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# What is String Theory?

Tom Banks and Michael Dine

*Santa Cruz Institute for Particle Physics and*
*Department of Physics, University of California, Santa Cruz CA 95064*

**Abstract**

We describe, for a general audience, the current state of string theory. We explain that nature is almost certainly not described by string theory as we know it, but that string theory does show us that quantum mechanics and gravity can coexist, and points to the possible theory of quantum gravity which describes the world around us. Directions for research, both on the nature of this theory and its predictions, are described.

# 1 Introduction

Over the past three decades, high energy physicists have developed an exquisite understanding of the laws of nature, governing phenomena down to distances scales as small as 10-17 cm. This Standard Model has proven so successful as to be, at some level, a source of frustration. There are many questions that we would like to understand, for which the Standard Model does not provide satisfying explanations. Some of these - what is the origin of the mass of the electron, quarks, and other particles, why is gravity so much weaker than the other forces, what is the nature of the dark matter - may be answered at the Large Hadron Collider, which, after some setbacks, is beginning operation in Geneva, Switzerland. Others require new theoretical structures. Perhaps the 1.Introduction. Over the past three decades, high energy physicists have developed an exquisite understanding of the laws of nature, governing phenomena down to distances scales as small as 10-17 cm. This most striking of these is the problem of reconciling two of the great scientific accomplishments of the twentieth century - Quantum Mechanics (QM) and Einstein's theory of General Relativity (GR). One of the greatest puzzles - which will figure heavily in our story - is the question of the Dark Energy. From observations of distant supernovae, we know that 70% of the energy of the universe is in some totally unfamiliar form, with negative pressure. This is likely Einstein's infamous cosmological constant (c.c). The dark energy is positive, and the universe is currently entering a phase of exponential expansion (when the universe is 100 times older than it is now, it will have expanded by a factor of $10^{43}$; by comparison, the universe is a million times older than when atoms formed, and has grown by a factor of 10,000. This rapidly inflating universe is known as a De Sitter space. The big surprise about the dark energy is that there is so little of it. Conventional approaches to physics (what we learn in high school as dimensional analysis) suggest that there should be a cosmological constant many orders of magnitude (perhaps 120) larger than observed. The Standard Model is firmly based in a picture in which the basic building blocks of nature - particles like the electron, neutrinos and quarks, and those, such as the photon, gluons and intermediate vector bosons which give rise to the forces - are structureless points. This framework is known as Quantum Field Theory (QFT). It is remarkable how successful this simple-minded picture is. But there is good evidence that this framework cannot accommodate gravity (GR) and QM. There is a long list of theorists who have unsuccessfully attempted to apply the principles of QM to GR. Physicists such as Richard Feynman realized long ago that if one simply applies the procedures that he so successfully developed to study electrons and photons, one obtains non-sensical results. The most profound issues were raised by Steven Hawking, who argued compellingly in the 1970's that the existence of black holes was incompatible with QM. We have known for two decades, however, that there are theories in which the basic entities are not point particles, and in which gravity and quantum mechanics comfortably coexist. These quantum gravity theories (QGT's) include String Theory and M theory (a theory in eleven dimensions, in which membranes seem to play an important role). These theories resolve both the issues of ill-defined mathematics and the problems of black holes; Hawking's arguments are incomplete. While these theories reconcile gravity and QM, that does not mean that they describe nature. There has been much debate about whether string theory is "true" or can be subject to experimental tests. But, as we will explain, the set of QGT's which we can claim to understand is very limited, and there is no question that they do not describe nature. Most string theorists proceed on the assumption that all that is needed is some small tweaking of these theories, but, as we will explain, there is little reason to think this is the case. Instead, in our view, the known string theories are either part of some much larger structure, of which we have only an inkling at present, or there may be many QGT's, of which string theories are interesting, but unrealistic, examples. Each of us pursues a very different candidate for the nature of the QGT. Both have the potential to make experimental predictions; each of these proposals can also fail, either for experimental or theoretical reasons. Each of these proposals grows out of our experience with string theory. Both are tentative; they cannot be said to be understood at nearly the level at which we understand simple string theories.

## 2 String Theory

After point particles, the next step up in sophistication is to consider the possibility that the basic entities are not points, but one dimensional objects - strings. The problem of making a quantum theory of strings is not beyond the capabilities of a good graduate student. If the student is sufficiently careful, he or she will discover that such a theory is automatically a theory containing particles and interactions like those of the SM, and even more remarkable, GR. These features emerge from the construction as an inevitable feature; they are not imposed. Had Einstein not lived, one could speculate that GR would have been discovered this way. String theory was discovered by a different route, but it soon became clear that the mathematical inconsistencies which so concerned Feynman and others are tamed in this framework. More recently, it has become apparent that string theory resolves Hawking's paradox. Hawking had argued that information disappears around black holes, violating basic principles of quantum mechanics. String theories contain black holes that are subject to exactly the same arguments that Hawking made about astrophysical black holes. But Hawking's problem simply does not arise; one can show that the information is perfectly well accounted for within the theory. This can happen because string theories are different than QFT's in a particularly important way: they are not local (the notion of locality has been central in physics since Einstein, who developed General Relativity, in no small measure, to banish Newton's "action at a distance"). In the Standard Model, for example, interactions between electrons occur when a (point) electron emits a (point) photon at a point, and the photon is subsequently absorbed by another electron. While string theory obeys Einstein's basic principles, it is not local in the strong sense of QFT's, because strings are extended objects. At the horizon of a black hole, for example, they can appear quite long. Locality was a key part of the argument that led to Hawking's paradox. These successes of string theory suggest that nature is described by some QGT, but this theory is not necessarily a string theory. Even within the bounds of well understood models, we know many examples of QGT's which do not contain string-like excitations. The questions of whether nature is described by string theory and whether the theory makes predictions for experiment have proven quite contentious. They are the subject of books and endless blog posts. But clearly one must first decide what the underlying QGT is. Is it simply a theory whose basic entities are stringlike objects, or is it something larger? Is it in fact one theory, or many different, competing theories, from which experiment must select one or another? Without resolving these questions, the problem of falsifying or verifying string theory is without meaning.

## 3 String Theory's Shortcomings

Symmetries play an important role in our understanding of the laws of nature. Newton's laws, for example, exhibit rotational symmetry; there is no preferred direction in space. Other symmetries are more subtle, and the microscopic laws of physics sometimes possess approximate symmetries ("broken symmetries"). One example is isotopic spin, first discussed by Werner Heisensberg. Protons and neutrons are nearly identical as far as the strong nuclear force is concerned. Their masses, for example, are nearly the same, and the symmetry is borne out by more detailed studies. But these particles are clearly different; the symmetry is said to be broken. One of the great theoretical discoveries made in string theory is a possible symmetry of nature known as supersymmetry. Supersymmetry is a hypothetical symmetry which relates fermions - particles like the electron and the quarks, which obey the Pauli exclusion principle - and bosons, like the photon, which prefer to share the same state. Independently of string theory, there has been widespread speculation that supersymmetry might represent the next layer of structure beyond the Standard Model. Supersymmetry can explain the weakness of gravity and the identity of the dark matter. It also predicts the strength of the strong nuclear force (through a phenomenon known as Grand Unification). Supersymmetry must be a broken symmetry; if it were not, the photon, for example, would have a fermionic partner (the photino) with zero mass; no such thing exists in nature. Our present understanding of string theory relies heavily on supersymmetry. There are many possible supersymmetric strings: strings with three spatial dimensions, but also with as many as nine and as few as one. There are strings with interactions like those of the Standard Model, and interactions which are quite different. For example, there can be electromagnetism, more or less like we experience it, or 16 copies of electromagnetism, or no electricity and magnetism at all. Strings can exhibit a single particle like the electron, or dozens of such particles, or none at all. A large class of supersymmetric string theories have vanishing cosmological constant; they describe a universe which is flat, infinite, and static. All of the exciting developments of the last few decades in string theory - the understanding of the high energy/short distance behavior, of black holes and the information paradox - have occurred in the context of the supersymmetric strings. Non-supersymmetric strings are at best poorly understood. Strings without supersymmetry can be constructed in a fashion parallel to supersymmetric ones, but as one tries to do more careful calculations, incorporating quantum corrections, "all hell breaks loose." As explained by the two of us some time ago, one inevitably finds a universe which either emerges from a singularity or collapses to one, and the theory breaks down. In other words, we do not know theories of quantum gravity which describe a universe without supersymmetry (a possible exception to this is provided by certain string theories with negative cosmological constant; the corresponding space-times are known as "Anti-de Sitter spaces", as opposed to the de Sitter type space-times which describe our universe).

There are a number of responses to this situation. One might reasonably adopt the attitude that, while string theories are interesting, they have nothing to do with nature. They are perhaps worthy of study in that they may lead us to formulate the correct theory at some stage. But there is then no cause for optimism that we might find some sort of final theory, which allow us to address the puzzles of the Standard Model in the near future. More than one leading string theorist has embraced this viewpoint, allowing that it may take decades, or longer, to find a satisfactory theory. Most theorists have adopted a different attitude, hoping that somehow nature is described by one of the supersymmetric theories that most resembles the world we know; that supersymmetry is broken a little bit in some way that we don't understand, and that, while perhaps one can't do reliable calculations, the unreliable calculations which one might do are not too misleading. We find this point of view most unsatisfying. First, one is left with no guiding principles as to what the actual theory might be. Among the huge array of supersymmetric strings, one simply makes some arbitrary choices, and hopes that these are somehow the correct ones. Second is the question of the cosmological constant. There is no reason to think that this sort of model - even if it works as its proponents hope - should yield anything like the observed value for this quantity. We believe that one must first confront these issues directly. No QGT we presently understand can describe the universe around us. However, we do not despair of making progress in uncovering the QGT which describes nature, or of exploring its possible connections to physics we can study experimentally. We both suspect that strings themselves are not the crucial underlying entities; the important lessons we take from string theory are the limitations of locality, embodied in something known as the holographic principle, and/or the discovery, within string theory, that the underlying theory may describe a vast array of possible universes (theorists call these "states"), each with very different properties. One of us (MD) pursues a set of ideas closely tied to this proliferation of universes, known as the Cosmic Landscape, and is optimistic about the prospects for predictions of LHC phenomena. The other (TB) has developed an entirely different approach, Cosmological Supersymmetry Breaking (CSB), which tries to relate the breaking of supersymmetry to the value of the c.c. and the holographic principle, and makes quite definite predictions for LHC physics.

## 4 The Cosmic Landscape

We both agree that the problem of the dark energy is central to any progress to these issues. In 1987, Steve Weinberg, a key figure in the development of the SM, proposed a possible mechanism to account for a small c.c., following a suggestion of T.B. and Andrei Linde. He suggested that the universe might be very much larger than what we currently observe, and that in different regions, the c.c. takes different values (in General Relativity, the notion of "region" is subtle, but this expresses the essence of the idea; these regions can also be thought of as the "states" or "universes" we discussed above). The typical value is large, consistent with general expectations. But if the distribution of possible values is random, and if the universe is large enough, there will be some states with very small c.c. He asked: how large can the c.c. be and still result in structures like galaxies? He found that the existence of galaxies demanded a very small value of the c.c., close to that which was later discovered! While not an economical explanation, this success of the "weak anthropic principle" gives pause; it is the only successful explanation (never mind prediction) of this strangely small number from some underlying principle. In 2000, R. Bousso (Berkeley) and J. Polchinski (UCSB) [Scientific American, 200*] suggested a mechanism by which such a vast set of non-supersymmetric states might arise in a QGT. Their construction was motivated by known features of string theory, but, as we explained with Lubos Motl, there was good reason for skepticism. Subsequently, Kachru, Kallosh, Trivedi and Linde (KKLT) provided a more plausible proposal. The KKLT construction invokes assumptions which require a barely glimpsed structure well beyond string theory (strings might appear as the important actors in a small subset of universes). . Many string theorists, if not completely convinced, find the KKLT proposal quite plausible. In the KKLT construction the number of different states has been estimated at greater than 10500, more than enough to accidentally find values of the c.c. as small as the one we observe. L. Susskind has dubbed this vast set of states "The Landscape of String Theory". It is at this point that the two of us part company. While we have written together about features of the landscape, Banks has become convinced that its theoretical underpinnings are unsound, and has adopted a totally different approach, which will be described below. Dine has been more open to the possibility that the landscape exists. Here, the problem of prediction is subtle. There are so many states in the theory that one cannot hope to find that which describes precisely the universe around us. Even if one somehow could find this state, would almost certainly not be able to perform calculations using known techniques. Prediction, if possible at all, is necessarily statistical. The hope is to find correlations between known phenomena and phenomena yet to be studied experimentally. Much effort has gone into "postdicting" the number of quarks and leptons, for example, but with limited success. Dine has argued, using basic physical principles, that a question which one might more realistically hope to answer is whether such a framework predicts that supersymmetry will be observed at the LHC. Douglas (SUNY Stony Brook) and Susskind have advanced plausible arguments that the answer is no. Their idea, roughly, is that there are likely to be vastly more states without supersymmetry than with, and that this overwhelms any other considerations. But MD counters that things may not be that simple. Most importantly, a typical, low c.c. non-supersymmetric state tunnels rapidly (typically $10^{-31}$ sec) to a universe with negative c.c. which immediately undergoes gravitational collapse States which are nearly supersymmetric, on the other hand, are also often unstable, but with unimaginably long half lives (typically $10^{10^30}$ years). Typical long-lived universes might well be supersymmetric, and thus, in the spirit of Weinberg's argument, we would more likely find ourselves in one of these. Other, more detailed considerations, point towards an energy scale quite close to that of the LHC, and make particular predictions about the supersymmetric particle spectrum. These questions are not yet settled, and there is not definite agreement about whether supersymmetry is or is not an outcome of an underlying landscape. But M.D. believes that the evidence for such a picture is strong, and likely to soon be stronger.

## 5 Cosmological Supersymmetry Breaking

T.B. believes that a more radical rethinking of QGT is necessary. He argues that there is no solid evidence that the states described by KKLT exist (on this we both agree), and that there is not yet a sensible definition for observable quantities in such a vast Landscape of states, let alone a way to relate such observables to actual laboratory measurements. TB's alternative proposal is based on the holographic principle of 't Hooft and Susskind. The principle holds that physics, in a region of space(time), is controlled by the dynamics on the boundary of the space-time. This is a bizarre idea, but it follows from the physics of black holes. One can't concentrate too much energy in a small region of space without forming a black hole. But, as Hawking showed long ago, all the information about black holes is encoded on the surface of the black hole (the Schwarschild radius). So it is the surface of any region which is important. The holographic principle can be verified in many string theories. Banks' approach starts from the observation that for positive cosmological constant, as observed in nature, the geometry of the universe is entering a period of extremely rapid expansion. The corresponding de Sitter (dS) space-time has the peculiar property that all experiments done by any observer, no matter how long they take, can only probe the properties of space out to a finite radius, determined by the c.c. This surface is called the cosmological horizon. TB and Willy Fischler argued that these facts about de Sitter space require that any quantum theory of de Sitter space has only a finite number of quantum states, determined by the value of the c.c. They proposed that an underlying structure which, rather than featuring strings or other objects moving in a continuous space-time, involves discrete structures. Something like a 4 dimensional version of M theory can be recovered in the limit of vanishing c.c. TB has gone on to argue that a universe with the observed value of the cosmological constant can only exist if the underlying theory is very nearly supersymmetric, and related the masses of supersymmetric particles to the value of the c.c. The supersymmetric partners of ordinary fields necessarily have masses in a range such that they can be observed at the LHC. TB's hypothesis predicts in some detail the properties of these new particles. His current research program seeks, in part, to classify the possible theories which describe dS spaces. Strings, as basic excitations, are not likely to appear in any of these, and probably are not important in the QGT which describes nature. 7. Conclusion These developments sharpen the question posed in the title of this article: what is string theory, and what might it mean to make predictions from this theory? We hope we have made clear that, while string theory is a remarkable structure that allows the exploration of many deep questions about the nature of quantum mechanics and general relativity, it is not, by itself, adequate to understand the nature of the theory that describes our universe. The observed value of the dark energy is likely the most important clue as to the nature of this theory. Most string theorists have adopted a wait and see attitude, hoping for some other outcome. Others have pursued structures very different than those we have discussed here, such as loop quantum gravity and ideas inspired by condensed matter physics. There is serious debate whether any of these alternatives are fully consistent, in the sense that string theories are (they have trouble satisfying Hawking's requirements, and the problems of meaningless mathematical expressions are not entirely eliminated), but given our viewpoint that string theory, as presently understood, cannot describe nature, we are certainly interested in such alternatives. To date, none of these offer any explanation of the nature of the dark energy, nor do they make predictions for LHC physics (the major prediction of loop quantum gravity has recently been ruled out by the FERMI satellite).

The two authors of this article are impatient; the LHC is starting to explore questions such as the existence of supersymmetry now. To make predictions for such phenomena, one cannot simply sample random string states, and assume that supersymmetry is broken in some mysterious way. To make concrete progress, we are aware of only the two possibilities we have discussed here: that advocated by TB, that there are many such theories, and that they incorporate principles that we have learned from String Theory (but the underlying theory does not look like a theory of strings). The second is that there is one, large theory of quantum gravity, which allows many possible universes, with different properties, which typically will not be well-described as theories of string. Both approaches point to discovery of supersymmetry and the LHC, but the details differ, and either or both may soon be ruled out.