# String as a Theory of Everything

## *If particles consist of string, then grand unification and quantum gravity come for free—and maybe all the rest of physics, too*

At first glance the change seems trivial, even silly: instead of describing quarks, neutrinos, electrons, and other such fundamental particles as infinitesimal points, the way traditional theories do, describe them as lines—tiny, wriggling strings.

For the theoretical physicists, however, that modification is not at all trivial. During the last year, in fact, it has produced an extraordinary wave of excitement in the community, with some researchers hailing the transition from point to string as being no less profound than the transition from real numbers to complex numbers in mathematics.

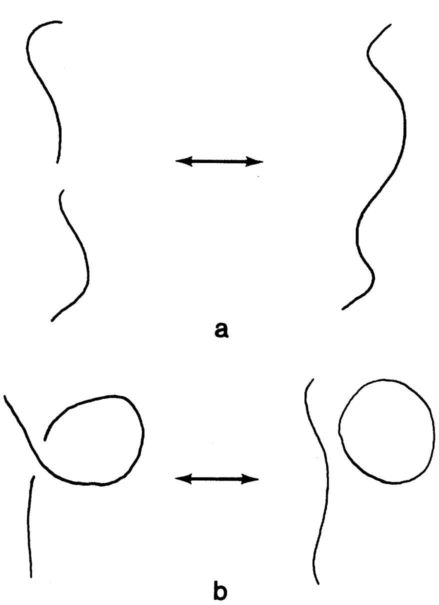
This "superstring" theory, as it is known, appears to be free of the infinities and inconsistencies that have plagued quantum field theories since they were invented in the 1930's. It combines the strong, weak, and electromagnetic interactions into a realistic, grand unified interaction—and more important, it specifies the details of that unification from first principles.

Most important of all, the superstring model at last seems to give the physicists their Holy Grail: a finite quantum theory of gravity. Indeed, the superstring unification does not just include gravity. It requires gravity for consistency.

The irony is that the physicists' newfound enthusiasm is being lavished on a theory that is 15 years old, with roots stretching back to the strong interaction physics of the late 1960's.

Theorists in those days were faced with a quandry. Traditional models of the elementary particles were based on quantum field theory, which in essence was a theory of dimensionless points. A particle was allowed to have mass, charge, spin angular momentum, and certain other quantum numbers such as hypercharge, but no internal structure at all. This worked beautifully for pure electromagnetic forces. In fact, quantum electrodynamics, the field theory of electrons and photons, is still the most accurate physical theory ever devised. But it failed dismally for the strong forces. Not only were the strong interactions far more complex than predicted by field theory, but the particles that participated in the strong interactions—the *hadrons*, a group that includes protons, neutrons, pi mesons, and many others—seemed to be relatively large, extended objects as ter). Physicists now believe that the hadrons are large and complex because they are bound states of quarks, described by a field theory known as quantum chromodynamics. But at the time, field theory had fallen out of favor and researchers were spending their time rather desperately searching for a viable alternative.

String theory was born in 1970, when University of Chicago physicist Yoshiro Nambu pointed out that one of the more fashionable of these alternatives, the so-called Dual Resonance Model, was mathematically equivalent to the interaction of bits of string. Originally the Dual Resonance Model was just a simple formula describing how one hadron should scatter off another. Nambu's version, however, seemed to open the way to a detailed dynamics of the process. The particles were pictured as being tiny strings roughly $10^{-13}$ centimeter long, or about the size of a proton. They interacted when two strings touched their tips together and fused into one, or conversely, when one string spontaneously split into two. In a collision the strings could also absorb energy and begin to ripple and rotate, with their ends whipping around at the speed of light. Thus, for every low-mass hadron, which presumably corresponded to a nonvibrating, nonrotating string, one would expect to find a series of more and more massive particles at higher and higher angular momentum, corresponding to vibrating, rotating strings. This is exactly what the Dual Resonance Model predicted, and this is exactly what was observed at the accelerators.




**The interaction of strings**

*Open-ended strings can interact by touching their tips together and fusing into a single string; alternatively, a single string can break into two (a). In some versions of the theory, a string can also cross over itself and pinch off a closed loop—a "graviton" (b).*

Nambu's string picture had an undeniable appeal, and in the early 1970's it was the subject of intense research. Perhaps the most intriguing thing about it was the rich mathematical structure that emerged as people tried to make the theory fully consistent with quantum mechanics and relativity. For example:

- Bose-Fermi symmetry. The original string theory was only able to describe bosons such as the pi-meson or the rho meson, which are particles having an integral number of spin angular momentum units (0, 1, 2, and so forth). At first there seemed to be no way to include fermions such as the proton and neutron, which have half-integral spin (½, 3/2, and so forth). Every attempt to do so produced pathological models that, among other things, predicted strings moving faster than the speed of light.

In 1976, however, the late French physicist Joël Scherk and his colleagues pointed out that a string model *could* represent fermions consistently if every fermion were matched with a corresponding boson. This was precisely the kind of correspondence called for by the principle of "supersymmetry," which has since become very popular among theorists (*1*). In fact, the fermionic string was one of the earliest examples of supersymmetry.

- The dimensionality of space-time. The universe we live in is patently four dimensional: every object can be measured in terms of length, breadth, height, and time. In string theory, however, it was realized quite early that boson strings are consistent with quantum mechanics only in a mathematical world of 26 dimensions (25 space, 1 time), and that fermion strings are consistent only in 10 dimensions (9 space, 1 time).

Obviously, this was not one of the strong points of string theory. On the other hand, it had always been a mystery why our world picked the number four. Why not seven dimensions, or 103? String theory at least offered a *mechanism* for singling out a specific dimensionality, even if the dimensionality did not seem to be the right one. And besides, as discussed below, there were reasons to think that the extra dimensions might not be a problem.

• Gauge interactions and gravity. In string theory the internal quantum numbers of a particle—hypercharge or color, for example—are carried on the tips of the string. Thus, whenever two strings join end-to-end, or whenever one string splits apart, quantum numbers are exchanged. In fact, calculations soon showed that when the interacting strings are in their lowest energy state—straight and nonrotating—the transfer of quantum numbers is equivalent to the exchange of a massless, spin-1 particle.

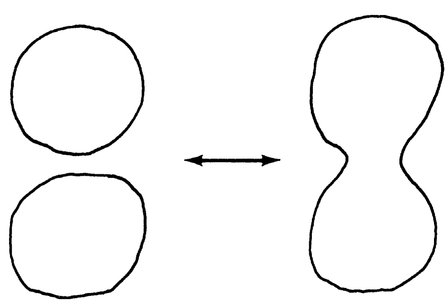
Now interactions of this type, which are known for historical reasons as gauge forces or Yang-Mills forces, were just then coming into their own as a basis for unified field theories. Among these theories were the highly successful Weinberg-Salam-Glashow model of the electromagnetic and weak interactions, quantum chromodynamics, and any number of grand unified theories. In fact, the gauge principle was emerging as one of the fundamental principles of physics—which is what made the string theory result so remarkable. It had never been clear *why* nature wanted to base everything on massless spin-1 particles. The gauge theories just seemed to work. And yet string theory, formulated without any mention of gauge interactions, produced them spontaneously .

There was more. The same interaction that allowed two separate strings to fuse into one string would allow a single string to touch its own ends together and fuse into a loop. (And vice versa, a loop would sometimes break and form an open string.) However, it turned out that the lowest energy state of a closed string would be massless and have a spin of 2—and a massless spin-2 particle, as it happens, is equivalent to a quantized gravity wave, or graviton. String theory thus produced not just gauge interactions, but gravity as well.

Ironically, these massless particles were an embarrassment in the context of strong interaction physics, since the hadrons are anything but massless. But by that point it hardly seemed to matter anymore. By the mid-1970's the Dual Resonance Model was already out of fashion, having been superceded by the much more fruitful theory of quantum chromodynamics, and it was becoming clear that string had much greater potential as a fundamental theory of nature. Indeed, as early as 1974 Scherk and John Schwarz of the California Institute of Technology, suggested how a fundamental string theory might work.

The nonvibrating, low-energy states of these fundamental strings would correspond to known "point" particles such as the quarks, electrons, muons, and neutrinos, they said, while the low-energy interactions of the strings would obviously correspond to the massless gauge particles and to the massless graviton. String theory would thus unify all the known forces from the start.

Of course, vibrating or rotating strings would produce high-mass quarks and leptons, which had never been observed. But that was not really a problem, said Scherk and Schwarz. If this was to be a theory of quantum gravity, then presumably the scale of a fundamental string would be set by the so-called Planck energy, the energy at which quantum gravity effects are known to become important. The Planck scale translates into a string about $10^{-33}$ centimeter long—twenty orders of magnitude smaller than a proton, which nicely accounts for the fact that quarks, neutrinos, and such appear to be infinitesimal points—and having a lowest energy excited state about $10^{-19}$ times as massive as the proton.



**Loop dynamics**

*Two closed loops of string can touch and merge, or conversely, a single loop can pinch into two. In theories where no open-ended strings are allowed, this is the only way strings can interact.*

Thus, said Scherk and Schwarz, the excited states of the fundamental strings have not been seen because they are beyond the reach of any conceivable accelerator. However, the excited string states would make a drastic difference in one of the chronic problem areas of conventional field theory: the fact that one often gets meaningless, infinite answers to even the simplest calculations. Physicists are constantly sweeping these infinities under the rug, so to speak, in order to get any useful answers at all. But the problems never really go away, because in field theory the particles are modeled as points, and can interact at zero distance. (One divided by zero is infinity.) Since strings are not points, however, and since even $10^{-33}$ centimeter is not quite zero, it seemed at least possible that string theory would cure these infinities once and for all.

Unfortunately, for nearly a decade the promise of string theory remained only a promise. Explicit string calculations continued to produce infinite answers, as well as certain other inconsistencies known as "anomalies," which are discussed below. Perhaps more important, string theory was still in a comparatively primitive state. Essentially it was just a set of rules for calculating string interactions. There seemed to be no fundamental principle behind the rules, certainly nothing like the beautiful geometrical principle that underlies Einstein's theory of gravity. The results on supersymmetry, dimensionality, gauge interactions, and gravity always seemed to arise out of purely technical considerations, and researchers in the field were often heard to use the word "miracle." Thus, lacking any compelling justification, string theory itself went out of fashion while the vast majority of theorists went off to work on the newly popular grand unified theories and supersymmetry.

In the early 1980's, however, string theory's fortunes suddenly revived: two longtime loyalists, Schwarz and Michael B. Green of the University of London, proved that under certain conditions the infinities *could* be eliminated, thus producing a theory that was completely finite. Then, in the summer of 1984, they announced an even more striking result: string theories existed that were not only finite, but free of the last inconsistency, anomalies (*2*).

Anomalies are quantum effects that violate such sacrosanct conservation laws as the conservation of energy, momentum, or electric charge. Unfortunately, anomalies are an ever-present threat in particle theory because they tend to crop up any time the equations distinguish between particles spinning in a clockwise direction and particles spinning in a counterclockwise direction—which happens to be a distinction made by the real world. (In the jargon, particle interactions do not conserve parity.) In fact, the only way to have a realistic theory that avoids anomalies is to balance it like a house of cards, with everything arranged to make the anomalies cancel out; the charmed quack, for example, was predicted several years before its discovery in 1974 at least partly because it was needed to cancel an anomaly of the weak interaction.

What made the anomaly cancellation so remarkable in string theory was that the balance was very delicate indeed. It worked if and only if the quantum numbers of the string corresponded to one of two very large symmetry groups, denoted SO(32) and $E_8 \times E_8$. Again, this result came about from purely technical considerations. But it was very suggestive: among the subgroups of one or the other of these behemoths were all of the symmetry groups that have been proposed as serious candidates for a grand unified theory. And better still, *these* symmetry groups were defined by the underlying model, instead of being adjusted by hand to fit the data. For the first time, there seemed to be a mechanism for nature to chose her symmetry group.

The upshot was that from the moment Green and Schwarz announced the anomaly cancellation, string became very fashionable indeed. It was irresistible: from a single mechanism—a relativistic, quantum string—one got a theory free of anomalies and infinities, a specification of the symmetry group of grand unification, supersymmetry, and a unification of the strong, weak, and electromagnetic forces with quantum gravity.

As one theorist put it, "String theory incorporates all known fashionable ideas."

Since the summer of 1984, work has proceeded on three major fronts: understanding the mathematics, making contact with the real world, and understanding the fundamental nature of string. An important development in the first campaign is the "heterotic" string model devised this year by David J. Gross and his colleagues at Princeton University (*3*), which is the first explicit model to incorporate $E_8 \times E_8$.

Of the two anomaly-free string groups, $E_8 \times E_8$ seems to include the known quarks and leptons in the most natural way, whereas in SO(32) the representation is rather forced. So there are good phenomenological reasons for preferring $E_8 \times E_8$. Unfortunately, for technical reasons, the only group possible on an ordinary, open-ended string is SO(32). That leaves closed strings for $E_8 \times E_8$. However, while it is logically possible to have a theory in which only closed loops of string are allowed—they are known as Type II theories to distinguish them from the Type I open-string theories—a closed loop is only a graviton; since a string is supposed to carry its quantum numbers on its endpoints, there at first seemed no way to associate a closed string with any kind of symmetry group or quantum numbers at all.

To get around this problem, Gross and his colleagues started from the observation that a closed loop can support ripples that run in both the clockwise and the counterclockwise directions. These ripples turn out to be totally independent of one another—so independent, the researchers realized, that they can even reside in different dimensions. Thus, the heterotic string: its clockwise ripples are 10-dimensional fermionic vibrations, while its counterclockwise ripples are 26-dimensional bosonic vibrations.

Now at this point the heterotic string is still just a graviton, albeit an exceeding strange graviton. However, it happens that the 26-dimensional space of the counterclockwise ripples is not flat; for the same infamous technical reasons that arise everywhere else in string theory, all but 10 of its dimensions have to be curled up, or "compactified," into a tight little torus. (Imagine a two-dimensional sheet of paper rolled up tightly into a kind of straw: it effectively becomes one-dimensional.) This compactification turns out to generate quantum numbers spontaneously. Moreover, these quantum numbers do not need endpoints: they are smeared out around the loop—and of necessity they have to belong to either SO(32) or $E_8 \times E_8$.

It's a complete mystery what string theory is at a fundamental level

The upshot is that the heterotic string comes very close to the ideal of unification: gravity, quantum numbers, and the symmetry group are really just different aspects of the same thing.

A similar kind of compactification process may also have relevence to one of the biggest barriers between string theory and the real world: the obvious fact that we do not live in a 10-dimensional (or 26-dimensional) universe. If string theory is to be a viable model of the four-dimensional world, then six of the ten dimensions will have to compactify and roll so tightly that we cannot detect them. The question is, why should they?

While theorists are still a long way from understanding all the mathematics of string theory, some interesting possibilities for compactification have begun to emerge. For example, Princeton's Edward Witten and his colleagues have shown that, under certain plausible conditions, compactification from 10 dimensions to 4 can break the symmetry group from $E_8 \times E_8$ to $E_6 \times E_8$, and in the process produce four "families" of elementary fermions (*4*). $E_6$ had already been proposed some time ago as one of the most promising groups for grand unification. And empirically, the elementary quarks and leptons do fall into at least three families, each of which has the same distribution of quantum numbers—a seemingly senseless duplication on nature's part that has long been an utter mystery.

If $E_6$ describes our world, however, then there arises an interesting cosmological speculation: the remaining $E_8$ factor might well describe another world—a "shadow" world, where shadow matter is governed by strong, weak, and electromagnetic forces completely independent of ours. There could easily be shadow galaxies, shadow stars, shadow planets, and shadow people, all occupying the same space we do, intermingling with all the stars and planets of our own universe, and yet totally undetectable to us except by their gravitational effects. Alas, there are strong cosmological arguments that shadow matter is *not* very abundant, if it exists at all (*5*). But the possibilities are intriguing nonetheless, and cosmologists have been following the string theory developments with interest.

Finally, despite all the manifold successes of string theory, there is still one nagging issue, which is ultimately the most important issue of all: Why string? Why should nature choose to build a universe out of little wriggling lines? And given string, why all the miracles? String theory is still just a set of calculational rules, with no underlying principle that anyone can see. "It's a complete mystery what string theory is at a fundamental level," says Princeton's Witten. On the other hand, he points out, if one tries to generalize string theory to a theory of two-dimensional quantum membranes, which seems an obvious thing to do, the result is a disaster: not only are the mathematics horrendous, but all the good results of string theory vanish irretrievably. So somehow the theory seems to be telling us that string is fundamental—if only we could read its message.

**—M. Mitchell Waldrop**

**References**


1. M. M. Waldrop, *Science* **220**, 491 (1983).
2. M. Green and J. Schwarz, *Phys. Lett.* **149B**, 117 (1984); *Phys. Lett.* **151B**, 21 (1985).
3. D. Gross, J. Harvey, E. Martinec, R. Rohm, *Phys. Rev. Lett.* **54**, 502 (1985).
4. P. Candelas, G. Horowitz, A. Strominger, E. Witten, *Nucl. Phys. B*, in press.
5. E. W. Kolb, D. Stekel, M. S. Turner, *Nature* **314**, 415 (1985).