SCIENTIFIC REALISM IN THE AGE OF STRING THEORY

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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. Focussing on implications for the realism debate in philosophy of science, it is argued that both poles of that debate become untenable in the context of string theory. On one side the claim of underdetermination of scientific theories, which represents a pivotal element of empiricism, looses its appeal. On the other side 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. An appreciation of string theory's considerable impact on basic conceptions of philosophy of science can also contribute to a clearer picture of string theory's status and relevance in a scientific context.

1: Introduction

In one respect quantum mechanics is like the music of Arnold Schönberg: Its restricted accessibility awards eternal youth. The conception that was created 75 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 intellectual community outside a small group of experts strangely insensitive to the significance of the newer developments in foundational 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. This understanding to some extent is still prevalent in the field of philosophy. To be sure, current physical theories like gauge theory or quantum gravity[1] are being analysed in philosophy of physics. Nevertheless, within the main debates in philosophy of science and metaphysics arguments from modern particle physics still have not achieved the level of recognition they would deserve. String theory in particular, which will be the primary subject of this article, plays a leading role in the evolution of contemporary particle physics but so far has remained fairly unknown territory even for specialised philosophy of physics.

The present article intends to demonstrate that a closer philosophical look at recent particle physics can have far-reaching implications. The concepts that have emerged during the last few decades within theories like gauge theory and string theory reveal deep and unexpected changes in physics' take on physical reality. They suggest philosophical

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

consequences whose significance easily compares to the philosophical impact of quantum mechanics. Modern particle physics can shed entirely new light on important questions in philosophy of science and, transcending that regime, touches the heart of the metaphysical realism debate.

The most advanced theory in physics today is string theory. Replacing the point-like elementary particles of traditional particle physics by miniscule but extended objects, it presently constitutes the only promising approach to provide a unified description of all known natural forces. Due to its physically advanced state string theory also shows the most dramatic philosophical implications. The focus of this work will be on the consequences of string theory for a pivotal debate in philosophy of science, the debate about scientific realism. The article opens with some remarks on the scientific realism debate and its unsolved questions. Thereafter general arguments derived from the status of contemporary physics will reduce the plausibility of scientific non-realism. After a short survey of string theory the two core sections will have a more specific look at two crucial notions in the debate about scientific realism and evaluate their respective status in the light of the new developments in particle physics. Finally an attempt will be made to draw a consistent conclusion from the seemingly contradictory messages which emerge when scientific realism meets strings.

2: Scientific Realism versus Empiricism

The debate about scientific realism derives 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.[2] Now, provided that statements must have an observational implication to be meaningful, the question arises, whether theoretical statements can have any subject beyond observational data at all. Scientific anti-realists 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 any directly visible objects. The scientific realist awards to the electron and the quark the same ontological status as to chairs and tables. His anti-realist opponent understands the concepts of invisible objects as mere technical tools to describe and predict visible phenomena. He claims that, while 'there is a table here' can be a true statement, the assertion 'there is an electron here' can at best be useful but cannot be given a truth value. To be precise two different positions have to be distinguished: The instrumentalist flatly denies that there are any true statements about invisible theoretical objects. Bas van Fraassen[3] pointed out however that there is a less radical way to reject scientific realism. His constructive empiricism acknowledges that statements about theoretical objects can have a truth value in principle but claims that it is impossible to collect sufficient evidence for the truth of any particular statement. Shunning the ontological quality of the instrumentalist assertion, constructive empiricism remains on an epistemological level.

[2] Excluded are solely mathematical statements, which are usually understood as meaningful but a priori.
[3] van Fraassen, 1980.

During the long history of the scientific realism debate realists as well as empiricists have produced a complex web of more or less interrelated objections against their respective opponents. At this point however, I want to narrow down the debate to two important conflicting arguments, which are often considered to represent the core of the dispute: The non-realist's pessimistic meta-induction[4] and the realist's no miracles argument[5].

The antagonism between these two positions finds an instructive formulation based on the principle of underdetermination of scientific theories by experimental data. This well established principle is widely acknowledged as a straightforward consequence of the nature of scientific research: Confronted with a confusing multitude of empirical data, the scientist has the job to concoct theoretical structures that put this data into context, reduce it to a small number of natural laws and allow to predict future behaviour of the known world according to the application of these laws. He has no reason to assume that his theoretical structures are the only ones consistent with the data since no such condition has ever entered his arguments. Thus he cannot expect that his present theories will be consistent with new phenomena discovered in future experiments but must expect them to be replaced eventually by alternative concepts. Philosophers like L. Laudan convincingly argued that new theoretical concepts which were introduced throughout the history of science due to new experimental results and deeper theoretical analysis often contradicted essential statements of their predecessors and even abandoned the older theories' scientific objects. History of science thus shows that not even the core elements of scientific theories are determined uniquely by empirical data. There is no reason to expect that the fate of present scientific theories will differ fundamentally from their predecessors'. Therefore any realist attempt to call statements about present scientific objects true or approximately true must be considered untenable. This is the pessimistic meta-induction.

There is another side to the story however. Natural science shows a distinctive tendency to favour one specific 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 seems at variance with an indiscriminate postulate of underdetermination.

Even more significantly the very same history of science that delivers uncounted examples of fundamental theory change also knows of many instances where theories successfully predicted utterly new phenomena. Newton's laws of gravitation which set out to account for the elliptic planetary movements ended up predicting (nearly) correctly their deviations from elliptic paths. Maxwell's theory of electrodynamics rightly predicted the existence of radio waves. Many similar stories give proof of the predictive power of science. Sometimes theories were not developed to remove a phenomenological anomaly but rather to cure some theoretical inconsistency and still proved able to predict actual new phenomena. The most splendid example is general relativity, which was invented in order to solve the theoretical problem how to reconcile special relativity with gravitation and led to new predictions like the bending of light which were famously confirmed later on.

Such remarkable prophetic qualities of theory choice seem to contradict the underdeterminist view that there exists an unlimited number of different options to fit any set of physical data. Scientific realists claim that scientific success and prediction of new phenomena in particular had to be seen as a miracle if it was not conceded that the statements of science are at least approximately true. This is called the no miracles argument.

We end up in an uncomfortable impasse: Scientific theories look too underdetermined to fit into a realist scheme but not sufficiently underdetermined to allow for empiricism. The history of philosophy of science bears witness how difficult it is to evade this dilemma.

The investigation of the underdetermination hypothesis in the context of contemporary particle physics will play a pivotal role in this work and eventually will show the described

[4] The seminal version of the argument was given in Laudan 1981.
[5] See e. g. Boyd 1990.

impasse in an entirely different light. Before setting out on this path however it is important to emphasise an equivocality in the notion of underdetermination. So far the concept was based on currently available empirical data. The philosophical discourse however also knows a generalisation of the underdetermination hypothesis championed pre-eminently by W. V. Quine[6]. Going beyond the analysis of actual scientific theories Quine claims that even a hypothetical ideal theoretical description that consistently covers all possible experimental data would not be unique. He conjectures the existence of theories which have identical phenomenological consequences but still are 'logically incompatible'. Quine's point of departure is not unproblematic. From a non-realist perspective it is by no means clear that the notion of a theory that matches all possible data is meaningful. An adherent of the modest form of underdeterminism might prefer to avoid all allusions to the doubtful posit of an end-point of scientific inquiry. The analysis of upcoming chapters however will reveal some properties of string theory which award new topicality to Quine's approach.

Though Quine's brand of underdeterminism formally looks like a mere extrapolation from its modest cousin, it is in fact a very different concept. The crux lies in the identification of alternative theories. Modest underdeterminism was able to distinguish its theories by their different predictions of future experimental data. Quine does not have this option. He must distinguish his different theories by purely conceptual means. Clearly he does not want to refer merely to different ways of expressing the same theory, to formulations in different languages or to similar trivial examples. To provide a basis for a more substantial interpretation of his assertion however, he has to rely on the notion of ontology. Quine conjectures the existence of different theories which are logically incompatible because they posit incompatible sets of ontological objects[7]. His statement is one about different ontologies while modest underdeterminism talks about different experimental consequences. Later stages of this paper will show the pivotal importance of this distinction.

3: A Plausibility Argument

The recent evolution of foundational physics has one message for the realism debate that can be appreciated without going into the details of new physical conceptions: Instrumentalism is most plausible in the context of underdeveloped 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.

There exist at least two reasons for this fact. 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 in modern cosmology. Most versions of instrumentalism want to uphold the claim that statements about the past can have a truth value. Now modern cosmology tells us that the universe evolves out of the so-called big bang and its early highly dense stages represent a world void of all macroscopic objects and remote from all classical physical conditions as we know them. The early universe thus does not allow direct visibility any more than microphysical processes today. The instrumentalist therefore is forced to deny 'real existence' to the early universe and, if staying on course, would consequently have to insert his own 'ontological big bang' to denote the point in time when the real world as he accepts it starts to exist. Everything before this point would just be

[6] Quine 1979.

[7] 'Logically incompatible' here actu ally means 'onto-logically incompatible'.

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. I think it is fair to call this conception too awkward to be taken seriously. It must be noted that the present argument does not concern constructive empiricism whose epistemological limits can be placed on the time axis without plausibility problems, thereby providing a nice example for the conceptual superiority of van Fraassen's approach over its more radical instrumentalist cousin.

The second reason for the correlation between increasing theoretical maturity and decreasing plausibility of scientific antirealism equally affects instrumentalism and constructive empiricism: Once the balance between theoretical effort and observational consequence has become too tilted, it gets quite problematic to hold that the theoretical physicist's sound motivations for his activity exclusively lie in the visible regime. A comparison of the situation at the heyday of quantum mechanics with the situation today clearly 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 particle physics, on the other side, the observed respectively expected phenomenological implications of theories like the particle Standard Model or supersymmetry 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 modern particle physics' elaborate theories are nothing more than tools to structure some miniscule lines in Geneva or Chicago[8] simply amounts to declaring the particle physics community a bunch of insane and money-wasting crackpots. Most philosophers nowadays would agree that any insinuation in this direction oversteps the authority of philosophy of science. Past unfortunate excursions of natural philosophy into the realm of scientific prediction have laid solid ground for the conviction of philosophy of science solely to interpret the scientific process and not to censor it. But to concede that the enterprise of particle 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 learn something about quarks, gauge bosons, the hot early universe or the big bang and not just about the weird pattern of lines on a photo. Particle physics by its very existence awards its scientific objects independent relevance. To adopt this attitude however bluntly contradicts the core claims of both instrumentalism and constructive empiricism.

What has been said so far suggests that the current status of experimentally testable particle physics is hardly compatible with the main forms of scientific antirealism – but the most advanced sector of particle physics was not even mentioned yet. For nearly 30 years by now a considerable segment of particle physicists deals with a theory that has never witnessed any direct experimental corroboration at all and is unlikely to do so in the foreseeable future. The theory's breakthrough in 1984, 10 years after its creation, was not caused by any experimental finding but by the solution of a serious mathematical problem that had hampered its evolution before. Still, from 1984 onwards this theory was able to attract an increasing share of the most gifted physicists and attained a highly influential position as the prime candidate for the most fundamental theoretical description of the physical world. String theory, the main character of this story finally enters the stage.

[8] The two locations where the big collider experiments take place these days.

The half way introduction given so far suffices to conclude that physicists who work in string theory are obviously not concerned with the production of tools for the prediction of visible phenomena. Their theory currently is completely incapable of fulfilling that task. String theorists can only be motivated by their interest in theoretical structure per se and, being physicists and not pure mathematicians, nevertheless believe that they learn something about the physical world. Admittedly even the string theorist must demand his statements to be testable by experiment in principle. Observability still constitutes a necessary precondition for attributing meaning to string theory's concepts. The assertion that its potential future visible consequences are the only motivation for string theory's present rich flourishing however just looks absurd. An empiricist position in this context appears as an inadequate attempt to enforce a beloved time-honoured scheme on a new world that has simply outgrown that scheme's range of applicability.

The acknowledgement of empiricism's inability to do justice to the scientific phenomenon of the emergence of string theory does not yet represent a solution to the scientific realism debate. As it has been described above, anti-realists have good reasons not to believe in scientific realism. The crucial question to be approached in this article must be, whether the evolution of particle physics, proving so successful in demolishing the plausibility of positions of scientific anti-realism, can offer a new perspective on the anti-realist's arguments against scientific realism as well. An analysis of this question however will require some knowledge of the physical theories we are dealing with. At this stage we therefore want to leave the philosophical discussion for a while to have a closer look at the world of strings.

4: String Theory

The early 20th century witnessed several epochal shifts in the conception of physical nature. In 1905 special relativity fundamentally changed the understanding of space and time; A decade later general relativity ingeniously expanded this new perspective, making it compatible with the phenomenon of gravity by giving the gravitational force an entirely geometric interpretation; In the 1920ies quantum mechanics opened a world of microphysics ruled by the strange principles of Heisenberg's uncertainty and quantum statistics. A few years later quantum physics had been made compatible with special relativity in the form of quantum field theory. In the 1930ies the heroic age of revolutions was over. The interested public found itself confronted with a physical world view light-years away from the classical conceptions of a generation ago and theoretical physicists were left to struggle with mathematical structures of overflowing complexity in quantum field theory or general relativity.

After world war II investigations into the deeper structure of nuclear interactions revealed an increasing number of new particle types which could only be created for a minimal period of time before decaying back into the standard particles that make up our material world. In the 1960ies it became clear that internal symmetries play a pivotal role in any theoretical description of these new particles. Gauge symmetry, a specific variation of such internal symmetries, proved crucial for a deep understanding of nuclear interactions and disclosed an entirely new understanding of the concept of interaction. The so called Standard Model of particle physics was successful in utilising the concept of gauge symmetry to provide a full description of all nuclear forces.

In the 1970ies there remained one fundamental obstacle to an overall description of all known foundational physical phenomena: Quantum physics stubbornly resisted all attempts to be reconciled with general relativity. As it became increasingly clear, the standard framework of quantum fields did not allow any satisfying solution to this problem. Something completely new was needed. The idea that stepped up to play this role was string theory[9].

Strings were suggested as a replacement for point-like elementary particles already in 1974.[10] However 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 doesn't exist any direct experimental evidence for string theory, today it is acknowledged by a majority of particle physicists as the only serious candidate for the construction of a truly unified theory of the universe. In particular in the United States but increasingly so also in other parts of the world string theory assumes a dominating position in the conceptual discussions and developments of today's particle physics.

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.[11] The fact that strings are extended objects 'smears out' the contact point between any two objects and thus provides a decisively improved framework that seems to allow finite calculations. The seemingly innocent step from point-like objects to strings implies an amazing host of complex structural consequences which create a scenario fully detached from intuitive or observational considerations.

It turns out that 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 so-called Planck length, the characteristic length scale of gravity 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.[12] Recent investigations have shown that the posit of one-dimensional elementary objects implies the additional

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[9] The topical standard work on string theory is Polchinski 1998. The classic book on the foundations of string theory is Green, Schwarz & Witten 1987. A popular presentation for the non-physicist that gives a nice picture is Greene 1999.

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

[11] 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.

[12] Recently it has been demonstrated that it is possible to construct scenarios of large 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. Thu s it is not entirely excluded that strings will some not too distant day become observable after all.

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 behaviour. A particle's characteristics like spin, charge or hypercharge, 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. Finally, 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.

Realistic string theories 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 concerning 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 side strings can also just move along a compactified dimension. Due to basic principles of quantum mechanics momenta in closed dimensions can only assume certain discrete 'quantised' levels. Thus there exist two basic discrete numbers which characterise the state of a closed string in a compactified dimension: The number of times the string is wrapped around this dimension and the number of its momentum state in that very same dimension.[13] Now one of the duality relations of string theory, so called T-duality, says that a model where a string with characteristic length[14] 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 'fuzzyness' 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 chapter 6 where this concept will assume an important role in the philosophical argument. For the time being we want to leave mere physical story-telling and return to the philosophical discussion.

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

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

5: Theoretical Uniqueness versus Underdeterminism

5.1: A sociological detour:

To set the stage for an analysis of string theory's implications for underdeterminism, I want to risk a sociologist's look at its current status. A peculiar disparity of views must be registered. The importance of string theory is rated quite differently by those who work in the field than by the more traditional phenomenological physicists who judge the situation from the distance. Traditional phenomenological physicists are often completely at loss how to understand the significance of string theory. They must acknowledge that a considerable part of the most gifted physicists works in that field but they do not really see why the assertions made by these people should be taken seriously. After all there doesn't exist a single experimental indication of strings. To many phenomenologists string theory therefore is just a rather weird conjecture; And many conjectures less weird and experimentally better corroborated have turned out to be misleading and futile in the past. In sharp contrast the string community itself is carried by an 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, to be sure, is generally acknowledged as a deplorable weak point. Nevertheless, except for an exceedingly sober minority whose exponents see themselves as mere mathematicians, string theorists are convinced to have reached deeper insight into the structure of physical matter than anyone before. 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 phenomenologists concede that string theorists 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.

At first sight the described disparity of views about the validity of a new theory might seem to resemble the side-effects of a normal paradigm change a la Kuhn[15]. However, this one is quite an unusual example for paradigm change if one looks at it carefully. The rift between believers and non-believers does not separate two parties working on the same problem as the Kuhnian picture would suggest. It rather separates those who work on the problem (the unification of gravity and particle physics) and those who don't.[16] This contradicts the generally viable picture Kuhn gives of the structure of the scientific community. Usually scientists believe the experts. If the experts agree on a new theory, the rest of the world, including scientists in adjacent fields, feels compelled to accept their verdict.

The situation gets clearer if one looks at the precise subject of disagreement. Phenomenological physicists do not doubt any specific perspective emanating from the string theoretical formalism. Clearly they would not feel legitimated to do so. They doubt the scientific nature of string theory in general. For them a theory without experimental backing, whatever the details, cannot be called part of natural science. The fundamental disagreement about the value of string theory is not a matter of physical detail, it is a matter of understanding the scientific paradigm itself. If one wants to use the word 'paradigm' as a

[15] Kuhn 1962.

[16] This statement might need some specification. There does exist the established field of quantum gravity that tries to quantise gravitation in analogy to canonical quantum mechanics. String theorists thus are not the only physicists to deal with the question how to reconcile gravitation and quantum physics. Quantum gravity at that level however merely tries to understand the basic problems that arise when gravity goes quantum and does not attempt to integrate gravitation into the full structure of modern particle physics. As far as true unification of gravitation and microscopic forces is concerned, string theory nowadays is adopted by anyone who works on the problem. Most string theorists would argue that the mechanisms which may be discovered in canonical quantum gravity eventually will turn out to merge into string theory.

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.[17] 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. String theory once again infringes on the dominance of observation in science. Theoretical analysis feels powerful enough to leave the regime of empirical evidence and becomes increasingly self-supporting. This implies a more dramatic shift of the scientific paradigm than in the case of the acceptance of invisible scientific objects. The latter changes the meaning of 'observable' by acknowledging the option to measure observables indirectly, but it keeps the experimental primacy fully intact. String theory really diminishes the role of experiment and therefore affects a pivotal pillar of the scientific principle. It does not question experiment's position as the ultimate judge over scientific theory, but it asserts by its self esteem and its flourishing without experimental support, that science can also make relevant statements about the real world on a purely theoretical basis. It says, experiment is important if we can carry it out, but if we cannot, scientific inquiry 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 20th century, scientific progress inevitably enforced this step as many newly discovered phenomena just did not find any other satisfactory explanation. Is there an equally forceful argument for theoretical autarky intrinsic to contemporary particle physics? A full answer to this question requires a closer examination of the structural specifics of modern particle physics. It has to start with a look at the early period of the ascent of gauge theory.

5.2: Early signs of Theoretical Uniqueness:

In the 1960ies particle physics faced a serious problem: It was known that there existed a so called weak interaction which was responsible for nuclear decay and neutrino production. One also had a phenomenological description of this interaction, but that description was not really consistent with quantum field theory.[18] Field theoretical calculations involving weak interaction produced a sequence of infinities that could not be controlled by the techniques developed to deal with similar problems in field theoretical

[17] 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 emphasised: 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 ideally scientific attitude which itself constituted a new position and had never been fully reflected in the scientist's perspective.

[18] The physicist's use of the term 'consistent' in this context does not refer to pure logical consistency. To the physicist a consistent physical description of physical phenomena is a description that integrates these phenomena into one theoretical framework that is able conclusively to provide finite quantitative predictions of the overall system's observable properties. The statement 'quantum field theory did not seem to be consistent with weak interaction' means that a conclusively predictive field theoretical description of weak interaction could not be found. It will be in this wide sense that the term 'consistency' will be used henceforth in connection with physical theories.

calculations of electromagnetic interactions. (Expressed in the language of physics, the theory of weak interaction was not renormalizable.) In order to solve this problem a new theory, non-abelian gauge field theory, was deployed, which led to the nowadays topical understanding of the experimentally testable world of elementary particles, expressed in the famous Standard Model of particle physics.

At the time of its formulation the Standard Model was not supported by any actual experimental evidence. It was rooted, to be sure, in the experiments of the past, which had been the basis for the prior set of theoretical descriptions. The step from these older theories to the standard model however was guided solely by consistency arguments. On this purely theoretical basis the standard model predicted a whole new world of elementary particles. It claimed that weak and strong interaction were carried by some new particles, the so-called gauge bosons, in a similar way as the electromagnetic interaction is carried by photons. It demanded that all matter particles had to fit into symmetry patterns according to their quantum numbers, thereby predicting new types of so far unobserved matter particles. Finally it predicted that there had to exist an enigmatic new scalar particle (the so-called Higgs particle) whose existence was theoretically necessary to understand the massiveness of elementary particles in general.

Two different ways would have been open to doubt the Standard Model's relevance for the actual world. First, one could have argued that another equally viable solution to the problem of renormalisability of the weak interaction might just have been overlooked so far. Second, one could have ventured the possibility that the whole framework of quantum field theory, which provides the basis to formulate the renormalisability problem at all, might be inadequate to describe weak interactions.[19] In the 30 years after its invention however most of the Standard Model's predictions have been experimentally verified, only the Higgs still awaits final experimental evidence. Today the Standard Model is an experimentally well tested theory and has proved an extremely viable guideline for experimental activity. Its success stands as an impressive demonstration that entirely new experimental phenomena can be predicted on a purely theoretical basis, guided by arguments of theoretical consistency.

Now, as described in chapter 2, the Standard Model is by no means the first theory to predict new phenomena successfully. The scope of these predictions and the focus on consistency arguments however create an unprecedented domination of theory over experiment.

Some specific aspects of this development should be emphasised: In traditional physics predictions of new by then unobserved phenomena did not constitute the principal focus of theory development. The structural complexity of a physical theory primarily reflected the complexity of observational data. Newton conceived his gravitational theory to structure the observed movements of massive bodies, Fresnel argued for the wave nature of light to describe observed luminary phenomena in the most suitable way and Maxwell created his electrodynamics to give a coherent structure to the body of observed electrical and magnetic phenomena. A consistent formulation of these theories implied new phenomena beyond the empirical data the theories had set out to describe, like deviations from elliptic planetary movements, unexpected light-spots in the shadow or radio waves. The theoretical deduction of these new phenomena from the new theory however often was not even noticed by the theories' creators and clearly was not what they were longing for. The prediction of new phenomena in those cases, for all its importance for bolstering the trust in the respective theories, might be called collateral benefit. The Standard Model tells an entirely different

[19] It should be noted that an argument of this type applies as soon as one takes the additional step to look for a joint description of microscopic forces and gravity. Gauge theory is not able to provide such a joint description, which leads the way towards string theory. The success of the Standard Model thus obviously cannot be taken to suggest that the old frameworks will work for ever. It merely exemplifies that theoretically satisfactory solutions within the old frameworks, if they exist, do not exist 'in vain'.

story. In its case the existence of a so far entirely unobserved structure of interaction with its host of new particles is the core claim of the theory. The posit of this new interaction structure does not reflect the structural complexity of the observational data available at the time of its introduction but is enforced by the need to formulate a theory that is internally consistent.[20]

Another difference between Standard Model physics and earlier theories lies in the theories' predictive reach. Traditional physics including quantum mechanics could posit the existence of new types of scientific objects solely by observing these objects' effects. A theoretical scheme could interpret some empirical data as the visible effects of a newly posited invisible object. (E. g. particles could be posited based on the observation of some particle traces in a detector.) The Standard Model knows an additional technique to posit new objects: It can deduce them based on consistency arguments. The power of consistency has become sufficiently strong to imply the existence of new objects whose physical effects have not been observed yet. The top quark for example was convincingly predicted long before experimentalists were able to produce any phenomenon which could be interpreted as a top quark effect.[21] Obviously the option to conjecture new objects without empirical backing provides a much stronger basis for theoretical considerations to venture into new lands on their own.

The described structural changes of theoretical power are reflected in a significant shift of the balance between theory and experiment in the physicist's working reality, which sets modern particle physics clearly apart from earlier micro-physics. For the last 30 years particle experiment has lost its role to present new and unexplained data to the theoreticians and mostly serves as a mere testing device for existing theoretical schemes. The truly novel statements are first formulated theoretically to be checked by experiment later. The fact that a theoretical argument has proved capable of determining the course of experimental progress for decades, predicting the discovery of W and Z bosons, new quark types and lepton generations without ever going wrong[22] dramatically increased the trust in pure theorising. The feeling grew that a theory, even if experimentally totally unsupported, can be just too good to be wrong. Theoreticians started to be quite sure about their theoretical predictions just because they seemed theoretically unavoidable. No-one had the slightest doubts about the existence of the top quark during the years of experimental search for it. Few theoreticians doubt today that some kind of Higgs particle does exist, even though it has so far eluded experimental detection. And many theoreticians would bet that supersymmetry will some day be found in collider experiments just because the concept is explanatorily too powerful to be 'neglected' by nature.

It was the strange balance between the astounding 'prophetic' quality of some scientific theories on one side and the pattern of empirical refutation of established theories on the other that created the dilemma of the scientific realism debate. This dilemma is based on the understanding that the scientific process is primarily driven by new experimental data. Though the amazing force of theoretical prediction can be felt regularly, theory in this picture

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[20] There is one physical theory older than the Standard Model that similarly posits entirely new structural riches based on the quest for a consistent theory: General relativity, which of course is the second big land to be covered by string theory. The reason why general relativity is slightly neglected in the present argument is based on the fact that it was modern particle physics that triggered the dynamics leading to string theory.

[21] The first instance of the prediction of particles based on consistency arguments actually is older than the Standard Model. The posit of the anti-particle becomes necessary in relativistic quantum mechanics.

[22] The phrase 'without ever going wrong' refers to those predictions of the standard model, which were understood to be essential to the survival of the gauge theoretical program. As it will be emphasised in a moment, the standard model cannot be fully derived from first theoretical principles and does not determine all physical parameters. Therefore there naturally existed alternatives to the standard model with different symmetry groups or other distinctive features which had to be tested experimentally to be excluded. However physicists were well able to distinguish these hypothetical constructions which might or might not have been corroborated by experiment from the theoretically unique predictions which 'had to be true' to keep the overall theoretical structure consistent.

is always kept on the lead by experiment. It may at times walk in front but can never escape, often has to wait and, if too far ahead, is likely to go astray. I want to suggest that elementary particle physics already at the stage of the Standard Model changes this status quo. Theoretical prediction suddenly is off the lead and wanders at will but nevertheless seems able to stay on track. The dynamics of theoretical evolution is increasingly driven by the attempt to join different elements of already existing theoretical descriptions into one consistent scheme. Though this mechanism becomes increasingly self-sufficient it still keeps being confirmed by empirical tests.

The venerable principle of underdetermination of scientific theories clearly must suffer from this development. For the first time in history of science it might be justified to see scientific progress pre-eminently and consistently characterised by a new principle, which I want to call the principle of theoretical uniqueness: Fully viable theoretical solutions to complex consistency problems tend to be theoretically unique in the sense that there is no alternative that is equally consistent but would predict different future observational scenarios in the disputed regime. The limits of such unique theoretical schemes can be set on a theoretical level by identifying new theoretical insufficiencies or inconsistencies. The dissolution of these inconsistencies once again can lead one step forward without new experimental input. Theoretical uniqueness appears both as a viable characterisation of the new theoretical dynamics based on consistency arguments and a necessary implicit precondition for the physicist's increased trust in experimentally unconfirmed theoretical predictions. The theoretical prediction of new phenomena, which used to play the role of a significant but limited side show of a scientific process mainly driven by empirical discovery, thus conquers centre stage.

Already at this point one might speculate that the old impasse between theoretical predictive power and the principle of underdetermination might be overcome based on the full replacement of underdetermination by theoretical uniqueness. However, while it is important to appreciate the entirely new quality of theoretical predictivity associated with the Standard Model of particle physics, one should not overlook its limitations. Theoretical uniqueness constitutes a crucial element in the evolution of particle physics but it does rule supreme. Neither do solutions which are taken to be theoretically unique precisely predict all aspects of nature nor are most speculative modern concepts in particle physics supported by any claim of theoretical uniqueness. The Standard Model predicts new particles for symmetry reasons but the choice of the actual symmetry group must be based on experiment. Theory does not fix the particles' masses, the strength of interactions and several other parameters. Some important fundamental properties of microphysics like parity violation cannot be derived from gauge theoretical premises at the present stage. Particle experiment therefore is not fully dethroned as the source of new and potentially surprising information. Beyond that, of course no-one can exclude that tomorrow an experiment will give some result that is totally unexpected and unexplainable within the framework of current theoretical understanding. (Actually many particle physicists hope for such a surprise, which would relieve the physicist community for a while from the dull and relentless inevitability of theoretical progress.) Recent theories like grand unified theories, supersymmetry, supergravity or theories of large extra dimensions do not present precise predictions but just give a spectrum of possibilities. Some theoretical structures like supersymmetry are theoretically so convincing that few people doubt they will be found experimentally some day. Others like large extra dimensions are just an interesting alternative that might or might not be realised. Particle physics today could be characterised as an enterprise to parameterise the theoretically possible. To put any effort into this enterprise only makes sense because the spectrum of the possible is strongly restricted. The very fact that physicists adopt it therefore can be seen as an argument for the surprising limitedness of theoretical options. Nevertheless the predictive status of particle physics in the age of gauge theory looks more like an intermediate stage than a radical end-point. The full force of theoretical uniqueness is finally revealed in string theory.

5.3: Theoretical Uniqueness and String Theory:

Gauge theory was introduced as the only discernible way to make weak and strong interactions renormalizable. Similarly string theory claims to be the only conceivable option to remove the infinities which threaten a unified description of quantum physics and gravity. In this sense string theory represents a straightforward continuation of the dynamical theoretical evolution based on consistency arguments that was inaugurated with the standard model. However, string theory has detached itself from experimental corroborations more than any of its predecessors. While the Standard Model in the 1960ies made experimental predictions which were within reach of the next generation of experiments, the experimental implications of sting theory lie so far beyond the grasp of experimentalists that it is not clear how they should ever be tested. The motivation to deal with this theory clearly cannot be based on hope for imminent experimental corroboration but must be based on the confidence that the theory, even while defying experimental testing, can give reason to be taken seriously as a valid candidate of a description of nature.

A good deal of the confidence string theorists have in their analysis is caused by the glorious success theoretical prediction had in the Standard Model. The case for the uniqueness of string theory actually appears more solid than it used to be for gauge theory. Arguably the options for alternatives to strings have been tested more carefully than the founding fathers of gauge theory had checked theirs in the 1960ies and 1970ies. There actually exist sketched arguments that a quite general approach to create solutions to the problems of unification of quantum physics and gravitation inevitably ends up creating string theory[23].

In addition to the plain argument of no choice, the credibility of string theory is enhanced by a considerable number of interconnections which surprisingly fall into place when string theory is pursued. I want to mention two examples to give the flavour of the reasoning involved.

A nice example is the history of supersymmetry. Supersymmetry is a symmetry between particles of different spin, based on an intertwining of the inner symmetries so crucial in gauge theories and the Lorentz symmetries of translations and boosts in special relativity. Initially interest in this concept was motivated mainly by the abstract mathematical question, whether any generalisation of the classical symmetry groups was possible. Soon after the construction of the first supersymmetric toy model it became clear that a formulation of supersymmetry as a gauge-symmetry (=local supersymmetry or supergravity) had an exciting potential to provide a fuller understanding of the particle character of gravity. (The particle corresponding to the gravitational force in a field-theoretical formulation of gravitation, the so called graviton, turns out to be the superpartner of the gauge particle of supersymmetry.) When string theory was developed (in order to get rid of the infinities of quantum gravity), it turned out that a string theory that involves fermions must necessarily be locally supersymmetric. The two ideas of supersymmetry and string theory, initially departing from quite different corners, therefore turned out to be closely connected.

Another example concerns a crucial topic of cosmology, black holes. Black holes are extreme concentrations of matter respectively energy, which lead to the formation of a space-time singularity. Nothing that has come closer to this singularity than a certain distance – the distance of the so called event horizon – can ever flee the black hole again. It was understood in the 1970ies that this situation makes it necessary to attribute a certain entropy to the black

[23] Polchinski 1999.

hole in order to preserve the global viability of the laws of thermodynamics and that the entropy of black holes must be proportional to the area of its event horizon. This was merely a theoretical posit however, lacking any deeper structural understanding. Now it has turned out in the 1990ies that in some special cases of supersymmetric black holes it is possible to give a string theoretical description of the system where the black hole entropy can be understood as the number of degrees of freedom of the string theoretical system. A deep problem of cosmology therefore seems to have a solution in the context of string theory though the development of string theory was never led by an attempt to provide such a solution.

Unexpected interconnections like the two presented above convince string theorists that their theory constitutes much more than a mere theoretical patchwork to deal with some specific theoretical problems. Theoretical constructs which are concocted to solve a certain problem but which do not give any reason to exclude the existence of different solutions cannot be expected to solve new independent theoretical problems which will arise in the future. (History of science knows uncounted examples for theories of that type.) If string theory repeatedly fits into contexts it was not made for, this is only understandable in the light of theoretical uniqueness or unbelievable luck.

The status of string theory can be characterised the following way: Like any other physical theory string theory is based on observations. Observations of the effects of gravitation and the phenomena of microphysics pose problems for a coherent theoretical description whose treatment eventually led to the creation of the string theoretical concepts. The peculiarity of this process lies in the huge 'theoretical distance' that has been laid between the currently observable phenomena and the concepts and scientific objects posited and deployed to integrate them into an overall consistent theoretical scheme. An orthodox scientific outlook that endorses the principle of empirical underdetermination of scientific theories cannot possibly admit that the 'theoretical distance' between present experiment and string theory can be bridged in a way that allows reliable statements about nature. There is only one possible motivation to accept string theory as a plausible candidate for a description of nature: The principle of underdetermination must be undermined by good arguments that string theory is the only consistent way to build a theory in its regime (the regime where both gravity and quantum physics are relevant). The last paragraphs have shown that such arguments do exist and in fact are responsible for the string theorist's trust in his theory.

It is important to appreciate the radical quality of this claim. String theory itself is a conceptually revolutionary theory that is ready to jettison many beloved principles of traditional physics like the point-like structure of elementary particles, the four dimensions of space-time or the formal structure of a quantum field theory. The claim that such a revolutionary novel concept still seems to be the only choice must be based on even more fundamental physical principles. It is a tedious and tricky task to try to list those principles in detail but they will encompass the principle of least action, basic quantum principles, the principles of special relativity, the existence of a gravitational force and probably a few more. The authority of string theory is inherently based on the claim: If you start from these principles and try to build an overall consistent theory, you will be forced to develop string theory.

There remains one problematic point in this picture. The arbitrariness in the selection of the foundational principles seems to reduce the significance of theoretical uniqueness. A fundamentally different choice of physical principles might allow a theory that is compatible with all experimental data but differs from string theory. These doubts cannot be entirely eliminated. Scientific practice however alleviates them by suggesting a coherent pattern of dynamical change of foundational physical principles that is itself guided by theoretical uniqueness. It may be expected that some of those principles which provide the basis for string theory today will be toppled in the future due to a deeper understanding of string theoretical structure. Now let us imagine that a solution of a certain consistency problem has been found by abandoning some foundational principles and leaving others intact. It cannot be excluded, that another solution to the same consistency problem may exist based on the removal of additional foundational principles. Theoretical uniqueness backed by scientific experience of the past implies however, that the phenomenological implications of this alternative solution in the disputed regime will not differ from those of the discovered solution. In this light alternative solutions must be understood as more far-reaching solutions which imply the discovered solution as its effective consequence. Giving up additional foundational principles may anticipate future theoretical evolution but will not change its direction. The example of gauge theory and string theory may be helpful to illustrate this point. Clearly it would have been an option already in the 1960ies to solve the renormalisation problem by giving up the principle of point-like particles, thereby making the theory finite. However, the resulting solution would not have been a conflicting alternative solution to gauge theory since gauge theory is implied by a consistent development of string theory.

Theoretical uniqueness thus prevails based on the following argument: The reduction and dissolution of physical postulates is part of the dynamics of theoretical evolution. Though theory at each stage relies on a specific set of physical postulates, it may become necessary to modify these postulates in further steps towards an overall consistent scheme. Theoretical uniqueness asserts that this ongoing erosion of physical postulates follows a uniquely determined linear path.

It is time to revisit the question posed in section 5.1.: The 'social phenomenon' of the disagreement between string theorists and phenomenological physicists about the status of strings now appears as a symptom of a dramatic shift in the characteristics of scientific theory: In modern particle physics the old conception of underdetermination of scientific theories gradually looses ground against the principle of theoretical uniqueness. In string theory this development finally becomes manifest and induces a new understanding of what can be called a scientific statement about nature. String theorists who experience on a daily basis the astonishing force of consistency arguments and the delicate inner coherence of the resulting conceptions consider the claim of theoretical uniqueness sufficient for the adoption of a full fledged new scientific theory with its own elementary objects and a full universe of strange and unheard of properties. Phenomenologists, having had less encounters with the power of consistency arguments in advanced theories, do not feel ready to follow that path. We witness how the evolution of a scientific discipline reshapes its exponents' understanding of the nature of science.

5.4: Theoretical Uniqueness full grown:

The two previous sections have explained the emergence of theoretical uniqueness by the rise of the power of consistency arguments. String theory in this light continues a development that can be discerned already in earlier particle physics. The following section will demonstrate however, that consistency arguments in string theory reach a qualitatively new level. For the first time one encounters a scientific theory that has theoretical uniqueness built into its structural fabric.

To construct a consistent string theory is extremely difficult. Many theoretical problems have to be solved on the way and it took physicists 10 years to come up with the first formulation of a string that was in principle consistent and able to be a candidate for a description of matter. The quest for a consistent string theory revealed a surprising limitedness of theoretical options. Many choices about the basic layout of the world which had remained free in all previous theories are uniquely defined in the new theory. So it turned out that a string theory capable of describing matter is only consistent in 10 (respectively 11 in case of M-theory) dimensions; That it must be supersymmetric; And that it must involve gravitational force. The arguably most significant restriction however concerns the interaction structure. Classical physical theories must take physical forces as they come. If a new force is being observed by nature, physics starts looking for a theoretical structure that fits its phenomenology. In quantum mechanics things get more complex since arbitrarily created new interactions produce uncontrolled infinities in calculations. Gauge theory offers a recipe how to create 'innocuous' interactions based on gauge symmetries. Still, as was noted above, lots of different gauge interaction structures remain possible. The actual choice must be based on experiment. String theory, due to the necessity of anomaly cancellation, allows only very few fundamental symmetry structures. In the 1980ies it was believed that there exist 5 possible types of superstring theory. In the 1990ies it turned out that even these 5 theories most likely just represent different formulations of the same theory. If you want to make a world out of strings, there is only one way to do it.

But the uniqueness of string theory does not stop here. Beyond the fact that there is only one string theory this theory has no free parameters. As it was emphasised above, the formulae of the Standard Model of particle physics involve many parameters like masses of particles or interaction strength, whose values are not determined by the theoretical structure but must be found out by experiment. In this respect the Standard Model is like all previous theories in the history of physics. Neither Newton's nor Einstein's laws explain the size of the gravitational constant, Maxwell's equations do not predict the charge of the electron and quantum mechanics does not derive the size of the fine structure constant. Physical theories describe forces but usually they do not explain their strength. String theory however, being the first theory to provide a consistent description of all known forces, does exactly that. Its structure does not allow the insertion of free parameters any more. The mere fact that the world can be described by string theory provides the univocal foundation for the unfolding of physics and its low energy phenomenology.

In how far the lack of free parameters of string theory translates into one inevitable set of parameters of low energy theories like the Standard Model is not clear at this point. String theory understands the Standard Model parameters as effective parameters which are uniquely determined by string theoretical features like the value of the string coupling constant or the radii of the compactified dimensions. These stringy features again are 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 energetically favoured ground state. The path towards this energetically favoured state however is not uniquely determined since string theory is a quantum theory whose probabilistic choices at the early stages of the universe can have grand effects later on[24]. Now if there exists one clearly distinguished energetic minimum it can be expected that the quantum physical dynamics of the universe will eventually find it.[25] In this case string theory would uniquely predetermine one set of low energy parameters. It might as well be the case however that the energy potential of string theory shows several or many local energetic minima which are nearly ore absolutely degenerate and which all have the potential to serve as the final state of string theory dynamics. For example different shapes of the space of the 6 compact dimensions could be energetically similar so that it depends on the accidental outcome of some quantum fluctuation which one is chosen during the early stages of the

[24] 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.
[25] If there exist several local minima but one minimum has a much lower energy level than the others it can be expected that the lower one will eventually be reached by quantum tunnelling.

universe.[26] Therefore a direct and unique translation of the structure of string theory into Standard Model parameters would be the most attractive outcome but cannot be taken for granted.[27] What is clear however and what constitutes the crucial statement for the present line of argument is the fact that the theoretical structure itself cannot be adapted to experimental results. If anything might remain open to experimental determination it is the specific dynamics of the world which is driven by probabilistic quantum processes.

We see that the widening of the overall scope of consistent theoretical description narrows down the freedom of choice within the theory until, once all physical forces are included in one scheme, nothing is left of it any more. It was argued before that the ambitious attempt to join gravity and quantum physics seems to leave the physicist with only one theoretical way to go – the way towards string theory. Now, having followed that path, we see that little to no freedom is left to experiment either. All experimental outcomes are predetermined modulo quantum fluctuations by string theory's structure. Joining the two arguments results in an amazing power demonstration of the consistency argument: The acceptance of a few very basic postulates of physics inevitably implies a theoretical structure without any fundamental free parameters and consequently determines all properties of the observed world.

The described development may be taken as a considerable further strengthening of the principle of theoretical uniqueness. It must be noted however, that the term 'theoretical uniqueness' has acquired a more complex meaning on the way: The concept was introduced to denote the univocal determination of theory dynamics by the experimental status quo. Now it is expanded to signify the univocal determination of quantitative empirical data by qualitative theoretical structure. Chapter 7 will reflect on the deeper philosophical significance of this more far-reaching interpretation. At the present stage it just remains to be emphasised how forcefully the mature form of theoretical uniqueness contradicts instrumentalism and modern empiricism. All associations of the theoretical scheme with a tool to structure the visible phenomena have disappeared. There remains neither the freedom to choose an appropriate tool nor to adjust the alleged tool to the object it is meant to be applied to.

The apparent omnipotence of the theoretical scheme in the context of string theory requires an essential qualification however: Theoretical claim and actual capability are farther apart than in any prior scientific theory. The overwhelming power string theory claims to have in principle stands in sharp contrast to the string theorist's modest daily reality. Though the theoretical uniqueness of string theory would in principle allow the determination of all parameters of low energy phenomenology, today the string theorist's ability to predict experimental results is non-existent.[28] Progress in string theory today is entirely restricted to

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[26] Once the universe has cooled down the lower energy density makes changes between different ground states more and more unlikely. The parameters chosen at the early stage of the universe are 'frozen' and usually don't change any more later on.

[27] The amazing drift towards uniqueness that has characterised the evolution of string theory so far might nourish the expectation that some surprising mechanism will show up once again to single out one unique string theory ground state at the end. No solid arguments today hint in this direction however.

[28] This sentence might need clarification. It was mentioned before, that a direct experimental test of string theory, i. e. a test of the extendedness of elementary particles, is far beyond the grasp of current experiments. Due to the theoretical uniqueness of string theory however, the mere fact that the theory is correct in principle would determine all low energy phenomenology of the world modulo a possible degeneracy of the string potential's energetic minima. Therefore it would be possible in principle to check whether all parameters of the microscopic world we know, from the mass of the electron to the number of particle generations, correspond to an energetic minimum of the string theory potential. If that was actually the case it clearly would constitute an overwhelming proof of the significance of string theory for nature, even if no one had ever seen a string directly in an experiment. It is this indirect way to test string theory by making theoretical contact with existing experiments that is addressed in the present context.

improvements of the understanding of the theoretical structure without ever reaching the spheres of actual predictions of any testable phenomena. The string theorist faces a huge mountain of unsolved conceptual and technical problems piled up between him and the actual acquisition of the mathematical power necessary to redeem string theory's fantastic predictive promises. These technical difficulties at times seem so inaccessible that one might be led to doubt whether they will ever be surmounted. It should be admitted at this point that this is not an absurd thought. The possibility that rational scientific inquiry eventually bites on granite cannot be trivially discarded. Inclinations to put aside such elementary doubts about the power of science are based on the prevalent feeling of scientific confidence, the encouraging examples of eminent scientific difficulties in the past that eventually found a solution, and the troublesome question, what a fundamental block to scientific progress would do to the status of rationality in general. Despite their actual inconclusiveness these 'arguments' suffice to make most physicists and most philosophers believe that at least questions clearly posed by science – if not those posed by philosophy – do have a scientific answer.[29]

Provided that science is in principle able to find solutions to the specific technical problems that stand between string theory and the fulfilments of its theoretical claims we face an interesting picture: string theory projects a far-reaching ideal realisation of its principles that is rather remote from the scientific state of the art but whose fundamental status and predictive force are well determined. No-one today is able to predict the shape of string theory at some more advanced stage. It might well be the case that on the way some foundational principles of today's physics will have to be modified and that foundational physics will become quite a different field than what it is today. But some things about the future evolution of string theory can be confidently predicted: The future theory won't have free parameters; And due to the theoretical uniqueness inherent in string theory the evolution towards the theory's full realisation could in principle be followed on a purely theoretical basis without any experimental guidance (which does not deny that experimental input might be of crucial importance in the actual process).

The underdeterminist picture of several alternative fully consistent theories able to match a certain experimental data set thus has been replaced by an entirely different picture: The fully consistent theory today serves as an ideal vanishing point of theoretical evolution, able to guide the evolutionary process. While the underdeterminist felt confident enough to boast with his ability to construct any number of consistent theories, for physicists at the age of string theory it would be the fulfilment of their ultimate dreams if they knew just one.

One more novel feature of string theory has to be mentioned to make the story complete. The classical picture since the beginning of the 20th century understands progress of physics in terms of sensitivity for ever smaller distances. The more closely one looks at things, the more unexpected phenomena become observable. At a certain distance scale physicists start to see atoms, at others they start to see step by step nuclei, nucleons, quarks, heavy particle generations and eventually – potentially – the extendedness of strings. The string scale lies close to the Planck scale, the characteristic scale where gravity becomes as strong as the nuclear forces and thus requires a joint description of all types of interaction. As we know by now, string theory is the only existing candidate for such a joint description. A certain finality is in the air as we finally face a theory that covers all known physical phenomena. But what does that mean for even smaller distance scales? Shouldn't it be expected that at even smaller characteristic distances new phenomena will emerge once again?

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[29] It must be conceded that the distinction between physical and philosophical questions is not always easy to draw. However, many questions current string theory attempts to answer, for example how to calculate string scattering without being in a perturbative regime, are univocally scientific.

String theory's answer to this question is based on the phenomenon of string dualities. As described in chapter 4 string dualities identify apparently very different theories with different values for some characteristic parameters. The example of T-duality has already been presented. Any theory with a compactification radius R lower than the characteristic string length *l* can also be formulated as a theory where the ratio compactification radius over string length is inverted. This fact eventually implies that all tests of distances smaller than the string scale can be understood as tests of correspondingly larger distances as well. String theory thus enforces a minimal length scale below which information becomes fully redundant. The sequel of ever new observable phenomena at ever smaller distance scales is terminated. If we know all phenomena down to the string scale, we have exhausted all phenomena the world can offer. The string scale therefore represents a truly distinguished marker: Besides being the scale where the specific phenomena become entirely determined by abstract physical principles it also represents the endpoint of possible new phenomenological information.

To be sure, this does not imply that string theory marks the end of scientific progress. It should be remembered that the 'microphysical period' of physics that found new information by focussing on ever smaller distances emerged from a previous situation where physics within the paradigms topical at that time seemed more or less to have come to an end. In the same vein it must be expected that once again new directions will open up for a further deepening of the understanding of physical nature. New progress that leads beyond string theory however will most probably not be a search for new ever smaller physical structures which can (in principle) be experimentally tested. It will be restricted to theoretical progress, providing a deeper understanding or further reduction of the foundational physical principles and explaining aspects of nature which do not look explainable by physics today.

Once again we register a clear departure from the underdeterminist scenario. The underdeterminist paradigm of science construed an isotropic space of scientific evolution where the state of science remains unaltered along the time axis modulo some rescaling of experimental success. In this world scientific progress is a never ending and ever unchanged continuous process of theory refutation and theory change based on an eternal stream of new experimental input. It is a process that offers no foot-angles for the notion of approximation towards truth. String theory tells a different story. It explicitly introduces a limit to new phenomenological observations and therefore breaks the underdeterminist 'continuum hypothesis'. This fits nicely into the picture of a fundamental turning point for the status of theory that was presented earlier on.

Putting all pieces together, string theory suggests a radically altered assessment of the old antagonism between underdetermination and theoretical prediction. To understand the significance of this shift, we start with another look at the impasse between realism and empiricism sketched in chapter 2. The uneasiness of the status quo was due to the significant elements of cogent theoretical conclusion and successful prediction in science which could not be reconciled with the equally undeniable elements of underdeterminism. This unsatisfactory balance can be observed in all classical philosophical attempts to undermine the status of underdeterminism. A nice example are the discussions around 'deduction from the phenomena', which have drawn some attention in recent years. [30] Newton had 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 claim and went on to stress the seemingly unique way physical theories are often enforced by experimental data. Norton for example re-emphasised how quantisation was forced upon physics by experiment. Indeed the emphasis on deduction from the phenomena seems to demonstrate that the case for underdetermination is

[30] See e. g. Norton 93 & 94 and Worrall 00

not as straightforward as some empiricists might want to believe. However this clearly does not come up to a full scale refutation of underdetermination. Deductions of theories 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. So 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 physical theory 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 to deal with the problem of pessimistic meta-induction. First there is the actual status quo of string theoretical research. String theory today is highly incomplete and actually looks more like a theoretical guideline towards future developments than like 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. Underdeterminism however cannot profit from this fact any more. In the traditional picture scientific evolution was taken to be carried by a sequence of fully consistent theories. Each of these theories described a limited data set correctly and some day became or was expected to become obsolete due to new significantly contradictive data.[31] The pessimistic meta-induction directly implied underdeterminism since each new theory had to be at least as 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 has to be seen as a merely partially consistent construct. The present theories must be understood to be preliminary because they are theoretically insufficient and incomplete. Underdetermination of the theoretical scheme by experiment does not follow since the whole process of theory change has been shifted to a theoretical level. On this theoretical level the preliminary character of topical theoretical schemes works against underdeterminism rather than in its favour. 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.[32] Directedness and power of this process suggest that theoretical uniqueness transcends its formerly restricted status and supersedes the principle of underdetermination as the defining characteristic of scientific progress.

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 confidently predicted already today. This knowledge suffices to justify the assertion that a full string theory must explicitly break the pessimistic meta-induction. If a full formulation of a consistent string theory could be found one day, only two options would be open to evaluate its status. Either this theory turns out to be a dead end without any relation to the physical world – which seems hard to imagine considering the arguments presented in the previous sections but which cannot be entirely ruled out today -, 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 cannot be considered a viable but refutable intermediate step in the evolution of science in the sense of the pessimistic meta-induction.

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

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

The emerging scenario overcomes the traditional impasse between underdeterminism and theoretical prediction by denying to underdetermination the status of an 'eternal' characteristic of scientific theory. The underdetermination of traditional scientific theories by experiment appears as a historic feature of a period of natural science that has not yet reached the level of theoretical interconnectivity necessary to feel the full force of internal consistency arguments. Those theories' successful predictions of new phenomena on the other hand can be understood as precursors of a quality of theoretical uniqueness that characterises science at a more mature stage.

String theory has turned out to be a substantially novel type of physical theory with significant implications for philosophy of science. It is important to emphasise once again however, that the radical messages of string theory do not come like a bolt from the blue bound up with an isolated hypothesis that might vanish as fast as it has appeared. We have seen that the disempowerment of observation and the emergence of theoretical uniqueness look back on a continuous evolution whose traces can be followed deep into physics' past. String theory opens a new chapter by showing these phenomena for the first time in a fully grown state. We face a continuous development that inescapably leads to an entirely new paradigm of physical progress. In this light it seems clear that value and substance of the findings of string theory cannot be adequately appreciated without acknowledging the thereby implied changes of the scientific paradigm. To deny string theory's status as a theory about nature on the basis of the time-honoured principle of the experimental monopoly on confirmation of theoretical hypotheses without considering the intrinsic arguments which support this theory in the eyes of its experts would mean to ignore scientific progress for the sake of prejudice. Obviously this does not imply that string theorists are infallible. It merely suggests that several decades of dynamical research which have resulted in a consistent overall shift in the understanding of the role and the status of scientific theory should be taken seriously.

At the end of this chapter the world looks bright for the realist. The dispute about underdeterminism, a core dispute between realists and anti-realists, seems to lean strongly towards the realist side once string theory has been taken into account. However, the game is not over yet. There remain other problems for the realist to address. One of them, the problem of ontology, will be the topic of the next chapter.

6: Duality versus Ontology

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 Niels Bohr to Bernard d'Espagnat[33], asserts the genuinely non-realist quality of the quantum world. This conviction rests on two argumentative pillars. First, 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. Second, the fact that the indeterminist element is not homogenously embedded in the physical equations but must be imposed 'by hand' using seemingly artificial notions like the contraction of the wave function, somewhat detaches this important part of quantum mechanics from what one could understand to be the external situation described by

[33] See e. g. D'Espagnat 85.

objective physical laws. The contraction of the wave function thus may appear attributable to the non-objective regime of human observation, which would render the whole body of quantum theory non-objective and therefore fundamentally non-realist.

The present status of quantum physics leaves enough room though to avoid anti-realist conclusions. To begin with, the hidden parameter models of Bohm[34] or Bell[35] are able to provide a deterministic and profoundly realist interpretation of quantum physics. They are forced to sacrifice locality due to Bell's inequalities and may show some deficiencies in plausibility and aesthetic appeal, but the mere fact of their existence suffices to demonstrate that realism is no forlorn case in the quantum world.

A canonical understanding of the laws of quantum mechanics does not imply non-realism either.[36] The claim that non-objectivity is enforced by the canonical laws of quantum physics mainly rests on the fact that no convincing integration of the contraction of the wave function into an objectified formal description of quantum processes has been found so far. This deficiency of the quantum mechanical state of the art however does not look like a very strong argument against the possibility of such integration in the future. In particular it may well be expected that a full integration of gravitational physics into quantum physics will lead to a fundamentally altered view of the phenomenon of the contraction of the wave function.[37] If the threat of non-objectivity should prove unfounded however, the probabilistic and indeterminist elements in quantum physics could well be treated as modifications of the conception of physical objects without abandoning the latter's status as external ontological objects. After all, the step to invisible objects itself or the acceptance of the new space-time structure of relativity required similar deviations from intuition and yet did not destroy scientific realism.

Still, there remains an irritating question for the scientific realist: 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 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?

Quantum mechanics cannot answer this question. Contemporary physics is in a quite different position. I think that the full dissolution of ontology is a characteristic process of particle physics whose unfolding starts with quantum mechanics and gains momentum in gauge field theory until, in string theory, the ontological object has simply vanished. This remarkable development in my eyes is closely related to the phenomenon of theoretical uniqueness and constitutes a natural consequence of the rising power of theory. A stringent step by step argumentation of this assertion would require an extensive discussion based on a thorough analysis of the concept of the ontological object, its core properties and its function in the philosophical realism debate. As the present work is not primarily concerned with metaphysics, it seems advisable to postpone that full discussion to a future more fitting occasion. In the present context I want to restrict myself to the '(un)happy end' of ontology's demise and will only discuss one specific feature of string theory, which constitutes the actual climax of modern physics' anti-ontological tendencies.

The concept to be considered is string duality, which already played a role in the previous chapter. There we encountered the remarkable phenomenon of T-duality according to which a string wrapped around a small compact dimension can as well be understood as a

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[34] Bohm 52.
[35] Bell 87.
[36] For a canonical but still realist interpretation of quantum mechanics see e. g. Redhead 87 & 95. As an example for the decidedly realist spirit of many standard textbooks on quantum mechanics, see Messiah 69, 'Mecanique Quantique', Dunod, Paris, chapter 4.4.1.
[37] 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.

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 undistinguishable 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 external world. They differ in the shape of space-time and they differ in form and topological position of the elementary objects. The fact that those characteristics are reduced to technical parameters whose values depend on the choice of the theoretical formulation contradicts ontological scientific realism in the most straightforward way. If a situation can be described by two different sets of elementary objects depending on the choice of the theoretical framework, how can it make sense to assert that these ontological objects actually exist in an external world?

The question gets even more virulent as T-duality by no means remains the only duality relation that surfaces in string theory. It turns out that the existence of dualities is one of string theory's most characteristic features. They seem to pop up wherever one looks for them. 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 6th 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 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 was mentioned in chapter 4, 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. So 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.

An evaluation of the philosophical implications of duality in modern string theory must first acknowledge that the problems to identify uniquely the ontological basis of a scientific theory are as old as the concept of invisible scientific objects itself. Complex theories tend to allow the insertion of ontology at more than one level of their structure. It is not a priori clear in classical electromagnetism whether the field or the potential should be understood as the fundamental physical object and one may wonder similarly in quantum field theory whether that concept's basic object is the particle or the field. Questions of this type clearly pose a serious philosophical problem. Some philosophers like Quine have drawn the conclusion to deny any objective basis for the imputation of ontologies. Philosophers with a stronger affinity for realism however often stress that there do exist arguments which are able to select a preferable ontological set after all. It might also be suggested that ontological alternatives at different levels of the theoretical structure do not pose a threat to realism but should be interpreted merely as different parameterisations of ontological reality. Without going any deeper into this debate, it may suffice to register that the problem 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[38] into space-time and the philosopher struggles with the question at which level ontological claims should be inserted.

The implications of string-duality have an entirely different quality. String duality really posits different ‘parallel’ empirically indistinguishable versions of structure in space-time which are based on different sets of elementary objects. This statement is placed at the physical level independently of any philosophical interpretation. Thus it transfers the problem of the lack of ontological uniqueness from a philosophical to a physical level and makes it much more difficult to cure. If theories with different sets of elementary objects give the same physical world (i. e. show the same pattern of observables), the elementary object cannot be seen as the unique foundation of the physical world any more. There seems to be no way to avoid this conclusion.

There exists an additional aspect of duality that underlines its anti-ontological character. 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 chapter. The significance of this remarkable process will become transparent later on.

Do there remain any loop-holes in duality’s anti-realist implications which could be used by the die-hard realist? 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 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.

In string theory the situation is very different. Duality is no ‘lucky strike’ any more, which just by chance arises in a certain scenario that is not the real one anyway. As we have seen, 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 behaviour of the quantum field. Dual

[38] 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.

theories from his perspective can be taken as different technical procedures to calculate the behaviour 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 favour of an ontologisation 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 to introduce 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 appears rather natural. The reason is related to another point that makes string dualities more dramatic than its field theoretical predecessor. String theory includes gravitation. Therefore object (the string geometry) and space-time are not independent. Actually it turns out that the string 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 realisations 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 shall 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 rise any hopes to redeem 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 choice is open 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 solution will 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 the solution lies in a region of parameter space where no theory clearly stands out in this sense. However, even if there was 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 looks more like a convention than anything else. 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 he can live with it.[39] 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

[39] 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.

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 characterise the new situation.

The demise of ontology in string theory opens new perspectives on the positions of Quine and Laudan. We remember that Laudan stressed the discontinuity of ontological claims throughout the history of scientific theories. String theory's comment on this observation is very clear: The ontological claim is no appropriate element of highly developed physical theories. External ontological objects are reduced to the status of an approximative concept that only makes sense as long as one does not look too closely into the theory's mathematical fine-structure. While one may consider the electron to be an object like a table, just smaller, the same verdict on, let's say, a type IIB superstring is not justifiable. In this light it is evident that an ontological understanding of scientific objects cannot have any realist quality and must always be preliminary. Its specific form naturally depends on the type of approximation. Eventually all ontological claims are bound to evaporate in the complex structures of advanced physics. String theory thus confirms Laudan's assertion and integrates it into a solid physical background picture.

In a remarkable way string theory awards new topicality to Quine's notion of underdeterminism. To begin with, the string theoretical scale-limit to new phenomenology that was discussed in chapter 5 makes Quine's concept of a theoretical scheme that fits all possible phenomenological data much more understandable. In a sense string theory moves Quine's concept from the regime of abstract and shadowy philosophical definitions to the regime of the physically meaningful. Quine's notion of underdeterminism also remains unaffected by the emerging principle of theoretical uniqueness, which so seriously undermines the position of modest underdeterminism. Since theoretical uniqueness reveals itself in the context of new so far undetected phenomenology, Quine's purely ontological approach remains safely beyond its grasp. But the best is still to come: The various equivalent superstring theories appear as empirically equivalent but 'logically incompatible' theories of the very type implied by Quine's underdeterminism hypothesis. Arguably they are the first truly convincing examples for Quine's concept. It is interesting to see how they underline the ontological quality of Quine's conjecture that has been emphasised in chapter 4: The different string theories are not theoretically incompatible and unrelated concepts. On the contrary they are merely different representations of one overall theoretical structure. Incompatible are the ontological claims which can be imputed to the various representations. It is only at this level that Quine's conjecture applies to string theory. And it is only at this level that it can be meaningful at all.

Having acknowledged Quine's rejuvenation, at this point I nevertheless want to depart from his path. Quine is no adherent of external realism and thus can afford a very wide interpretation of the notion 'ontological object'. For him a world view's ontology can well comprise oddities like space-time points or mathematical sets. In this light the duality phenomenon could be taken to imply a shift of ontology away from an external 'corporal' regime towards a purely mathematical one. Quine himself suggested the appropriateness of such a move based on the messages from quantum field theory.

In my eyes however, to put external and mathematical ontologies into the same category blurs the central message the new physical developments have in store for philosophy of science. This message emerges much clearer if formulated within the conceptual framework of scientific realism: An extrapolation of the notion 'external ontological object' from the visible to the invisible regime remains possible up to quantum field theory if one wants to have it. It fails fundamentally at the stage of string theory. String theory simply is no theory about invisible external objects.

7: Synthesis

Three distinct statements about string theory's impact on the scientific realism debate have evolved in the previous chapters 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 or instrumentalist stance highly implausible. Second and fully in line with the realist tendency of the first point, string theory (and to a certain extent already gauge theory) gives rise to a principle of theoretical uniqueness that is at variance with the core argument of underdeterminism. 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 just evaporates in the presence of strings. A joint resume of all three statements conveys a clear message: Neither the established brands of scientific anti-realism nor the conventional ontological formulation of scientific realism are compatible with spirit and content of modern particle physics. One natural conclusion from this assessment comes to mind: Particle physics seems to suggest a non-ontological formulation of scientific realism.

There does exist a widely discussed attempt in recent philosophy of science to formulate a kind of realism that does not rely on ontology[40]. John Worrall's Structural Realism[41] is an answer to Laudan's arguments against the cumulative character of scientific evolution. Worrall agrees with Laudan's judgements as far as the ontological interpretation of scientific theories is concerned. He argues however, that it is possible to isolate a 'structural' dimension of scientific theories that shows continuity from one scientific paradigm to the next and therefore allows a cumulative understanding. He gives the example of the ether theories where the ontological aspect (the ether itself) was refuted but the structural aspect (the wave equations describing radiation) prevailed. Based on this observation Worrall suggests to attribute reality solely to the structural aspect of science without ontological underpinnings.

The idea is interesting but faces a serious problem.[42] Clearly any experimental data that suggests a shift in ontology must also affect structural aspects of the theoretical scheme. An ontological claim without structural implications remains beyond the grasp of natural science. Therefore a strict dichotomy between preserved structure and volatile ontology cannot describe scientific progress. Worrall acknowledges this fact and retreats to the claim that those structures which are abandoned during physical evolution, unlike the abandoned ontological claims, constitute approximations of their respective successors. There always exists a limiting case in which old and new structure become identical. Based on this structural similarity Worrall wants to hold that structural statements are at least approximately true, which would be sufficient to allow meaningful Structural Realism. Worrall's notion of similarity is quite problematic however. A line is a limiting case of a rectangle, but should it be called its approximation? In a similar way Einstein's gravity suggests a totally different structure than Newton's. The fact that the approximation argument makes sense is based entirely on the phenomenological perspective. If human observation up to a certain precision

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[40] The line of ancestors of this approach goes back to H. Poincare, see e. g. Poincare 1902.
[41] Worrall 89.
[42] A recent criticism of structural realism can be found in S. Psillos 99.

cannot distinguish between the phenomenological implications of two theoretical structures, one can be called the other's approximation. Once phenomenology has entered the definition of similarity however, the bottom line of Worrall's statement becomes: Successive theoretical structures are similar because they describe the same phenomenology up to a certain precision. The topical theoretical structure thus cannot tell anything about future structures beyond the trivial fact, that they will be compatible with current experiments. This looks like an entirely empiricist position. It is rather doubtful whether it can serve as a foundation for any type of scientific realism. Structural Realism has serious problems to delimit itself from empiricism because it lacks an intrinsic non-empiricist guideline towards real structure.

The following paragraphs will show that the principle of theoretical uniqueness naturally leads the way towards a form of realism that bears quite some resemblance with Structural Realism but does not share its main problem. The very arguments from particle physics which stress the need for a non-ontological version of scientific realism are fair enough to offer a strategy as well that might bring it to life.

In order to understand the cogency of a non-ontological form of realism in the context of contemporary particle physics, it is helpful to approach the situation from a slightly different angle. Arguments based on theoretical uniqueness can be understood as an extension of inductive reasoning. Induction presupposes that the patterns suggested by observations of the past are in a well defined way applicable to the future and therefore allow the prediction of future events. Theoretical uniqueness asserts that the patterns suggested by observation of a subset of phenomena have a unique consistent theoretical structure and therefore justify the prediction of yet unknown observable phenomena. While classical inductive reasoning predicts the continuation respectively new occurrence of known phenomena, consistency arguments based on theoretical uniqueness predict genuinely new phenomena.

This extension of the predictable regime however enforces an extension of the notion of reality. The principle of induction can be incorporated into - and actually constitutes an indispensable element of - the notion of the ontological object. The latter includes a future perspective and thus works on the basis of the expectation that the object's fu ture appearance can be recognised due to some kind of continuity leading from past to future. Whether visible objects suffice to support the inductive reasoning of natural science may be disputed between instrumentalism and ontological scientific realism, but both parties agree that physical reality can be exhaustively characterised by external objects existing in space and time.

Theoretical uniqueness can not be incorporated into the notion of the ontological object. It tells something about an interconnectivity of all phenomena that is not placed in space and time and is not a property of any specific object. It constitutes an irreducible characteristic of overall reality. Understanding reality thus cannot be reduced to understanding ontological objects and their properties. An example might elucidate the difference between the position of reality in classical inductive reasoning on one hand and in consistency arguments on the other: The expectation that some massive body will behave according to Newton's laws is based on inductive reasoning and can be understood as an appraisal of that body's properties. It is fully compatible with a notion of reality that is restricted to bodies in space and time. To the contrary, the statement that the top-quark must exist in order to make particle theory consistent neither stresses a property of the top quark nor of any other part of the world. It must be taken as a statement about overall reality. Two options remain to define the relation between this statement and reality. One could deny that statements of this type tell anything about reality at all. This would deprive the majority of discoveries in modern physics of all reality content, ignore the important shift in the character of scientific theories that stands behind the new type of scientific statement and fail to respect the physicist's appreciation of his own investigations. For the physicist it is as important a discovery that the top quark MUST BE as that it simply IS. The alternative is to award reality to the consistent structure itself.

Now having acknowledged the need for what I want to call 'Consistent Structure Realism', the question remains how such a concept can be made meaningful. The extended form of theoretical uniqueness that arises in string theory according to section 5.4. proves to be crucial in this respect. Theoretical uniqueness in its 'modest' form singles out one theoretical scheme based on phenomenological data. Theory remains dependent on observation since experimental data is necessary to fix the theoretical parameters. To attribute reality to theoretical structure at this stage thus can only posit a subordinate real aspect of the observational world. Theoretical uniqueness in the extended form discovered in string theory however enforces one single viable theoretical scheme without free parameters and thereby emancipates theoretical structure from the empirical primate. The global description of the world can be obtained exhaustively on a theoretical level without further reference to experiment. If the epistemological access to theoretical structure is decoupled from observation however, it becomes easier to understand what is meant by 'real structure'. Just like the posit of an external reality is based on the understanding that there exists one unique observed world, full-scale theoretical uniqueness may serve as the foundation for a realist posit on a structural level.

Chapter 6 already stressed a remarkable 'coincidence' that lends additional force to this idea: The concept that finally establishes the extended principle of theoretical uniqueness in string theory is duality. The 5 seemingly separate string models of older string theory, which are characterised by 5 different sets of uniquely defined ontological objects, due to duality turn out to be merely different ways to tell one unique story. The degradation of different ontological sets to different formulations of the same theoretical scheme however concurrently gives the lethal blow to ontological realism. Thus the quality of uniqueness is being transferred smoothly from one level to another. While ontological uniqueness, the notion that the theoretical scheme comprises one uniquely identifiable set of elementary ontological objects in space and time, must be abandoned, uniqueness survives in form of theoretical uniqueness, the notion that the basic layout of our observational world only allows one consistent theoretical scheme which precisely determines the global characteristics of observation. In this light Consistent Structure Realism appears as a natural heir of outdated ontological realism.

'Consistent Structure Realism' transforms the principle of theoretical uniqueness from a conspicuous aspect of scientific research into a philosophical posit: It asserts that theoretical uniqueness is an essential quality of our world. Once this posit has been accepted, the realist status of the unique consistent theoretical structure follows as a direct consequence. In a conventional theoretical setting hypothetical theoretical models must be distinguished from the one theoretical model that is actually realised in our world. Real existence thus represents a quality that has to be attributed to a certain scenario based on observation. Once the physical description has become theoretically unique however, consistence becomes synonymous with real existence. No additional quality has to be awarded to the consistent scheme in order to show its distinction.

Being totally constrained by consistency requirements, phenomenology looks like theory's creature in a string theoretical context. It is tempting to understand real consistent structure in a reductionist way as the fundamental level of reality from which all observational reality can be derived. There still exists a subtle and complex interdependence between theoretical structure and phenomenology however, which renders such an understanding untenable. Theoretical structure remains dependent on phenomenology in three different ways. First, scientific theories still are theories about observables. They predict observable properties and their uniqueness must be understood with respect to their observational predictions. Second, the physical principles which lay the foundations for the evolution of a theory like string theory are still rooted in observation. Without a considerable amount of observational data about the world none of the physical consistency arguments could get off the ground. Third, the power of theory remains confined to a global level. The specifics of the spatio-temporal distribution of physical objects are still undetermined by present day physical theories and therefore remain an exclusively observational aspect of reality.

The overall picture thus shows an intricate compound of phenomenological and theoretical aspects that constitutes reality. It is unavoidable to attribute reality to the structural aspect of the world in order to retain a full appreciation of the world's interconnectivity and the formative power of consistency. But it is still important to keep the notion of reality of the visible object as theory's anchoring place. This hybrid form of realism might appear less than satisfactory from a metaphysical point of view – a few words on that topic will follow in the concluding paragraph – but to my eyes it looks sufficiently stable to be of value at the level of philosophy of science.

It is quite straightforward to understand the new concept's similarities with and advantages over Structural Realism. Consistent Structure Realism resembles Structural Realism in avoiding ontological posits for scientific objects, but, unlike the latter, is able to establish a realist foundation that is independent from phenomenological arguments and therefore stays clear of empiricism. The postulate of the uniqueness of the consistent structure able to match a basic set of phenomenological observations allows to understand the consistent and therefore real structure as the object of scientific inquiry without having to rely on the problematic notion of conceptual similarity. Real structure is connected to the actual scientific theories by the claim that it is the only possible fully consistent improvement of the merely partly consistent theoretical structures available today. Current scientific theories thus approach structural reality by extending their own consistent regime.

Structural Realism shows a certain ambivalence concerning the ontological status of its posits. Worrall is often understood to champion an epistemological version of scientific realism, asserting that structural reality is all that can be grasped by human inquiry but not necessarily all there is. Ladyman[43] and others have considered an ontological restriction to structural reality necessary for the sake of coherence. Consistent Structure Realism doesn't leave any choice in this point. It is conceivable only at an ontological level. Since consistent structure inherits the quality of uniqueness from the perishing ontological interpretation, it must obviously be understood as an exhaustive concept of micro-reality and not as a visible tip of a realist iceberg. The quite exhaustive realist characteristics of unique consistent structure leave neither any need for nor any plausibility of further hidden realist aspects of micro-physics.

An important difference between Consistent Structure Realism and both ontological and structural realism lies in their respective positions on the issue of truth values of current theories. Structural as well as ontological realism assert the approximate truth of statements of present scientific theories. The position of Consistent Structure Realism is more timid in this respect and must be developed carefully. Generally theoretical argumentation reveals truth content in the form of negative statements. The exclusion of options due to inconsistencies constitutes stable assertions which can be held true while the positive theoretical conjectures which are put forward at some stage of the scientific evolution must be understood to be preliminary. Theoretical physics might be seen as the science that finds out which structural features are impossible. The impossibility of an ever increasing number of simple structural solutions leads to more elaborate solutions, enforces the modification of foundational postulates and thereby reveals the complexity of reality.

Now the limitedness of theoretical options, which emerges ever more clearly with the growing complexity of the theoretical schemes, at some stage leads to the phenomenon of theoretical uniqueness. Theoretical solutions to specific consistency problems then imply univocal predictions like the existence of the top quark or the number of space-time

[43] Ladyman 98

dimensions in string theory. This way highly developed theories do produce individual positive statements which can be called true in asserting a unique consistent solution to a certain problem within a certain framework. Still, as long as there remain unresolved theoretical problems, it must be expected that some new theoretical step will change the perspective on the general situation. This new step will not refute the old theoretical conclusions if they are sound, but it will put them into a new framework and thus change the overall structure. Therefore, as long as the end of scientific enquiry has not been declared, it will not be justified to call any overall theoretical structure true. To use the example of the top quark prediction once again, the fact that gauge theory does not work consistently without the introduction of the top quark could be held to be most likely true even before the top-quark was discovered experimentally. This did not allow any final definition of the top quark however and a wider context of consistency arguments that includes gravity and drops the precondition of the point-like character of elementary objects does suggest today to replace the point like top-quark by an oscillating string. A certain conclusion within gauge theory thus merits a truth value but to call gauge field theory itself true clearly is not justified.

Consistent Structure Realism thus is a modest form of realism. It does not claim 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. Nevertheless any discovery of new theoretical interconnections necessitated by consistency arguments produces new logically true statements and thus reveals something about reality. Modern scientific theories still can 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 foundational 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 reality that is being described.

It was the primary goal of this article to reconcile the physical state of the art in the age of string theory with philosophy of science. As it has turned out, the messages from physics coincide remarkably with internal needs of the scientific realism debate and show important aspects of that debate in a new light. The impasse between the pessimistic meta-induction and the no miracles argument, often understood as the central element of the dispute about scientific realism, is string theory's first prominent victim. It is overcome by string theory's deconstruction of the principle of underdetermination and the ensuing invalidation of the pessimistic meta-induction. Nevertheless string theory confirms the widely held philosophical suspicion that full scale empiricism as well as full scale realism are somewhat unsound. The dissipation of unique ontology in string theory provides the new main argument against straightforward scientific realism. The search for an intermediate position able to avoid the problems faced by the classical rivals once again finds support from the physical side. Theoretical Uniqueness hints towards a new candidate for non-ontological realism, presented in this work under the name 'Consistent Structure Realism'. All this shows a remarkably forceful influence of physical arguments on philosophy of science, an influence that appears to be truly helpful in providing new answers to old philosophical problems. On the other side philosophy gains new importance for physics as well. Section 5.4 showed 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 physics and philosophy of science. At a time when both fields feel the need to transcend the traditional frameworks their rapprochement comes at hands.

I want to close with a speculative outlook. So far all that has been said remained within the limits of philosophy of science. Yet there exists a deeper level of the realism debate. The same impasse between realist and anti-realist positions that we have witnessed in the context of philosophy of science at a grander scale characterises the metaphysical realism debate in analytical philosophy. The central question there asks for meaning and necessity of the concept of an external reality independent of the human mind. Many analytical philosophers doubt that this concept can be given any viable interpretation. On the other side there exist good arguments which depict it as the only functioning barrier against radical relativism. In this light the emergence of a non-ontological realist concept as it is suggested by Consistent Structure Realism might lead the way towards a new intermediate position in the metaphysical realism debate as well, thereby opening an exciting new interconnection between modern physics and core questions of analytical philosophy. Crucial for a successful formulation of a metaphysical form of Consistent Structure Realism would be the disentanglement of the compound of consistent structure and observation characterised in this section. Any further reflection on the prospects and difficulties of considerations along this line lies far beyond the scope of this article. Yet the remoteness and non-intuitive abstraction of recent particle physics that has for a long time blocked any serious philosophical radiation from that field might turn out to be the basis for a philosophical significance far greater than what one would be ready to concede to classical physical theories.

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