausibility. On the other hand, the dissolution of any meaningful notion of an external ontological object destroys the basis for conventional versions of scientific realism. String theory seems to suggest an intermediate position akin to Structural Realism that is based on a newly emerging principle, to be called the principle of theoretical uniqueness.

Keywords: Scientific realism, string theory, underdetermination, ontology, structure

1 Introduction

In one respect, quantum mechanics resembles the music of Arnold Schönberg: its restricted accessibility awards eternal youth. The conception that was created 80 years ago to replace the failing laws of classical physics in the microscopic world still looks fresh and exciting and remains the paragon of a modern scientific theory. The unshakable status of the quantum principle as the grand enigma at the base of modern physical inquiry has a peculiar consequence however: it keeps the scientific and philosophical community beyond a small group of experts strangely insensitive to the significance of the newer developments in fundamental physics. Hidden from the outsider behind an impenetrable forest of mathematical formalism, the conceptual novelties of those developments are usually taken as complex but minor addenda to the epoch-making events of the quantum revolution. Though current physical theories like gauge theory or quantum gravity[1] are being analyzed in philosophy of physics, the general discourse in philosophy of science has remained largely untouched by arguments from recent elementary high energy physics. String theory in particular, which will be the subject of this article, plays a leading role in contemporary high energy physics but so far has remained fairly unknown territory even for specialized philosophy of physics.[2]

String theory is the most ambitious theory in fundamental physics today. Replacing the point-like elementary particles of traditional high energy physics by miniscule but extended objects, it presently constitutes the only promising approach to provide a unified description of all known natural forces. Despite a history of more than thirty years of string theoretical research, however, string theory still remains an empirically unconfirmed and theoretically incomplete theory. While it has been argued elsewhere (Dawid 2006) that a philosophical analysis of the structure and dynamics of string theoretical research can open up new perspectives on the evaluation of string theory's current scientific status, the present article will not directly discuss the question of string theory's viability. It will rather ask the conditional question: if string theory were an empirically viable physical theory, what would be its philosophical implications? Assessing the outcome of this discussion, one should bear in mind, however, that string physics represents a natural continuation of the particle physics research program. It is intricately entangled with other fields of particle physics model building and shares many core concepts with well established and empirically well tested theories in the field. Philosophical implications identified in the context of string physics thus often can be understood as an intensification of trends already perceptible in the context of empirically confirmed theories of high energy physics.

The present work will focus on string theory's potential consequences for a pivotal debate in philosophy of science: the debate about scientific realism. It will be argued that the scientific concepts and techniques that have emerged during the last few decades in particle physics and found their most universal realization in string theory imply deep and unexpected changes in physics' take on physical reality. If string theory is scientifically viable, they may have philosophical consequences whose significance can well be compared to the philosophical impact of quantum mechanics. Following a sketch of string theory, a short introduction into the scientific realism debate will set the scene for the main discussion. Sections 4 and 5 will present two different kinds of arguments against empiricism which can be derived from high energy physics and string theory in particular; Section 6 will then give a string-based argument against scientific realism. Finally, an attempt will be made to draw a consistent conclusion from the seemingly contradictory messages which emerge when scientific realism meets strings.

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[1] An instructive recent collection of articles on quantum gravity can be found in Callender/Huggett (2001).

[2] Some of the rare examples of philosophical reflections on string theory are Weingard (2001), Butterfield/Isham (2001), Hedrich (2002) and Hedrich (2007).

2 String Theory

String theory[3] was first suggested as a universal theory of microphysics in 1974.[4] The approach had to struggle with big conceptual difficulties in the beginning and was seen as an exotic fantasy until its breakthrough ten years later, when some important consistency problems were finally resolved. Although there still doesn't exist any direct experimental evidence for string theory, today it is acknowledged by a majority of high energy physicists as the only promising candidate for the construction of a truly unified theory of all natural forces.

The basic idea of string theory is to replace the point-like elementary particles of traditional particle theories by one-dimensional strings in order to provide a basis for the unification of quantum physics and gravity. The core obstacle to an integration of gravity in the context of quantum field theory is the occurrence of untreatable infinities in calculations of particle interactions due to the possibility of point particles coming arbitrarily close to each other.[5] The extendedness of strings 'smears out' the contact point between any two objects and thus provides a decisively improved framework that seems to allow finite calculations[6]. String theory represents a natural continuation of the high energy physics research program that has close ties with other theories in high energy physics like supersymmetry, supergravity or large extra dimensions. It requires mathematical methods beyond those of traditional elementary particle physics, however, due to the highly complex structure of one- or more-dimensional objects moving in higher-dimensional backgrounds.

The seemingly innocent step from point-like objects to strings implies an amazing host of complex structural consequences. A string theory able to describe matter can only be consistently formulated in 10 space-time dimensions (respectively 11 space-time dimensions in one specific formulation). This prediction marks the first time in the history of physics that the number of spatial dimensions can be derived from a physical theory. The obvious fact that only 4 space-time dimensions are macroscopically visible is taken into account by the assumption that 6 dimensions are "compactified". They have the topological shape of a cylinder surface where, after some translation in the "compactified" direction, one ends up again at the point of departure. The compactification radius as well as the string length are assumed to be so small that both the extension of the string and the additional dimensions are invisible to the current particle experiments. Both scales are expected to lie close to the Planck length, the characteristic length scale of gravity

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[3] The topical standard work on string theory is Polchinski (1998). A classic earlier book is Green/Schwarz/Witten (1987). A more accessible presentation for the general physicist can be found in Zwiebach (2004). An instructive popular presentation for the non-physicist is Greene (1999).

[4] The history of the concept of strings even goes back to the late 1960ies, when it was discussed in a different context however.

[5] The reason why this problem is more dramatic in the presence of gravitation than in a calculation of nuclear interactions has to do with the fact that the gravitational force grows with increased energy density.

[6] Though the finiteness of string theory is not proven conclusively, it is supported by fairly strong evidence.

where the gravitational force becomes comparably strong to the nuclear forces. According to conventional wisdom, the Planck scale lies so far beyond the reach of particle experiments that there is no hope ever to observe strings with the established methods of particle experiment.[7] It turns out that the posit of one-dimensional elementary objects implies the additional introduction of even higher dimensional objects like two dimensional membranes or, to put it generally, d-dimensional so called d-branes.

In conventional quantum physics, elementary particles carry quantum numbers which determine their behavior. A particle's characteristics like spin or charge, which are expressed by quantum numbers, constitute intrinsic and irreducible properties. Strings do not have quantum numbers but can differ from each other by their topological shape and their dynamics: Strings can be open, meaning that they have two endpoints, or closed like a rubber band. If they are closed, they can be wrapped around the various compactified dimensions in different ways. Both, open and closed strings can assume different oscillation modes. These characteristics define the macroscopic appearance of the string. To the observer who does not have sufficient resolution to perceive the stringy structure, a string in a specific oscillation mode and topological position looks like a point-like particle with certain quantum numbers. A change of, let's say, its oscillation mode would be perceived as a transmutation into a different particle. Strings at a fundamental level do not have coupling constants either. The strength of their interaction with each other again can be reduced to some aspect of their dynamics (the ground state of a certain mode of the string expansion, the dilaton, gives the string coupling constant). All characteristic numbers of a quantum field theory are thus being dissolved into geometry and dynamics of an oscillating string.

String theories which are able to describe matter fields have to be supersymmetric, i. e. they must be invariant under specific transformations between particles of different spin. Models which have this property are called "superstring" models. It turns out that superstrings automatically

include gravitation and thus represent a natural candidate for a unification of gravity and microphysics.

One very important feature of string theory remains to be mentioned. The string world shows a remarkable tendency to link seemingly quite different string scenarios by so-called duality relations. Two dual theories are exactly equivalent with respect to their observational consequences, though they are quite differently constructed and may involve different types of elementary objects and different topological scenarios. The phenomenon can be best introduced by an example. As it was mentioned above, closed strings can be wrapped around compactified dimensions. On the other hand, strings can also just move along a compactified dimension. Due to basic principles of quantum mechanics momenta in closed

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[7] There do exist theoretical scenarios of large or "warped" extra dimensions where the extremely high four-dimensional Planck scale we know is understood as an artefact of extra dimensions which "hide" a fundamental Planck scale that lies much closer to the observable regime. Thus it is not entirely excluded that strings will some not too distant day become observable after all.

dimensions can only assume certain discrete “quantized” levels. Thus there exist two basic discrete numbers which characterize the state of a closed string in a compactified dimension: The number of times the string is wrapped around this dimension and the number of its momentum state in that very same dimension.[8] One of the duality relations of string theory, T-duality, implies that a model where a string with characteristic length[9] l is wrapped n times around a dimension with radius R and has momentum level m is dual to a model where a string is wrapped m times around a dimension with radius l^2/R and has momentum level n. The two descriptions give identical physics. The key precondition for this remarkable phenomenon is the quantum uncertainty that provides the “fuzziness” necessary for such unlikely identification. It is only in string theory, however, that dualities become a characteristic feature of physical theories. A little more about dualities will be said in Section 6 where this concept will assume an important role in the philosophical argument.

3 Scientific Realism versus Empiricism

The scientific realism debate, which shall be confronted with string physics in the following, descends from the age-old problem of the relation between observation and theory. While pre-modern philosophy generally tended to rank the place-value of theoretical reasoning higher than profane observation, the success of the scientific method with its strong emphasis on experimental confirmation inverted that hierarchy. Observation became the ultimate judge over the justification of theoretical statements.[10] Provided that statements must have an observational implication to be meaningful, the question arises whether theoretical statements can constitute knowledge about anything beyond observational data at all. Scientific antirealists deny this while scientific realists want to retain at least some trace of the “golden age” of theoretical autarky. In the context of modern scientific theories, the question circles around the status of theoretical concepts which do not refer to directly observable objects. The scientific realist awards to the electron and the quark the same ontological status as to chairs and tables. Her antirealist opponent asserts that the concepts of unobservable objects are of importance merely as technical tools to describe and predict visible phenomena. Two classical antirealist positions can be distinguished. The instrumentalist flatly denies that statements about unobservable theoretical objects can be literally true. Bas van Fraassen[11] pointed out, however, that there is a less radical way of rejecting scientific realism. His constructive empiricism acknowledges that statements about theoretical objects can be literally true in principle but claims that it is impossible to collect sufficient evidence for the truth of any particular statement. Shunning

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[8] The two numbers are called winding number respectively Kaluza-Klein level.

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

[10] Excluded are solely mathematical statements, which are usually understood as meaningful but a priori.

[11] van Fraassen (1980).

the ontological quality of the instrumentalist assertion, constructive empiricism remains on an epistemological level.

During the long history of the scientific realism debate, realists as well as empiricists have produced a complex web of interrelated objections against their respective opponents. The core of the dispute may be represented by the non-realist's pessimistic meta-induction[12] and the realist's no miracles argument[13]. According to the pessimistic meta-induction, the history of science shows that new empirical or theoretical developments have often led to the replacement of formerly successful theories by new concepts with a significantly different ontology. Since there is no reason to assume that this pattern will terminate today, it is implausible to hold that the present theories are approximately true or contain scientific objects which refer to anything in the outside world. The no miracles argument, on the other hand, asserts that the conspicuous ability of scientific theories to predict new phenomena correctly would be a miracle if the theories in question were not approximately true and did not contain scientific objects which referred to something in the outside world. Further arguments on both sides enhance the impression of an uncomfortable impasse: antirealists doubt the validity of the realist strategy to explain scientific predictive success and question whether realists can even give a satisfactory definition of what makes a scientific object "real"; realists point out that the antirealist does not offer a satisfactory way of delimiting observable from unobservable objects and ignores the striking realist connotations of the technical treatment of well understood unobservable objects. The plausibility of the realist's assertion that antirealism misses something important about science stands against the antirealist's convincing claim that the conventional forms of realism are not satisfactory. We will leave aside for now a discussion of attempts in philosophy of science to find some middle ground between realism and empiricism, and approach the problem from a different angle. It shall be analyzed to what extent contemporary high energy physics, and in particular string theory, might contribute to an altered understanding of the question of realism.

4 Theoretical Complexity against Empiricism

The recent evolution of fundamental physics may be understood to carry one message for the realism debate that can be appreciated without going into the details of new physical conceptions: empiricism is most plausible in the context of moderately developed theory. The higher developed the theoretical apparatus gets, the more difficult it becomes to retain any plausibility of the assertion that its subject must not be anything but observation.

At least two reasons for this claim may be stated. First, the ascent of theory can open new frontiers of the visible whose identification with frontiers of existence appears less plausible than in the classical cases. A good example can be found

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[12] The seminal version of the argument was given in Laudan (1981).

[13] See e. g. Putnam (1975) and Boyd (1996).

in modern cosmology. Most versions of instrumentalism uphold the claim that statements about the past can have a truth value. Now modern cosmology tells us that the early highly dense stages of our universe represent a world void of all macroscopic objects and remote from all classical physical conditions as we know them. The early universe thus is just as adverse to direct visibility as microphysical processes today. The instrumentalist therefore is forced to deny "real existence" to all objects in the early universe and, if staying on course, would consequently have to insert her own "ontological big bang" to denote the point in time when the real world as she accepts it start to exist. Everything before this point would just be a mathematical construction to structure the later evolution. Things would start their existence "out of nothing" just because any earlier evolution could not satisfy the visibility condition. This partition of a physically continuous causal process by an arbitrary ontological distinction looks quite unconvincing. It is particularly awkward since the ontological posit must rely entirely on abstract physical arguments about the physical conditions of the universe at a stage that was void of and adverse to any form of intelligent life. The argument thus lacks any connection with actual human observation, which clearly runs counter to the initial motivation of instrumentalism to emphasize the special status of actual human observation in contrast to abstract theory building. Constructive empiricism is less affected by this problem because its epistemological limits can be placed on the time axis with less argumentative effort.

The second point equally affects instrumentalism and constructive empiricism: once the balance between theoretical effort and observational consequence gets strongly tilted towards theory, it becomes quite problematic to hold that the theoretical physicist's sound motivations for her activity exclusively lie in the visible regime. A comparison of the situation at the heyday of quantum mechanics with the situation today shows the problem: The observable consequences of quantum mechanics are enormous, culminating in the explosions of atomic bombs which are impossible to overlook even for the staunchest sceptic of theoretical physics. In that context, the microscopic structuring done by theoretical quantum physicists for all its complexity might still be understood as a reasonable technical effort to produce and predict its stunning observable effects. In modern high energy physics, on the other hand, the characteristic phenomenological implications of theories like the particle physics Standard Model or supersymmetry look marginal if taken out of their theoretical context. Often they are limited to a few unusual lines on a set of photos taken in a collider experiment. It requires a multi billion dollar build-up of huge particle colliders and the sustained work of thousands of experimentalists to see these lines at all. To explain them, equally large numbers of theoretical physicists devote all their time and energy and feel compelled to develop theories of unprecedented complexity. The claim that the development of modern high energy physics' elaborate theories cannot be justified by the quest for truth about the micro-world but solely by these theories' technical ability to structure and predict some miniscule lines in Geneva or Chicago[14]

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[14] The two locations where the collider experiments at highest energies take place these days.

simply would amount to declaring the high energy physics community a bunch of insane and money-wasting crackpots. Most philosophers of science nowadays would agree that any insinuation in this direction oversteps the authority of philosophy of science.[15] But to concede that the enterprise of high energy physics is justified means to accept justification from somewhere within the theoretical body of its theories, beyond the dry and minimalist phenomenological surface. It means to accept that we spend money and time to acquire knowledge about quarks, gauge bosons, the hot early universe or the big bang and not just about the weird pattern of lines on a photo. In order to acquire knowledge of the latter kind, we must be confident that at least some of the statements contained in the theories in question are approximately true in a literal sense. To adopt this attitude, however, bluntly contradicts the core claims of both instrumentalism and constructive empiricism.

String theory constitutes a further step towards a conception of scientific activity that is at variance with an empiricist stance. It is unclear when - if at all - there will be an experiment that can test string theory directly and how that experiment would look like. The focus of string theoretical interest today therefore must lie on the theoretical structures developed. If string theorists claim - as many of them do - that they gain new insights into nature by developing their theory, they can only refer to (potential) knowledge about theoretical objects or structures and not to knowledge about visible phenomena.

5 Scientific Underdetermination

5.1 A Disparity of Views

String theory creates serious problems for empiricism at an entirely different level as well. A look at string theory's current status shall set the stage for the discussion of this point. A peculiar disparity of views has been noticeable since the rise of the theory in the mid 1980s and has recently developed into a sometimes vitriolic dispute between exponents and opponents of the string theoretical research program. String physicists themselves have the at times euphoric feeling to work on a pivotal and historic step towards a fuller understanding of the world. String theory's lack of experimental corroboration and its sadly incomplete state, to be sure, are generally acknowledged as deplorable weak points. Nevertheless, except for a minority who see themselves as mere mathematicians, string theorists are convinced to have reached deeper insight into the structure of physical matter than anyone before. This understanding is shared in a slightly more cautious way by many exponents of adjacent fields like particle physics model building or cosmology. The majority of physicists in other fields, from phenomenological

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[15] Past unfortunate excursions of natural philosophy into the realm of scientific prediction have laid the ground for the widespread conviction that philosophy of science should solely interpret the scientific process and abstain from censoring it. There do exist philosophers of science, however, who, feel confident to give advice to scientific goal definition from a philosophical perspective (see e.g. Cartwright 1999).

high energy physics over canonical quantum gravity to applied physics, as well as most philosophers of science, have a substantially more critical perspective on the status of string theory. It is their understanding that, considering the lack of empirical confirmation, string theory has never left the phase of pure speculation. After more than thirty years of intense work on the subject that has neither produced any testable prediction nor even anything close to a complete theory, outspoken critics of the string theoretical research program recommend to focus on the search for alternatives rather than stick for ever to an enormously demanding but potentially futile enterprise. Despite the sometimes polemic wording, the disagreement between the two sides is not of a fundamentalist nature. String theorists do not dare to be absolutely sure about the existence of strings and their critics concede that they might turn out to be on the right track after all, if an experimental test can be found. Still the degree of mutual alienation is quite significant.

The described disparity of views about the validity of a new theory has characteristics of a paradigm change *à la* Kuhn (Kuhn 1962). The rift goes deeper, however, than in standard cases of paradigm change in science. In the eyes of the critics of string theory, a theory without experimental backing, whatever the details, cannot be called a well established theory. Exaggerated trust in that theory thus leaves the path of sober natural science. For the string theorist, to the contrary, her trust in the theory is based on a careful scientific analysis of the theory's theoretical merits and its contextual embedding. The fundamental disagreement about the value of string theory therefore is not a matter of physical detail, it is a matter of defining the authority and power of purely theoretical reasoning within the scientific process. If one wants to use the word "paradigm" as a technical term solely applicable to perspectives within a scientific field, one might call the rift between string theorists and phenomenologists a meta-paradigmatic rift. The two sides do not agree on the definition of science.

Similar situations have occurred before. A prominent example is the opposition of empiricist physicists like Ernst Mach to the posit of invisible scientific objects like atoms in physics at the turn of the 19th century. Their understanding of science was so closely bound to the principle of direct observation that they considered talk about invisible objects unscientific.[16] The dispute receded from the physical regime in the 20th century, when it became generally accepted scientific standard to argue on the basis of invisible structures, but continued on a philosophical interpretational level, where it constitutes the core motive of instrumentalism and constructive empiricism.

The different points of view on string theory can be understood as a sequel of the old empiricist dispute. The string theorists' self-confidence without empirical backing once again infringes on the dominance of observation in science and

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[16] An important difference between the earlier reservations against the status of invisible scientific objects and the present ones against the relevance of string theory should be emphasized: Contrary to the latter, the Machian arguments were not based on the consensual position of the traditional scientific community. They rather construed an artificial notion of an ideal scientific attitude which itself constituted a new position and had never been fully reflected in the scientist's perspective.

seems to suggest a more dramatic shift of the scientific paradigm than in the case of the acceptance of invisible scientific objects. The latter changed the meaning of "observable" by acknowledging the option to measure observables indirectly, but it kept the experimental primacy fully intact. String theorists, though still subscribing to experiment's position as the ultimate judge over scientific theory, in fact seem to diminish its role by assuming that scientists can develop a considerable degree of confidence in the viability of scientific statements on a purely theoretical basis. In a nutshell, they claim: experiment is important if we can carry it out, but if we can not, scientific progress can proceed without it.

What drives string theorists towards this significant shift in their conception of science? When physics fully endorsed scientific objects like atoms at the beginning of the 20^{th} century, scientific progress inevitably enforced this step as many newly discovered phenomena just did not find any other satisfactory explanation. Does contemporary high energy physics offer an equally forceful argument for string theory's apparent theoretical autarky?

5.2 Scientific Underdetermination

The following attempt to answer this question will crucially rely on the concept of underdetermination of scientific theory building by the available data (henceforth to be called scientific underdetermination, following Dawid 2006). Scientific underdetermination must be clearly distinguished from two more prominent forms of underdetermination. On the one hand, it must be delimited from Quinean underdetermination as formulated in Quine (1970), which asserts the existence of scientific theories that are empirically equivalent with respect to all possible empirical data. Scientific underdetermination, to the contrary, asserts the existence of several or many theories which fit the presently available data but may differ in their predictions with respect to future data. On the other hand, scientific underdetermination differs from Humean underdetermination by taking for granted certain pre-assumptions and pre-conditions of scientific theory building. While Hume points out the logical impossibility of deducing any future phenomenology from past observations, science relies on the inductive inference from observed regularity patterns to predictions of future events. Furthermore, satisfactory scientific theories are expected to satisfy a number of general conditions like a certain degree of universality or the avoidance of ad-hoc posits which account for individual events. Scientific underdetermination is realized only if several or many theories which satisfy the stated conditions and therefore qualify as serious scientific contenders can be built in accordance with the available empirical data. Whether or not scientific underdetermination is considered a characteristic of the scientific process at a certain stage thus does not have any implications for the more elementary problem of induction.

In the following discussion of scientific underdetermination, we will disregard empirically equivalent theories and focus on theories which, while all in agreement with the presently available data, can be distinguished by future experiments. The term "scientific underdetermination" thus will be used synonymously with the notion of "transient underdetermination" introduced by Sklar (1975) and discussed e.g. by Stanford (2001).[17]

It is generally assumed that scientific theory building is underdetermined by the available empirical data. If scientific theory building were not scientifically underdetermined, scientific progress would have to be exclusively accumulative. The replacement of temporarily successful theories by conceptually different successors would be excluded since any such replacement would imply that at least two theories, the old and the new one, were compatible with the available empirical data at the time when the old theory was valid. History of science shows, however, that scientific progress in the past was by no means purely accumulative. The scientific underdetermination of contemporary scientific theories can then be inferred from the historic examples of theory replacement based on the pessimistic meta-induction cited in Section 3.

The importance of scientific underdetermination is not confined to instances of theory replacement. In many scientific fields it seems clear that large numbers of theories could be constructed which would be compatible with the currently available data but would make predictions of future phenomena which just do not agree with nature. Any such diversity of theoretical options exemplifies scientific underdetermination.

Still, it seems clear that entirely unrestrained scientific underdetermination does not accord with the observed characteristics of scientific research. Natural science shows a distinctive tendency of favoring one specific fundamental theory about a certain subject at each stage of its evolution. This fact delimits natural science from other fields like history or social sciences and is at variance with an indiscriminate postulate of scientific underdetermination. In addition, the very same history of science that delivers uncounted examples of fundamental theory change also knows of many instances where theories successfully predicted entirely new phenomena. If there existed an unlimited number of equally promising alternative scientific theories which fit any given set of physical data but make different empirical predictions with respect to future experiments, it would be unclear how scientists could manage to pick the correct theory so often (see e.g. Dawid 2007). The predictive success of science, which, as noted in Section 3, is deployed against antirealist positions by the no-miracles argument, therefore also indicates the existence of limitations to underdetermination.

The degree of scientific underdetermination thus emerges as a highly nontrivial characteristic of the scientific process; a characteristic that will be crucial for the present discussion for one reason: it largely determines the status of empirically unconfirmed scientific theory building. To a hypothetical scientist who denies scientific underdetermination, the viability of empirical predictions which stem

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[17] We do not use the term "transient" in the present article since it would be a little misleading in our context. Transient underdetermination is transient only with respect to a specific set of empirically distinguishable theories. The classical understanding of scientific progress as a never ending sequence of empirically motivated theory changes implies, however, that the underdetermination of theory building by the available data is not transient in a wider sense: there is no finite program of empirical testing that would remove it.

from a coherent theoretical description of the available data would seem just as reliable as the assumption that a viable scientific description of the given phenomena exists at all. Given that scientific underdetermination seems to be a matter of fact, though, its suspected limitations may still justify a certain degree of confidence with respect to an empirically unconfirmed theory's validity. Totally unlimited scientific underdetermination, finally, would destroy all hope of choosing the right theory without direct empirical guidance.

At this point, string physics enters the stage. While science knows instances where purely theoretical arguments have instilled some degree of confidence in empirically unconfirmed theoretical schemes, the principle of scientific underdetermination has been considered sufficiently strong to prevent the full endorsement of those theories. The primate of empirical confirmation has always remained uncontested. String physics may be the first example where the theory's appraisal by its exponents may be taken to suggest otherwise. It thus may be suspected that, in the eyes of its exponents, string theory provides reasons for assuming unusually strong limitations to scientific underdetermination which justify a higher emphasis on theoretical arguments for evaluating the viability of scientific statements. This understanding would offer a plausible explanation for the striking antagonism between string theorists and the theory's external critics: while string physicists themselves feel impressed by the new kinds of indications of strong limitations to underdetermination which they encounter in their daily work, physicists who don't share that experience or feel particularly fond of the traditional scientific paradigm cannot understand the string physicists' disregard for the traditional and well established principles of theory appraisal.

5.3 Limitations to Scientific Underdetermination in String Theory

Dawid (2006) offers arguments for the claim that strong indications of new limitations to scientific underdetermination can indeed be found in string theory. Since these arguments will play an essential role in the later analysis, they shall be sketched in the present subsection. The reader who looks for a thorough argumentation, however, should resort to Dawid (2006).

Arguments in favor of limitations to scientific underdetermination emerge at two different levels. The first kind of reasoning is based on general characteristics of the research process that leads towards string theory.[18]

Maybe the most conspicuous argument in the eyes of string physicists is the "argument of no choice". String physicists claim that, after intense investigations in various directions, their approach has remained the only viable approach leading towards a unified theory of gravity and nuclear interactions that has been even

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[18] The three arguments to be presented in this context reproduce in a structured way what may be called "common lore" in string physics. It is difficult to pin down a *locus classicus* for each of these arguments. A combination of all three can be found in Chapter 1 of Polchinski (1998) and in Polchinski (1999). The argument of no choice and the argument of conceptual coherence appear in Greene (1999) (see e.g. Chapter 1).

remotely successful. Loop-quantum gravity and other approaches in canonical quantum gravity from that perspective can not count as alternatives because they only discuss the reconciliation of gravity with basic principles of quantum physics without offering strategies to include a full theoretical description of nuclear interactions. With respect to fully unified theories, string physicists offer some qualitative arguments to demonstrate that very different points of departure which seem to have nothing to do with string physics, after more careful examination turn out to lead back towards string theory (see e.g. Polchinski 1999).

The significance of these statements is taken to be supported by past experience in particle physics: if physicists knock on many doors to solve a conceptual problem and exactly one opens that in turn leads towards rich and coherent new structure, chances apparently are good that this solution will turn out to be empirically viable. The most impressive witness to this claim is the standard model of particle physics. Crucial elements of the standard model like the gauge structure of interactions have been suggested without immediate empirical evidence based on purely theoretical argumentation in order to solve theoretical consistency problems. Eventually, the deployment of these concepts has been confirmed by experiment and has led to a large number of empirically viable predictions. String physicists argue that alternatives have been checked more carefully in the case of string physics than it had been at the time of the development of the standard model, which may instil a certain amount of trust in the viability of string theory's conceptual claims.

An additional argument is based on surprising instances of conceptual coherence in the context of string theory. It is generally accepted that a scientific theory is convincingly confirmed by empirical data that did not influence the construction of the theory but is correctly predicted by it. In a similar way, a theory may be corroborated on purely theoretical grounds. It may provide improvements of the theoretical understanding of interconnections between different physical phenomena even though the construction principles applied when creating the theory did not aim at that kind of improvement. String physicists argue that such theoretical confirmation should be taken seriously as a basis for judging a theory's viability. String physics offers a number of surprising instances of conceptual coherence. Three of the most important ones are the fact that a theory of quantized extended objects implies gravity, the fact that a string theory of matter requires supersymmetry (which joins two important directions of particle physics research) and the fact that string theory in certain special cases can explain the connection between black hole entropy and the black hole event horizon.

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 directly 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. The empirical success of the particle physics research program as well as string theory's tendency to create unexpected internal coherence may be taken as indirect signs of significant limitations to scientific underdetermination since unlimited underdetermination would render the occurrence of both unlikely.

While the three arguments presented up to this point have precursors in earlier scientific theory building and may be understood in terms of (preliminary) highpoints of longstanding developments, string theory also offers genuinely new arguments which hint in the same direction at a different level: the theoretical structure of string physics itself seems to suggest a devaluation of scientific underdetermination.

Of crucial importance in this context are two related properties of string theory. Unlike all other known physical theories, string theory at a fundamental level does not have any free parameters. Neither does it have any dimensionless parameters which can be freely adjusted to fit empirical data nor does it have any dimensionful parameters whose values can be tuned with respect to characteristic parameters of a relevant measuring apparatus.[19] Beyond that point, based on some very basic assumptions like the existence of matter and of more than one spatial dimension, string theory shows an even higher degree of uniqueness. Due to the phenomenon of string duality, which will be addressed in Section 6, there seems to remain no freedom of constructing different types of string theory at a fundamental level. Rather, there seems to be only one way to construct the fundamental structure of string theory. The lack of structural freedom of choice together with the lack of free parameters shall be called the “structural uniqueness” of string theory.

It is not clear at this point in how far string theory’s structural uniqueness translates into one inevitable set of parameter values of low energy theories like the Standard Model. From a string theoretical perspective, the Standard Model parameters are effective parameters which are uniquely determined by string theoretical features like the value of the string coupling constant, the radii of the compactified dimensions or the number of D-branes. These stringy features again must be understood as the result of a dynamical process that is based on the fundamental equations of string theory (which, as described, do not have any free parameters) and leads from the big bang towards some ground state of the theory. If string theory would have one theoretically enforced energetic ground state where all those values are uniquely determined, that would uniquely determine the low energy parameter values as well. According to the present understanding, however, there seem to exist huge numbers of theoretically coherent stable or meta-stable[20] ground states in string theory, which could all be reached in

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[19] The latter fact is due to the theory’s universal character which necessarily also covers the physics that describes the experimental apparatus.

[20] If there exist several local minima of the potential at different energy levels, it can be expected that the lower minimum will eventually be reached by quantum tunneling. However, depending on the size of the potential barrier and the energy difference between the ground states, the time until such quantum tunneling can be statistically expected to occur may be huge, even greater than the present age of the universe. Thus, we might live such a meta-stable state of the universe.

the early quantum processes of our universe[21]. While an as yet unknown vacuum selection mechanism that singles out one or a reasonably small number of specific energetic minima may emerge trough a better understanding or substantial reshaping of string physics, its existence appears questionable at this point. The alternative would be a scenario where the selection from a huge number of physically allowed local ground states would depend on the accidental outcome of quantum fluctuations at the initial stages of our universe.[22] As different ground states correspond to different parameter values of the effective theories at low energies, that scenario could dramatically reduce string theory's predictive power (see e.g. Douglas 2003 and Susskind 2007).

Though the question of string theory's predictive power thus remains a matter of speculation, it is important to notice that both ends of the spectrum of possible answers suggest a fundamentally altered understanding of scientific underdetermination. If the predictive power of string physics were indeed dramatically reduced by the irreducibly statistical nature of quantum physics, this would significantly alter the perspectives for further physical inquiry. Since it would be difficult to understand how quantitative aspects which are a matter of quantum statistics in one scheme should be calculable in another, one might suspect a fundamental block to scientific progress, which clearly would change the understanding of theory succession and presumably should have an impact on the related question of scientific underdetermination as well. No more specific analysis of that point shall be attempted here, however.

If, on the other hand, some as yet unknown vacuum selection mechanism reduces the number of physically allowed ground states to an extent that makes string theory highly predictive[23], an even more far-reaching argument could be applied. In short, a highly predictive structurally unique theory changes the basis for assessing the plausibility of scientifically viable alternatives. Since (i) structurally unique theories appear to be much more rare than conventional ones and (ii), if highly predictive, they cover a far smaller part of the parameter space of imaginable observable characteristic numbers, the traditional assessments of scientific underdetermination do not apply any more. It is quite implausible to expect that alternative highly predictive structurally unique theories exist which can to some accuracy reproduce the parameter values of a given theory of that kind. If a highly predictive structurally unique theory would turn out to be empirically viable to a certain degree of accuracy (under a certain set of empirical data), one thus should be led to presume that this theory cannot be replaced by another theory that fulfills the condition of highly predictive structural uniqueness. A

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[21] This of course applies to the canonical understanding of quantum physics. Deterministic hidden parameter theories would have to determine one unique path towards a predetermined ground state.

[22] Conceptions dealing with eternal inflation and multiverse models embed the universe we inhabit in a grander background scheme.

[23] "Highly predictive" here 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.

replacement by a new theory that does not meet that condition would be implausible as well, since the highly predictive structural uniqueness of its predecessor would then appear like a miracle. Together, the two statements suggest that such a theory would have to be expected to be a final theory that will not be replaced any more by any empirically different alternative at all.

Interestingly, similar final theory claims occur in the context of string theory at other levels as well. String theory is the first physical theory that seriously claims to provide a full conceptual unification of all known elementary physical phenomena, which makes it the first final theory candidate if full conceptual unification is taken to be a scientific goal. A more powerful final theory claim is related to an interesting implication of string dualities (see e.g. Witten 2001). T-duality, which has been briefly described in Section 2, implies an absolute minimum length in the sense that all empirical tests of distance scales smaller than the critical scale can, based on duality relations, be understood as tests of distance scales larger than the critical scale. 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.

While none of the presented arguments in itself constitutes a disproof of the principle of scientific underdetermination, the remarkable multitude of different arguments which point in the same direction justifies the claim that a substantial devaluation of the principle of scientific underdetermination in the context of string physics seems plausible. Of course, this statement only acquires significance if string physics turns out to be a viable physical conception. If that were the case, however, there are many reasons to suspect that it will not any more be superseded by a successor theory. It should be emphasized that this claim does not come up to an announcement of an imminent end of fundamental physical research. The history of string theoretical research suggests that a completion of the theory may be just as elusive a goal as a final theory had seemed to be at earlier stages of the scientific evolution.

5.4 Theoretical Uniqueness

In the light of the previous subsection, string theory suggests a radically altered assessment of the old antagonism between underdetermination and theoretical prediction. The significance of this shift may be understood by reconsidering the impasse between realism and empiricism sketched in Section 2. The uneasiness of the *status quo* was due to the significant elements of successful prediction in science which seemed to favor realism while the equally undeniable elements of underdetermination seemed to support empiricism. The same kind of unsatisfactory balance characterizes all classical philosophical attempts to undermine the status of underdetermination. A nice example are the discussions around "deduction from the phenomena", which have drawn some attention in recent years.[24] Newton claimed that his physical theories were nothing but deductions from the phenomena. Norton and some others set out a few years ago to justify Newton's

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[24] See e. g. Norton (1993), Norton (1994) and Worrall (2000).

claim and went on to stress the seemingly unique way physical theories are often enforced by experimental data. Norton, for example, re-emphasized how quantization was forced upon physics by experiment. The argument of deduction from the phenomena indeed seems to demonstrate that the case for underdetermination is not as straightforward as some empiricists might want to believe. However, this judgment does not come up to a full-scale refutation of underdetermination. As it was emphasized in Worrall (2000), deductions from the phenomena are always based on a certain conceptual framework that implicitly constitutes part of the theoretical scheme. The "deductive" character of a theory's creation thus cannot prevent this theory from being superseded by a new one once its conceptive foundations have been revised. To give a prominent example, Newton "deduced" the laws of gravitation based on the concept of flat space and general relativity rejected that point of departure. Deduction from the phenomena shows that there is a considerable element of uniqueness in the evolution of physical theory building but it cannot refute the pessimistic meta-induction. It therefore merely sharpens the impasse between the realist and the empiricist side.

In the case of string theory, the situation is very different. Two levels of discussion can be distinguished, which provide two different strategies of dealing with the problem of the pessimistic meta-induction. First, there is the actual status quo of string theoretical research. String theory today is highly incomplete and in some respects looks more like a theoretical guideline towards future developments than a fully fledged theory. The core claim of the pessimistic meta-induction remains intact since string theoretical scientific concepts today are surely no less preliminary than the scientific concepts in previous periods of science. The posit of scientific underdetermination, however, cannot profit from this fact any more. In the traditional picture, the scientific evolution was taken to be carried by a sequence of fully consistent theories. Each of these theories correctly described a limited data set and some day became or was expected to become obsolete due to new significantly contradictive data.[25] The pessimistic meta-induction directly implied scientific underdetermination since each new theory had to be at least as convincingly compatible with the old data as its predecessor. In string theory, the traditional picture is no more applicable. The theoretical scheme at each stage of physical progress must be understood to be preliminary because it is theoretically insufficient and incomplete. Progress may be expected to arise based on a more far-reaching understanding of the theory under investigation rather than on theory replacement. The theoretical work on a deeper understanding and a fuller and more coherent formulation of string theory establishes purely theoretical progress as an equivalent and independent second path towards physical knowledge besides experimental progress.[26]

Far beyond the present state of the art lies the projected ideal of the fully consistent string theory. Some characteristics of this "final" theory like its lack of free parameters or the fundamental lower limit to physical length scales can be

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[25] Naturally, that was always just an idealization of the actual process, but at least it seemed fairly close to what was actually happening.

[26] As we have seen, it is currently the only path open to the physicist.

confidently predicted already today. Following the arguments of Subsection 5.3, this knowledge may be taken to justify the assertion that a fully developed string theory breaks the pessimistic meta-induction. If a full formulation of a consistent string theory could be found one day, one should expect that this theory is related to the observable world in one of two ways. Either it turns out to be a dead end without any relation to the physical world at all, or it constitutes a final theory in the sense that it describes all possible experimental data based on a set of foundational principles without any adjustable fundamental parameters. In both cases, the fully consistent string theory can not be considered a viable but refutable intermediate step in the evolution of science in the sense of the pessimistic meta-induction.

The emerging scenario overcomes the traditional impasse between underdetermination and theoretical prediction by denying to underdetermination the status of an "eternal" characteristic of all scientific theories. The underdetermination of traditional physical theories by experiment appears as an historic feature of a period of fundamental physics that has not yet reached the level of theoretical interconnectivity necessary to feel the full force of internal consistency arguments. Already at these earlier stages of the scientific process, the predictive power of scientific theories provides an indication that scientific underdetermination is not entirely limitless. The increasing lopsidedness towards theory and the impressive range of empirical confirmations associated with high energy physics since the 1970s can be read as suggesting significant limitations to scientific underdetermination with particular force. String theory or what it will have become after completion, finally might terminate the rule of scientific underdetermination.

At this point, a crucial question arises: if scientific underdetermination looses its eminent position in the face of string physics, what can be said about the paradigm that replaces it? Let us once again recall the three messages from string physics which undermine the old picture of scientifically underdetermined theory dynamics.

- Characteristics of theory development and internal coherence bolster the notion of strict limitations to underdetermination that was already inherited from standard model physics.
- Arguments at various levels support the suspicion that string theory might be a final theory.
- Unlike all previous physical theories, string theory is structurally unique at a fundamental level.

The three messages jointly lay the foundation for the introduction of a principle I want to call

The Principle of Theoretical Uniqueness: at a certain stage of scientific inquiry, a general set of empirical data together with general preconceptions about the necessary conditions a theory must fulfill for being considered scientific don't leave freedom anymore for choosing theoretical concepts, structural details or fundamental parameter values. There is exactly one scientific theory (modulo empirically equivalent alternative formulations, maybe) that fits the empirical data. As it seems, the data does not even have to be very specific but merely has to establish some elementary qualitative statements about the character of the physical world.

While the basic principle of theoretical uniqueness finds considerable support by our current knowledge about string physics, the principle's strength remains an open question even under the assumption that string theory is a valid theory about nature. In order to discuss the range of possibilities, we shall distinguish three different specifications of the term "theoretical uniqueness".
The above definition of theoretical uniqueness does not imply any statement about the predictive power of the theoretically unique theory. This reflects the fact, discussed in Subsection 5.3, that string theory at the present stage does not offer a clear picture of its capability of predicting low energy physics parameters. Depending on its final predictive power, string physics may eventually fulfill one of the following two degrees of theoretical uniqueness.

- *Weak Theoretical Uniqueness* denotes theoretical uniqueness that is not connected to a unique pattern of low energy parameter values.

- *Extended Theoretical Uniqueness* denotes the univocal determination of all quantitative empirical data by the unique theoretical structure.

A theory that fulfills extended structural uniqueness still can not be expected to determine the local specifics of the spatio-temporal distribution of physical objects. The prediction of local matter distribution from first principles is traditionally considered to lie beyond the range of scientific theories. Transgressing these limits would lead to a third kind of theoretical uniqueness.

- *Strong Theoretical Uniqueness* applies if a hypothetical theoretically unique scientific theory offers a unique prediction of matter distribution.

While there is nothing in today's understanding of string physics that would suggest strong theoretical uniqueness, the perspective that the latter concept might some day be applicable to physical theory building is less farfetched than it appears at first sight. First, it must be noted that the differences between fixing theoretical low energy parameter values and fixing the distribution of specific individual objects get increasingly blurred in the context of string cosmology. The D-branes whose positions and numbers are presumed to play an important role in determining the parameter values of the natural laws that guide physics at low energies are produced by the same quantum oscillations in the early universe which are also responsible for the universe's matter distribution. A mechanism that uniquely determines all local aspects of matter distribution thus would not have to be fundamentally different from a mechanism that leaves just one choice for low energy parameter values. Extended and strong theoretical uniqueness might not be too far apart. In addition, it is interesting to remember that one of the leading interpretations of quantum physics, the Everett interpretation (Everett 1957), is based on the notion that all possible outcomes of a quantum process are realized and form a complex system of "many worlds" that constitutes reality. If one applied this concept to string cosmology, where matter distribution and low energy parameter values stem from quantum oscillations in the early universe, this would imply that all possible low energy parameter values as well as all possible matter distributions are instantiated in one of the many worlds and thus must be taken to be real. Merging this understanding with the assumption that string theory is theoretically unique would indeed give the conception of one unique material realization of reality and therefore establish strong theoretical uniqueness.[27]

The demise of scientific underdetermination and the ascend of theoretical uniqueness clearly run counter to an antirealist stance. The faltering of the pessimistic meta-induction removes one of the antirealist's central arguments against realism. Moreover, the general spirit of empiricism seems hardly compatible with the concept of theoretical uniqueness. Empiricism suggests a highly underdetermined scientific environment where useful theoretical instruments for describing the phenomena may be expected to be constructible in fairly arbitrary numbers and kinds, in analogy to the freedoms of building technical instruments for some practical purpose. This understanding, which clearly is constitutive of instrumentalism, is shared, by and large, also by constructive empiricism, whose arguments against realism rely on a general assumption of underdetermination without addressing the question of the latter's limits.

At this point, string physics thus plainly seems to favor a position of scientific realism. The next section will demonstrate, however, that things are a little more involved than that.

6 Duality versus Ontology

6.1 Ontology and Quantum Physics

For a short moment, it is necessary to return to the opening theme of this article, to quantum mechanics. A venerable tradition among philosophers and philosophy-minded physicists, ranging from early exponents of the "Copenhagen Interpretation" to Bernard d'Espagnat[28], asserts the genuinely non-realist quality of quantum mechanics. One important motive for antirealism with respect to quantum physics is the understanding that the irreducibly statistical quality of statements in canonical quantum mechanics and the indeterminist element of the quantum world contradict our intuitive notion of a well ordered and well defined reality. Many philosophers would agree with the assessment, though, that

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[27] Note that the Everett interpretation on its own does not imply theoretical uniqueness since it does not remove the freedom of theory choice.

[28] See e. g. d'Espagnat (1989).

the present status of quantum physics leaves enough room for avoiding antirealist conclusions. Non-canonical interpretations of quantum mechanics like the hidden parameter models of Bohm (Bohm 1952) and Bell (Bell 1987) and the Everett interpretation offer deterministic and profoundly realist interpretations of quantum physics. A canonical understanding of the laws of quantum mechanics does not straightforwardly imply non-realism either, but arguably allows for specific formulations of scientific realism.[29] In addition, it may well be expected that basic conceptions of quantum physics will have to be altered to achieve a full integration of gravitational physics into quantum physics[30], which could offer entirely new perspectives on the question of realism.

Still, there remains an irritating question for the scientific realist that connects to the aforementioned general motive for antirealism in quantum physics: if the intuitive quality of the external ontological object is diminished piece by piece during the evolutionary progress of physical theory (which must be acknowledged also in an Everettian or a hidden parameter framework), is there any core of the notion of an ontological object at all that can be trusted to be immune against scientific decomposition and therefore can provide a promising foundation for realism?

Quantum mechanics cannot answer this question. Contemporary physics is in a slightly different position because the erosion of the ontological object has already proceeded much further. The dissolution of ontology that starts in quantum mechanics gains momentum in gauge field theory until, in string theory, the ontological object has simply vanished. The present section will focus on the "(un)happy end" of ontology's demise and discuss one specific feature of string theory, which constitutes the actual climax of modern physics' anti-ontological tendencies.

6.2 Ontology and String Dualities

The concept to be considered is string duality, which already played a role in the previous section. As described in Section 2, T-duality implies that a string wrapped around a small compact dimension can also be understood as a string that is not wrapped but moves freely along a large compact dimension. The phenomenon is rooted in the quantum principles but clearly transcends what one is used to in the quantum world. It is not a mere case of quantum indeterminacy concerning two states of the system. We rather face two theoretical formulations which are indistinguishable in principle so that they cannot be interpreted as referring to two different states at all. Nevertheless, the two formulations differ in characteristics which lie at the core of any meaningful ontology of an exter-

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[29] For a canonical but still realist interpretation of quantum mechanics see e. g. Redhead (1987) and Redhead (1995). As an example of the decidedly realist spirit of many standard textbooks on quantum mechanics, see Messiah (1969), Chapter 4.4.1.

[30] Speculations about linking the contraction of the wave function to gravity were for example formulated by R. Penrose. The question of the genuine non-objectivity of quantum physics will not be addressed any further in this article. String theory so far has nothing new to say about the contraction of the wave function.

nal world. They differ in the shape of space-time and they differ in form and topological position of the elementary objects.

T-duality is not the only duality relation encountered in string theory. The existence of dualities turns out to be one of string theory's most characteristic features. Probably the most important role played by duality relations today is to connect all different superstring theories. Before 1995, physicists knew 5 different types of superstring theory. Then it turned out that these 5 theories and a 6^{th} by then unknown theory named "M-theory" are interconnected by duality relations. Two types of duality are involved. Some theories can be transformed into each other through the inversion of a compactification radius, which is the phenomenon we know already under the name of T-duality. Others can be transformed into each other by inversion of the string coupling constant. This duality is called S-duality. Then there is M-theory, where the string coupling constant is transformed into an additional 11th dimension whose size is proportional to the coupling strength of the dual theory. The described web of dualities connects theories whose elementary objects have different symmetry structure and different dimensionality (as it turns out, each string theory needs a well-defined set of higher dimensional D-branes to be consistent). M-theory even has a different number of spatial dimensions than its co-theories. Duality nevertheless implies that M-theory and the 5 possible superstring theories only represent different formulations of one single actual theory. This statement constitutes the basis for string theory's uniqueness claims and shows the pivotal role played by the duality principle. In recent years, string-theoretical analysis has discovered even more surprising duality relations. For example, there exists a duality relation between certain theories that include gravitation and certain pure gauge theories without gravitation in a space reduced by one spatial dimension. More discoveries in this context might well follow in the future.

The fact that different string theories with different elementary ontologies are empirically equivalent constitutes an example of the Quinean kind of underdetermination referred to in Subsection 5.2. In Quine (1970), Quine asserts that one can always construct scientific theories which are empirically equivalent but logically incompatible. In order to delimit this claim from the trivial statement that there are always different ways to tell the same story, Quine distinguishes simple "reconstruals of predicates" from ontologically different scientific concepts (Quine 1975). Reified objects are taken to be the essential elements of the theory, whose existence claims and observable properties cannot be changed without creating a new theory. The simple renaming of these objects that does not alter their properties (e.g. calling the electron proton and vice versa) or the redefinition of parts of the theory that are not reified (e.g. the change of coordinate systems) do not generate a new theory. Quine's "logically incompatible theories" thus actually represent ontologically incompatible theories. The corresponding kind of underdetermination thus shall be called "ontological underdetermination" from now on.

Ontological underdetermination, like scientific underdetermination, constitutes a threat to scientific realism. If the totality of all possible empirical data uniquely determines one ontology of microphysics, a scientific realist interpretation of the corresponding theory would seem natural at least in principle.[31] If several or many possible ontological interpretations existed, however, the scientific realist, who wants to establish her realist interpretation of microphysics based on abductive inference, would have to find good arguments why she rejects one ontological interpretation and endorses another. Ontological underdetermination cannot strictly refute realism, to be sure. The metaphysical realist may insist that, even if the selection of one set of ontological objects cannot be decided upon on empirical or rational grounds, there is a true choice after all.[32] It will turn out, however, that ontological underdetermination creates serious problems for the metaphysical antirealist stance to remain coherent with basic conceptions of philosophy of science.

Theories related to each other by string dualities are by no means the first examples of empirically equivalent ontologies in science. Two general types of examples may be distinguished. First, one theoretical scheme can allow various ontological interpretations. The phenomenon in this case is created at a philosophical level by imputing an ontology to a physical theory whose structure neither depends on nor predetermines uniquely that imputation. The physicist puts one compact theoretical structure[33] into space-time and the philosopher struggles with the question at which level ontological claims should be inserted. A prominent example of this situation is quantum field theory where the status of elementary objects may be attributed either to particles or to fields. Some philosophers have taken underdetermination at this level as an argument against a realist basis for the imputation of ontologies. It might be suggested, however, that ontological alternatives at different levels of the theoretical structure, even if they were equally viable, would not pose a threat to realism per se but should be interpreted merely as different possible parameterizations of one unique external reality.

Second, and resembling more closely the Quinean conception of "ontological" underdetermination, there can exist mathematically different scientific schemes which are ontologically incompatible but describe the same observational world. Examples are the various empirically equivalent ways to formulate a theory of gravitation (see e.g. Lyre/Eynck 2003).

String duality posits different "parallel" empirically indistinguishable versions of structure in space-time which are based on different sets of elementary objects. These posits are placed at the physical level independently of any philosophical interpretation and therefore fall into the second class of ontological underdetermination. String theory differs from other examples of that kind, however, since

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[31] The question whether the limited scientific theories available to us can identify this real ontology still would remain to be answered, of course.

[32] Philosophers like Dummett actually define realism as a position that allows this kind of statement (Dummett 1991).

[33] To be sure, sometimes there do exist alternative ways to express a physical theory. Quantum mechanics can be formulated in the Heisenberg- or the Schrödinger-picture and quantum field theory in the field formalism or the path integral formalism. These alternatives however are generally taken as alternative mathematical formulations without differing ontological interpretations.

it interrelates the ontologically incompatible but empirically equivalent physical descriptions within one overall scientific theory.

A number of important problems which have marred previous exemplifications of ontological underdetermination are softened in the context of dual string theories. First, there is the question how to distinguish reconstructions of predicates from other empirically equivalent theories. Unfortunately, it is not always clear which parts of a theory precisely should be reified. To give one example, Poincaré's reformulation of classical mechanics in infinite flat space as a theory with altered physical laws in a finite space (Poincaré 1902) may look like a genuinely new theory if one reifies infinite flat space. Still, the conception is often understood as a mere reparameterization of classical mechanics and therefore as an example of a reconstruction of predicates.

Of course, the fundamental question whether it makes sense at all to distinguish between reconstructions of predicates and empirically equivalent but ontologically incompatible theories remains unchanged in the context of string dualities. However, if one decides to introduce such a distinction at all, dual string theories can be viewed as particularly clear examples of incompatible ontologies. The dimensionality and the topological shape of elementary objects seem to be essential characteristics of any meaningful external ontology. To deny ontological quality to these characteristics would mean withdrawing into an entirely abstract regime where an ontology cannot any more be understood in terms of a characterization of the external world. The existence of dual theories thus proves particularly problematic for an ontologically realist interpretation of scientific theories.

The case of string dualities is also better suited than other examples of ontological underdetermination to deal with the problem of the preliminary status of scientific theories. Quine asserts that the totality of all possible empirical evidence underdetermines the choice of a scientific scheme. Attempts to find scientific theories which can serve as examples of underdetermination usually fall short of exemplifying Quine's assertion for a simple reason: scientific theories in general cannot be expected to fit all possible empirical evidence. The specific status of string theory changes this situation in two respects. First, as has been discussed already in Section 5, string theory offers a number of reasons for being called a final theory. Therefore, the assertion that string theory, if fully understood, could fit all possible empirical evidence, has a certain degree of plausibility. Second, in the context of string theory the claim of ontological underdetermination is not based on the accidental occurrence of several empirically equivalent theoretical schemes but on a physical principle, the principle of duality, which represents a deep characteristic of the involved theories and may be expected to be a stable feature of future fundamental physics. It seems plausible to assume that the duality principle will continue to play an important role even if string theory changed substantially in the course of future research.

The occurrence of ontological underdetermination thus does not any more look accidental but is made a core physical statement. This can be understood as a genuinely physical argument against the assumption of one "real" scientific ontology. The method of abductive reasoning, to which the scientific realist wishes to resort, in this case suggests the abandonment of ontological realism. The posit of one real ontology just does not seem to be the best explanation of the observation that nature is characterized by the existence of empirical equivalent but ontologically incompatible theoretical descriptions. The die-hard metaphysical realist can resist this argument but, by doing so, puts herself at variance with a core principle of scientific realism, the principle of abduction.

There exists an additional aspect of string duality that strengthens the anti-ontological message of string duality compared to other exemplifications of ontological underdetermination. Duality does not just spell destruction for the notion of the ontological scientific object but in a sense offers a replacement as well. By identifying theories with different sets of elementary objects, it reduces the number of independent possible theories eventually down to one. While the uniqueness of the elementary objects is lost, duality thus provides a different quality of uniqueness, the theoretical uniqueness that played the main role in the previous section. The significance of this remarkable process will become transparent later on.

6.3 The Demise of Ontology

Do there remain any loop-holes in duality's antirealist implications? A natural objection to the asserted crucial philosophical importance of duality can be based on the fact that duality was not invented in the context of string theory. It is known since the times of P. M. Dirac that quantum electrodynamics with magnetic monopoles would be dual to a theory with inverted coupling constant and exchanged electric and magnetic charges. The question arises, if duality is poison to ontological realism, why didn't it have its effect already at the level of quantum electrodynamics. The answer gives a nice survey of possible measures to save ontological realism. As it will turn out, they all fail in string theory.

In the case of quantum-electrodynamics, the realist has several arguments to counter the duality threat. First, duality looks more like an accidental oddity that appears in an unrealistic theoretical scenario than like a characteristic feature of the world. No one has observed magnetic monopoles, which renders the problem hypothetical. And even if there were magnetic monopoles, an embedding of electromagnetism into a fuller description of the natural forces would destroy the dual structure anyway.

As discussed already, the situation is very different in string theory. Duality is no "lucky strike" any more, which just by chance arises in one specific scenario. It rather represents a core feature of the emerging theoretical structure and cannot be ignored. Due to the described termination of new phenomena below the string scale it cannot be expected either that new phenomena will arise which could destroy the duality relations.

A second option open to the realist at the level of quantum electrodynamics is to shift the ontological posit. As it was alluded to above, some philosophers of quantum physics argue that the natural elementary object of quantum field theory is the quantum field, which represents something like the potentiality to produce elementary particles. One quantum field covers the full sum over all variations of particle exchange which have to be accounted for in a quantum process. The philosopher who posits the quantum field to be the fundamental real object discovered by quantum field theory understands the single elementary particles as mere mathematical entities introduced to calculate the behavior of the quantum field. Dual theories from this perspective can be taken as different technical procedures to calculate the behavior of the univocal ontological object, the electromagnetic quantum field. The phenomenon of duality then does not appear as a threat to the ontological concept per se but merely as an indication in favor of an ontologization of the field instead of the particle.

The field theoretical approach to interpret the quantum field as the ontological object does not have any pendent in string theory. String theory only exists as a perturbative theory. There seems to be no way of introducing anything like a quantum field that would cover the full expansion of string exchanges. In the light of duality, this lack of a unique ontological object arguably looks rather natural. The reason for that is related to another point that makes string dualities more dramatic than its field theoretical predecessor. String theory includes gravitation. Therefore, object (the 1+1-dimensional string "world-sheet") and space-time are not independent. Actually, it turns out that the string world-sheet geometry in a way carries all information about space-time as well. This dependence of space-time on string-geometry makes it difficult already to imagine how it should be possible to put into this very space-time some kind of overall field whose coverage of all string realizations actually implies coverage of variations of space-time itself. The duality context makes the paradoxical quality of such an attempt more transparent. If two dual theories with different radii of a compactified dimension are to be covered by the same ontological object in analogy to the quantum field in field theory, this object obviously cannot live in space and time. If it would, it had to choose one of the two space-time versions endorsed by the dual theories, thereby discriminating the other one. It might well happen that at some time string theorists will find a more fundamental theoretical basis for string theory that is unique and non-perturbative and from which all 6 theories known today can be derived. This theory, however, should not be expected to be a theory of objects in space-time and therefore does not raise any hopes of redeeming the external ontological perspective.

A third strategy to save ontological realism is based on the following argument: In quantum electrodynamics the difference between the dual theories boils down to a mere replacement of a weak coupling constant which allows perturbative calculation by a strong one which does not. Therefore, the physicist faces the choice between a natural formulation and a clumsy untreatable one which maybe should just be discarded as an artificial construction.

Today, string theory cannot tell whether its final solutions – given they exist - put its parameters comfortably into the low-coupling-constant-and-large-compact-dimension-regime of one of the 5 superstring theories or M-theory. This might be the case but it might as well happen that solutions lie in a region of parameter space where no theory clearly stands out in this sense. However, even if there were one preferred theory, the simple discarding of the others could not save realism as in the case of field theory. First, the argument of natural choice is not really applicable to T-duality. A small compactification radius does not render a theory intractable like a large coupling constant. The choice of the dual version with a large radius thus rather looks like an arbitrary convention. Second, the choice of both compactification radii and string coupling constants in string theory is the consequence of a dynamical process that has to be calculated itself. Calculation thus stands before the selection of a certain point in parameter space and consequently also before a possible selection of the ontological objects. The ontological objects therefore, even if one wanted to hang on to their meaningfulness in the final scenario, would appear as a mere product of prior dynamics and not as a priori actors in the game.

Summing up, the phenomenon of duality is admittedly a bit irritating for the ontological realist in field theory but she can live with it.[34] In string theory however, the field theoretical strategies to save realism all fail. The position assumed by the duality principle in string theory clearly renders obsolete the traditional realist understanding of scientific objects as smaller cousins of visible ones. The theoretical posits of string theory get their meaning only relative to their theoretical framework and must be understood as mathematical concepts without any claim to "corporal" existence in an external world. The world of string theory has cut all ties with classical theories about physical bodies. To stick to ontological realism in this altered context, would be inadequate to the elementary changes which characterize the new situation. String theory simply is no theory about invisible external objects.

7 Consistent Structure Realism

Three distinct statements about string theory's impact on the scientific realism debate have evolved in the previous sections and now await to be put into context. First, the increasing disproportion between the richness of the theoretical structure in modern physical theories and the minimalism of their directly visible effects renders an empiricist stance highly implausible. Second and fully in line with the realist tendency of the first point, string theory gives rise to a principle of theoretical uniqueness that is at variance with the conceptual basis of empiricism. Third, however, the philosophical doubts of scientific non-realists about the stability of the ontological basis of scientific realism are maximally confirmed by string theory. The notion of the external ontological object evaporates in the presence of strings. A joint resume of all three statements conveys a clear message: neither the established brands of scientific antirealism nor the conventional ontological formulation of scientific realism are compatible with spirit and content of string physics.

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[34] From a string theoretical perspective, Dirac's electromagnetic duality of course foreshadows the upcoming situation and represents a good example how what fully emerges in string theory has its roots in prior physical concepts.

String theory thus suggests a middle position in the realism debate, which establishes the objective status of a final scientific theory without ontological connotations. The cogency of this suggestion is enhanced by the fact that the realist and antirealist tendencies of string physics find their sharpest expression based on the same physical concept: the concept of string duality. By reducing the five seemingly independent models of superstrings to different formulations of the same theoretical scheme, string dualities lay the ground for theoretical uniqueness but concurrently deliver the lethal blow to ontological realism. An intermediate position between ontological realism and empiricism thus appears as an immediate consequence of the theoretical structure of string physics.

Moreover, the string-induced arguments pro and contra realism are related to the markedly different fates of two distinct versions of one basic philosophical principle: the principle of underdetermination. While ontological underdetermination assumes a central position in string physics, scientific underdetermination loses its former position. Couched in terms of the concept of uniqueness, the statement may be made more precise: ontological uniqueness, the notion that the theoretical scheme comprises one uniquely identifiable set of elementary ontological objects in space and time, must be abandoned, but uniqueness reappears in the new form of theoretical uniqueness, the notion that the basic layout of our observational world allows only one universal scientific theory (modulo what Quine calls "reconstrucals of predicates"[35] at a fundamental level.

Given that the uniqueness of the real constitutes a core element of any realist conception, it is plausible to interpret the transfer of uniqueness as an indication of a transformation from an ontological towards a structural form of realism. It is instructive to make one step backwards and distinguish two steps of a transfer of the quality of uniqueness which both can contribute to a structural realist understanding. First, the realist posit simply must recede from an ontological to a structural level because the uniqueness claims recede the same way. While no unique ontology of objects in space and time can be imputed any more, there still remains the fact that the various empirically equivalent ontological sets are all covered by one overall theoretical scheme. Thus, at a higher level of abstraction at which a scientific theory cannot anymore be conceived of in terms of putting a specific structure into spacetime, a unique structure can be identified and understood in realist terms. This may be taken to be sufficient for positing some kind of structural realism. The highly abstract level at which structural reality is placed may be considered to be a problematic foundation for an intuitively satisfactory form of realism, however, if no other arguments support a realist conception.

Theoretical uniqueness obviously goes far beyond the uniqueness argument deployed in the last paragraph and thereby adds an important new element to a structural understanding of realism. In a conventional scientific setting that does not imply theoretical uniqueness, one must at each stage of the scientific process expect the possibility of theories which are compatible with the available empirical data but differ from the one specific theory that is realized in the actual world. Two problems therefore arise. On the one hand, it remains unclear how

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[35] See Subsection 6.2.

the currently chosen scientific structures can be related to the real structure in a way that goes beyond the strictly empiricist point that the two are observationally indistinguishable up to a certain level of experimental precision.[36] On the other hand, it seems difficult to pinpoint in what sense the empirically adequate structure acquires reality. The latter problem becomes more troublesome in a scenario where, as discussed above, the real structure cannot be put into space and time.

If the physical description is theoretically unique, however, consistency in connection with the correctness of the deployed basic preconceptions about the characteristics of a scientific theory turns into a sufficient condition for the real existence of fundamental structure. Once there remains only one universal consistent scientific scheme, from that point onwards exhaustive knowledge about the real theoretical structure can not only be acquired by empirical testing but also by pure theorizing. Thus, both questions posed above can find a more satisfactory answer. First, there is a clear way in which the present scientific theories are related to real structure. The real structure is the only possible universal and fully consistent improvement of the limited or not fully developed theoretical structures available today. Current scientific theories thus approach structural reality by extending their own consistent regime. Second, by acquiring a significant degree of epistemic independence from phenomenology, structure assumes a role that goes far beyond what would be acceptable from an empiricist point of view, which justifies a realist interpretation.

In order to use the concept of theoretical uniqueness as a foundational element of a structural kind of realism, the notion that string physics suggests theoretical uniqueness must be turned into the philosophical posit that theoretical uniqueness constitutes an essential quality of our world. Real structure then can be taken to be defined by the fact that it constitutes the unique consistent universal scientific structure. A position along these lines shall be called "consistent structure realism".

Consistent structure realism clearly is related to the kinds of structural realism proposed by Worrall (1989) and Ladyman (1998) based on quite different lines of argument. Worrall argues for structural realism by reassessing the validity of the pessimistic meta-induction. The latter, he claims, successfully undermines the long-term stability of ontological objects but does not offer reasons for doubting the stability of the fundamental structural characteristics of scientific theories (which, according to Worrall, mostly survive theory change). Worrall therefore suggests that structural reality is all that can be grasped by scientific inquiry - though not necessarily all there is. Ladyman questioned the coherence of Worrall's epistemological form of structural realism and suggested an ontic version instead

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[36] This problem was discussed e.g. in Psillos (1999) in the context of structural realism. Since not all aspects of structure are fully transferred from one scientific theory to its successor theory (if so, that would imply the empirical equivalence of the two theories), structural realism must be based on the qualified claim that the structures of present scientific theories can be expected to be similar to the real structure. Based on this similarity claim, the present theories' structural statements may be expected to be approximately true. It is difficult, however, to pin down in which way the similarity between structures can be defined.

that denies reality beyond structure. The string-theory-based arguments which suggest consistent structure realism obviously do not rely on the pessimistic meta-induction, which, according to Section 5, loses most of its significance. Instead, they crucially rely on the demise of ontological uniqueness. While a lack of ontological uniqueness at face value is compatible with the metaphysical posit of ontological reality, it has been argued in Section 6 that core elements of the conception of scientific realism would be at variance with such a posit. In the context of the scientific realism debate, structural implications of string physics thus should work at an ontological rather than at an epistemological level and suggest an ontic form of structural realism. Still, consistent structure realism differs from Ladyman's ontic structural realism in its reliance on purely theoretical epistemic access to structural reality.

Because of the latter, consistent structure realism can be more timid than structural realism with respect to the question of the approximate truth of current scientific statements. Since a theory's closeness to true structure can be gauged by its closeness to the fully universal and consistent theoretical scheme, consistent structure realism can provide a meaningful notion of realism without relying on claims about the truth or approximate truth of current scientific theories. For the consistent structure realist, the unique consistent structure constitutes a crucial but somewhat remote aspect of reality. Any discovery of new theoretical interconnections necessitated by consistency arguments produces new logically true statements, thereby contributes to a better understanding of the character of the true structure and thus reveals something about reality. In case of a fully universal theory like string theory, the true theory is approached by acquiring a better and more complete understanding of the theory in question. At earlier stages of theory development, where fundamental theories have a limited scope, truth is approached by extending the theories' scope. Of course, modern theories in fundamental physics can get and must be hoped to get important input from phenomenology in the form of experimental checks of the scientific statements based on consistency arguments. But phenomenology is not what modern fundamental physical theories are about. It is a long way from the lines on a picture in a particle scattering experiment to the structures of the Standard Model and a longer way still from the falling apple to superstrings. The consistency arguments which lead this way univocally are the true discoveries of modern physics and they represent the microphysical reality that is being described.

Up to this point, consistent structure realism has been developed based on the weak form of theoretical uniqueness. The uniqueness of structure has been exploited without any reference to empirical prediction. The conceptual power of consistent structure realism might be significantly enhanced, though, if it were based on extended or strong theoretical uniqueness. It may be of interest to spend a few thoughts on these scenarios in order to assess the more far-reaching perspectives opened up by the presented kind of analysis.

Extended theoretical uniqueness provides scientific theoretical analysis with the capacity to determine and predict phenomenological regularities uniquely from a certain stage onwards. While weak theoretical uniqueness implied epistemic independence of real structure from phenomenology, its extension thus attributes to real structure the unique observable realization of phenomenological laws. It is not quite clear whether this step can be taken to add substantial strength to the concept of consistent structure realism. On the one hand, it might seem that realism based on unique consistent structure gains plausibility if uniqueness extends to the regime of observable physical objects at some level, since only that step can provide an understanding how consistent structure realism connects to intuitive notions of realism. On the other hand, one might argue that not much is won besides deceptive intuitiveness, since the difference between local and global characteristics of the world loses its fundamental character in string theory and modern cosmology (see Section 5). At a fundamental level, the step towards extended uniqueness thus does not seem to change the character of consistent structure realism.

Strong theoretical uniqueness would constitute a far more fundamental change. It would imply the unique determination of the global and local realization of the world based on theoretical arguments. No room would be left for potentiality once the basic preconceptions about scientific theory building and some qualitative phenomenological information about our world were taken for granted. On that basis, then, reality could be identified with internal consistency, which would offer an interesting new foundation for the concept of realism. If modality were fully dissolved, the question of pinpointing reality would become a mere question of consistency. In the analyzed case, modality is not dissolved entirely but has receded dramatically to the acceptance of basic preconceptions and observations. Reality then becomes a question of consistency on the basis of a core of observational data and the validity of the basic preconceptions. The grasp of the notion of structural reality can be improved by analyzing and specifying the amount of empirical data and the character of basic preconceptions necessary for reaching the regime of theoretical uniqueness. The farther both of these can be rolled back, the stronger a realist position can become.

It is clear that even under the condition of strong theoretical uniqueness theoretical structure remains dependent on phenomenology. As mentioned above, the physical principles which lay the foundations for the evolution of theory building are still rooted in observation. Without a certain amount of observational data about the world none of the physical consistency arguments could get off the ground. In addition, scientific theories still are theories about observables. They predict observable properties and their uniqueness must be understood with respect to their observational predictions. On the other hand, the specific realization of the observational world in a strongly theoretically unique scenario appears like a secondary aspect of consistency arguments. Thus emerges an intricate compound of mutual dependence between observational and structural aspects of reality whose full disentangling lies beyond the scope of the present article.

In conclusion, string physics seems to suggest a position in the scientific realism debate that may be called realist for a number of reasons but differs from classical realist positions in several respects. In the light of what has been said in Section 3, this assessment can be set against the background of genuinely philosophical reasoning that indicates the importance of the search for intermediate positions between classical realism and empiricism. The messages from string physics thus coincide remarkably well with internal needs of the scientific realism debate and could show crucial aspects of that debate in a new light. Physical arguments therefore might turn out to be truly helpful in providing new answers to old philosophical problems. On the other hand, philosophy gains new importance for fundamental physics as well. Subsection 5.4 has alluded to the point that a new philosophical perspective may become necessary to acquire an appropriate understanding of the relevance and status of string theory as a physical theory. We witness strong signs for a novel fertile interdependence between contemporary fundamental physics and philosophy of science. At a time when both fields feel the need to transcend the traditional frameworks their rapprochement comes at hands.

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