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Realism, underdetermination and string theory dualities

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Abstract String theory promises to be able to provide us with a working theory of quantum gravity and a unified description of all fundamental forces. In string theory there are so called 'dualities'; i.e. different theoretical formulations that are physically equivalent. In this article these dualities are investigated from a philosophical point of view. Semantic and epistemic questions relating to the problem of underdetermination of theories by data and the debate on realism concerning scientific theories are discussed. Depending on ones views on semantic issues and realism different interpretations are possible of the dualities.

Keywords Underdetermination · Realism · Structural realism · String theory · Philosophy of physics

1 Introduction

In the attempt to formulate a theory of quantum gravity, string theory has for the past decades been the dominant research programme.[1] The basic assumption in string theory is that what we previously had thought to be pointlike particles are instead different vibrational states of one-dimensional extended objects i.e. strings. String theory is also trying to incorporate and unify all fundamental interactions within one theoretical framework.

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[1] I use the expression 'string theory' in an inclusive sense. As part of string theory I hence include work on related developments such as M-theory. String theory is deliberately called a 'research programme' and this is meant in Lakatos' sense. See 'Falsification and the Methodology of Scientific Research Programmes' in Lakatos and Musgrave (1970).

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Despite the dominant position that string theory now has in the theoretical physics community, no new empirical predictions have been precisely formulated and empirically confirmed. So, string theory has not successfully been connected with experimental physics. This is of course disappointing. Due to the lack of empirical results critics question the scientific status of string theory. In this paper the debate on the value of performing research in string theory will not be discussed. Instead the focus is on another question; namely, how to interpret the so called 'dualities' that play a prominent role in string theory. For now it suffices to say that we have a duality when two described systems that prima facie seem to be very different still are physically equivalent; or maybe even not two systems at all but rather just one system under different descriptions. Various ways of understanding dualities will be presented in this article and different interpretations are given depending on various views on semantic and epistemic questions.

For those who take string theory seriously the work is of relevance to their understanding and interpretation of what string theory tells us about reality. The discussion on how to understand dualities is also of interest as an example of how to think about theoretical claims, and gives relevant input to the debate on scientific realism.[2]

2 What is string theory?

What happens when it is assumed that elementary objects are not pointlike but instead one-dimensional and extended? This seemingly innocuous assumption implies some rather startling consequences. For instance string theory must contain states of spin two that can be interpreted as gravitons: the quantum of gravity. It seems that string theory gives rise to a finite and renormalizable version of quantum gravity. The other fundamental interactions can also be incorporated within this framework.[3]

That string theory unifies the fundamental forces, including gravity, is a great success for the theory. Due to these results string theory was, and still is, widely considered to be the most promising approach to formulate a theory of quantum gravity, but there are other predictions that are not immediately appealing. For instance, a quantized version of string theory is not consistent unless there are a specific number of spacetime dimensions. For the bosonic string the preferred dimension is 26, but such a string theory does not contain fermions; and hence, could not be a theory that describes our universe. To include fermions one must instead use string theories involving supersymmetry, i.e. superstring theories. Five different versions of superstring theory have been formulated; namely, type I, type IIA, type IIB, heterotic SO(32) and heterotic E8 x E8. According to the superstring theories spacetime is 10-dimensional.

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[2] Works closely related in topic to what is discussed in this text are Dawid (2006, 2007) and Rickles (2011). More on quantum gravity written by philosophers can be found in Callender and Huggett (2001), Rickles et al. (2006) and Rickles (2008), see also the comments in Sect. 3.7.2 of Ladyman and Ross (2007).

[3] Standard textbooks in string theory are Green et al. (1987), Polchinski (1998), Zwiebach (2004) and Becker et al. (2007). Good accounts for the layman that are optimistic regarding the future prospects of string theory are Greene (1999; 2004). A reader looking for a more pessimistic evaluation of string theory may consult the books by Smolin (2006) and Woit (2006).

One might think that the prediction of a different number of spacetime dimensions than the four we were previously familiar with would directly refute string theory. However, it can be explained why these extra dimensions are invisible to us. One way is to let the extra dimensions be curled up to form a small compact manifold which would not be observable with present day technology. Another proposal is that we live on a restricted part of the complete spacetime; such scenarios are possible using D-branes which are dynamical objects which can have different numbers of spatial dimensions. The motion of endpoints of open strings are constrained on these D-branes.

The different versions of superstring theory are connected to each other via various dualities. It is these dualities that will be the main topic of discussion in this article. That the different string theories are related in this fashion makes physicists believe that they are different limits of one and the same underlying theory called 'M-theory'.

3 Underdetermination and scientific realism

3.1 Underdetermination

The problem of underdetermination is that we cannot rule out that more than one theory is compatible with our empirical data. There are different kinds of underdetermination. We can talk about underdetermination with respect to currently available data; this kind of underdetermination is called 'transient underdetermination' or 'scientific underdetermination'. Theories might differ in their predictions concerning what have not yet been empirically tested and still be underdetermined in this sense.[4]

The other kind of underdetermination is between theories or theory formulations with respect to all possible data. This means that all their predictions are exactly the same. This is the kind of underdetermination that will be considered in this paper. How one responds to this problem depends to a certain extent on ones views on scientific theories. If one supports something like an instrumentalist position, and individuate theories only in terms of their empirical content, the problem disappears. If so one must consider the differences that seem to exist between various formulations to be without any real significance; the theories say the same thing. Our talk about the unobservable is just empty words, which should not be taken seriously. If on the other hand we, assume that alternative theory formulations describe different scenarios, the threat of underdetermination must be taken as real.

Quine is associated with underdetermination and the claim that two logically incompatible theories can both be consistent with data. However, as can be seen in Quine (1975), his views are quite complex. There he states that if there exists a mapping between two theory formulations, they do not describe different theories at all; instead they are to be understood as different variants of one and the same theory; Quine calls this 'reconstrual of predicates'. So, he did not consider *any* two formulations that give

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[4] See Sklar (1975), Stanford (2001) and Dawid (2006, 2007). Dawid argues that string theory and the dualities can be used as an argument against the importance of this kind of underdetermination. I do not address this question in this paper.

rise to the same empirical content as being a genuine example of underdetermination. Note, however, that this does not mean that he rules out examples of genuine underdetermination that cannot be understood in terms of a reconstrual of predicates, but it can be difficult to find such examples.

Quine's view, that theory formulations that can be mapped to each other using a reconstrual of predicates should be understood as different formulations of the same theory, would not be satisfying for all. It can be claimed that the formulations present two genuine alternative theories after all, despite the structural similarity. A person claiming this would give more importance to what is stated in the two formulations beyond what is captured in the structural properties of the formalism. They would find Quine's views still too positivistic in spirit. They could argue that there are relevant semantic differences that are lost in the mapping; the mapping can only be done for that part of the theory that is logically or mathematically formalized. So here we note that we must ask if there is more to a theory formulation than what is captured in the logico-mathematical structure. This is a central question for this article.

3.2 Scientific theories and realism

Do our theories correctly describe the world even beyond what we can empirically measure or are they just tools for prediction? This has been debated for a long time and questions concerning realism have been discussed many times in the history of science and philosophy.

Roughly a scientific realist thinks that our best scientific theories are approximately true and that theoretical terms that are introduced in the theory typically refer to entities that really exists. Hence, we are justified in believing that there really are electrons. A scientific realist normally thinks that we should take what scientific theories say literally. Exactly how one should understand what we mean by 'literally' is not completely clear. Here it suffices to say that when using a literal understanding of theoretical statements it is assumed that they have semantically relevant content that goes beyond the empirical content. In short one can claim that there are two main components in scientific realism. Following Bain (Draft) these are:

1. The semantic component: The theoretical claims of certain theories are to be interpreted literally.
2. The epistemic component: There are good reasons to believe the theoretical claims of certain theories.

To be a *semantic realist* is to accept the first claim and to be an *epistemic realist* is to accept the second claim. To be a traditional *scientific realist* you must accept both claims. For a careful discussion and defence of scientific realism see Psillos (1999). See also Churchland and Hooker (1985).

It should be noted that a scientific realist would only consider a mature well-tested theory that has been used for novel prediction to be considered among those to be taken realistically. Obviously string theory does not yet, and perhaps may never, live up to this. So why would considerations of string theory be relevant for questions concerning scientific realism? The answer is that the investigation in this article is concerned with what string theory would imply if it is taken seriously as a description of the real world. The dualities in string theory provide a very interesting case study where it is difficult to defend a traditional form of scientific realism. I also believe that the discussion elucidates questions concerning how modern theoretical physicists can interpret theoretical claims. I think this will be of value even if string theory will not live up to its expectations.

Underdetermination of theories by data is a problem for scientific realists. To solve this problem realists may argue that we can give good reasons for choosing one theory instead of another using virtues such as simplicity, lack of ad-hocness, explanatory power, etc. These criteria have been criticized as being vague and also nonindicative of truth, but I will not review this debate. Alternatively one can argue that what seems to be an example of underdetermination are just two ways of describing the same theory. When using this approach one must be careful not go too far in the instrumentalist or positivist direction; this would effectively turn one into an anti-realist.

In general, arguments using underdetermination are supposed to force the scientific realist to abandon either semantic realism or epistemic realism. I quote from Bain (Draft) where he describes the general form of an underdetermination argument like this:

> For any version of semantic (epistemic) realism, there are theories T and T' such that if we are semantic (epistemic) realists about T and T', we cannot be epistemic (semantic) realists about T and T'.

Traditional logical positivists, are a kind of anti-realists. They regard the cognitively significant part of a theory to be restricted to its empirical content. Hence according to that view string theory is not very impressive. On the other hand if string theory in the future would be empirically successful, the dualities would not cause any problems. They would just be seen as semantically equivalent since only the empirical content would be thought of as relevant. However, logical positivism is by present day philosophers of science judged to be an unacceptable view on scientific theories and I agree with this assessment.[5]

A more modern form of anti-realism is defended by van Fraassen. In contrast to the logical positivists he does not tie his anti-realism to a theory of meaning. Just like scientific realists he claims that theories ought to be taken literally. He considers a well formed sentence to be true or false regardless of whether or not it is epistemically possible to decide what the truthvalues are; he is hence a semantic realist. But what is important for a scientific theory, according to van Fraassen, is only that it is empirically adequate, i.e. that it correctly predicts empirical data and hence 'saves the phenomena'. We do not really need to believe what a scientific theory claims concerning what lies behind the phenomena. This is beside the point, since the aim of science is just to find empirically adequate theories; see van Fraassen (1980).

Structural realism is an attempt to find a position between realist and anti-realist views on scientific theories. The modern discussion concerning structural realism

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[5] For an extensive description of the formulation, development and problems that faced logical positivism see Suppe (1977).

goes back to Worall (1989).[6] It is an ongoing debate how the doctrine of structural realism is to be understood and what insights it really gives concerning questions of epistemology and metaphysics.

Structural realists argue that ‘structures’ are preserved even when we radically change our theories of the world; the clarification of what these structures are supposed to be is unfortunately not very clear even though it seems that the structures are supposed to be intimately connected to the mathematical or logical elements of a theory formulation. For example, equations in older theories can be retained or at least be shown to follow approximately from new theories.

It is possible to explicate the position in various ways. Ladyman (1998) introduced the distinction between epistemic structural realism (ESR) and ontic or metaphysical structural realism (OSR). A proponent of ESR argues for structural realism due to epistemic reasons; we can only know or have good reasons for believing in the structural parts of a scientific theory. They do not, in contrast to a proponent of OSR, think that we need to adopt a structuralist ontology i.e. assume that the structure as a whole and the relations in the structure are ontologically more fundamental than the relata. So a defender of ESR typically thinks that the structure supervenes on separate individuals with certain properties and so forth. People have tried to explicate this notion using Ramsey-sentences, but this approach is problematic.[7]

I will not assume that ESR *must* be understood in such a fashion that it presupposes an ontology of separate individuals. This might deviate slightly from the normal way of describing the difference between ESR and OSR. A main difference, as I understand it, between ESR and OSR is whether one considers talk about what is beyond the ‘structural’ to be meaningful in a more substantial sense so that it can be used to describe real alternative situations. In Ladyman and Ross (2007) where OSR is defended they argue for a form of verificationism, but not a verificationism of the logical-positivists kind which is tied very tightly to a semantic theory. I think that it is important to address the issues concerning the semantics of scientific theories in more detail and this will be done to some extent later on in this text.

In Lyre (2009) it is asked whether structural underdetermination is possible. Given that the notion of structure is not very clear it is of course difficult to decide this. Lyre concludes that it could not be ruled out.

While I find structural realism compelling and am sympathetic towards structural realism as a project, I find the lack of a reasonably precise and useful description of structure in the context of scientific theories quite disturbing. Due to this ‘structure’ might not be the best word to use. We could use the expression ‘intermediate realism’ for any intermediate position in the realism debate. Structural realism, if it could be explicated in a satisfying manner, would be a species of this, but not necessarily the only possible kind of intermediate-realism. Another kind of intermediate realism would be the semi-realism which is developed in Chakravartty (2007).

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[6] It ought to be mentioned that similar ideas have been formulated earlier. Worall himself argue that Poincaré advocated a position that could be thought of as a form of structural realism. No attempt is however made to discuss the historical roots of structural realism any further.

[7] This is discussed in Psillos (1999) and Ladyman and Ross (2007). See also the original texts by Newman (1928), English (1973) and Demoupoulos and Friedman (1985).

4 Formalisms and physical content

Mathematics plays an important role in formulating physical theories but mathematics by itself is not physics. Part of the mathematical formalism must be interpreted so that it refers to something physical. Details on exactly how this is supposed to be done will not be given. It should nonetheless be clear that I do *not* presuppose a traditional positivist line in which *every* concept must be given a definition, partial or complete, in terms of operations and measurements. So, for example, even though string theory has not been empirically successful, there is an understanding of how the theory is supposed to be related to earlier theories that have been empirically successful. For instance, one understands how the worldsheets of strings are supposed to be related to Feynman diagrams in quantum field theory and which calculations in string theory are supposed to be used to calculate scattering amplitudes and so forth. So string theory has *some* physical content. By ‘physical content’ I mean something less strict and less directly connected to observations and experiment compared to empirical content even though it at least indirectly should be connected to empirical content. I am aware that this distinction is vague but the example above hopefully indicates what I am trying to say.[8]

But string theory has unfortunately been quite removed from experimental input. The formalism has been ‘flying freely’ to a certain extent and this has caused some confusion. For instance it is very difficult to immediately distinguish the purely mathematical from the physical content. For this reason I will discuss the use of the word ‘duality’ in string theory.

4.1 On how the word ‘duality’ will be used

The word ‘duality’ is not new in physics or in mathematics. It has been used for quite some time and in many contexts. The focus in this article is on how the word ‘duality’ is used in the context of string theory. While there is some similarity to other contexts where the word ‘duality’ is used, such as in discussions on wave-particle duality in quantum mechanics, there are also important differences. To clarify, a few suggestions on how to restrict the use of the word ‘duality’ will be given.

A few things that must be distinguished from dualities in this context are the following:

1. It is well known that many equations and mathematical formalisms appear in different contexts describing completely different physical systems. For example the wave-equation and Poisson’s equation. These are not examples of dualities since it is clear that we describe different empirically distinguishable systems. What the equations are used to describe are then obviously different. Hence, even if there is

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[8] The importance of giving the mathematical formalism a physical or empirical interpretation was stressed also in Cao (2003) and Lyre (2009). The defenders of OSR are often accused of trying to describe theories purely mathematically. Given the exposition in Ladyman and Ross (2007) I do not think this is true but they come dangerously close to such a view.

a mapping, isomorphism or structural similarity at the purely mathematical level it is not a duality since the *application* is not the same at the empirical level.
2. When it is *clear* that we are just discussing two alternative coordinate descriptions of one and the same system it will not be considered to be a duality. Hence different choices of gauge or coordinates should not be thought of as dualities. This is however something that might need further clarification. It might be the case that some dualities could be understood just in terms of a change of coordinates, but this should at least not be *obvious* from the start.

I believe that most physicists would agree that these are suitable restrictions for the use of the word ‘duality’ in string theory.

It is when we talk about variables and parameters that are not given an empirical or at least physical interpretation that we get into a more problematic situation. If we do not want to adhere to some form of strict operationalism/positivism we will think that we can meaningfully talk about alternative situations even on a more theoretical level. A physical theory is formulated using a combination of mathematics, physical interpretation of empirical parameters and analogies or metaphors from other linguistic practices to convey what we want to say. The question is which importance we attach to our way of describing the theories.

4.2 Purported dualities outside of string theory

Here I will briefly discuss two ‘dualities’ taken from Zwiebach (2004). There they are introduced as introductory pedagogical tools to prepare the reader for the dualities in string theory. Since they are introduced mainly for pedagogical purposes to prepare the readers for the dualities in string theory I do not claim that Zwiebach consider these examples to be dualities of the kind that appears in string theory. The purpose of the discussion that follows is to clarify the criteria for relevant dualities in string theory that I gave above. I think that an explanation for why the examples are not dualities according to these criteria will be instructive for the reader.

4.2.1 The harmonic oscillator

The first example is a simple harmonic oscillator consisting of a mass m hanging from a spring with spring constant k. The Hamiltonian is,

$$H(m, k) = \frac{p^2}{2m} + \frac{1}{2}kx^2. \tag{1}$$

This harmonic oscillator has angular frequency $\omega = \sqrt{k/m}$ as can be deduced using elementary physics.

Zwiebach then suggests that there is a ‘duality’ transformation changing the parameters as,

$$(m, k) \to \left(\frac{1}{k}, \frac{1}{m}\right). \tag{2}$$

Neither the Lagrangian nor the Hamiltonian is preserved when this mapping is made, but the equations of motion for x is preserved ie $m\ddot{x} = -kx$. The parameter x indicates the position away from equilibrium. He shows that given a canonical transformation of the new Hamiltonian we can get back to the form of the old one. However, in a canonical transformation we actually talk about different new variables with different interpretations and this does not change the fact that we have two situations that can be distinguished.

There is, of course, nothing wrong with the calculations in terms of the mathematical derivations. But if we assume a physical interpretation, and express the results in physical units, then the transformation only refers to the numerical values. For instance what is said is just that the oscillation of the coordinate x and the angular frequency ω are the same in two different and *empirically distinguishable* situations. Hence, it should not be considered to be a duality according to the first criterion given above.

The two situations are for instance: when we have a mass of 1 kg and a spring constant of 3 N/m = 3 kg/s^2 compared to when we have a mass of 1/3 kg and a spring constant of 1 kg/s^2. These situations are different and empirically inequivalent even though the equation for x would be the same.

If physics is supposed to be connected to empirically accessible results then we cannot talk about this as a significant example of a duality, at least according to the criteria I have formulated. The reason for this is that not only the value of x is empirically accessible but also k and m. It is important not to accept this example as an example of a duality unless we risk to make the term ‘duality’ too general as to make it more or less uninteresting.

As has been argued above, for there to be a relevant kind of duality we are not allowed to consider a duality to exist between two systems that are distinguishable at the empirical level, otherwise the point with dualities is lost. On the other hand the purpose with the example is pedagogical and is introduced to give students a simple example of similar calculations as the one they will encounter in the dualities in string theory. I do not claim that Zwiebach himself is not aware of this, he would probably agree with the point I have made. Nonetheless I do find it important to mention this example to illustrate an important point namely how we must not forget to distinguish between a purely mathematical formalism and its physical interpretation.

4.2.2 Classical electromagnetism

The second example taken from Zwiebach is Maxwell’s equations in the absence of sources:

$$\nabla \cdot \vec{E} = 0, \quad \nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$
$$\nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

These equations are invariant under the following transformation,

$$(\vec{E}, \vec{B}) \rightarrow (-\vec{B}, \vec{E})$$

The point is made that this symmetry is not existent in the Lagrangian since we get a change of sign but still the equations of motion are the same.

But is this not just a possible change in terminology made possible from the symmetries in the equations without any substantial importance? If we have electric charges and no magnetic monopoles we can empirically decide which fields are to be interpreted as electric. That is we can decide which labels, E or B to assign to represent electric fields.

If there are magnetic monopoles the symmetry can be extended to include magnetic monopoles and electric charges. The mapping is more a question of conventionality in terminology and empirical interpretation than anything substantial. It seems more like we have one and the same situation and the question is what we decide to call what. Hence, this should not be considered to be a duality due to the second criterion above. I would like to point out that by saying this I do not mean that this symmetry is uninteresting or that we should ban the use of calling this a 'duality'. It is very interesting, but I do find the dualities in string theory to be more profound. They seem on the face of it to be more extreme and not immediately understandable in terms of a purely conventional choice made between interpretations of the mathematical symbols.

5 Dualities in string theory

In what follows a brief and rather nontechnical description will be given of string theory dualities. The point with these examples is not to explain the calculations or physical assumptions in any detail, the point is just to show what differs between dual descriptions.[9]

A number of different dualities have been formulated within the framework of string theory such as T-duality and S-duality. A more general version of T-duality is called mirror symmetry.[10] Another kind of duality that has received a considerable amount of attention is the AdS/CFT correspondence.

These dual descriptions, if they are understood in a straightforward or literal way, present views of the world containing different kinds of objects and different descriptions of spacetime which can even differ in topology. Nevertheless they are thought to describe the same physics. This means that they give rise to the same set of particles, symmetries, scattering amplitudes and other empirically measurable, or at least *potentially* empirically measurable, quantities.

Some of these purported dualities are not rigorously proven mathematically. They are rather conjectures which most string theorists believe to be true. There are many

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[9] For more details see Polchinski (1998), Zwiebach (2004), Becker et al. (2007), and references therein. In the following I have also included references to a few important early research articles and review articles on the topic of dualities. For literature more directly addressed to philosophers see Rickles' own contribution in Rickles (2008) and Witten's contribution to Callender and Huggett (2001).

[10] This must not be confused with the more familiar kind of mirror symmetry where things are symmetric with respect to the inversion made in an ordinary mirror.

mathematical tests of these conjectures and a host of different calculations have been done.

5.1 T-duality and mirror symmetry

When one of the extra dimensions used in string theory is compactified as a circle something surprising happens. It turns out that physically there is no real difference between a very small circle and a bigger one. If the radius in one solution is R this can not be distinguished from a solution with radius l_s^2/R where l_s is the so called string length.[11]

How is this equivalence supposed to be understood? Let me first try to explain how the mass-spectrum will be the same for the two different radii. Observe that the moving string is supposed to be quantized. Since the dimension is a circle we get quantization conditions deciding which quantum states are possible. This would be the same even if we had a point particle and not a string. Roughly the 'wave-function' of the string must obey periodic boundary conditions since the coordinate $X \equiv X + 2\pi R$. For large values of R the allowed energies lie close to each other. Let these states be described by the quantum numbers n. When we have strings there will also be another effect. A string may be wound many times around the circular dimension. An analogy can be made with a rubberband wound many times around a rod. The larger R is, the more energy is required to stretch the string many times around the compact dimension. Let w be the winding-number that tells us how many times the string is wound around the circular dimension. The mass spectrum for a certain radius R is given by,

$$M^2(R; n, w) = \frac{n^2}{R^2} + \frac{w^2 R^2}{l_s^4} + \frac{2}{l_s^2}(N^\perp + \bar{N}^\perp - 2). \tag{3}$$

It is the two first terms that are of relevance here. $N^\perp$ and $\bar{N}^\perp$ depend on the internal vibrational state of the string and the constraint $N^\perp - \bar{N}^\perp = nw$ must hold. If the following exchange of radii is done,

$$R \longleftrightarrow \frac{l_s^2}{R} \equiv \tilde{R}, \tag{4}$$

Then we get the spectrum,

$$M^2(\tilde{R}; n, w) = \frac{n^2 \tilde{R}^2}{l_s^4} + \frac{w^2}{\tilde{R}^2} + \frac{2}{l_s^2}(N^\perp + \bar{N}^\perp - 2) \tag{5}$$

So we see that,

$$M^2(R; n, w) = M^2(\tilde{R}; w, n). \tag{6}$$

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[11] An early article on T-duality is Kikkawa and Yamasaki (1984), in that article the expression 'T-duality' is however not used.

This may convince us that the mass spectra are the same for the two dual radii. But it does not tell us that the theories are indistinguishable in all respects, since prima facie the radii of the compact dimensions are very different. However, there is a possible reinterpretation of the mathematical formulae such that a large dimension again appears instead of a small radius. I claim that a necessary precondition for this to be acceptable is that we do not have any *independent* empirical interpretation of the radii. This precondition is fulfilled here in contrast with the example concerning the harmonic oscillator that was given above.[12]

This is interpreted by saying that there is a minimal radius. This is due to the expectation that a classical description of spacetime is not reliable at the Planck-length scale. This does however show that even if we in the mathematical formalism first chooses a radius well below the Planck length this radius is *not* to be interpreted as describing physical space.

When we are dealing with superstrings T-duality also changes the kind of string theory, so a type IIA string theory is mapped to a type IIB string theory and vice versa.

An even more radical form of duality is given by the so called 'mirror symmetries'. In these the extra six dimension are compactified in such a way that they form examples of a specific kind of manifold, they are Calabi-Yau manifolds. It turns out that pairs of manifolds $\mathcal{M}_1$ and its mirror $\mathcal{M}_2$ that are *topologically* different nevertheless give rise to the same physics. When the underlying manifold is switched the type of string theory is also switched just as in the case with T-duality, so a type IIA string theory on $\mathcal{M}_1$ is equivalent to a type IIB string theory on $\mathcal{M}_2$.[13]

From this it follows that according to string theory the description of the geometry and topology of spacetime can differ in formulations that are thought to be physically equivalent. However, it should be noted that in the case with the ordinary T-duality we found that only one of the dual radii is allowed to be given a physical interpretation.

5.2 S-duality

In S-duality different formulations of string theory with different coupling constants are found to be dual. The coupling constant decides the strength of interaction between the strings and is not really a constant but depends on the specific solution. If g_s is the value of the coupling constant there can be a dual theory with coupling constant $1/g_s$. The type IIB string theory is dual to itself under S-duality. The heterotic SO(32) string theory is S-dual to, the type I string theory.[14]

One interesting result that appears here is that what seems to be fundamental objects in one formulation gets mapped to composite objects in the other. A composite object consisting of many strings, will in a dual formulation be treated as consisting of one

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[12] The above equations can be found in standard textbooks such as Polchinski (1998) or Zwiebach (2004), the choice of notation differ slightly between the different texts.

[13] An early paper on mirror symmetry is Greene and Plesser (1990). A useful review article discussing both T-duality and mirror symmetry is Giveon et al. (1994).

[14] The self duality of the IIB theory was established in Hull and Townsend (1995). For the duality connecting heterotic SO(32) to type I string theory see Polchinski and Witten (1996).

fundamental string and vice versa. This means that what is treated as fundamental building blocks would be dependent on the description.

5.3 AdS/CFT

In the AdS/CFT correspondence a string theory is supposed to be dual to a quantum field theory defined on a different number of dimensions.[15]

The expression ‘AdS’ stands for ‘anti-de Sitter’. An anti-de Sitter space is a space of constant negative curvature with Lorentzian signature. The expression ‘CFT’ stands for ‘conformal field theory’. A conformal field theory is an ordinary quantum field theory, with point particles and not strings, that is invariant under conformal transformation. The conformal field theory that is dual to the string theory that is defined on the AdS-space is defined on the ‘boundary’ of AdS.[16]

The AdS/CFT is an example of a holographic theory. In general this means that a theory in Y dimensions is equivalent to another theory in X dimensions. So if this is the case, the number of dimensions is dependent on the formulation. Also the kind of theory and whether or not we talk about strings or ordinary particles is formulation dependent.

5.4 Some general remarks on the dualities

Dual descriptions apparently describe very different physical situations. The geometry and topology including the dimension of spacetime can differ between dual descriptions. Which objects that are thought of as fundamental is also formulation dependent.

Then how are we to understand the dualities in string theory? We have theoretical formulations or descriptions of physical systems that seem very different but nevertheless result in the same physics. Here the word ‘physics’ is used by physicists in a way so that it refers to what can at least *potentially* be empirically testable. This is of course a somewhat questionable way of defining physics and it should be noted that there is a clear positivistic/instrumentalistic tendency in this way of speaking.

In Zwiebach (2004, p. 386) we find the following:

> Duality symmetries are some of the most interesting symmetries in physics. The term “duality” is generally used by physicists to refer to the relationship between two systems that have very different descriptions but identical physics.

It is interesting to note that he writes ‘two systems with different descriptions’ and not one system under different descriptions. Well what does he mean, are there two systems or one? If they were different systems no one would be surprised that the

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[15] The seminal paper on AdS/CFT is Maldacena (1998) which has inspired much further research in the area and a huge number of paper have been published. One important review article on AdS/CFT is Aharony et al. (2000).

[16] This description is somewhat sloppy, the space in which the strings live is not just an AdS space, the whole manifold is the product of an AdS space and a sphere. Also the ‘boundary’ is not strictly speaking a real boundary but the conformal boundary, this is however of no real importance for the argument.

descriptions are different, but after all they have identical physics. So on what basis are we to believe that there really are two systems?

6 Different views on string theory dualities

Various interpretations of the dualities in string theory are possible:

- Interpretation 1.
  Accept the different dual descriptions as describing two different situations. If this view is taken we have a clear example of underdetermination. That is, the world may in reality be more like one dual description than the other but we have no empirical way of knowing this. This way of looking at the situation would accept that we are faced with some form of underdetermination.
  Given this interpretation there are two alternatives:
  - Interpretation 1A.
    The two descriptions have the same empirical content, or at least potential empirical content, but besides that we can *not* say that they have an important X in common, where X could be a shared structure. If we accept this alternative we have an example of real underdetermination. This suggests that we can not know which, if any, theory or theory formulation it is that describes our world more accurately. This means that we must accept epistemic anti-realism since in this situation it is hard to find any reason for preferring one alternative before another.
  - Interpretation 1B.
    We accept them as two genuine alternatives that have an important X in common, where X could be a shared structure. This leads us to a position compatible with some weaker form of realism. If we can explicate the notion of structure and claim that there really is a shared structure this would be some form of structural realism.
- Interpretation 2. We do not accept that they really describe different situations; instead they are descriptions of the same underlying reality which is given in terms of X. We might of course still accept the heuristic value of the alternative descriptions and the different 'pictures' used but we do not take descriptions concerning them literally. If this reality is purely structural we see the situation in the way a defender of OSR would.

The argument and possible interpretations given above can be seen as a special example of the general phenomenon where one can avoid epistemic anti-realism by dropping semantic realism or alternatively if one wants to keep semantic realism one needs to drop epistemic realism.

In the following it will be assumed that 'X' stands for 'structure'. If we can find an alternative X we would consider other forms of intermediate realism than structural realism. Similar arguments to the following on structure could then *mutatis mutandis* be given.

Comparing views on structural realism; the differences between Cao, who defends a form of ESR, and the defenders of OSR can be described as follows. Cao would prefer Interpretation 1B while the defenders of OSR would prefer Interpretation 2. So the main difference is about the question about what is meaningful to take literally in a theory formulation. By this we see that there is a difference at the level of semantics and the proponents of OSR have taken a step in the positivist direction.[17]

Ladyman and Ross (2007) argues for OSR. Like the logical positivists they argue for a kind of verificationism, but their verificationism is not a theory about meaning, as the positivists version was. Instead their verificationism concerns what would be relevant to talk about in a scientific context.[18] Since they describe their verificationism not in terms of meaning but what is scientifically relevant they do not think that their version of verificationism will face the same problems as the traditional logical positivistic version. Given this they would have to say that interpreting the different dualities as describing different scenarios is not just jibberish and empty words, but they would not endorse any such interpretation. For this to be consistent they would accept different dual descriptions as meaningful but literally speaking false; that is if they want to distinguish themselves from an epistemic reading of structural realism. It is important to note that their verificationism, even though it is not a theory of meaning, still have consequences for how we should understand physical theories and that it leads to a non literal understanding of large chunks of the theory.

I think that physicists usually do not consider dual formulations as describing different genuine physical scenarios; so they would, if pressed, choose interpretation 2 just like the defenders of OSR. Note one important consequence of this: Since they claim that dual formulations are just descriptions of the same reality they can not then claim that literally everything in the formulations refer to something in physical reality. If it is the same underlying reality that is described one time with one manifold and another time with another topologically inequivalent manifold we can not take these statements at face value. This means that the large ‘old’ four dimensions epistemically and semantically receive a different status even though they are treated in the same way as the extra dimensions within the mathematical formalism of the theory. This is because they do receive an empirical interpretation, thus constraining what weird mappings we are allowed to do within the mathematical framework and still claim that we ‘describe the same thing’. What I would like to point out is that we have a complicated mathematical formalism which is only very loosely connected to a physical interpretation. I would like to stress the importance of distinguishing between the mathematical formalism itself and the physical interpretation.

String theorists should say that the world is not literally like any of the dual descriptions in string theory as long as they defend a position similar to OSR and say that dualities describe the same underlying reality. For instance if one accept formulations, with prima facie topologically different spacetimes in the mathematical formalism, as

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[17] This is based on my reading of Cao (1997, 2003), French and Ladyman (2003) and Ladyman and Ross (2007). And their differing views on how to interpret quantum field theory.

[18] On pages 29–30 of Ladyman and Ross (2007), they describe their version of verificationism in further detail. They describe it as more resembling the view of Peirce than the view of the logical positivists.

descriptions of the same reality; one must find claims that the *physical* spacetime has any of the suggested topologies to be literally false.

It is important for any version of structural realism to carefully explain how their position differs from a view in which a theory is only decided by its empirical content. To do this we must further clarify what we mean by ‘structure’ in this context. It has been problematic to give a clear definition of structure. We cannot just use a simple definition of structure from logic and mathematics. I think one needs to carefully look at many different examples from actual physics and the dualities in string theory would be one such example. Any attempt to define structure in purely mathematical terms is bound to fail for reasons given above. The practice of making a physical interpretation of a theory and how it is supposed to connect to the empirical world must be made. Note for instance the case that in T-duality the interpretation of the parameter R as a very small radius below the Planck-length was disqualified, but this conclusion was not made solely on the basis of the mathematical formalism but depends heavily on a general understanding of physics. Note also that at the purely mathematical level different formulations might not even share the same structure there might be surplus structure in the formulation that is convenient but should not be thought of as representing anything physical, for examples and discussions of this see Healey (2007) and Lyre (2009). It might be that another kind of intermediate realism than structural realism would be the best way to understand our theories in physics.

7 Conclusions

What conclusions can be drawn from the discussion above? One thing is that it is not immediately clear how one should understand or interpret the existence of dualities in the context of string theory. The questions seem to be answerable only if certain semantic issues are clarified.

Physicists argue about string dualities in a way that seems most compatible with some form of structural realism. Since most string theorists do not seem to think that dual descriptions give rise to real alternatives they are closer to OSR. They choose a specific formulation based on pragmatic reasons. They might for instance find certain ‘pictures’ to be heuristically valuable for certain purposes. The most important reason for why a specific formulation is used is to allow for perturbative calculations. Depending on the state of the system one formulation might be tractable while another might not. This might suggest that in certain situations one description is better than another. Sure this is the case in terms of how easy we can perform calculations. But can it be said that for a certain state the tractable formulation gives a better description of the underlying reality? This is not obvious, and what are we to say when the state is such that both formulations can be used? I think it is fair to say that the common view among physicists concerning the dualities is such that it cannot be understood as endorsing a view where everything in a theory formulation is taken to be literally true, not even tentatively.

While most physicists would understand the dualities in a way similar to OSR, alternative views are possible. The different views depend on the semantic question regarding what to take literally in a theory formulation.

I think that semantic issues concerning theories are important and should be further discussed. After the fall of positivism that endorsed a very strict empiricist semantics I think that many philosophers of science have treated this question too lightly and just assumed that any reasonably understandable expressions has a clear meaning. It is important to understand that when scientists formulate and develop new theories the meaning of what they say is not immediately clear. It is fair to say that the physicists, in a sense, do not really know what they are talking about and a physical interpretation cannot be read directly from the formalism. This is however not meant as criticism; physicists who develop new theories understand that their present formulations at best only giving us an approximate description and also that even the reference of their terms can be vague. Given this I think it is important to further readdress these questions and discuss the difference between a mathematical formalism and its physical interpretation. We should avoid the excesses of logical positivism but I believe that we should accept some weaker form of empiricist semantics. The way I have discussed the different ways in which we can view dualities in string theory is a step in this direction.

When describing theories and what they mean and how they are used there is one point that I find very important to make. That is, that even if one denies any deeper importance to the 'pictures' and 'images' that a certain formulation of a theory convey, I think it is very important to not try to avoid the use of such pictures. There is an undeniable heuristic value of an interpretation containing pictures. Different pictures might suggest different possible extensions of the theory or inspire new hypotheses. So regardless of which view to take on the semantic issues it is imperative that this should not be used to argue that we must formulate a theory in a pure form which only contain what is deemed completely acceptable according to the standards of the semantic theory. We do not want to put the physicists in a semantic straitjacket.

The question on realism and anti-realism is important for physicists to consider. There is a tension between realist and anti-realist tendencies. When it comes to the dualities in string theory they deny semantic realism, and I think rightly so, but in other situations string theorists have opted for a very realist understanding. For instance in the debate on the so called 'Landscape' of string theory, where different solutions to string theory are considered, some string theorists think that we should interpret this as different parallel and really existing universes.[19] I will not discuss the rather controversial debate concerning the 'Landscape' in this article any further, I only want to point out that string theorists need to perform a rather delicate balancing act between realism and anti-realism in their attitude towards their theoretical constructions. Some form of intermediate realism such as a version of structural realism seems to be recommended. The physicists view seems to be most compatible OSR. I also think that OSR is the most promising way of understanding the dualities. However, as has been argued above I harbour some doubts as to whether 'structure' can be explicated in a satisfying manner or whether or not 'structure' is the best word to use to describe a defensible kind of intermediate realism concerning physical theories.

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[19] For a popular description of this view see Susskind (2005).

That the dualities of string theory strongly suggest something akin to structural realism was also argued in Dawid (2007). He also explains that the dualities can be used to undermine a view that takes the specific ontologies of the dual descriptions seriously. In this article I have described in more detail how the arguments behind these conclusions are connected with certain semantic issues concerning the physical interpretation of theory formulations that rely heavily on mathematics and are not directly tied to observable data.

I will finish this article with another lesson that I think that we can learn from the dualities in string theory. If it is possible to find dualities between seemingly very different formulations within one research programme one should acknowledge that it might not be suitable to only study one research programme. The hostility that from time to time has appeared between proponents of different research programmes in quantum gravity might be a serious mistake. If something like a duality would be found between the research programmes, then they could actually merge. A general methodological suggestion can be given to the effect that only if a research programme is empirically progressive, would it be rational to completely 'stick with the programme'. When a theoretical research programme does not produce empirical results then a broader perspective ought to be adopted.

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