THE SECOND SUPERSTRING REVOLUTION

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Recent developments in superstring theory have led to major advances in understanding. After reviewing where things stood earlier, we sketch the impact of recently identified dualities and D-branes, as well as a hidden eleventh dimension.

It is my honor and pleasure to speak at this conference in memory of Andrei Sakharov on the occasion of his 75th birthday. Even though I never met with Sakharov personally, I understand from my good friend Professor Fradkin that Sakharov expressed considerable interest in superstring theory during his exile in Gorky. I would have enjoyed discussing the subject with him, but after his return to Moscow he had other more urgent matters to deal with. I admired him for his courage and persistent efforts on behalf of human rights and disarmament.

Major advances in understanding of the physical world have been achieved during the past century by focusing on apparent contradictions between well-established theoretical structures. In each case the reconciliation required a better theory, often involving radical new concepts and striking experimental predictions. Four major advances of this type are indicated in Figure 1. These advances were the discoveries of special relativity, quantum mechanics, general relativity, and quantum field theory. This was quite an achievement for one century, but it leaves us with one fundamental contradiction that still needs to be resolved, namely the clash between general relativity and quantum field theory. Many theorists are convinced that superstring theory will provide the answer. There have been major advances in our understanding of this subject, which I consider to constitute the “second superstring revolution,” during the past two years. The plan for this brief report is to sketch where things stood after the first superstring revolution (1984-85) and then to describe the recent developments and their implications.

There are various problems that arise when one attempts to combine general relativity and quantum field theory. The field theorist would point to the breakdown of renormalizability – the fact that short-distance singularities become so severe that the usual methods for dealing with them no longer work. By replacing point-like particles with one-dimensional extended strings, as the fundamental objects, superstring theory certainly overcomes the problem of perturbative non-renormalizability. A relativist might point to a different set
of problems including the issue of how to understand the causal structure of space-time when the metric has quantum-mechanical excitations. There are also a host of problems associated to black holes such as the fundamental origin of their thermodynamic properties and an apparent loss of quantum coherence. The latter, if true, would require a modification in the basic structure of quantum mechanics. The relativist’s set of issues cannot be addressed properly in a perturbative setup, but the recent discoveries are leading to non-perturbative understandings that should help in addressing them. Most string theorists expect that the theory will provide satisfying resolutions of these problems without any revision in the basic structure of quantum mechanics. Indeed, there are indications that someday quantum mechanics will be viewed as an implication (or at least a necessary ingredient) of superstring theory.

When a new theoretical edifice is proposed, it is very desirable to identify distinctive testable experimental predictions. In the case of superstring theory there have been no detailed computations of the properties of elementary particles or the structure of the universe that are convincing, though many valiant attempts have been made. In my opinion, success in such enterprises requires a better understanding of the theory than has been achieved as yet. It is very
difficult to assess whether this level of understanding is just around the corner or whether it will take many decades and several more revolutions. In the absence of this kind of confirmation, we can point to three general “predictions” of superstring theory that are very encouraging. The first is the existence of gravitation, approximated at low energies by general relativity. No other quantum theory can claim to have done this (and I suspect that no other ever will). The second is the fact that superstring vacua generally include Yang–Mills gauge theories like those that make up the “standard model” of elementary particles. The third general prediction, not yet confirmed experimentally, is the existence of supersymmetry at low energies (the electroweak scale). There are tantalizing hints that it may show up this century at CERN or Fermilab.

The history of string theory is very fascinating, with many bizarre twists and turns. It has not yet received the attention it deserves from historians of science. Here we will settle for a very quick sketch. The subject arose in the late 1960’s in an attempt to describe strong nuclear forces. It was a quite active subject for about five years, but it ran into theoretical difficulties, and QCD came along as a convincing theory of the strong interaction. During this period (in 1971) it was discovered that the inclusion of fermions requires world-sheet supersymmetry. This led to the development of space-time supersymmetry, which was eventually recognized to be a generic feature of consistent string theories (hence the name “superstrings”). In 1974 Joël Scherk and I proposed that the problems of string theory could be turned into virtues if it were used as a framework for realizing Einstein’s old dream of “unification,” rather than as a theory of hadrons. Specifically, we pointed out that it would provide a perturbatively finite theory that incorporates general relativity. One implication of this change in viewpoint was that the characteristic size of a string became the Planck length $L_{PL} = (\hbar G/c^3)^{1/2} \sim 10^{-33} \text{cm}$, some 20 orders of magnitude smaller than previously envisaged. (More refined analyses lead to a string scale $L_{ST}$ that is about two orders of magnitude larger than the Planck length.) In any case, experiments at existing accelerators cannot resolve distances shorter than about $10^{-16} \text{cm}$, which explains why the point-particle approximation of ordinary quantum field theories is so successful.

In 1984-85 there was a series of discoveries that convinced many theorists that superstring theory is a very promising approach to unification. Almost overnight, the subject was transformed from an intellectual backwater to one of the most active areas of theoretical physics, which it has remained ever since. By the time the dust settled, it was clear that there are five different superstring theories, each requiring ten dimensions (nine space and one time), and that each has a consistent perturbation expansion. The five theories, about which I’ll say more later, are denoted type I, type IIA, type IIB, $E_8 \times E_8$ heterotic
HE, for short), and SO(32) heterotic (HO, for short). The type II theories have two supersymmetries in the ten-dimensional sense, while the other three have just one. The type I theory is special in that it is based on unoriented open and closed strings, whereas the other four are based on oriented closed strings.

A string’s space-time history is described by functions \( x^\mu(\sigma, \tau) \), which map the string’s two-dimensional “world sheet” \((\sigma, \tau)\) into space-time \( x^\mu \). There are also other world-sheet fields that describe other degrees of freedom, such as those associated with supersymmetry and gauge symmetries. Surprisingly, classical string theory dynamics is described by a conformally invariant 2D \textit{quantum} field theory

\[
S = (1/L_{ST})^2 \int d\sigma d\tau \mathcal{L}(x^\mu(\sigma, \tau), \ldots). \tag{1}
\]

What distinguishes one-dimensional strings from higher dimensional analogs is the fact that this 2D theory is renormalizable. (Objects with \( p \) dimensions, called “\( p \)-branes,” have a \((p + 1)\)-dimensional world volume.) Perturbative quantum string theory can be formulated by the Feynman sum-over-histories method. This amounts to associating a genus \( h \) Riemann surface to an \( h \)-loop string theory Feynman diagram. The attractive features of this approach are that there is just one diagram at each order of the perturbation expansion and that each diagram represents an elegant (though complicated) mathematical expression that is ultraviolet finite. The main drawback of this approach is that it gives no insight into how to go beyond perturbation theory.

To have a chance of being realistic, the six extra space dimensions must curl up into a tiny geometrical space, whose size should be comparable to \( L_{ST} \). Since space-time geometry is determined dynamically (as in general relativity) only geometries that satisfy the dynamical equations are allowed. The HE string theory, compactified on a particular kind of six-dimensional space called a Calabi–Yau manifold has many qualitative features at low energies that resemble the standard model. In particular, the low mass fermions occur in families, whose number is controlled by the topology of the CY manifold. These successes have been achieved in a perturbative framework, and are necessarily qualitative at best, since non-perturbative phenomena are essential to an understanding of supersymmetry breaking and other important matters of detail.

The second superstring revolution (1994-??) has brought non-perturbative string physics within reach. The key discoveries were the recognition of amazing and surprising “dualities.” They have taught us that what we viewed previously as five theories is in fact five different perturbative expansions of a
single underlying theory about five different points! It is now clear that there is a unique theory, though it may allow many different vacua. For example, a sixth special vacuum involves an 11-dimensional Minkowski space-time. Another lesson we have learned is that, non-perturbatively, objects of more than one dimension (membranes and higher \( \text{“} p \text{-branes”} \)) play a central role. In most respects they appear just as fundamental as strings (which can now be called one-branes), except that a perturbation expansion cannot be based on \( p \)-branes with \( p > 1 \).

Three kinds of dualities, called \( S, T, \) and \( U \), have been identified. It can sometimes happen that theory \( A \) at strong coupling is equivalent to theory \( B \) at weak coupling, in which case they are said to be \( S \) dual. Similarly, if theory \( A \) compactified on a space of large volume is equivalent to theory \( B \) compactified on a space of small volume, then they are called \( T \) dual. Combining these ideas, if theory \( A \) compactified on a space of large (or small) volume is equivalent to theory \( B \) at strong (or weak) coupling, they are called \( U \) dual. If theories \( A \) and \( B \) are the same, then the duality becomes a self-duality, and it can be viewed as a (gauge) symmetry. \( T \) duality, unlike \( S \) or \( U \) duality, can be understood perturbatively, and therefore it was discovered between the string revolutions.

The basic idea of \( T \) duality (for a recent discussion see [5]) can be illustrated by considering a compact dimension consisting of a circle of radius \( R \). In this case there are two kinds of excitations to consider. The first, which is not special to string theory, are Kaluza–Klein momentum excitations on the circle, which contribute \( (n/R)^2 \) to the energy squared, where \( n \) is an integer. Winding-mode excitations, due to a closed string winding \( m \) times around the circular dimension, are special to string theory. If \( T = (2\pi L_{ST}^2)^{-1} \) denotes the string tension (energy per unit length), the contribution to the energy squared is \( (2\pi RmT)^2 \). \( T \) duality exchanges these two kinds of excitations by mapping \( m \leftrightarrow n \) and \( R \leftrightarrow L_{ST}^2/R \). This is part of an exact map between a \( T \)-dual pair \( A \) and \( B \). One implication is that usual geometric concepts break down at short distances, and classical geometry is replaced by “quantum geometry,” which is described mathematically by 2D conformal field theory. It also suggests a generalization of the Heisenberg uncertainty principle according to which the best possible spatial resolution \( \Delta x \) is bounded below not only by the reciprocal of the momentum spread, \( \Delta p \), but also by the string scale \( L_{ST} \). (Including non-perturbative effects, it may be possible to do a little better and reach the Planck scale.) Two important examples of superstring theories that are \( T \)-dual when compactified on a circle are the IIA and IIB theories and the HE and HO theories. These two dualities reduce the number of distinct theories from five to three.
Suppose now that a pair of theories \((A \text{ and } B)\) are S-dual. This means that if \(f\) denotes any physical observable and \(\lambda\) denotes the coupling constant, then \(f_A(\lambda) = f_B(1/\lambda)\). This duality, whose recognition was the first step in the current revolution,\(^6\) generalizes the electric-magnetic symmetry of Maxwell theory. The point is that since the Dirac quantization condition implies that the basic unit of magnetic charge is inversely proportional to the unit of electric charge, their interchange amounts to an inversion of the charge (which is the coupling constant). S-duality relates the type I theory to the HO theory and the IIB theory to itself. This explains the strong coupling behavior of those three theories. The understanding of how the IIA and HE theories behave at strong coupling, which is by now well-established, came as quite a surprise. In each of these cases there is an 11th dimension that becomes large at strong coupling, the scaling law being \(L_{11} \sim \lambda^{2/3}\). In the IIA case the 11th dimension is a circle, whereas in the HE case it is a line interval (so that the eleven-dimensional space-time has two ten-dimensional boundaries). The strong coupling limit of either of these theories gives an 11-dimensional Minkowski space-time. The eleven-dimensional description of the underlying theory is called “M theory.” As yet, it is less well understood than the five 10-dimensional string theories. The various connections among theories that we’ve mentioned are sketched in Figure 2. \((S^1\text{ denotes a circle and } I\text{ denotes a line interval.})\) There are many additional dualities that arise when more dimensions are compactified, which will not be described here.

Another source of insight into non-perturbative properties of superstring theory has arisen from the study of a special class of \(p\)-branes called Dirichlet \(p\)-branes (or D-branes for short). The name derives from the boundary conditions assigned to the ends of open strings. The usual open strings of the type I theory have Neumann boundary conditions at their ends, but \(T\)-duality implies the existence of dual open strings with Dirichlet boundary conditions in the dimensions that are \(T\)-transformed. More generally, in type II theories, one can consider open strings with

\[
\frac{\partial x^\mu}{\partial \sigma} \bigg|_{\sigma = 0} = 0 \quad \mu = 0, 1, \ldots, p
\]

\[
x^\mu \bigg|_{\sigma = 0} = x^\mu_0 \quad \mu = p + 1, \ldots, 9.
\]

At first sight this appears to break the Lorentz invariance of the theory, which is paradoxical. The resolution of the paradox is that strings end on a \(p\)-dimensional dynamical object – a D-brane. D-branes have been studied for a number of years, but their significance was explained by Polchinski only recently.\(^7\) They are important because they make it possible to study the excitations of the brane using the renormalizable 2D quantum field theory of
the open string instead of the non-renormalizable world-volume theory of the D-brane itself. In this way it becomes possible to compute non-perturbative phenomena using perturbative methods! Many (but not all) of the previously identified p-branes are D-branes. Others are related to D-branes by duality symmetries so that they can also be brought under mathematical control.

D-branes have found many interesting applications, but the most remarkable of these concerns the study of black holes. Strominger and Vafa \(^8\) (and subsequently many others) have shown that D-brane techniques can be used to count the quantum microstates associated to classical black hole configurations. The simplest case, which was studied first, is static extremal charged black holes in five dimensions. Strominger and Vafa showed that for large values of the charges the entropy (defined by \(S = \log N\), where \(N\) is the number of quantum states that system can be in) agrees with the Bekenstein–Hawking prediction (1/4 the area of the event horizon). This result has been generalized to black holes in 4D as well as to ones that are near extremal (and radiate correctly) or rotating. In my opinion, this is a truly dramatic advance. It has not yet been proved that there is no loss of quantum coherence, but I expect that result to follow in due course.

I have touched on some of the highlights of the current revolution, but there is much more that does not fit here. For example, I have not discussed the dramatic discoveries of Seiberg and Witten \(^9\) for supersymmetric gauge
theories and their extensions to string theory. Another important development due to Vafa \textsuperscript{10} (called F theory) has made it possible to construct large new classes of non-perturbative vacua of Type IIB superstrings.

Despite all the progress that has taken place in our understanding of superstring theory, there are many important questions whose answers are still unknown. It is not clear how many important discoveries still remain to be made before it will be possible to answer the ultimate question that we are striving towards – why does the universe behave the way it does? Short of that, we have some other pretty big questions. What is the best way to formulate the theory? How and why is supersymmetry broken? Why is the cosmological constant so small (or zero)? How is a realistic vacuum chosen? What are the cosmological implications of the theory? What testable predictions can we make? Stay tuned.

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References