1

String theory

1.1 A brief introduction to string theory

The evolution of fundamental physics can be construed as a series of unifications. Its beginnings can be traced back to Newton's introduction of a universal gravitational force that provided a unified explanation of celestial phenomena and gravitational phenomena on earth. About two centuries later, Maxwell developed a unified description of light, electric and magnetic phenomena. In 1905, Einstein's special relativity provided a coherent framework for classical mechanics and electrodynamics. A decade later, general relativity expanded this new perspective, making it compatible with the phenomenon of gravity. After quantum mechanics had opened a new world of microphysics ruled by the principles of Heisenberg's uncertainty and quantum statistics in the 1920s (which itself may count as the exception to our rule since it was motivated by accounting for new phenomenology rather than by a quest for unification), quantum physics was soon made compatible with special relativity by the introduction of quantum field theory. In the 1960s and early 1970s, the standard model of particle physics made another step towards unification: a specific form of internal symmetries, gauge symmetry, provided a basis for a coherent description of all three nuclear forces that had been discovered in nuclear and particle physics.

In the 1970s, there remained one fundamental obstacle to an overall description of all known fundamental physical phenomena: the theories of nuclear interactions, which were based on the principles of quantum physics, stubbornly resisted all attempts to be reconciled with general relativity. It became increasingly clear that the standard framework of quantum fields did not allow for any satisfying solution of this problem. Something completely new was needed. The idea that stepped up to play this role was string theory.[1]

[1] The topical standard work on string theory is Polchinski (1998). The classic book on the foundations of string theory is Green, Schwarz and Witten (1987). A more easily accessible

String theory was first proposed as a universal theory of microphysics in 1974 (Scherk and Schwarz, 1974).[2] The approach had to struggle with big conceptual difficulties in the beginning. For a long time, it was not clear whether string theory met the most basic requirements for providing a theory of matter. In 1984, Green and Schwarz (1984) finally succeeded in writing down a coherent Lagrangian of a quantized string that included matter fields (the so-called superstring). From that time onwards, string theory has constituted the most prominent and influential attempt to formulate a universal theory of all known interactions. String theory builds on the conceptual foundations that have been established in elementary particle physics in the 1970s. It is a quantum theory that aims at reproducing the interaction and symmetry structure of a gauge field theory. Within this framework, the basic idea of string theory is a fairly simple one: the point-like elementary particles of traditional particle theories are replaced by one-dimensional strings.

In order to understand why this looks like a promising step towards providing a basis for the unification of quantum physics and gravitation, we have to say a few words about the core obstacle to an integration of gravity in the context of quantum field theory: the non-renormalizability of quantum gravity.[3] The calculation of a scattering process in quantum field theory is based on a perturbation expansion that sums up all possible patterns of particles being emitted and absorbed in the process. These possible patterns are represented by the so-called Feynman diagrams which can be calculated. In the calculation of Feynman diagrams one encounters infinite terms which, roughly speaking, arise due to the possibility of point particles coming arbitrarily close to each other. Once we have infinite terms in our calculation, however, we risk losing the capacity of making meaningful quantitative predictions. In gauge field theories, this problem is solved based on the technique of renormalization: the infinities can be ejected from all phenomenologically relevant quantitative results by introducing a finite number of counter-terms to the infinite terms that arise in the calculation. In other words, all ratios between observable quantities have well-defined finite values because the infinities which arise in the calculations cancel

textbook is Zwiebach (2004). More recent books are Becker, Becker and Schwarz (2006) and Ibanez and Uranga (2012). A popular presentation for the non-physicist that gives an instructive picture is Greene (1999). The early history of string theory is told by its main exponents in Capelli, Castellani, Colomo and Di Veccia (2012). Early philosophical texts on string theory are Weingard (1989), Butterfield and Isham (2001) and Hedrich (2007a, 2007b).

2 The history of the concept of strings even goes back to the late 1960s, when it was discussed as a candidate for a description of strong interactions (Veneziano, 1968). Only after it had turned out to fail in that context did it find its new purpose as a universal theory.

3 A good survey of topical approaches to quantum gravitation can be found in Murugan, Weltman and Ellis (2012). A collection of philosophical papers on the topic can be found in Callender and Huggett (2001).

each other in a controlled way. If one includes gravity in a gauge field theoretical description, however, the renormalization program fails. This failure is related to the fact that the gravitational force grows linearly with increasing energies of the interaction process. As a consequence, the infinities which arise in a perturbative expansion of the gravitational interaction process are particularly "dangerous" and it is no longer possible to cancel all of them by a finite number of counter-terms.

Calculations can still be carried out by introducing an energy cut-off (i.e. integrating energies only up to a certain energy scale). As the result then depends on the cut-off value, however, this approach must be based on the assumption that a new, more fundamental theory that is renormalizable or finite can explain the choice of the cut-off scale. A gauge field theoretical approach to quantum gravity thus can work as an effective theory but cannot serve as a fundamental theory. String theory is understood to offer a solution to the problem of intractable infinities in quantum gravity. The extendedness of the strings "smears out" the contact point between any two objects and thus provides a decisively improved framework that seems to allow finite calculations.[4]

The introduction of extended elementary objects that leads up to string theory thus is chosen for entirely theoretical reasons, in order to provide a coherent unification of the particle physics research program with gravity. So far, no immediate empirical signatures of the extendedness of elementary objects have been observed. We therefore know that, if string theory is a viable theory at all, the string length must be too small to be measurable by current experiments. Since the string length is quite directly related to the gravitational constant, the most natural expectation would be that the string scale lies quite close to the Planck scale, the scale where the gravitational coupling constant (which grows linearly with the interaction energy) becomes of order one. If that was the case, canonical scenarios would imply that the string scale lies about 13 to 14 orders of magnitude beyond the so-called electroweak scale,[5] that is the energy scale testable by the current LHC experiment at CERN. Under some specific circumstances, however, which will be discussed a little later, the string length might lie much closer to empirical observability.

String theory relies on the core principles of a perturbative expansion of relativistic quantum mechanical interaction processes and offers a conceptual modification that seems capable of solving the coherence problems of that

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

[5] The electroweak scale corresponds to the masses of the heaviest particles of standard model physics. Technically, it is the scale where the electroweak symmetry is spontaneously broken (see Section 4.1).

approach in the context of gravitational interaction. In this sense, string theory represents a natural continuation of the high energy physics research program. It turns out, however, that the seemingly innocent step from point-like objects to strings has a wide range of complex structural consequences which lead far beyond the conceptual framework of point-like high energy physics.

A first important implication can be derived directly from the quantization of the string. It turns out that a coherent (i.e. anomaly free) quantization of the string is possible only if the string is moving in a spacetime with a specific number of dimensions. In particular, a string theory that can describe matter particles (and not just photons and other particles of integer spin) can only be consistently formulated in ten spacetime dimensions. This prediction marks the first time in the history of physics that the number of spatial dimensions can be derived in a physical theory. The obvious fact that only four spacetime dimensions are macroscopically visible can be taken into account by the assumption that six dimensions are "compactified": they have the topological shape of a cylinder surface – or, if more than one dimension is compactified, of a higher-dimensional torus – where, after some translation in a "compactified" direction, one ends up again at the point of departure.[6] Just like the string length, the compactification radius must be assumed to be so small that the additional dimensions are invisible to the current experiments in high energy physics and gravitational physics. The canonical picture would put the compactification radii more or less at the string length and close to the Planck length. There do exist theoretical scenarios of large or "warped" extra dimensions, however, where Planck scale and string scale merely give the misleading impression of lying many orders of magnitude beyond the electroweak scale as long as one does not account for the propagation of gravity through the large or warped extra dimensions.[7] In such scenarios, the string scale could be low enough even for becoming observable at the LHC.

[6] Technically, the space of compact dimensions is described by a Calabi–Yau manifold.

[7] Those scenarios are based on models where some of the extra dimensions are transgressed only by gravitation while nuclear interactions are bound to the other spatial dimensions. Large extra dimensions which are only transgressed by gravity (Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, 1998) can be close to the micrometer range without contradicting present experiments because precision measurements of gravity have not yet been carried out below that scale. If gravity radiated off into large extra dimensions, it would get strongly diluted. The effective four-dimensional gravitational constant we observe would therefore be very small even if the higher-dimensional gravitational coupling were rather strong. From our four-dimensional perspective this would create the impression of a large scale difference between the electroweak scale and the Planck scale. Warped dimensions (Randall and Sundrum, 1999) are characterized by a peculiar geometry that 'thins out' propagation through those dimensions. Models of warped extra dimensions explain the weakness of the gravitational coupling by utilizing this "thinning out" effect. A warped extra dimension can have the effect that gravitons are very unlikely to be found close to the lower dimensional subspace to which nuclear interactions are confined. This amounts to a suppression of the effective gravitational constant on that subspace.

In conventional quantum physics, elementary particles carry quantum numbers which determine their behavior. A particle's characteristics like spin or charge, which are expressed by quantum numbers, constitute intrinsic and irreducible properties. Strings, to the contrary, do not have quantum numbers. They can differ from each other only by their topological shape and their dynamics. Strings can be open, meaning that they have two endpoints, or closed like a rubber band. If they are closed, they can be wrapped around the various compactified dimensions in different ways. Both open and closed strings can assume different oscillation modes. These characteristics determine the macroscopic appearance of the string. To the observer lacking experimental tools of sufficient resolution for perceiving 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 the oscillation mode of the string 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 dissolved into geometry and dynamics of an oscillating string. It turns out that the string necessarily contains an oscillation mode that corresponds to the graviton (a massless spin 2 particle). Therefore, string theory automatically includes gravity. String theories which are able to describe matter fields are more difficult to formulate. They have to be supersymmetric, i.e. they must be invariant under specific transformations between particles of different spin. String theoretical models which have this property are called "superstring" models.

A fundamental problem faced by string physicists may be characterized the following way. String theory has started from a perturbative point of view. As noted above, a perturbative approach to a relativistic quantum theory describes interaction processes by expanding them as a series of Feynman diagrams. These Feynman diagrams can in principle be arbitrarily complex and involve an arbitrarily high number of particle exchanges. In a case like electroweak interaction, we know from experiment that the coupling constant is small so that Feynman diagrams with high numbers of particle exchanges (which are suppressed by a high factor of the coupling constants) can be neglected in approximate calculations.[8] Perturbation theory has thus proved to be a highly powerful technique in the context of weakly coupled quantum field theory.

[8] In fact, no rigorous mathematical proof of the convergence of perturbation theory in quantum field theory, and therefore no proof of the viability of perturbation theory to all orders, has been found so far. We just know from comparisons of perturbative calculations with experimental data that an expansion up to some rather low order in the expansion parameter provides a good approximation to the overall theory.

In string physics, the situation is more difficult than in quantum field theoretical descriptions of nuclear interactions. Neither the overall theory behind the perturbative expansion nor the size of the expansion parameter are known. In fact, as we have mentioned above, the string coupling, which constitutes the expansion parameter of a perturbative expansion of string theory, is no fundamental free parameter but itself emerges from the dynamics of the fundamental theory. String theorists thus cannot trust perturbative calculations. They have to look for non-perturbative information about the theory in order to acquire an understanding of the theory's general characteristics. Some limited progress has been made in this direction.

An important feature of string physics which has shed some light on the non-perturbative structure of string theory is the occurrence of string dualities. The string world shows a remarkable tendency to link seemingly different string scenarios by so-called duality relations. Two dual theories or models are exactly equivalent concerning their observational signatures, though they are constructed quite differently and may involve different types of elementary objects and different topological scenarios. An example of a duality relation that conveys the basic idea of duality in a nice way is T-duality. String theory, as has been mentioned above, suggests the existence of compactified dimensions. Closed strings can be wrapped around compactified dimensions like a closed rubber band around a cylinder and they can move along compactified dimensions. Due to the basic principles of quantum mechanics, momenta along closed dimensions can only assume certain discrete quantized eigenvalues. Thus, two basic discrete numbers exist which characterize the state of a closed string in a compactified dimension: the number of times the string is wrapped around this dimension, and the eigenvalue of its momentum state in that very same dimension.[9] Now, T-duality asserts that a model where a string with characteristic length[10] l is wrapped n times around a dimension with radius R and has momentum eigenvalue m is dual to a model where a string is wrapped m times around a dimension with radius l^2/R and has momentum eigenvalue n. The two descriptions give identical physics.

T-duality is not the only duality relation encountered in string theory. The existence of dualities turns out to be one of string theory's most characteristic features. Duality relations are conjectured to connect all different types of superstring theories. Before 1995, physicists knew five different possible types of superstring theory which differed by their symmetry structure and therefore seemed physically different. Then it turned out that these five string

[9] The two numbers are called "winding number" and "Kaluza–Klein level," respectively.
[10] The characteristic string length denotes its length when no energy is being invested to stretch it.

theories[11] and a sixth by then unknown theory named "M-theory" were interconnected by duality relations (Witten, 1995; Horava and Witten, 1996). Two kinds of duality are involved in this context. Some string theories can be transformed into each other through the inversion of a compactification radius, which is the phenomenon just discussed 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, which can be reached from specific types of string theory[12] by transforming the coupling constant into an additional 11th dimension whose size is proportional to the coupling strength of the corresponding string theory. M-theory contains two-dimensional membranes rather than one-dimensional strings.[13] Despite their different appearances, duality implies that the five types of superstring theories and M-theory 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.

Another important duality relation is the AdS/CFT correspondence that also goes under the name holographic principle. String theory (that is, a theory that contains gravity) in a space with a specific geometry (so-called anti-de Sitter space, in short AdS) is conjectured to be empirically equivalent to a pure supersymmetric gauge theory (which is a theory that contains no gravity) on the boundary of that space (that is, on a space whose dimension is reduced by one compared to the AdS space). In other words, a duality relation is conjectured to hold between a theory with gravity and another one without gravity. Each gravitational process that takes place in AdS space can be translated into a corresponding non-gravitational process on the boundary space.

The AdS/CFT correspondence has recently led to highly fruitful applications which lie far beyond the limits of string theory proper and do not address the question how to unify all physical interactions (Policastro, Son and Starinets, 2001; Kovtun, Son and Starinets, 2004). It has turned out that the AdS/CFT correspondence can be used in contexts of complex QCD-calculations (calculations of scattering processes involving strong interactions) where all conventional methods had failed. In that case, the physical situation can be described by a gauge theory and

[11] Generally, the term string theory denotes the overall theory that describes the five types of string theory and their relations to each other. However, string physicists often address the individual types of string theory in short as individual string theories as well. Though this is slightly misleading – in particular in the light of their connectedness by dualities – we will stick to that manner of speaking. It should become clear from the context when the term string theory is used in the general sense and when in its more limited sense.

[12] Type I and type IIA string theory.

[13] M-theory is insufficiently understood at this point. It may have the potential to lead towards a more fundamental understanding of string theory.

AdS/CFT correspondence leads from there to a gravitational theory that can be calculated more easily. Though strictly speaking the investigated systems cannot be described by a gauge theory that has a gravitational dual (they are not supersymmetric and involve massive fermions), calculations in the dual picture in many cases turn out to provide significantly better results than more conventional methods. The successes of these calculations have recently led to the spread of string-based methods far beyond the borders of the theory itself. The present book will not be concerned with those investigations any further. They must be mentioned, however, as a striking example of the wide range of string theoretical reasoning in present-day physics.

Coming back to genuine string theory, the analysis of non-perturbative aspects of string physics based on dualities has led to important new insights. It was understood that the spectrum of physical objects in string theory was far wider than initially expected. Beyond the initially posited one-dimensional elementary objects, consistency required the additional introduction of a spectrum of various higher-dimensional objects. These objects are called D-branes, where an added number can denote the number of spatial dimensions. (A D5-brane, to give an example, is an object with five spatial dimensions.)

In recent years it has been better understood how to construct string theory ground states with stable compact dimensions based on combined systems of D-branes and fluxes.[14] It turns out that the freedom for constructing such states is huge. Estimates regarding the number of possible ground states go up to 10^{500} or even higher. Working on the question of how to deal with the variety of ground states – which is often called the string landscape (Susskind, 2003) – is one important task for string theory today. One intensely discussed suggestion is to turn the large number of ground states from a problem into a blessing and use it for explaining the fine-tuning of the cosmological constant.[15]

String theory lies at the core of many important developments in high energy physics and cosmology today. Supersymmetry, a highly influential theory that is currently being searched for at the LHC experiments at CERN, is predicted by string theory (though not necessarily at energy scales accessible to the LHC) and constitutes one of the theory's core characteristics. Supergravity, which for some time was seen as a promising candidate theory for a unification of nuclear interactions and gravity, today is mostly deployed as an effective theory of string theory. Discussions of grand unified theories, another highly influential theory in high energy physics, today are often led within a string theoretical

[14] Fluxes are oscillation modes of the string which do not correspond to particles known from point-like particle physics.
[15] See Section 7.5.

framework. Eternal inflation, the leading theory on the early evolution of the universe, is closely linked to string theory with regard to the theory's basic layout as well as with regard to more far-reaching considerations based on the anthropic principle.[16] One can speak of an interrelated web of theories in contemporary high energy physics and cosmology that is held together by the conception of string theory.

The current theoretical state of development of string theory may be characterized the following way. Four decades of intense work on the theory carried out by large numbers of theoretical physicists and mathematicians have not resulted in the construction of a complete theory. String theory today constitutes a complex web of reasoning consisting of elements of rigorous mathematical analysis, of general conjectures which are based on reasoning in certain limiting cases, of modeling that is done within specified frameworks and of some approximate quantitative assessments. The resulting understanding provides a vast body of structural information and theoretical interconnections between various parts of the theory but leaves unanswered many crucial questions. No real breakthrough has been achieved that would allow specific quantitative calculations of observables from the fundamental principles of string theory. The tediously slow progress witnessed by string physicists over the last few decades does not raise expectations of finding a completion of string theory in the foreseeable future. It seems more realistic to expect a continuation of the kind of development that has characterized the theory's evolution so far: a sequence of small steps of theoretical progress, interspersed with some significant conceptual breakthroughs and periods of slowed down theory dynamics.

Empirically, the situation is similarly complicated. String theory has not found empirical confirmation up to now. In order to understand the chances for future empirical tests, it is important to distinguish between the theory's core characteristics and its implications for physics at lower energy scales. The core property of strings, their extendedness, is expected to show only close to the Planck length. In classical scenarios, that means that the extendedness of the string becomes empirically testable only about 13 orders of magnitude[17] beyond the energy scales that can be reached by the most powerful high energy experiment today, the LHC experiments at CERN. There is no hope to reach those scales within the framework of collider physics. We have mentioned above, however, that some scenarios imply a far lower Planck and string scale and thus move both of them towards regions that might be testable by collider physics. A second core prediction of string physics is the existence of extra dimensions. An empirical

16 A little more on the theories mentioned in this paragraph will be said in Section 4.2.
17 Which corresponds to a factor of 10 trillion.

discovery of extra dimensions could not be taken as full confirmation of string theory since extra dimensions might also occur in non-stringy scenarios. However, they are not implied by any contemporary theory other than string theory. If a prediction as "esoteric" as extra dimensions turned out to be vindicated by experiment, this discovery would clearly be considered strong corroborative evidence for string theory. The empirical perspectives for the discovery of extra dimensions are similar to those for the discovery of extended elementary objects. The classical scenarios put the size of extra dimensions about 13 orders of magnitude beyond the reach of the LHC. Some scenarios of large or warped extra dimensions would imply, however, that large extra dimensions could be testable by precision measurements of gravity at short distances or by the LHC. To conclude, there is no clear indication that core predictions of string theory can be tested by experiments conceivable today. However, under certain specific conditions, such empirical confirmation might be possible.

String theory may also be supported based on predictions regarding physics at the electroweak scale. If empirically measured parameter values of standard model physics which are not implied by the standard model itself or its GUT or SUSY extensions turned out to be predicted by string theory, this would be taken to constitute strong corroboration of string theory. Depending on the range of such successful predictions, they could assume the status of outright empirical confirmation of string theory even in the absence of direct evidence for extended strings. To consider the most extreme example, let us assume that all standard model parameter values turned out to be precisely predicted by string theory. In that case, it would seem very plausible to believe in string theory's validity even without having ever observed an extended string. At this point, the chances that any specific predictions of low energy parameter values could be derived from string physics are difficult to assess. While the fundamental structure of string theory is understood to be determined uniquely based on very general pre-assumptions, the current understanding of string physics suggests that a vast number of string theory ground states can be constructed from string physics. The selection of the ground state "we are living in" determines the values of all those parameters which define our observable world. Since this selection constitutes the outcome of a quantum process, its prediction must remain of a statistical nature, just like the outcome of some individual microphysical process. This implies a considerable reduction of string theory's predictive power. The present incomplete understanding of string theory does not allow a clear assessment as to what extent string theory retains predictive power under the stated conditions. Though speculations that string physics might end up predictively empty seem hardly tenable based on the current physical understanding, the unclear situation naturally adds to the impression that string physics is unsatisfactorily detached from empirical confirmation.

This “statistical” problem is superimposed by the problem of the insufficient understanding of string theory dynamics. As of today, it is not possible to derive any quantitative predictions from basic principles of string physics. Therefore, even to the extent that string theory may predict low energy parameter values, string physicists today are not able to specify and calculate those predictions. The most promising strategy for making some contact with observation may consist in trying to analyze to what extent some general properties of physics at the electroweak scale are implied by or seem likely in the context of string physics. If found, coherence of that kind between string theory and the observed world could provide some degree of corroboration for string physics.

Given its unsatisfactory theoretical state and the lack of empirical confirmation, string theory clearly must be called an unconfirmed speculative hypothesis according to the canonical paradigm of theory assessment. This does not square well, however, with the theory’s actual status in the field of high energy physics. String theory has attained a pivotal role in fundamental physics and has been treated as a well-established and authoritative theory for quite some time by the community of string theorists and by physicists in related fields. As we have described above, large parts of fundamental physics are influenced by string theoretical analysis. The string community is one of the largest communities in all of theoretical physics and for many years has produced the majority of the field’s top-cited papers. Moreover, many string theorists express a remarkably strong trust in their theory’s viability. Though they certainly acknowledge their theory’s theoretical incompleteness and the lack of empirical evidence for it as deplorable obstacles, most of them believe that the theoretical quality of string theory in itself justifies the claim that the theory constitutes an important step towards a deeper understanding of nature. The serious mismatch between the status one would have to attribute to string theory based on the canonical paradigm of theory assessment and the status the theory actually enjoys is being reflected by the intense dispute that has arisen about the status of string physics in recent years. The next section will have a closer look at that discussion.

1.2 The conflicting assessments of the current status of string theory

Before entering into the details of the dispute about the status of string theory, it is important to clarify the role that dispute is going to play in the context of this book. Primarily, the book aims to explain the mechanisms of theory assessment in string theory and related theories. The dispute among physicists that will be discussed in this section is not essential to that analysis. If the dispute had not arisen, the philosophical motivation for developing the arguments presented in this book would have remained unaffected and the core of those arguments would have remained unchanged. However, the dispute may be understood as an additional indicator that something philosophically interesting is happening in physics today that is capable of creating serious divides within the physics community at a deep conceptual level. In other words, the dispute can serve as a marker that theoretical physicists currently face a situation where philosophical considerations on the conceptual foundations of their ways of reasoning can be of interest to them. On that basis, the ensuing analysis of the dispute can serve as a test case for the philosophical perspective suggested in this book. If, as I hope to be able to convey, the suggested perspective is capable of providing a convincing explanation of the dispute, it may be taken to be supported by this explanatory success.

So let us take a closer look at the conflict. Soon after the theoretical breakthrough of string theory in 1984, some degree of skepticism developed among physicists in other fields with respect to the string theorists' high level of trust in their theory. This skepticism grew with time, as string theory remained empirically unconfirmed and theoretically incomplete whereas its exponents showed no sign of abandoning their strong self confidence. In recent years, criticism of string physics has been presented in an increasing number of articles and books, which made the conflict about the status of string physics clearly visible to a wider public. Let me illustrate the irreconcilably different points of view by citing four remarkably different statements on string physics.

> During the last 30 years of his life, Albert Einstein sought relentlessly for a so-called unified field theory – a theory capable of describing nature's forces within a single, all-encompassing, coherent framework. [. . .] Einstein never realized his dream [. . .]. But during the past half-century, physicists of each new generation – through fits and starts, and diversions down blind alleys – have been building steadily on the discoveries of their predecessors to piece together an ever fuller understanding of how the universe works. And now long after Einstein articulated his quest for a unified theory but came up empty-handed, physicists believe they have finally found a framework for stitching these insights together into a seamless whole – a single theory that, in principle, is capable of describing all phenomena. The theory [is] string theory.
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> *Brian Greene,* The Elegant Universe *(1999, p. IX)*

> The moment you encounter string theory and realize that almost all of the major developments in physics over the last hundred years emerge – and emerge with such elegance – from such a simple starting point, you realize that this incredibly compelling theory is in a class of its own.
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> *Michael Green (1997), quoted in Greene,* The Elegant Universe *(1999, p. 139)*

> Imagine a tourist trying to locate a specific building in a vast and completely unfamiliar city. There are no street names (or at least none that make any sense to the tourist), no maps and no indication from the totally overcast sky as to which directions are north, south or whatever. Every so often there is a fork in the road. Should the tourist turn right or left, or perhaps try that attractive little passageway hidden over to one side? The turns are frequently not right angles, and the roads are hardly ever straight. Occasionally, the road is a dead end street, so steps must be retraced and another turning made. Sometimes a route might then be spotted that had not been noticed before. There is no-one around to ask the way; in any case, the local language is an unfamiliar one. At least the tourist knows that the building that is sought has a particular sublime elegance, with a supremely beautiful garden. That, after all, is one of the main reasons for looking for it. And some of the streets that the tourist chooses have a more obvious aesthetic appeal than the others. [. . .] Each successive choice of turn is a gamble, and on frequent occasions you may perhaps feel that a different one held more promise than the one [. . .] actually chosen. [. . .]
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> If there are too many of these [“choices”], the chance of guessing right each time may become exceedingly small.
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> *Roger Penrose on string physics' chances of success in* The Road to Reality *(2005, p. 888f)*

> Despite a number of tantalizing conjectures, there is no evidence that string theory can solve several of the big problems in theoretical physics. Those who believe the conjectures find themselves in a very different intellectual universe from those who insist on believing only what the actual evidence supports. The very fact that such a vast difference of views persists in a legitimate field of science is in itself an indication that something is badly amiss.
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> *Lee Smolin,* The Trouble with Physics *(2006, p. 198)*

While the four citations may be particularly outspoken, they do represent the two main positions which pertain among physicists with regard to the current status of string physics. On one side of the divide stand most of those physicists who work on string physics and in fields like inflationary cosmology[18] or high energy particle physics model building, which are strongly influenced by string physics. That group represents a slight majority of physicists in theoretical high energy physics today. Based on an internal assessment of string theory and the history of its development, they are convinced that string theory constitutes a crucial step towards a better and more genuine understanding of the world we observe. On the other side stand many theoretical physicists of other fields, most experimental physicists and most philosophers of physics. They consider string theory a vastly overrated speculation.

We witness a confrontation of two sharply diverging positions without much appreciation of the respective opponent's arguments. It is no big exaggeration to

18 A little more about inflationary cosmology will be said in Section 4.2.

say with Smolin that the string theorists and the critics cited above, though they are all theoretical physicists, live in different worlds. Remarkably, they do so despite the fact that they largely agree on the problems string theory faces. All problems discussed in the previous section with regard to the chances of string theory making contact with empirical data are acknowledged fully by string physicists as well as critics of string theory. The differences between the two sides lie in the conclusions drawn.[19]

In the dispute described, the string critics play the role of defenders of the classical empirical paradigm of theory assessment. Therefore, it makes sense to start the characterization of the two diverging positions by looking at their perspective. The string critics' case shall be presented largely based on Lee Smolin's book (Smolin, 2006) and Roger Penrose's remarks on the topic in Penrose (2005). Similar arguments can be found e.g. in Woit (2006) and Hedrich (2007a, 2007b). By and large, the sketched arguments are representational of the considerations which have led many physicists who do not work in string physics or particle physics model building towards adopting a skeptical assessment of the current status of string physics.

Penrose and Smolin base their assessments on their canonical understanding of the scientific process: scientific theories must face continuous empirical testing in order to avoid going astray. As formulated suggestively in Penrose's citation above, the steady sequence of theoretical alternatives which open up in the course of the evolution of a research program makes it seem highly implausible that the scientific community could consistently make the right theoretical choices in the absence of empirical guidance. If empirical testing remains absent for a long period of time, the chances seem high that scientists will find themselves – to use Penrose's picture – lost in a wrong part of town. Therefore, in order to be conducive to scientific progress, scientific theories are expected to fulfil a certain pattern of evolution. A theory is expected to reach a largely complete theoretical state within a reasonable period of time. Only after having reached a fairly complete state does a theory allow for a full assessment of its internal consistency and can it provide quantitative predictions

[19] It should be mentioned at this point that Lee Smolin, one of the few exponents of the string critical camp with working experience in string physics, does differ substantially from other string physicists in his scientific assessment of string theory's structure as well. In particular, he doubts the viability of most of those mathematical conjectures which constitute the backbone of string physics. Regarding these arguments, the dispute can be understood as a conventional example of the occurrence of different opinions within a scientific field. In this narrower context, however, the divergent position of one individual scientist would be of limited interest to philosophy of science and would not suffice to motivate the fundamental debate that arose in recent years. Therefore, the present discussion will leave aside Smolin's internal string theoretical assessments and stick to those arguments which drive the debate at a more general level.

of empirical data. The theory then can be expected to undergo empirical testing within a limited time frame in order to decide whether further work along the lines suggested by the theory makes sense or, in the case the theory was empirically false, would be a waste of time.

Looking at the present condition of string theory about four decades after it was first proposed as a fundamental theory of all interactions, we can see that it has achieved neither of the goals described in the last paragraph. Even in the eyes of most of its critics, this does not imply that the theory should be fully abandoned. It has happened before that theories have taken too long to reach maturity and empirical testability and have been shelved until, after some period of general experimental or theoretical progress, they turned out to have the capacity of contributing to scientific progress after all. The critics' point is, however, that one cannot know whether or not such late success will occur before a theory has found empirical confirmation. A theory that has not reached theoretical completion and empirical confirmation therefore cannot be called successful by classical scientific standards. Given the large number of physicists who have worked on string theory with high intensity over the last 30 years, the theory may actually be called remarkably unsuccessful by those standards. Thus, its critics take string theory as a scientific speculation that may deserve a certain degree of attention due to its interesting theoretical properties but is unfit to play the role of a pivotal, let alone dominating, conceptual focal point of an entire scientific discipline. Still, this is exactly what string theory has been doing for more than a quarter of a century now.

Smolin and Penrose criticize string theorists for ignoring the canonical rationale for theory assessment that was presented above and for developing an unwarranted degree of trust in their theory's validity. According to Smolin, string theorists systematically overestimate their theory's "performance" by creating their own criteria of success which are tailored to be met by string physics. Examples of this strategy would be the straightforward interpretation of mathematical progress as physical progress without empirical backing or the string theorists' frequent allusions to structural beauty (see e.g. Michael Green's citation in this section). Smolin argues that such "soft" criteria create arbitrary mirages of genuine scientific success. Their application in his eyes impedes the field's ability to carry out an objective assessment of its progress and moves the field away from legitimate scientific reasoning with respect to theory appraisal. The resulting overestimation of the theory's status, according to Smolin, disturbs a healthy scientific process since it binds to string physics too many resources whose allocation to other parts of physics could produce more significant results. It is important to emphasize that the thrust of the string-critical arguments questioning the scientific viability of string physics focuses on the strategies of theory evaluation deployed by string physicists. It does not target the methods applied in the construction of string theory, the scientific quality of which remains largely uncontested.

The question as to how a considerable share of the most eminent physicists can jointly commit the described serious methodological blunder is answered by Smolin at a sociological level by deploying the concept of groupthink. The latter phenomenon allegedly tends to occur in professional groups with high status, strong internal competition and intense internal interaction. Under such circumstances, the members of a group may be forced into the unreflected adoption of the group's standard positions by a mix of intellectual group pressure, admiration for the group's leading figures and the understanding that fundamental dissent would harm career perspectives. An all too positive and uncritical self-assessment of the group is the natural consequence.

Let us now turn to the string theorists' perspective. No string theorist would deny the problems the theory faces. But most of them believe there to be strong theoretical reasons for placing trust in the theory's viability despite these problems. String theorists adopt an altered understanding of the balance between empirical and theoretical methods of theory appraisal that amounts to a massive strengthening of the status of non-empirical theory assessment in the absence of empirical confirmation.

Before entering the analysis of the conceptual reasons for the described shift, I want to address an interesting general aspect of the view string theorists have of their critics. As described above, critics of string theory take string theorists to violate principles of canonical scientific behavior by having undue trust in an empirically unconfirmed theory. String theorists have a similar kind of complaint about many critics of string theory. They tend to consider the disregard shown by many non-string physicists for their theory-based reasons to believe in string theory a blatant violation of the scientific expert principle. The latter principle establishes an informal code of mutual respect for scientific specialization among scientists in different fields, which is taken to be conducive to an optimized appreciation of the overall body of scientific knowledge by scientists and external observers. According to this principle, non-experts are expected to base their opinion about the content and status of theories in a well-established scientific field largely on the assessments by those who have established themselves as experts in the field. In the case of string physics, this principle often seems to be discarded. Most critics of string theory from other fields base their criticism largely on their own general scientific intuition, bolstered by the statements of a couple of prominent opponents of string theory who do have expertise in the field but are not amongst the field's foremost figures. Exponents of string theory tend to locate the reasons for this unusual phenomenon in a lack of openness and flexibility with respect to the acceptance of new and unusual physical ideas on the side of the string critics.[20]

The debate between string physicists and critics of string theory on the legitimate assessment of the theory's success and viability thus is characterized to a significant extent by allusions to psychological or sociological aspects which are alleged to impede a sober scientific assessment on the side of the respective opponent. While the present book does not aim at offering a psychological or sociological study of modern fundamental physics, it seems appropriate to make a few comments on the plausibility of the involved arguments at that level.

It is probably fair to say that both sides do have a point. The community of string physicists indeed may be characterized by high status, close interaction among its members, and a research dynamics that is largely guided by a few key figures (this may actually be less true in 2012 than in the 1990s). Presumably, few in the community would deny that aspects of groupthink can be identified in the community's patterns of interaction and behavior. Equally, it is difficult to deny the point stressed by many string theorists that the antagonism between string theorists and physicists who are critical of string physics shows the characteristics of a dispute between the exponents of a new way of thinking and more conservative scientists who are less open to fundamentally new developments and prefer staying closer to known territory.

Still, it appears questionable whether psychological and sociological arguments of the described kind can on their own offer a satisfactory explanation of the dispute about the status of string theory. Regarding the groupthink argument, it may be pointed out that one could very well detect elements of groupthink at several stages of the evolution of theoretical physics throughout the twentieth century. The founding period of quantum physics or the emergence of gauge field theory, to give just two examples, arguably show similar sociological constellations with tightly knit high status groups of physicists who believed in work on a revolutionary new theory, strong leading figures who largely determined the course of events and many followers who just wanted to be part of the game. There are other examples of theories which were supported

[20] It should be emphasized that physicists on both sides of the divide are aware of the slightly precarious character of the "non-physical" arguments deployed in the debate. Lee Smolin has applied the concept of groupthink to the community of string physicists (which, incidentally, seems a quite accurate representation of what many critics of string physics do think about string physicists) but is careful not to present it as a core argument. String theorists, when entering a discussion with their critics (see e.g. Polchinski in his reasoning against Smolin (Polchinski, 2007)), try to keep the debate at an entirely physical level. Still, it seems important to mention the sentiment behind the dispute that is not so much expressed in written form as it is in private communication.

by leading figures of physics but still were considered mere speculations due to the lack of empirical confirmation. Throughout twentieth century physics, the scientific method has proved strong enough to keep scientific control mechanisms intact despite the presence of elements of groupthink. A convincing groupthink argument thus would have to explain why it is just now that groupthink has succeeded in sustaining an irrationally positive assessment of a theory for more than a quarter of a century.

Moreover, describing the string community solely in terms of groupthink would be grossly one-sided and inadequate. Many of today's most creative and innovative physicists work in the field. The string community is arguably characterized by a particularly high degree of openness for new ideas and a marked tendency to question old ways of reasoning. This is reflected by the large number of new ideas and ideas coming from other fields of physical research which have been adopted in string physics. The picture of a sheepish group following the directives of a few prophets would be an obvious misrepresentation of the actual situation in the field.

On the other hand, the string theorists' allusions to their opponents' backwardness does not provide a fully convincing explanation of the emergence of the string-critical point of view either. A number of strong critics of string physics have contributed important and innovative physical concepts themselves (Roger Penrose and Lee Smolin both are examples). It seems implausible to relate their string criticism to a generally conservative scientific attitude. As an overall phenomenon, the degree to which physicists working in other fields refuse to adopt the string theorists' assessment of their theory and thereby implicitly distance themselves from the expert principle is as striking as it is atypical in twentieth century physics.[21] It seems to require an explanation that goes beyond a simple attestation of scientific conservativism.

Irrespective of the actual explanatory power of the involved scientists' allusions to psychological and sociological arguments, it is significant, however, that such arguments are addressed by physicists at all. Differences of opinion in physics usually tend to be discussed by evaluating the argumentative content of the opposing position. A retreat to criticism at a psychological level may be taken to suggest that the opponents are no longer able to reconstruct the opposing position in a rational way. Such a situation can arise when the two sides enter the discussion with incompatible predispositions which are themselves not sufficiently addressed in the dispute. In the following, it shall be argued that this is exactly what is happening in the dispute on the status of string theory.

[21] Comparable developments did occur during the initial stages of relativity and quantum physics but soon degenerated into pseudo-scientific fringe phenomena.

Let us reconstruct the argument between string physicists and string critics in a little more detail. String theorists have built up considerable trust in their theory based on the theory's internal characteristics and the history of its evolution. Critics of string theory protest that the string theorists' trust in their theory is not tenable on the basis of generally acknowledged scientific criteria of theory assessment. String theorists retort that the convincing quality of string theory, being based on the theory's specific structural characteristics, only reveals itself to the string theory expert, which implies that most of the critics are just not competent to evaluate the situation. The critics, in turn, do not feel impressed by this argument, since, according to their own understanding, they make a general point about the character of the scientific process, which should remain unaffected by any specific analysis of the theory's technical details.

The dispute can be construed as a discussion that fails to be productive due to a paradigmatic rift between the two disputants: each side bases its arguments on a different set of fundamental preconceptions. This paradigmatic rift, however, differs from the classical Kuhnian case in two respects.

First, it is placed at a different conceptual level. In Kuhn's picture, paradigmatic differences can be identified by looking directly at the involved scientific theories. To give an example, Newtonian physics represents the paradigm of deterministic causation while quantum mechanics introduces a new paradigm that allows for irreducible stochastic elements in the dynamics of physical objects. Paradigmatic shifts of this kind may have far-reaching implications at all levels of the understanding of the scientific process. Still, they are rooted in and implied by conceptual differences between the corresponding theories themselves. The paradigmatic rift between proponents and critics of string theory is of a different kind. It cannot be extracted directly from conceptual differences between specific scientific theories but only arises at the meta-level of defining the notion of viable scientific argumentation. In the dispute, the critics of string theory mostly do not contradict claims of string theory itself but question the strategies of theory assessment applied in the context of string physics. One could thus call the rift between string theorists and their critics "meta-paradigmatic" in the sense that it cannot be discussed without focussing on the meta-level question of the choice of viable criteria of scientific theory assessment.

Second, the development of the new paradigm did not happen in a revolutionary step. Rather, the understanding of theory assessment evolved gradually based on the scientific experiences of scientists in the field. Only once that gradual process had lasted for some time and scientists then looked outside the limits of their field, did they discover the paradigmatic rift that had opened up between their understanding and the canonical paradigm of theory assessment prevalent in other parts of physics.

A mutual understanding between string theorists and their critics is prevented by the fact that the meta-paradigmatic character of the rift between the two sides is not addressed as such in the discussion. While string theorists proudly point out the conceptual novelties of their theory, they tend not to emphasize the meta-paradigmatic shift at the level of theory assessment that was induced by the evolution of string theory. A number of reasons may be responsible for this fact. First, being physicists rather than philosophers, string theorists naturally focus on their theory's direct physical import and consider the functionality of the scientific process a pre-condition that is more or less taken for granted. Second, since the meta-paradigmatic changes evolved gradually for the scientists in the field, they look less dramatic to them than to outside observers. And third, conceding a deviation from canonical scientific praxis would invite a level of criticism that string physicists have no interest to incur.

The critics of string theory, on the other hand, develop their arguments without acknowledging the possibility that a shift of the scientific paradigm might constitute a scientifically legitimate development under some circumstances. Therefore, they discuss string physics strictly based on the canonical scientific paradigm and interpret each mismatch between the two straightforwardly in terms of string theory's failure to meet scientific standards.

Both sides thus agree in disregarding the meta-paradigmatic aspect of their discussion. In doing so, however, they actually lead the discussion based on incompatible sets of hidden preconceptions and therefore must miss each other's point. Seen from either perspective, the respective opponent's position does not have legitimacy based on the preconceptions taken to provide the valid framework for the entire debate. The recourse to mutual imputations of personal insufficiencies follows as a natural consequence. Claims of scientific hubris thus are summoned against claims of insufficient intellectual acuteness.[22]

[22] A recent paper by Johannsen and Matsubara (2011) attempts an assessment of the current status of string theory while explicitly denying the "meta-paradigmatic" character of the changes associated with the evolution of string theory. Thereby, Johannsen and Matsubara run into a problem that is closely related to the one described above. They discuss the status of string theory within the framework of the Lakatossian concept of research programmes (Lakatos, 1970) and try to determine whether string theory has constituted a progressive or a degenerative research program in recent decades. Applying the canonical criteria of theory assessment, they come to the conclusion that string theory constitutes a degenerative research program: for three decades it has been developed without generating new and specific empirical predictions. As they do acknowledge, however, this flies in the face of the string theorists' own assessment of their research program. Most string physicists would consider their research program progressive due to the new theoretical insights they have won on its basis. Seen from the perspective presented in this book, there is a clear reason for the difficulties faced by Johannsen and Matsubara: by denying the meta-paradigmatic character of the shifts related to string theory, they forsake the freedom of modifying the criteria for the progressive character of the theory. Thus they end up with an assessment that cannot do justice to the arguments presented by the scientists in the field.

Framing the controversy in terms of a shift of the scientific paradigm allows acknowledgement of the reasonability of both positions on the basis of their respective preconceptions. Largely unintentionally, string physicists have been led towards a novel conception of scientific theory appraisal by their scientific research, which they had carried out in accordance with all standards of scientific reasoning. The scientific process itself thus has led beyond the canonical limits of scientific reasoning. The rise of the new understanding of theory evaluation was clearly accelerated by the fact that the stronger role of purely theoretical argumentation it suggested came in handy in view of the lack of available empirical support for string theory. The lack of empirical support was not the primary source of the former development, though. As will be shown in the next sections, the theory itself and the circumstances of its evolution provide substantial reasons for the altered perspective. Those reasons, however, remain invisible to physicists in other fields who have not experienced the scientific dynamics that instigated the described shift of the scientific paradigm. Therefore, they must understand the described shift as a purely defensive ad hoc measure instigated by the long empirical drought and see no sound scientific reason to follow it. Within the framework of their traditional and well-tested scientific paradigm, they find ample justification for repudiating the string theorists' assessments of string theory's status.

Is the string theorists' move a legitimate one? Can it be legitimate if good arguments support it within the string theorists' own framework of reasoning? Clearly, a shift of the scientific paradigm that is induced by the dynamical evolution of a research field must be considered a legitimate option in principle. No paradigm of scientific reasoning has been installed as a god-given law before the commencement of scientific research. Rather, such paradigms have emerged based on the successes and the failures of scientific reasoning witnessed by scientists in the past. Novel scientific input thus must be expected to alter the scientific paradigm in the future. The question whether an emerging shift of the scientific paradigm actually constitutes an improvement over the prior situation can be very difficult to answer, however.

In one respect, characterizing the dispute between string physicists and their critics in terms of a paradigmatic rift seems particularly apt. To a greater extent than in most cases of scientific theory change, the debate on string physics is affected by fundamental difficulties to decide between the two positions on an "objective" basis, i.e. without anticipating the outcome by employing the preconceptions related to one or the other position. Since the difference in the understanding of what counts as scientific success is crucial to the difference between the two paradigms, it is obviously impossible to decide straightforwardly between the two paradigms by assessing scientific success. Both paradigms allow for plausible criticism of the respective opponent on their own grounds. Seen from the critic's perspective, it is quite plausible to argue that a modification of the scientific paradigm in times of crisis is counter-productive, as it carries the risk of overlooking a solution that would satisfy the criteria set up by the old paradigm. Seen from the perspective of the new paradigm, sticking to the old criteria too long inhibits scientific progress by sticking to a misguided chimera of the static nature of scientific principles. All one can do in this case is assess the internal coherence and attractiveness of the old and new positions on their own terms and compare the two internal assessments on a more general – and therefore necessarily more vague – argumentative basis.

I argued in Section 1.1 that the traditional paradigm of theory assessment has run into a substantial crisis in the context of present-day fundamental physics. The next chapters will have a closer look at the question whether and to what extent the newly emerging paradigm of theory assessment in string physics and some other fields can provide a viable basis for overcoming that crisis. Let us begin by looking at the conceptual reasons string theorists rely on for believing in their theory. Later, an attempt will be made to put those reasons into a philosophical perspective.

1.3 Three contextual arguments for the viability of string theory

Why do string physicists invest trust in the viability of their theory? The main problem in this respect is addressed clearly in Penrose's cited text. Penrose raises one fundamental worry with regard to overly confident assessments of theories that have not been empirically confirmed: those assessments are always threatened by the possibility that other scientific explanations of the available data have been overlooked so far. Kyle Stanford has called this general problem of scientific reasoning the problem of unconceived alternatives (Stanford, 2001, 2006). Any reliable assessment of a theory's status on theoretical grounds must answer Penrose's worry by addressing the question of unconceived alternatives in some way. It shall be argued in the following that the current assessments of the status of string physics rely on a number of arguments which indeed amount to addressing that question.

Roughly, string theorists rely on two basic kinds of arguments when developing trust in their theory. Arguments which address structural characteristics of string theory itself shall be discussed in Part III of this book. Part I will focus on the other group of arguments, the contextual arguments which are based on general characteristics of the research process that leads towards string theory.