Empirical Equivalence, Scientific Realism and String Theory

The phenomenon of duality in string theory provides an example of the underdetermination of the theoretical scheme by all possible empirical data. Empirically equivalent theories which arise due to string dualities differ in essential characteristics like the dimension and the topological position of their elementary objects and the form and dimensionality of spacetime. The obvious ontological incompatibility of dual string theories and the status of the duality principle as a core concept of string physics reveal serious tensions between string theory and ontological realism.

1: Introduction

The claim that our observable world does not uniquely determine the choice of the scientific scheme plays an important role in the scientific realism debate. The underdetermination of scientific theory by all possible data was formulated classically in (Quine 1975) and deployed e.g. in (van Fraassen 1980) as a central argument against the use of the concept of truth in statements about scientific objects. Its validity, however, still remains doubtful. (Wilson 1980), (Laudan & Leplin 1991) In particular, as pointed out by Quine himself and recently emphasised e.g. in (Lyre & Eynck 2003), it is not easy to find convincing examples of Quinean underdetermination among actual scientific theories.

In this paper I want to present an example of Quinean underdetermination that is based on the concept of string duality. Irrespectively of the question of the validity of string theory, the presented example can provide a case study of a scientific scheme where underdetermination can be clearly shown to arise. Under the condition that string theory is a viable physical theory, the phenomenon of string dualities could lead to a new understanding of the actual role of underdetermination in modern high energy physics. After a short introduction of the conception of string duality in section two, section three will address the question of underdetermination. Section four, finally, will discuss the implications for scientific realism.

2: String Duality

The basic idea of string theory is to replace point-like elementary particles by extended objects. This seemingly simple step leads to the development of a highly complex theoretical scheme that aims at providing a joint description of gravitation and microphysical

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1 In this paper I will use the term ‘underdetermination’ mostly in the Quinean sense of ‘underdetermination of the theoretical scheme by all possible empirical data’. It should be emphasised at this point that there exist other forms of underdetermination whose analysis had to be based on entirely different considerations. (See e.g. the concept of ‘scientific underdetermination’ discussed in (Dawid 2004).)

2 Standard Textbooks on String Theory are (Polchinski 1998) and (Green, Schwarz & Witten 1987). A popular introduction is (Greene 1999).
interactions. One property of this scheme is of particular interest for the present paper: the string world shows a remarkable tendency to link seemingly quite different string scenarios by so-called duality relations. Dual theories are exactly equivalent in their observational implications, though they are quite differently constructed and may involve different types of elementary objects and different topological scenarios.

The phenomenon can be introduced best by the example of T-duality, which involves less interpretational complications than other instantiations of the duality principle. Superstring theory (The kind of string theory able to describe both bosonic and fermionic fields) can only be quantized consistently in 10 spacetime dimensions. Those 6 dimensions which are not visible to our eyes are taken to be compactified: they have the topological shape of a cylinder surface, where, after some very small translation in the ‘compactified’ direction, one ends up again at the point of departure. Closed strings (which have the topological structure of a rubber band) can be wrapped around compactified dimensions or just move along a compactified dimension. Since momenta along closed dimensions can only assume certain quantized eigenvalues, two basic discrete numbers characterise the state of a closed string in a compactified dimension: the number of times the string is wrapped around this dimension and the number of its momentum state in that very same dimension.³

T-duality asserts that a state where a string with characteristic length

\[ l \]

is wrapped \( n \) times around a dimension with radius \( R \) and has momentum level \( m \) is dual to a state where a string is wrapped \( m \) times around a dimension with radius \( l^2/R \) and has momentum level \( n \). The two descriptions give identical physics. The phenomenon is not a case of quantum indeterminacy concerning two states of the system. We rather face two theoretical formulations which describe the same physical situation so that they cannot be interpreted as referring to two different states at all. Nevertheless, the two formulations differ in characteristics which lie at the core of any meaningful ontology of an external world. They differ in the shape of space-time and they differ in form and topological position of their elementary objects.

T-duality is not the only duality relation encountered in string theory. It turns out that the existence of dualities is one of string theory’s most characteristic features. Duality relations play the crucial role of connecting all different types of superstring theory. Before 1995 physicists knew 5 different ‘superstring theories’.⁵ Then it turned out that these 5 theories and a 6th by then unknown theory named ‘M-theory’ are all interconnected by duality relations. This web of dualities connects theories whose elementary objects have different symmetry structure and different dimensionality. (Each string theory needs a well-defined set of higher dimensional so called d-branes to be consistent.) M-theory even has a different number of spatial dimensions than its co-theories. Duality nevertheless implies that M-theory and the 5 possible superstring theories only represent different formulations of one single fundamental theory. In recent years, string-theoretical analysis has discovered even more surprising duality relations. For example, there exists a duality relation between certain theories that include gravitation and certain pure gauge theories without gravitation in a space reduced by one spatial dimension. More discoveries of duality relations might well follow in the future.

3: Underdetermination

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³ The two numbers are called winding number respectively Kaluza-Klein level.
⁴ The characteristic string length denotes its length when no energy is being invested to stretch it.
⁵ String theorists use the word ‘string theory’ for the general theoretical scheme as well as for the specific realisations of that general scheme which are based on specific choices of internal symmetry structures.
The fact that different string theories with different elementary ontologies are empirically equivalent constitutes an example of Quinean underdetermination. Remarkably, two important problems which have marred previous exemplifications of underdetermination are softened in the context of dual string theories.

First, there is the question how to distinguish reconstructions of predicates from other empirically equivalent theories. The claim of underdetermination would be of little interest for the philosopher of science if it merely held that there are different ways to tell the same story. Such simple ‘reconstructions of predicates’ usually are distinguished from substantially different scientific concepts by introducing an ontology of the scientific objects. ‘Ontologically charged’ or reified objects are taken to be the essential elements of the theory, whose existence and whose observable properties cannot be changed without creating a new theory. The simple renaming of these objects that does not alter their properties (e.g. calling the electron proton and vice versa) or the redefinition of parts of the theory that are not reified (e.g. the change of coordinate systems) do not create a new theory. In this sense, Quine’s ‘logically incompatible theories’ actually represent ‘ontologically incompatible theories’. Unfortunately, it is not always clear which parts of a theory precisely should be reified. To give one example, Poincaré’s reformulation of classical mechanics in infinite flat space as a theory with altered physical laws in a finite space (Poincaré 1902) may look like a genuinely new theory if one reifies infinite flat space. Still, the conception is often understood as a mere reparameterisation of classical mechanics and therefore as an example of a reconstruction of predicates.

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

The case of string dualities is also better suited than other examples of Quinean underdetermination to deal with the problem of the preliminary status of scientific theories. Quine asserts that the totality of all possible empirical evidence underdetermines the choice of a scientific scheme. Attempts to find scientific theories which can serve as examples of underdetermination usually fall short of exemplifying Quine’s assertion for a simple reason: Scientific theories in general cannot be expected to fit all possible empirical evidence. The specific status of string theory changes this situation in two respects. First, string theory offers a number of reasons for being called a final theory. (see e.g. (Witten 1996), (Dawid 2004).) Therefore, the assertion that string theory, if fully understood, could fit all possible empirical evidence, has a certain degree of plausibility. Second, in the context of string theory the claim of Quinean underdetermination is not based on the accidental occurrence of several empirically equivalent theoretical schemes but on a physical principle, the principle of duality, which represents a deep characteristic of the involved theories and may be expected to be a stable feature of future fundamental physics. It seems plausible to assume that the duality principle will continue to play an important role even if string theory changed substantially in the course of future research.
4: Scientific Realism

The question of underdetermination exerts considerable influence on the scientific realism debate. It is clear that the plausibility of an attribution of reality to scientific objects must suffer from any indication that more than one set of scientific objects is compatible with our observable world. If one ontological interpretation of the scientific description were enforced uniquely by the totality of all possible empirical data, a scientific realist interpretation of that description would seem natural at least in principle. If several or many possible ontological interpretations of the observable world existed, however, the scientific realist, who wants to establish her realist interpretation of microphysics based on abductive inference, would have to find good arguments why she rejects one ontological interpretation and endorses another. Still, underdetermination cannot strictly refute realism. The metaphysical realist may insist that, even if the selection of one set of ontological objects cannot be decided upon on empirical or rational grounds, there is a true choice after all.

A comparison between the empirical equivalence due to string dualities and other examples of ontological underdetermination indicates that the former might carry particular force in the realism debate. Classically, two types of assertions about empirically equivalent scientific ontologies can be distinguished. On the one hand, one theoretical scheme can allow various ontological interpretations. Quantum field theory, to give an example, might allow to attribute the status of elementary objects either to particles or to fields. The variety of ontological interpretations in this case exists at the level of the philosophical interpretation of one specific physical theory. On the other hand, there may exist different mathematical schemes which describe the same observational world. Examples are the different empirically equivalent ways to formulate a gravitational theory. (see e.g. (Lyre & Eynck 2003).) String theory does not quite fit into any of these groups. It offers a variety of ontologically incompatible but empirically equivalent physical descriptions which are integrated in one scientific theory. The occurrence of ontological underdetermination thus does not any more look accidental but is made a core physical statement. This can be understood as a genuinely physical argument against one ‘real’ scientific ontology. The method of abductive reasoning, to which the scientific realist wishes to resort, in this case suggests the abandonment of ontological realism. The die-hard metaphysical realist can resist this argument but, by doing so, puts herself at variance with a core principle of scientific realism, the principle of abduction.

There exists an additional aspect of duality that underlines the conception’s anti-ontological character. Duality does not just spell destruction for the notion of the ontological scientific object but in a sense offers a replacement as well. As it was described above, by identifying theories with different sets of elementary objects, string dualities reduce the number of independent possible string theories down to one. While the uniqueness of the elementary objects is lost, duality thus introduces a different quality of uniqueness, the uniqueness of the string theoretical structure implied by the basic postulates of the theory. Given that the uniqueness of the real constitutes a pivotal element of any realist conception, the replacement of ontological by structural uniqueness seems to suggest to the realist a structural realist approach. (Dawid 2003)

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6 The question whether the limited scientific theories available to us can identify this real ontology would remain, of course.

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

8 The significance of structural uniqueness of string theory is further enhanced by the fact that string theory does not have any free parameters, i. e. there are no numbers in the theory that can be varied to fit phenomenology. The basic postulates of string theory thus enforce one unique entirely rigid structure.
Literature:

Dummett, M. 1991 The Logical Basis of Metaphysics, Duckworth.
Poincaré, H 1902 La science et l’hypothèse, Paris Flammarion.