String Theory and the Scientific Method

Håkon Enger

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Introduction

String Theory is a relatively new disipline which has lately grown into dominating the field of theoretical high energy physics. As it is a theory claiming to be able to unite all the known fundamental forces of nature and solve many long-standing problems of theoretical physics, it has recieved interest also outside the physics community. However, the theory is intense in mathematics and not easily accesible for non-physicists, so it is difficult for laymen to judge the validity of the claims made by string theorists.

Many attempts have been made at defining the method of science, the qualities that separates science from non-science. It is not obvious that it is possible to define science in this way, but there is widespread belief both within and outside the scientific community that there is some method which guarantees that science is the preferred way to gain knowledge about nature. I will investigate whether String Theory is compatible with various theories of science.

The history of String Theory has shown that it has interesting consequences not (only) for our understanding of nature but for our insight into mathematical and geometrical problems. For this reason, ST may be seen as a branch of mathematics rather than physics, but the view taken by most string theorists seems to be that ST is physics. This means that most string theorists are employed at physics departments and call themselves physicists.

In this essay I will take the position that since physics departments around the world are allowing scientists to do research in the field of string theory, grants to science foundations for funding of such research are accepted, and universities regularly advertise available positions in the field of string theory, String Theory is accepted in at least a part of the scientific community as a science.

The essay is organised as follows: First, I will review briefly modern theoretical high energy physics. Then, I will give a short history of string theory as an introduction to the field. The main part of the essay is concerned with attempting to apply some of the most important theories about the method of science to String Theory.

Modern Physics

The "traditional" view in theoretical physics is that there are two kinds of fundamental forces in nature. One kind is the gravitational force, which is described by Einstein's General theory of Relativity. The other kind is known as a "gauge theory". Electromagnetism and the weak and strong nuclear forces are described mathematically by gauge theories. These "theories" are mathematical *models*; equations and rules for manipulating them in order to make predictions about observations to be made in an experiment. General Relativity is a geometrical model where the structure of space and time is described as a geometric object in terms like curvature. Gauge theories are *quantum* models, describing the world in more abstract mathematical terms.

In the field of particle physics, the current knowledge about the laws of nature are summed up in the *Standard Model of Particle Physics*. The Standard Model is a gauge theory modelling the interactions of fundamental particles collectively known as fermions: electrons, neutrinos and quarks. The forces causing interactions between these particles are mediated by other fundamental particles, the (gauge) bosons. All these particles are assumed to be point-like, i.e. they have no "internal structure". The quarks bind together to create composite particles which are confusingly called "elementary particles". Examples of elementary particles are the protons and neutrons that again combine to create nuclei of atoms.

The Standard Model does not contain the force of gravity. The main reason for this is that gravitation is so weak that it is not observed in particle physics experiments, where the other forces are completely dominant. However, there are also mathematical problems involved if one were to attempt introducing General Relativity into the Standard Model. A gauge theory, like the Standard Model, is an example of a *quantum field theory*, a model which describes nature in terms of space-filling fields that experience quantum fluctuations at a sub-microscopic level. These fluctuations are governed by Heisenberg's uncertainty principle, which says that the magnitude of the fluctuations is inversely proportional to the scale at which they are observed.

The quantum fluctuations create problems when a particle physicist attempts to use a quantum field theory to make predictions about an experiment. A typical calculation will attempt to find the probability of an observation, given certain initial conditions in an experiment. But in this calculation there will appear infinite quantities known as *divergences* which at first sight makes it impossible to arrive at a final answer in the calculation. Fortunately, a technique known as "renormalisation" has been established which allows one to replace the infinite quantities by parameters, and the calculation will then give a result expressed in terms of these parameters. The value of the parameters introduced in this way must be found by doing additional experiments, they can not be calculated from "first principles".

For this technique to work, it is essential that there is a finite number of such parameters that must be established by experiments, otherwise one would have to make an infinite number of experiments in order to make any predictions at all. A number of mathematical constraints have been found for a quantum field theory to be *renormalisable*, and it is known that all gauge theories are renormalisable. However, the General Theory of Relativity is not renormalisable, so it is impossible to make a consistent quantum field theory by "quantising" General Relativity.

History of String Theory

String Theory is a model where one assumes that the fundamental particles, like photons and electrons, are string-like objects. It has been proposed as a "theory of everything", in the reductionist sense of "everything", i.e. a theory capable of explaining all the laws of nature at the "lowest level" or smallest scale.

String Theory was born in 1968, when physicist Gabriele Veneziano attempted to develop a mathematical model of the strong nuclear force, which was not understood at the time. Veneziano's model was developed further in 1970 by Yoichiro Nambu, Holger Bech Nielsen, and Leonard Susskind. This model asserted that the particles responsible for mediating this force were string-like. The stringy nature of these particles could explain the so-called Regge slopes, the observed tendency of elementary particles to group into families with mass proportional to their spin.

In 1974, John Schwarz and Joël Scherk showed that String Theory could also model the force of gravity in addition to the strong nuclear force. By this time, another theory of the strong nuclear force was emerging, the theory of Quantum Chromodynamics (QCD). This theory is a gauge theory of point particles called quarks and gluons and does not require the existence of strings. Furthermore, it seemed at the time as if strings could not explain the elementary particles as well as QCD, so interest in String Theory was dwindling at this time.

An important development occurred in 1977 when Gliozzi, Scherk and Olive extended the string model to include particles known as fermions. Fermions, mainly electrons and quarks, are the building blocks of matter, while the particles responsible for the forces are known as bosons. Gliozzi, Scherk and Olive created a string theory where there is a symmetry between these two fundamental kinds of particles which is known as supersymmetry. In a supersymmetric model there is a one-to-one correspondence between the kinds of bosons and the kinds of fermions. In 1984, Michael Green and John Schwarz managed to prove that "Superstring theory", the supersymmetric string theory, does not have many of the problems of self-inconsistency that appear in most quantum field theories. This proof generated much interest for String Theory in the physics community, a phenomenon referred to as the "first superstring revolution".

The interest in String Theory decayed again during the second half of the 1980s and the first half of the 1990s. This was due to the fact that String Theory seemed to raise more questions than it answered. Although String Theory could in principle model the forces and particles we observe in one unified model, the mathematics involved was so complicated that it seemed impossible to actually make any predictions from String Theory. Moreover, it was shown to exist five different superstring theories in the sense that there were five ways to extend the original bosonic String Theory into a supersymmetric theory. It seemed that at most one of these could actually be a true fundamental model of nature, but there was no obvious way to select which one.

Then, in 1995, there was renewed interest in String Theory after Polchinski and Witten made discoveries concerning something known as *D-branes*. These "branes" are objects whose existence is implied by the axioms of String

Theory. The D-branes were a key to the understanding that the five different string theories were related by *dualities*. These dualities made Witten propose that the different string theories were only different aspects of one more fundamental theory, which was called *M-theory*.

Recently much of the focus of string theorists has been on developing an idea coined by Maldacena in 1997. Maldacena showed that through String Theory one could find a duality between a gauge theory and a gravitational theory. Using this duality one can explore the "traditional" gauge theories (or, at least their supersymmetric extensions) using methods from gravitational physics. For this approach to work it is not necessary that the fundamental particles are in fact strings, the mathematical duality works independently of this assumption.

String Theory and Logical Positivism

Logical positivists believe that the scientific method amounts to deriving models of nature from observations. Although String Theory was initially based on an observed fact, the Regge slopes are no longer believed to be due to the stringy nature of gluons by most supporters of the theory. There is agreement in the community that no direct evidence of the existence of strings has been observed.

But even though there has been no direct observation of strings, the belief in String Theory is rooted in the fact that quantum field theory seems to contain problems of inconsistencies. This is not an observational fact, but rather a mathematical fact. However, it seems that saying that this fact in some way leads us to conclude that strings must exists would be stretching the truth. Instead, this fact is used to support String Theory, while the theory was and continues to be developed independently of it.

In fact, most string theorists seem to be completely unconcerned with experiments and observations, but rather concerned with the "elegance" of the mathematical formulation of the theory. Peat (1988, p. 276) writes:

> "Yoichiro Nambu, the creator of the original string theory, has called this situation "Postmodern Physics." Theory has moved so far ahead of experiment that, he suggests, physics must now be developed in new ways. When a new theory is created, rather than thinking in terms of crucial experiments and observations, physicists have to begin by investigating the theory's formal mathematical structure. The theory and its mathematical language are probed, recast, and related to other theories. Eventually it will be possible to discover its most fundamental form."

It seems impossible in light of this to reconcile the development of String Theory with that of logical positivism.

String Theory and Falsification

A common claim is that a theory has to be *falsifiable* in order to be scientific, a philosophy defended fiercely by Karl Popper: "A theory which is not refutable by any conceivable event is nonscientific." (Popper 1998) This demarcation criterion seems to be sensible if we want to make claims about the truth of a statement which is supposed to describe nature in some way. In the words of Chalmers (1999, p. 63), "If a statement is unfalsifiable, then the world can have any properties whatsoever, and can behave in any way whatsoever, without conflicting with the statement."

It is not unusual to hear String Theory being characterised as an unfalsifiable theory:

> "If we allow ourselves to be beguiled by the siren call of the "ultimate" unification at distances so small that our experimental friends cannot help us, then we are in trouble, because we will lose that crucial process of pruning of irrelevant ideas which distinguishes physics from so many other less interesting human activities." (Georgi 1989), quoted by Greene (2000, p. 213).

It is definitely the case that with current technology, it does not seem possible to build experiments with enough precision to falsify String Theory. However, the theory is in a sense "potentially" falsifiable. The model makes certain predictions, such as the existence of extra dimensions, that could make the theory falsifiable in the future, given enough technological progress. In addition, it is clear that all the mathematical consequences of the axioms of the theory have not been worked out, and it might very well be that someone will realise that an undeniable consequence of the theory is in fact in conflict with the observed reality.

The fact that String Theory is currently not falsifiable, does not seem to trouble string theorists. Nevertheless, there is some work on finding ways to observe effects of stringiness in experiments. Since the mathematics of the theory does not give any precise prediction about the size of fundamental strings, or of the extra dimensions, there is speculation that some effects, like extra dimensions, may be observed in the next major experiment in particle physics, the Large Hadron Collider (LHC) at CERN, Geneva, which is scheduled to begin collecting data in 2007. But if these effects are not seen, it would not be seen as a falsification of String Theory, since the extra dimensions might just be a little bit smaller than the scale at which the experiments at LHC would show any effect of them.

Since string theorists do not seem to be looking for ways to falsify their theory, but rather ways to confirm it, it seems that the view that the scientific method is all about falsification does not fit this theory. Thus, we must conclude that either this is not a proper description of the scientific method, or String Theory is not a science. Since I take the position that this theory is indeed scientific in this essay, it seems that Popper's ideas are not the whole truth of the scientific method.

However, to some extent the condition of falsifiability is still important to scientists doing String Theory. If a string theorist is confronted with the claim that his theory is not falsifiable, he or she will typically respond with a partial denial of this, such as the fact that better experimental technology may be available in the future, or that theoretical and mathematical progress within the field of String Theory itself may lead to predictions that are falsifiable. So falsifiability seems to be accepted as a norm that a scientific theory should follow, even be string theorists. Greene (2000, p. 210) writes, "Nothing would please string theorists more than to proudly present the world with a list of detailed, experimentally testable predictions." It seems unlikely that String Theory can continue indefinitely as a branch of physics unless some there appears some hints from experiments that it is a better description of nature than the established models.

String Theory and Kuhn's Paradigms

Thomas Kuhn believes that the progress of science is driven by changing "paradigms", periods where a given set of rules and theories are taken for granted and may not be questioned.

It is tempting to view the ascent of String Theory as a new paradigm in high energy physics. After all, a fundamental assumption never questioned during the first two-thirds of the 20th century was that fundamental particles are point-like. This accepted truth, which might be called the old paradigm of high energy physics, is obviously challenged by the "new paradigm". Although String Theory is still not accepted by the full physics community, this is in fact a general law of paradigm shifts—many scientists will keep on to the old paradigm well after a new one is introduced.

However, a paradigm shift is supposed to be characterised by a breakdown of the old paradigm, known as a "crisis". During the crisis, there are anomalies, observations contradicting the rules of the old paradigm, which the scientists are not able to get rid of. [The crisis state] "is a response by some part of the scientific community to its awareness of an anomaly in the ordinarily concordant relationship between theory and experiment." (Kuhn 1977, p. 202) The important thing is that these anomalies are supposed to be discrepancies between theory and experiment. But at we have already seen, no such observations have been made. There are problems of a mathematical nature in the "paradigm" of the Standard Model, but these problems have been known for almost as long as quantum field theory has existed. They do not seem to contradict any observations that have been made. All the observations made in particle physics experiments seem to be "in concordant relationship" to the Standard Model. Furthermore, String Theory does not seem to be able to explain or predict *any* observations in detail and so can not be seen to be better than the "paradigm" consisting of the Standard Model and Quantum Field Theory.

If in future experiments, such as at the LHC, observations are made contradicting to the Standard Model and this leads to a new paradigm based on String Theory, then this could be seen as a confirmation of Kuhn's theory. However, it does not seem to be possible to explain the current status of this theory within the theory of paradigms and scientific revolutions.

String Theory and Feyerabend

From the discussion so far, it seems that there is little reason to believe that String Theory is a better description of nature than the Standard Model of particle physics and Quantum Field theory of point-like particles. The Standard Model is able to explain all the experiments that have been made within the field, and String Theory is currently unable to explain any of them with any detail. What part of "the scientific method" might it then be that makes this theory into an acceptable part of physics?

At first, it seems that this reasoning confirms Feyerabend's view that there is no "method" of science. String Theory is an idea that might seem to be no more believable than than religious theories.

However, one might then ask, why is String Theory accepted as physics, while other theories are not? There must still be some quality that separate this theory from others that are not regarded as science by physicists. One such quality is the language that the theory is phrased in. Like other models in theoretical physics, String Theory is phrased in a mathematical language. The theory has clear definitions and no breaches in the logic of deductions. It is clearly rooted in and extends quantum field theory and the general theory of relativity. One very important fact about this theory is that it can be proven mathematically to reproduce the traditional gauge theories and General Relativity when the strings are observed at a distance so that their stringy nature is not visible. If this was not the case, the theory could not have the following it currently has within the physics community.

Moreover, even though it is not currently possible to device experiments to confirm or falsify String Theory, it is essential that technology might be, and is expected to be, available in the future that would make the theory falsifiable. If the theory did not have any such potential, it would presumably not be taken seriously. It is certainly also important that the theory does not make any predictions that have already been falsified.

There may also be a case of history dependence to the status of string theory. Since the theory started out as a "phenomenological" description of the strong nuclear force, it may have a stronger standing in part of the physics community than if this had not been the case.

It is not clear if these considerations may be generalised enough to provide a description of the Scientific Method. Obviously, it is not true that a theory must be formulated in mathematical language in order to be scientific. However, it may be possible to generalise this to saying that important topics should have clear definitions and that arguments based on logic should be trusted. We have also seen that falsifiability is important even to string theorists, so this might be conjectured to be an important norm for the scientific method, even if limitations in the available technology or other limitations make it difficult to follow this norm constantly.

Mathematical Elegance

Important to this discussion may also be what makes String Theory attractive to scientists. There is in the theoretical high energy physics community an understanding that there is a need for a new theory to unify the two separate worlds of quantum gauge theories and the general theory of relativity.

Therefore, the theory attempts to explain a real accepted problem in theoretical physics, the incompatibility of General Relativity and quantum field theory.

The approach of theoretical physics is to simplify the axioms, or fundamental assumptions, necessary to reproduce the already existing laws of nature. Thus, when the number of "elementary particles" became very large in the 1960s, it became important to find a new fundamental law with a smaller number of fundamental particles. The theory that eventually emerged was that of Quantum Chromodynamics (QCD), which contains six types of quarks as its fundamental entities. QCD is now accepted as a fact, even though an intrinsic property of this model is that quarks can not be observed directly.

In the same manner, String Theory simplifies the fundamental assumptions by uniting the Standard Model and General Relativity, and is in this sense a "better" model even if it does not make any new predictions. String theorist Michael Green has said, "The moment you encounter string theory and realize that almost all of the major developments in physics over the last hundred years emerge—and emerge with such elegance—from such a simple standing point, you realize that this incredibly compelling theory is in a class of its own." (quoted by Greene (2000, p. 139).)

But in this quote one can see that it is not only the property of solving the puzzle of unification that is attractive, but also the "elegance" of the solution. The simplicity of the fundamental axioms compared to the far-reaching consequences of them is highly attractive by the mathematically inclined physicists. This is also illustrated by the following quote by John Schwarz: "The mathematical structure of string theory was so beautiful and had so many miraculous properties that it had to be pointing toward something deep." (quoted by Greene (2000, p. 137).)

Conclusion

From the discussion in the previous sections, the mentioned theories of science all seem to fail when applied to String Theory. The only principle that seems to hold completely is Feyerabend's "Anything goes", but this is not meant to be a true principle for the scientific method. Also, it is clear that everything would not be accepted as physics, and also not as String Theory.

The principle of falsifiability seems to have a string standing in the physics community, also among string theorists, as an important norm to stribe after. But it seems that in the daily research of string theorists this is not the main guiding principle. Rather, string theorists are concerned with mathematical elegance and simplicity. Also, there is some research into how effects of strings might be discovered in experiments, but the aim is not to provide opportunities to falsify the theory.

Within physics, there are important demarcation criterions concerning the language and logic of the theory. But these criterions are not easily generalised to other branches of science. There also might be some dependence on the history of the theory, as String Theory started as a theory to explain an actual anomaly (in Kuhn's sense), the strong nuclear force. We must in any case conclude that it is difficult to pin-point what makes String Theory different from non-science using a general principle.

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