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Introduction

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1.1 What Is This Book?

Fundamental physics today faces increasing difficulty in finding conclusive empirical confirmation of its theories. Some empirically unconfirmed or inconclusively confirmed theories in the field have nevertheless attained a high degree of trust among their exponents and are de facto treated as well-established theories. String theory, cosmic inflation, and to a certain extent the multiverse are particularly noteworthy examples. This situation raises a number of questions that are of substantial importance for the future development of fundamental physics. The essays in this volume bring together the views of leading physicists, philosophers, and historians of science on the interconnected web of issues that are united by the theme of whether we need to reconsider in light of the particular situation that modern physics finds itself in.

One theme of this book follows on the highly visible debate over the status of string theory that has been ongoing for more than a decade and that has (rather hyperbolically) been baptised ‘The String Wars’.[1] A second and related issue is the status of inflationary cosmology and the multiverse.[2] The goal of this volume is to find a constructive level of analysis for a debate that so far has played out in a fairly antagonistic and often emotional way. In particular, we believe that the best path to progress in methodological debates over modern physics will emerge from constructive engagement regarding the scientific considerations rather than the sociological points at issue. The contributions to this volume stake out and respond to the main positions in the debate.

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[1] Two well-known very critical public books are *The Trouble with Physics* Smolin (2006) and *Not Even Wrong* Woit (2007). Notable responses are from Polchinski (2007) and Duff (2013).

[2] This controversy recently reached an apogee with Ijjas et al. (2017), a highly critical assessment of the status of inflationary cosmology, and a forceful letter in response signed by a large number of leading cosmologists.

This book's interdisciplinary approach accounts for the philosophical nature of the meta-level issues that arise in the given context. Of course, exchanges between scientific and philosophical ideas have long been of relevance for the scientific process. From the scientific revolution up until the modern day, there have been disputes, involving philosophers and scientists alike, regarding both what science is and how science should be practiced. A crucial issue running through these many centuries of debate concerns the circumstances in which we should place *trust* in our scientific theories. In particular, a persistent matter of controversy has been the specification of legitimate methodologies through which scientific theories can be established as adequate and reliable guides to the empirical world. The theme of this book is wedded in this long-standing controversy.

We hope that this book will be of interest, and also of benefit, not only to professional physicists and philosophers of physics but to scientists and philosophers of science more generally. That said, the issues at question here are too important not to also be of concern to a general-interest audience. While the focus in this volume is on the various scientific methods used in fundamental physics, the relevance of this discussion goes beyond fundamental physics. The argumentative strategies followed within the various methods discussed may be, and probably are, similarly applied in other sciences where there is need to assess theories based on scarce empirical data. The wider societal relevance of the questions about what science is and in what circumstances we should trust it are difficult to overstate. An open and rigorous interrogation of such issues is a legitimate requirement if science is to maintain its privileged status within human systems of knowledge.

1.2 Fundamental Physics in the Twenty-First Century

To set the stage, it may be helpful to briefly sum up the current state of fundamental physics. Recent decades have seen important developments and significant progress on a universal conceptual understanding of physical phenomena that goes beyond that provided by the standard model of particle physics and standard Big Bang cosmology.

At the most ambitious conceptual level, string theory has provided a scenario that brings the description of all fundamental interactions into a coherent whole. String theory started out as a perturbative theory of one-dimensional quantum objects. Particle spectra and quantum numbers of low energy theories could, on that basis, be explained in terms of the topologies and oscillation modes of the quantized string. Consistency arguments led to the identification of a number of unusual characteristics of the theory, including compactified extra dimensions and higher-dimensional extended objects, the so-called branes. The latter discovery was related to an improved understanding of the crucial role of duality relations in string theory,

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which provided a basis to conjecture the equivalence of seemingly very different realizations of string theory. One striking example of a duality relation, known as the AdS/CFT correspondence, asserts the empirical equivalence of string theories proper and specific kinds of gauge field theories. In recent years, it has led to a much wider but also more confusing view of what string theory amounts to at a fundamental level.

Focusing on gauge interactions, substantial conceptual work has been invested in developing models beyond the standard model of particle physics, in particular in the context of supersymmetry, grand unification, and large extra dimensions. Focusing on gravity, various approaches to quantum gravity have been developed that solve a number of formal problems which previously barred the direct quantization of general relativity.[3] An important testing bed for these ideas is consistency with the more firmly established field of black hole thermodynamics, which in turn has received significant indirect support from developments in the field of analogue gravity. Despite its diversity, contemporary work on quantum gravity is founded upon a number of widely trusted results that are expected to persist within future theories. In particular, recovery of the black hole entropy law is used as a benchmark for the description of black holes in any viable theory of quantum gravity.

In a cosmological context, attempts to explain core characteristics of the observed universe, such as flatness and the isotropy of space, have led to the development of cosmic inflation. Inflation posits a phase of exponential expansion at the earliest stages of our universe that is followed by the ‘normal expansion’ phase we find ourselves in today. An improved understanding of the way in which inflation and the transition from an inflationary phase to the universe we witness today can play out has led to the conclusion that models of inflation generically lead to eternal inflation. An inflationary background gives rise to an infinite series of expanding hot ‘bubbles’ of slower expansion. Eternal inflation is joined with the string theoretical concept of the landscape, which implies a huge number of ground states of the theory, each corresponding to a different set of characteristic numbers for the corresponding low energy effective theory. In conjunction, the landscape and eternal inflation lead to the concept of the multiverse, which conjectures a vast number of universes with a wide spectrum of parameter values. The multiverse, in turn, is claimed to provide a framework for explaining fine-tuning of parameter values in our world based on anthropic reasoning.

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[3] Non-stringy approaches to quantum gravity have proliferated in recent years. A non-exhaustive list includes loop quantum gravity (Rovelli, 2004, Thiemann, 2007); causal set theory (Bombelli et al. 1987, Dowker 2005, Henson 2006); causal dynamical triangulation (Ambjørn et al. 2001, Loll 2001); spin foams (Baez 1998, Perez 2013); functional RG approaches (Lauscher and Reuter 2001); and group field theory (Oriti 2009).

1.3 The Empirical Problem

The remarkable conceptual innovations that have occurred in fundamental physics during recent decades share one common problem: Several decades after they were first proposed, they still have difficulties in connecting to empirical data. Two developments seem to pull physics in different directions. On the one hand, it is getting increasingly difficult to obtain conclusive empirical evidence. While collider experiments like the Large Hadron Collider (LHC) have shifted upwards the energy scales of empirical testing and have led to the discovery of the Higgs particle, the last missing building block of the standard model, the energy scales accessible by experiments will remain many orders of magnitude below the expected characteristic scale of quantum gravity for the foreseeable future. The characteristic predictions of advanced theories in high energy physics, quantum gravity, and cosmology thus lie either entirely or in part beyond the grasp of currently conceivable experiments. Some predictions can be tested by cosmological observations, but the interpretation of those observations is more complex and less univocal than in designed experiments. In some cases, it is a matter of debate to what extent the given theories are predictive at all.

On the other hand, some theories in high energy physics and cosmology are strongly believed to be true or viable by many of their exponents despite the inconclusive nature (or entire absence) of empirical confirmation. String theory and cosmic inflation, in particular, exert a strong influence on adjacent fields and in many respects are treated like well-established scientific theories. Reasons for trusting in those theories are based on observations of the respective theory's properties and the research process that led up to its current state. In recent years, sharply conflicting positions have emerged on the status of string theory and cosmic inflation as well as the legitimacy of the reasoning in support of those theories' viability. Exponents and supporters of both theories emphasise that the credit they give to the theories in question is based on carrying out further methods of theory assessment that have been part of physics all along. Critics, to the contrary, observe an exaggerated reliance on subjective criteria of non-empirical theory assessment and a deviation from the core principles of empirical science.

1.4 This Has Happened Before

While at its core the current debate over theory assessment in fundamental physics is led by scientists assessing the status of individual theories, it hinges on profoundly philosophical questions. What can count as empirical evidence? How should we define theory confirmation? How can we understand the scientific process in a wider context? The debate thus illustrates the importance of philosophical considerations in defining the norms of scientific discourse.

In recent decades, scientific reasoning in the field of physics has progressed largely without explicit reference to such meta-level issues. Physicists have felt safely embedded within a stable framework of principles that guided scientific reasoning in their field. They have seen no need to address questions of 'scientificality' to proceed with their work. This has not always been the case in the history of physics. When the paradigm of scientific reasoning was developed and established by early modern thinkers like Francis Bacon, René Descartes, Galileo Galilei, and Isaac Newton, their achievements were embedded in philosophical reasoning about human epistemic access to the external world. Significant changes of scientific methodology at later stages were at times accompanied by recurring meta-level debates on the nature of scientific reasoning.

One striking example of a period when such meta-level debates did play an important role in physics and chemistry is the debates on atomism in the late nineteenth and early twentieth centuries. At the time, opponents of atomism perceived the atomic hypothesis as an unacceptable intrusion of philosophically charged ontological reasoning into physics that was incompatible with the empiricist principles of modern science. Atomists defended their commitment to atomism by stressing the position's predictive and explanatory power. The scientific debates at the time provoked leading physicists like James C. Maxwell, Ernst Mach, Ludwig Boltzmann, and Henri Poincaré to write genuinely philosophical and highly influential texts about the scientific process and the epistemic status of scientific results.

A slightly more recent example is the debates on the epistemic and ontological implications of quantum mechanics. Early participants to the debate, from Niels Bohr and Albert Einstein to Werner Heisenberg, agreed on the point that quantum mechanics had implications for basic principles of scientific reasoning, and therefore revealed the interconnectedness of physical and philosophical analysis.

1.5 Core Discussion of This Book

The contemporary controversies regarding the epistemic status and future perspectives of theories in fundamental physics can be understood as following from this broad tradition of philosophical debate regarding the methodological foundations of science. Two overlapping main aspects may be distinguished in those controversies and will be conspicuous in the contributions to this volume.

The first aspect relates to the question of how serious the crisis of empirical testing in contemporary fundamental physics actually is. Many theoretical physicists emphasise the continuity between previous stages of physics and the current situation. They argue that physics can adhere to the very same strategies of hypothesis testing that were developed and deployed throughout the twentieth century and before. While they concede that the process may be more extensive and complex today than at earlier stages of physics, they believe that no fundamental shift of strategy is required. Exponents of this position point to the wide range of empirical data that are relevant to the appraisal of fundamental physical theories today and emphasise perspectives for strengthening the connection between those theories and empirical data in the future. Others claim that physics does face a new category of problems – one substantial enough to raise doubts about the sustainability of traditional strategies of empirical testing. In important cases, they point out, empirical testing, though possible in principle, is so far beyond the reach of current experimental methods that it is questionable whether it can ever be achieved. Notably, in the context of the multiverse scenario, theoretical claims may even be untestable in principle. If so, the question arises whether one can call such claims scientific at all. A number of authors in this text deal with the described issues from various perspectives.

This leads us to the second aspect of the debate: the status of non-empirical strategies for theory assessment. As long as empirical testing of a theory remains unavailable or insufficient, scientists may resort to other, theory-based considerations in an effort to assess a theory's prospects. Participants in the debate generally agree that such considerations are part of science, and have played a crucial role in establishing research programs, such as string physics, as preeminent within the community. However, the value of non-empirical strategies for theory assessment is hotly contested. A first question that arises in the given context is how to define non-empirical theory assessment. The contributions to this volume vary in their choices in this respect. Some authors address the entire range of arguments a physicist may cite in the absence of empirical support for a given theory. Others, in particular those using the term 'non-empirical confirmation', emphasise the importance of specifying a subset of arguments that, due to their specific structural characteristics, may carry particular epistemic significance.

Based on a given understanding of what non-empirical theory assessment entails, the authors in this volume raise a number of questions. Is the degree to which strategies of non-empirical theory assessment have generated a preference for individual theories among scientists justified? Are those strategies of purely pragmatic value or are they epistemically significant? Does the extent to which those strategies are deployed in contemporary fundamental physics amount to a qualitative shift of the scientific method or can it be understood fully within known categories of scientific theory assessment? What are the risks when such strategies become very influential in a scientific world that is bound to rely on them to an increasing degree due to the scarcity of empirical data?

1.6 Book Summary

This volume is divided into four parts. The first part discusses the relevant background for the discussion from various perspectives. **Helge Kragh** argues that there are historical precedents for the situation the field finds itself in today. By studying these analogous historical episodes, in particular the nineteenth-century vortex theory of matter, Kragh argues that we will not find guidance regarding how to proceed methodologically today, but rather a way to adequately identify the epistemic situation we are actually in. **Peter Achinstein** also relies on historical case studies to provide a philosophical evaluation of the status of empirically unconfirmed theories. He offers conceptual reasons why non-empirical arguments in their favour, even if significant, do not amount to evidence for the given theory. Empirically unconfirmed theories thus can play an important role in the scientific process and should be taken seriously under certain conditions but still must be treated as scientific speculations. Scientists use a variety of methods to assess theories: from evidence obtained through direct and indirect experiments, to analogue experiments and non-empirical methods. **Radin Dardashti** and **Stephan Hartmann** argue that Bayesian confirmation theory provides an adequate tool for both a descriptive and a normative treatment of these various methodologies. By applying Bayesian confirmation theory to various scientific methodologies, they provide examples of the fruitfulness of this approach. In the final contribution in this part of the volume, **Massimo Pigliucci** argues that, while Popper still plays a significant role as friend or foe in the current debates on the status of physical theories, his positions are often misrepresented in those debates. Drawing parallels to biology, Pigliucci points out that an overly vitriolic public appearance of debates in a scientific field carries the risk of impeding the public's ability to distinguish between science and pseudoscience.

In the second part of this volume, several papers introduce and discuss the viability of methodologies that do not rely on direct empirical evidence. In the first of these chapters, **Richard Dawid** discusses the philosophical foundations of non-empirical theory assessment and addresses several objections that have been put forward against his account. He argues that the potential significance of specific forms of non-empirical confirmation hinges on their similarity to empirical confirmation in a number of respects. Contrary to Dawid, **Carlo Rovelli** argues that the reliance on non-empirical confirmation poses a threat to one of the crucial features of science – namely, its reliability. He illustrates the danger of non-empirical theory confirmation with the example of its application to string theory. Similarly, **Daniele Oriti** considers critically the dangers of non-empirical theory confirmation, while admitting that in situations where empirical data are scarce, especially in the context of theories of quantum gravity, non-empirical theory assessment is even necessary and possibly the only methodological response to a degenerative research programme. **Radin Dardashti** analyzes the normative implications of non-empirical theory assessment for scientific practice. He identifies three problems scientists confronts when applying non-empirical theory assessment and provides possible ways to address these problems. These strategies, he argues, amount to the necessity to change scientific practice in circumstances where non-empirical theory assessment is to be applied. **Elena Castellani** considers the early development of string theory as a historical analysis of the interplay between empirical and non-empirical theory assessment. She argues based on this historical analysis that the relevant question is not one of which methodology to rely on, but rather finding and justifying the right balance between empirical and non-empirical theory assessment.

A recent alternative proposal for theory assessment relies on the use of analogue table-top experiments to test features of inaccessible target systems elsewhere. **Karim Thébault** discusses recent experiments by Steinhauer on analogue black holes and identifies the conditions under which these can provide evidence for phenomena such as black hole radiation in the inaccessible target system. The final paper of Part II discusses the role of Bekenstein entropy in assessing theories of quantum gravity. While there is no empirical confirmation of the Bekenstein formula, its recovery in theories of quantum gravity is widely considered as providing evidence in support of the theory. **Christian Wüthrich** argues that the information theoretic justification of the formula given by Bekenstein himself does not license the use of this formula in theory assessment.

In the third part of this volume, the possibilities and limitations of *empirical* confirmation in cosmology are discussed. Understanding such possibilities is crucial for identifying where, and to what extent, non-empirical and other alternative methods of theory assessment will have to supplement the available empirical assessment. **Joseph Silk** describes how the standard model of cosmology emerged and how its more phenomenal aspects have found empirical confirmation by precision data. He discusses ways in which future precision measurements could shed light on deeper conceptual claims in cosmology. Silk emphasises that, in the end, establishing hypotheses like inflation must be based on confirming precision data. **Björn Malte Schäfer** analyses of the relation between cosmology on the one hand and the theory of general relativity and the statistics of structure formation on the other hand. This provides the necessary background to assess the possible empirical viability of the various assumptions involved in the standard model of cosmology. Based on this analysis he discusses various argumentative strategies to assess the elements of the ΛCDM model. One specific controversial approach within cosmology is the multiverse idea. **George Ellis** discusses the variety of multiverse proposals and their testability. He argues that, except for some specific cases, the multiverse idea is not empirically testable. Its endorsement therefore requires a weakening of principles of scientificality. Even if non-empirical theory assessment were applicable to the multiverse idea, to Ellis, it would not provide sufficient support. Contrary to Ellis, **Sean Carroll** argues that reasoning in support of the multiverse can be fully understood in terms of conventional empirical hypothesis testing and therefore does not require a weakening of scientificality principles. According to Carroll, the evaluation of multiverse models relies on abduction, empirical success, and Bayesian reasoning – just like the evaluation of any other theory in physics. In the final chapter of this part, **Chris Smeenk** discusses the problem of underdetermination in the context of cosmology. He suggests that a theory that is consistently empirically successful indexempirical success in a given domain in effect rules out the possibility of alternative theories in that domain. He then argues that in the case of eternal inflation, empirical confirmation systematically lacks the strength to eliminate rival theories, which seriously limits the chances for conclusively establishing the theory.

In the final part of this volume, several string theorists discuss different possibilities to assess string theory. **Joseph Polchinski** starts by providing an argument for why string theorists rely on the theory despite the lack of empirical data. He considers five remarkable features of string theory which, according to his analysis, justify a considerable degree of trust in string theory's viability. He then offers a rough Bayesian assessment of the multiverse hypothesis to illustrate the claim that it is reasonable to attribute a high probability to this controversial hypothesis. While Polchinski's work reasons at a general conceptual level, the three following chapters discuss concrete models relating string theory to empirically accessible systems. **Eva Silverstein** argues that string theory provides a plethora of fruitful ideas that can be of use for empirically accessible systems. Concretely, she considers the role that string theory played in developing and motivating mechanisms for dark energy and inflation. Thus, even if it may be too early to assess the empirical viability of string theory itself, it has already produced a fruitful interpretational framework for existing empirical data. **Gordon Kane** argues that there are substantial data-based reasons to take a positive attitude towards string theory. Some concrete compactifications of string theory recover many desirable features at lower energies. Kane argues that considering predictions of those specific models as testable predictions of string theory is in line with standard principles of scientific reasoning. In the final chapter, **Fernando Quevedo** presents the current status and prospects of string phenomenology. After introducing several generic predictions of string theory, he considers ways in which observational data can constrain string theoretical model building and addresses several objections against string phenomenology. Quevedo points to a number of specific implications of string theoretical models that could be testable at energies far below the Planck scale.

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