Introduction

Fundamental physics at the beginning of the twenty-first century is faced with a confusing situation. On the one hand, physicists sense that for the first time in the long and successful history of their discipline they may have a realistic chance of fulfilling its most ambitious and longstanding goals. The two large complexes of physical reasoning, micro-physics and cosmology, finally seem to offer hope for a genuine unification within one overall physical conception. String theory, in conjunction with new theoretical concepts in cosmology, has revealed the contours of a truly universal theory of all fundamental aspects of the physical world. On the other hand, many physicists believe that fundamental physics is facing a serious crisis. This crisis seems to be generated by a conjunction of two problems. First, physics is losing contact with empirical testing. While microphysics was driven by a continuous stream of empirical data throughout most of the twentieth century, recent decades have witnessed the increasing importance of theories whose characteristic predictions lie far beyond the reach of contemporary experimental testing. The control of the theoretical evolution by empirical data, a crucial element of the natural sciences, thus appears in danger. Moreover, the attempts to come up with a consistent fully universal theory have led to a staggering increase of mathematical complexity, resulting in a wide spectrum of speculative and empirically unconfirmed, in some cases maybe empirically unconfirmable, new hypotheses. Examples range from the spatial extra-dimensions and higher-dimensional objects of string theory to the prediction of many unobservable universes in cosmic inflation. To make things worse, the analysis of the mathematical structures implied by those hypotheses seems to transcend the capabilities of present-day physicists and mathematicians to an extent that renders a completion of the corresponding theories unlikely for the foreseeable future.[1]

While both described aspects of contemporary fundamental physics, the positive as well as the negative one, are in principle acknowledged by all physicists and knowledgeable observers, strong disagreements have arisen with regard to their significance. Many string physicists and modern cosmologists emphasize an optimistic perspective based on the promises provided by the theories they are working on. The problematic aspects of the present situation to them appear as complications of the kind that have always inhibited scientific progress, just to be overcome at the end by improved methods and more ingenious thinking. Quite to the contrary, many physicists working in other research fields feel that the decoupling from experimental testing virtually destroys the relevance of optimistic claims based on string physics and related theories. These claims in their eyes shrink to delusory hopes fed by a dangerous surrender of scientific restraint.

The present book aims at offering a philosophical interpretation of the ambivalent situation characterized above. It will be argued that the criteria of theory assessment have been significantly transformed in fundamental physics in recent decades. Conceptual characteristics of an individual theory as well as characteristics of the research context within which the theory evolves play an increasingly powerful role in assessing the theory's status and viability. While this does not affect the role of empirical data as the ultimate judge of a theory's viability, it substantially raises the status a theory can acquire in the absence of empirical confirmation. It would be too simple to discredit this development as a deviation from solid scientific reasoning and reject it on those grounds. Such a move would mean to petrify the scientific method at one point in time while ignoring that it has always been volatile and in the end must be seen as the product of the successes and failures of scientific reasoning throughout its history. A serious analysis of the indicated changes therefore must aim at identifying the conceptual basis for the new aspects of scientific reasoning and search for the reasons why this altered conceptual basis has emerged. In the end, the specification of what is acceptable as valid reasoning in a scientific field must be up to the involved scientists. A philosophical analysis like the one to be carried out in this book can have the role of providing a wider conceptual framework within which some of the arguments deployed by scientists may appear in a clearer light.

[1] Behind the described problem, and independent from it, still looms a second defining problem of fundamental physics, the old but unresolved foundational problem of quantum mechanics. The present book will not address the latter, however.

Of crucial importance for our analysis is the concept of the underdetermination of scientific theory building by the available empirical data. This "scientific underdetermination," as I shall call it, will be argued to constitute an implicit but crucial object of investigation in contemporary fundamental physics. The most important reasons for the trust scientists have in some theories which lack empirical confirmation can be understood in terms of arguments that scientific underdetermination in the given context is severely constrained. The increasing reliance on those argumentative strategies leads to a substantial empowerment of non-empirical theory assessment. Part I of the book aims at identifying the structure of arguments which infer limitations to scientific underdetermination in the context of string theory. While these arguments can be called non-empirical in a certain sense, they are nevertheless rooted in observation and may be understood in terms of an extension of the conventional horizon of observational input.

The important role played by non-empirical theory assessment in the context of string theory, inflationary cosmology and other parts of contemporary fundamental physics seems disturbing to many observers because that kind of reasoning has no place in the canonical understanding of scientific progress that has emerged over the last two centuries. Part II of the book demonstrates that the actual significance of non-empirical theory assessment in physics, and specifically the significance of assessments of limitations to scientific underdetermination, has always been much higher than conceded by the standard philosophical reconstructions of the scientific process. The empirical confirmation of microphysical objects implicitly rests on argumentative strategies of the very same kind as those deployed in non-empirical theory assessment. From the early empirical confirmation of the atom to the current measurements of the Higgs particle, elements of non-empirical theory assessment are necessary for taking claims of the empirical discovery of microphysical objects seriously. The very strong position of non-empirical theory assessment in theories like string physics in this light appears as the strengthening of an already well-established element of scientific reasoning.

Once one accepts the scientific significance of assessments of limitations to underdetermination, a second striking feature of string theory becomes more easily comprehensible. By many of its exponents, string theory is understood to be a candidate for a final theory, a theory that can, at a fundamental level, account for all physical phenomena observable in our world. It is a genuinely philosophical question whether a final theory claim can make epistemological sense at all. Many scientific observers deny this and take the final theory claims put forward in the context of string theory to indicate the over-optimistic mind-set prevalent among string physicists. It is argued in Part III that a universal rejection of final theory claims as epistemologically unjustified is based precisely on the canonical perspective on theory assessment that fails to account for the scientific role of assessments of underdetermination. Once taken into account, assessments of underdetermination can provide a foundation for meaningful final theory claims. Assessments of scientific underdetermination thus have the potential to alter our view of scientific theories in two ways. They can push our understanding of a theory's viability beyond the limits of what is currently empirically testable and can provide a basis for understanding the absolute position of current scientific theories within the framework of possible scientific theory building. The latter point has a significant impact on the scientific realism debate, which is discussed in the final chapter of this book.

The present book does not constitute an attempt to demonstrate at a philosophical level the viability of string theory or the related final theory claims. Both questions are of a genuinely scientific nature and must be evaluated by applying the apparatus of scientific reasoning to the emerging empirical and non-empirical evidence. The book's core message may be formulated in the following way. The novelty of current theories in fundamental physics is not confined to the conceptual level of those theories themselves. Rather, it extends to the meta-level of theory assessment where a shift of the balance between empirical and theoretical elements can be observed. That shift influences how contemporary physicists in high energy physics and cosmology see their theories. Beyond that, it may eventually alter the philosophical understanding of the relation between a physical theory and the world.

PART I

Delimiting the unconceived

An observer looking at elementary particle physics at the beginning of the 1970s would have found a fairly optimistic scientific community that felt at the brink of a substantially improved understanding of microphysics. Previous decades had produced a steady influx of novel and often confusing empirical data that seemed to require new ideas beyond the well-established techniques of quantum field theory and quantum electrodynamics. In answer to that data, a series of new theoretical conceptions had been developed and had sharpened the understanding of the consistency problems which stood between the status quo and a satisfactory theory of all nuclear interactions. The emerging new theory, later to be called the standard model of particle physics, seemed to be the first convincing candidate for a coherent description of all nuclear interactions and was quickly establishing a new framework of thinking about microphysics. It made a wide range of empirical predictions which awaited empirical testing. Physicists could reasonably expect the next decade to decide the theory's fate.

Forty years later, we find fundamental physics in a more ambivalent mood. Recent decades have impressively fulfilled the expectations physicists were having in the 1970s. The standard model has indeed been vindicated experimentally and has led to a remarkable sequence of consistent predictive success. The last standard model prediction found empirical confirmation in the summer of 2012 at the Large Hadron Collider (LHC) experiments at CERN and thereby concluded an important phase in the evolution of fundamental physics. Moreover, theoretical progress has continued far beyond the standard model and led to a number of far-reaching new theories. Grand unified theories (GUTs) conjecture a more unified structure of nuclear interactions. Supersymmetry (SUSY) posits a more extensive symmetry structure that connects particles of different spin. Supergravity extends that concept towards a theory of gravity. String theory has been developed as the first powerful and promising candidate for a unified theory of all interactions.

Finally, inflationary cosmology substantially altered our perspective on the early universe and brought a rapprochement of cosmological model building and high energy physics. All mentioned theories which reach out beyond the standard model share one common problem, however. Though each of them was first formulated several decades ago, none of them has found empirical confirmation up to now. The canonical experimental strategy of testing ever higher energies by building ever larger particle colliders is becoming increasingly difficult to sustain due to the enormous efforts required for raising the energy levels of those machines. The huge LHC experiment at CERN might be the last experiment of its kind. Supersymmetry is the only main theory that reaches out beyond the standard model and may have good chances of getting empirical confirmation during the LHC experiments. All other theories have characteristic energy levels which must be expected to lie far beyond the range of feasible collider experiments. Cosmic inflation shows some promising consistency with cosmological data, but its basic tenets look difficult to confirm conclusively. The other mentioned theories have little hope of getting significant empirical confirmation in the foreseeable future at all. The increasing detachment of theory building from empirical confirmation may be taken – and indeed is taken by many – as the dawn of a serious crisis of fundamental physics. The shining example of microphysical progress from early atomic physics to the confirmation of the standard model demonstrates how strongly scientific success depends on the close interaction between theory building and empirical confirmation. Once that connection gets too loose, scientific progress may be suspected to slow down significantly or even come to a halt.

Nevertheless, a number of characteristics of contemporary high energy physics and cosmology suggest a more optimistic picture. First and foremost, the theoretical development after the advent of the standard model has provided concrete perspectives for a genuine unification of all known interactions. Thus, the evolution of physics arguably has made significant progress towards a goal that constituted a distant focal point of physical research ever since the times of Newton: the construction of a truly universal physical theory. Moreover, a look at the dynamics of theory building over the last 40 years shows a situation that differs in several respects from what one might expect in a scientific field that has spent those 40 years without empirical guidance. A lack of empirical data might be expected to lead to a proliferation of fundamentally different scientific approaches whose merits cannot be conclusively tested as long as the empirical dearth continues. The scientific community might split up into small groups adhering to those various approaches. The actual situation in particle physics shows a very different picture, however. One observes a high degree of directedness and uniqueness of theory-building at the most fundamental conceptual level. In a number of contexts, one preeminent theory dominates research and is being developed consistently by a large community of physicists over several decades.[1] Directly related to this focus and directedness of theory building, scientists often have a high degree of trust in their theories despite the lack of empirical confirmation. String theory and cosmic inflation are the prime examples in this respect.

The dearth of empirical data, though clearly constituting an obstacle to scientific progress, thus seems to get alleviated to some extent by characteristics of the research process. One may try to explain this situation by purely sociological means, e.g. by assuming that the involved physicists share some ingrained tendency to stick to the ideas of their group and believe its theories. The alternative explanation, which shall be investigated in the following, is based on the understanding that the conceptual environment in which the theories are developed in some way favors the observed directedness of theory building. If that were the case, the same mechanisms which are responsible for the directedness of theory building could also indicate the viability of the corresponding theories and thus constitute the basis for the trust physicists have in contemporary theories despite the absence of empirical confirmation. The following analysis looks for mechanisms of the described kind. It will be argued that such mechanisms indeed exist and incur a substantial shift of the strategies of theory assessment in contemporary fundamental physics.

One particular physical theory may be called the prime example of the situation characterized in the previous paragraphs. String theory aims at giving a unified description of all physical interactions and thereby provides the most far-reaching perspective on a universal understanding of fundamental physics. It may be called the conceptual center of contemporary fundamental physics that connects many other important theories. It is arguably more detached from empirical testing than any other current theory in fundamental physics. At the same time, trust in string physics among its exponents is particularly high. The theory thus provides the most adequate basis for the ensuing analysis of the structure of non-empirical theory assessment.

[1] At the level of specific model building, to the contrary, one often finds the very kind of proliferation of theoretical models one would expect in the absence of empirical data. The difference between the vast spectrum of models, that is of possible specific realizations of the physical principles which define a fundamental theory, and the conspicuous lack of alternatives at the most fundamental level of theory building is a striking feature of the present situation in high energy physics.

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Excerpt
More information

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).