M-Theory: The Mother of all SuperStrings

An introduction to M-Theory

Every decade or so, a stunning breakthrough in string theory sends shock waves racing through the theoretical physics community, generating a feverish outpouring of papers and activity. This time, the Internet lines are burning up as papers keep pouring into the Los Alamos National Laboratory's computer bulletin board, the official clearing house for superstring papers. John Schwarz of Caltech, for example, has been speaking to conferences around the world proclaiming the "second superstring revolution." Edward Witten of the Institute for Advanced Study in Prince- ton gave a spell-binding 3 hour lecture describing it. The after- shocks of the breakthrough are even shaking other disciplines, like mathematics. The director of the Institute, mathematician Phillip Griffiths, says, "The excitement I sense in the people in the field and the spin-offs into my own field of mathematics … have really been quite extraordinary. I feel I've been very privileged to witness this first hand."

Cumrun Vafa at Harvard has said, "I may be biased on this one, but I think it is perhaps the most important development not only in string theory, but also in theoretical physics at least in the past two decades." What is triggering all this excitement is the discovery of something called "M-theory," a theory which may explain the origin of strings. In one dazzling stroke, this new M-theory has solved a series of long-standing puzzling mysteries about string theory which have dogged it from the beginning, leaving many theoretical physicists (myself included!) gasping for breath. M-theory, moreover, may even force string theory to change its name. Although many features of M-theory are still unknown, it does not seem to be a theory purely of strings. Michael Duff of Texas A & M is already giving speeches with the title "The theory formerly known as strings!" String theorists are careful to point out that this does not prove the final correctness of the theory. Not by any means. That may make years or decades more. But it marks a most significant breakthrough that is already reshaping the entire field.

Parable of the Lion

Einstein once said, "Nature shows us only the tail of the lion. But I do not doubt that the lion belongs to it even though he cannot at once reveal himself because of his enormous size." Einstein spent the last 30 years of his life searching for the "tail" that would lead him to the "lion," the fabled unified field theory or the "theory of everything," which would unite all the forces of the universe into a single equation. The four forces (gravity, electromagnetism, and the strong and weak nuclear forces) would be unified by an equation perhaps one inch long. Capturing the "lion" would be the greatest scientific achievement in all of physics, the crowning achievement of 2,000 years of scientific investigation, ever since the Greeks first asked themselves what the world was made of. But although Einstein was the first one to set off on this noble hunt and track the footprints left by the lion, he ultimately lost the trail and wandered off into the wilderness. Other giants of 20th century physics, like Werner Heisenberg and Wolfgang Pauli, also joined in the hunt. But all the easy ideas were tried and shown to be wrong. When Niels Bohr once heard a lecture by Pauli explaining his version of the unified field theory, Bohr stood up and said, “We in the back are all agreed that your theory is crazy. But what divides us is whether your theory is crazy enough!”

The trail leading to the unified field theory, in fact, is littered with the wreckage of failed expeditions and dreams. Today, however, physicists are following a different trail which might be “crazy enough” to lead to the lion. This new trail leads to superstring theory, which is the best (and in fact only) candidate for a theory of everything. Unlike its rivals, it has survived every blistering mathematical challenge ever hurled at it. Not surprisingly, the theory is a radical, “crazy” departure from the past, being based on tiny strings vibrating in 10 dimensional space-time. Moreover, the theory easily swallows up Einstein’s theory of gravity. Witten has said, “Unlike conventional quantum field theory, string theory requires gravity. I regard this fact as one of the greatest in- sights in science ever made.” But until recently, there has been a glaring weak spot: string theorists have been unable to probe all solutions of the model, failing miserably to examine what is called the “non-perturbative region,” which I will describe shortly. This is vitally important, since ultimately our universe (with its wonderfully diverse collection of galaxies, stars, planets, sub- atomic particles, and even people) may lie in this “non-perturbative region.” Until this region can be probed, we don’t know if string theory is a theory of everything — or a theory of nothing! That’s what today’s excitement is all about. For the first time, using a powerful tool called “duality,” physicists are now probing beyond just the tail, and finally seeing the outlines of a huge, unexpectedly beautiful lion at the other end. Not knowing what to call it, Witten has dubbed it “M-theory.” In one stroke, M-theory has solved many of the embarrassing features of the theory, such as why we have 5 superstring theories. Ultimately, it may solve the nagging question of where strings come from.

“Pea Brains” and the Mother of all Strings

Einstein once asked himself if God had any choice in making the universe. Perhaps not, so it was embarrassing for string theorists to have five different self-consistent strings, all of which can unite the two fundamental theories in physics, the theory of gravity and the quantum theory.

Each of these string theories looks completely different from the others. They are based on different symmetries, with exotic names like E(8)xE(8) and O(32).

Not only this, but superstrings are in some sense not unique: there are other non-string theories which contain “super- symmetry,” the key mathematical symmetry underlying superstrings. (Changing light into electrons and then into gravity is one of the rather astonishing tricks performed by supersymmetry, which is the symmetry which can exchange particles with half-integral spin, like electrons and quarks, with particles of integral spin, like photons, gravitons, and W-particles.

In 11 dimensions, in fact, there are alternate super theories based on membranes as well as point particles (called super- gravity). In lower dimensions, there is moreover a whole zoo of super theories based on membranes in different dimensions. (For example, point particles are 0-branes, strings are 1-branes, membranes are 2-branes, and so on.) For the p-dimensional case, some wag dubbed them p-branes (pronounced “pea brains”). But because p-branes are horribly difficult to work with, they were long considered just a historical curiosity, a trail that led to a dead-end. (Michael Duff, in fact, has collected a whole list of unflattering comments made by referees to his National Science Foundation grant concerning his work on p- branes. One of the more charitable comments from a referee was: “He has a skewed view of the relative importance of various concepts in modern theoretical physics.”) So that was the mystery. Why should supersymmetry allow for 5 superstrings and this peculiar, motley collection of p-branes? Now we realize that strings, supergravity, and p-branes are just different aspects of the same theory. M-theory (M for “membrane” or the “mother of all strings,” take your pick) unites the 5 superstrings into one theory and includes the p-branes as well. To see how this all fits together, let us update the famous parable of the blind wise men and the elephant. Think of the blind men on the trail of the lion. Hearing it race by, they chase after it and desperately grab onto its tail (a one-brane). Hanging onto the tail for dear life, they feel its one- dimensional form and loudly proclaim “It’s a string! It’s a string!”

But then one blind man goes beyond the tail and grabs onto the ear of the lion. Feeling a two-dimensional surface (a membrane), the blind man proclaims, “No, it’s really a two-brane!” Then another blind man is able to grab onto the leg of the lion. Sensing a three-dimensional solid, he shouts, “No, you’re both wrong. It’s really a three-brane!” Actually, they are all right. Just as the tail, ear, and leg are different parts of the same lion, the string and various p- branes appear to be different limits of the same theory: M- theory. Paul Townsend of Cambridge University, one of the architects of this idea, calls it “p-brane democracy,” i.e. all p- branes (including strings) are created equal. Schwarz puts a slightly different spin on this. He says, “we are in an Orwellian situation: all p-branes are equal, but some (namely strings) are more equal than others. The point is that they are the only ones on which we can base a perturbation theory.” To understand unfamiliar concepts such as duality, perturbation theory, non-perturbative solutions, it is instructive to see where these concepts first entered into physics.

Dualty

The key tool to understanding this breakthrough is something “duality.” Loosely speaking, two theories are “dual” to each other if they can be shown to be equivalent under a certain interchange. The simplest example of duality is reversing the role of electricity and magnetism in the equations discovered by James Clerk Maxwell of Cambridge University 130 years ago. These are the equations which govern light, TV, X-rays, radar, dynamos, motors, transformers, even the Internet and computers. The remarkable feature about these equations is that they remain the same if we interchange the magnetic B and electric fields E and also switch the electric charge e with the magnetic charge g of a magnetic “monopole”: $E \leftrightarrow B$ and $e \leftrightarrow g$ (In fact, the product eg is a constant.) This has important implications. Often, when a theory cannot be solved exactly, we use an approximation scheme. In first year calculus, for example, we recall that we can approximate certain functions by Taylor’s expansion. Similarly, since $e^2 = 1/137$ in certain units and is hence a small number, we can always approximate the theory by power expanding in e^2. So we add contributions of order $e^2 + e^4 + e^6$ etc. in solving for, say, the collision of two particles. Notice that each contribution is getting smaller and smaller, so we can in principle add them all up. This generalization of Taylor’s expansion is called “perturbation theory,” where we perturb the system with terms containing e^2. For example, in archery, perturbation theory is how we aim our arrows. With every motion of our arms, our bow gets closer and closer to aligning with the bull’s eye.) But now try expanding in g^2. This is much tougher; in fact, if we expand in g^2, which is large, then the sum $g^2 + g^4 + g^6$ etc. blows up and becomes meaningless. This is the reason why the “non-perturbative” region is so difficult to probe, since the theory simply blows up if we try to naively use perturbation theory for large coupling constant g. So at first it appears hopeless that we could ever penetrate into the non-perturbative region. (For example, if every motion of our arms got bigger and bigger, we would never be able to zero in and hit the target with the arrow.) But notice that because of duality, a theory of small e (which is easily solved) is identical to a theory of large g (which is difficult to solve). But since they are the same theory, we can use duality to solve for the non-perturbative region.

S, T, and U Dualty

The first inkling that duality might apply in string theory was discovered by K. Kikkawa and M. Yamasaki of Osaka Univ. in 1984. They showed that if you “curled up” one of the extra dimensions into a circle with radius R, the theory was the same if we curled up this dimension with radius 1/R. This is now called T- duality: $R \leftrightarrow 1/R$ When applied to various superstrings, one could reduce 5 of the string theories down to 3 (see figure). In 9 dimensions (with one dimension curled up) the Type IIa and IIb strings were identical, as were the E(8)xE(8) and O(32) strings.

Unfortunately, T duality was still a perturbative duality. The next breakthrough came when it was shown that there was a second class of dualities, called S duality, which provided a duality between the perturbative and non-perturbative regions of string theory. Another duality, called U duality, was even more powerful.

Then Nathan Seiberg and Witten brilliantly showed how another form of duality could solve for the non-perturbative region in four dimensional supersymmetric theories. However, what finally convinced many physicists of the power of this technique was the work of Paul Townsend and Edward Wit- ten. They caught everyone by surprise by showing that there was a duality between 10 dimensional Type IIa strings and 11 dimension- al supergravity! The non-perturbative region of Type IIa strings, which was previously a forbidden region, was revealed to be governed by 11 dimensional supergravity theory, with one dimension curled up. At this point, I remember that many physicists (myself included) were rubbing our eyes, not believing what we were seeing. I remember saying to myself, “But that’s impossible!”

All of a sudden, we realized that perhaps the real “home” of string theory was not 10 dimensions, but possibly 11, and that the theory wasn’t fundamentally a string theory at all! This revived tremendous interest in 11 dimensional theories and p- branes. Lurking in the 11th dimension was an entirely new theory which could reduce down to 11 dimensional supergravity as well as 10 dimensional string theory and p-brane theory.

Detractors of String Theories

To the critics, however, these mathematical developments still don’t answer the nagging question: how do you test it? Since string theory is really a theory of Creation, when all its beautiful symmetries were in their full glory, the only way to test it, the critics wail, is to re-create the Big Bang itself, which is impossible. Nobel Laureate Sheldon Glashow likes to ridicule superstring theory by comparing it with former Pres. Reagan’s Star Wars plan, i.e. they are both untestable, soak up resources, and both siphon off the best scientific brains.

Actually, most string theorists think these criticisms are silly. They believe that the critics have missed the point. The key point is this: if the theory can be solved non-perturbatively using pure mathematics, then it should reduce down at low energies to a theory of ordinary protons, electrons, atoms, and molecules, for which there is ample experimental data. If we could completely solve the theory, we should be able to extract its low energy spectrum, which should match the familiar particles we see today in the Standard Model. Thus, the problem is not building atom smashers l,000 light years in diameter; the real problem is raw brain power: of only we were clever enough, we could write down M-theory, solve it, and settle everything.

Evolving Backwards

So what would it take to actually solve the theory once and for all and end all the speculation and back-biting? There are several approaches. The first is the most direct: try to derive the Standard Model of particle interactions, with its bizarre collection of quarks, gluons, electrons, neutrinos, Higgs bosons, etc. etc. etc. (I must admit that although the Standard Model is the most successful physical theory ever proposed, it is also one of the ugliest.) This might be done by curling up 6 of the 10 dimensions, leaving us with a 4 dimensional theory that might resemble the Standard Model a bit. Then try to use duality and M- theory to probe its non-perturbative region, seeing if the symmetries break in the correct fashion, giving us the correct masses of the quarks and other particles in the Standard Model. Witten's philosophy, however, is a bit different. He feels that the key to solving string theory is to understand the under- lying principle behind the theory.

Let me explain. Einstein's theory of general relativity, for example, started from first principles. Einstein had the "happiest thought in his life" when he leaned back in his chair at the Bern patent office and realized that a person in a falling elevator would feel no gravity. Although physicists since Galileo knew this, Einstein was able to extract from this the Equivalence Principle. This deceptively simple statement (that the laws of physics are indistinguishable locally in an accelerating or a gravitating frame) led Einstein to introduce a new symmetry to physics, general co-ordinate transformations. This in turn gave birth to the action principle behind general relativity, the most beautiful and compelling theory of gravity. Only now are we trying to quantize the theory to make it compatible with the other forces. So the evolution of this theory can be summarized as: Principle -> Symmetry -> Action -> Quantum Theory According to Witten, we need to discover the analog of the Equivalence Principle for string theory. The fundamental problem has been that string theory has been evolving "backwards." As Witten says, "string theory is 21st century physics which fell into the 20th century by accident." We were never "meant" to see this theory until the next century.

Is the End in Sight?

Vafa recently added a strange twist to this when he introduced yet another mega-theory, this time a 12 dimensional theory called F-theory (F for "father") which explains the self-duality of the IIb string. (Unfortunately, this 12 dimensional theory is rather strange: it has two time co-ordinates, not one, and actually violates 12 dimensional relativity. Imagine trying to live in a world with two times! It would put an episode of Twilight Zone to shame.) So is the final theory 10, 11, or 12 dimensional?

Schwarz, for one, feels that the final version of M-theory may not even have any fixed dimension. He feels that the true theory may be independent of any dimensionality of space-time, and that 11 dimensions only emerges once one tries to solve it. Townsend seems to agree, saying “the whole notion of dimensionality is an approximate one that only emerges in some semiclassical context.” So does this means that the end is in sight, that we will someday soon derive the Standard Model from first principles? I asked some of the leaders in this field to respond to this question. Although they are all enthusiastic supporters of this revolution, they are still cautious about predicting the future. Townsend believes that we are in a stage similar to the old quantum era of the Bohr atom, just before the full elucidation of quantum mechanics. He says, “We have some fruitful pictures and some rules analogous to the Bohr-Sommerfeld quantization rules, but it’s also clear that we don’t have a complete theory.”

Duff says, “Is M-theory merely a theory of supermembranes and super 5-branes requiring some (as yet unknown) non- perturbative quantization, or (as Witten believes) are the under- lying degrees of freedom of M-theory yet to be discovered? I am personally agnostic on this point.” Witten certainly believes we are on the right track, but we need a few more “revolutions” like this to finally solve the theory. “I think there are still a couple more superstring revolutions in our future, at least. If we can manage one more superstring revolution a decade, I think that we will do all right,” he says. Vafa says, “I hope this is the ‘light at the end of the tunnel’ but who knows how long the tunnel is!” Schwarz, moreover, has written about M-theory: “Whether it is based on something geometrical (like supermembranes) or some- thing completely different is still not known. In any case, finding it would be a landmark in human intellectual history.” Personally, I am optimistic. For the first time, we can see the outline of the lion, and it is magnificent. One day, we will hear it roar.