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String Theory

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Abstract After reviewing the original motivation for the formulation of string theory and what we learned from it, I discuss some of the implications of the holographic principle and of string dualities for the question of the building blocks of nature.

1 String Theory and Hadrons

There is no doubt that hadrons are quarks and anti-quarks bound together by strings. That was not known until Nambu and I, and very shortly after, H.B. Nielsen, realized that the phenomenological Veneziano amplitude described the scattering of objects, that at the time, I called rubber bands [1–3]. Mesons were the simplest hadrons: they were envisioned to be quark anti-quark pairs bound together by elastic strings. Today we would call them open strings. Open strings interacted when the quark at one end of a string annihilated with the antiquark at the end of another string. In fact it was very quickly realized that the quark and antiquark at the ends of a single string could annihilate and leave a closed string, in those days called a Pomeron; today a glueball. Baryons were more complicated: three strings tied together at a junction, with quarks at the ends.

From the very beginning sometime in late 1968 or early 69, until today, string theory has been the inspiration for every successful description of hadrons that deals with their large scale properties. The reason is that hadronic matter really is string-like. Here are a few things that string theory explained.

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- Confinement. The most important fact about the structure of hadrons is quark confinement. Confinement was easily explained by string theory. According to the theory, the elastic strings are unbreakable unless a new quark anti-quark pair is created at the breaking point.
- Linear Regge Trajectories. The fact that rotational excitations of hadrons lie on parallel, almost straight lines when mass-square is plotted against angular momentum was known by the time string theory was discovered. In fact it was part of the inspiration for Veneziano's discovery of the Veneziano amplitude. But the reason for the simple pattern was only explained by the properties of the rubber-band-like strings. It was no more than the fact the strings behave like springs—harmonic oscillators—when stretched.
- Hadronization. When a quark is struck hard during a collision, instead of escaping, it produces a jet of mesons. This is an easy process to visualize. As the quark starts to separate from the parent hadron, a string is created. The energy to create the string comes from the kinetic energy of the quark. But if the quark is sufficiently energetic, the energy in the string will get large enough so that a quark anti-quark pair can be produced. The string breaks but the quark is still connected to an anti-quark. If the quark still has enough energy it will continue to move away, dragging a string, which will then produce another pair, and so on, until the energy is used up. The segments of string (with quarks and anti-quarks) form the meson jets.

The simple string theory—today it is called bosonic string theory—has undergone big changes but the basic picture is the same. The biggest change was the introduction of QCD a few years after the introduction of string theory. The connection between QCD and string theory was made right after the discovery of asymptotic freedom. 't Hooft and I simultaneously realized that the nonlinear strong coupling of QCD might have the effect of binding the chromo-electric flux lines between color-charges, into narrow tubes. That and Wilson's lattice gauge theory made clear that gluonic matter is very stringy.

Many things happened since then including 't Hoofts large N limit [4], which suggested that gluons organize themselves into strings; Polyakov's important suggestion that QCD might really be best understood as a 5-dimensional theory; Polchinski's discovery of D-branes [5], and Maldacena's discovery of the ADS/CFT connection [6]; and more. But nothing has changed the basic picture of hadrons as quarks bound by "rubber bands."

2 Gravity

String theory was not without difficulties as the theory of hadrons. It had tachyons which were soon removed by supersymmetry, but more stubborn was the existence of massless spin-1 open strings, and even worse, a massless spin-2 closed string. These were not good things for someone trying to build a theory of hadrons; they would have to be gotten rid of. But a few brave souls said forget hadrons. Call them gravitons and photons and make a theory of fundamental forces. Indeed reconciling quantum mechanics with gravity has been the other really great accomplishment of string theory. Before I list a few successes, just a word about whether string theory is really the right theory of nature.

Just to be precise about what constitutes string theory, let me give a narrow definition—no doubt much too narrow for many string theorists. But it has the virtue that we know that it mathematically exists. By string theory I will mean the theory of supersymmetric string backgrounds including 11-dimensional M-theory and compactifications that preserve some degree of supersymmetry. These backrounds are generally either flat (zero cosmological constant) or anti de Sitter space with negative cosmological constant.

With that definition of string theory, there is no doubt: string theory is *not* the theory of nature—the world is not supersymmetric, and it has positive cosmological constant. Exactly how the definition has to be expanded in order to describe the observed universe is not known. Nevertheless string theory has had a profound, and I believe lasting, influence on how gravity and quantum mechanics fit together.

In order to illuminate the conceptual problems of quantum gravity it may not be important to discuss the precise form of the theory that describes our corner of the universe. What may be more important is to know what is, and what is not consistent; what kinds of things are possible; what kinds of structures to expect. One should not underestimate the importance of having a mathematically consistent structure that contains both quantum mechanics and gravity.

For example, Hawking had very good reasons to believe that the principles of quantum mechanics and the principles of general relativity could not coexist. It seemed to almost everyone, up until the mid 1990's that information-conservation—a foundation-stone of quantum mechanics—would be destroyed by the evaporation of black holes. Hawking's arguments were extremely convincing.

It did not matter that string theory (the precise version) is not the theory that describes the universe. The fact that information is not destroyed in certain supersymmetric examples proved that those arguments are wrong. The specific examples were unrealistic—matrix theory of 11-dimensions, D1/D5-brane constructions in type IIB string theory, ADS/CFT theories, but that was not important. They were persuasive counterexamples to a claim which was supposed to apply to any theory combined quantum mechanics with the general theory of relativity. That is no small thing.

Perhaps the most far-reaching idea that has come out of black hole physics is the holographic principle put forward by 't Hooft and myself [7, 8]. In 't Hooft's case he was not driven by string theory at all. He was just trying to rescue information conservation. In my case I was, at least in part, motivated by some strange facts about strings that I knew from the old hadronic days; namely, that when examined with infinite time resolution, they fluctuate out to infinity. But whatever the motivation, the holographic principle did not gain any real traction until it was embedded in the precise mathematics of supersymmetric string theory. Matrix theory, and even more, ADS/CFT were the catalysts that turned the holographic principle from a speculative claim to a widely accepted working tool of theoretical physics.

3 The End of Reductionism

3.1 What Are the Building Blocks?

Reductionism is the idea that big complicated things are made of smaller simpler things; and that the properties of the bigger things are explainable in terms of the laws governing the smaller things.

There are two kinds of reductionists: those who believe the hierarchy of structure goes on forever, and those who believe it will come to an end when we uncover the smallest, most fundamental, simplest objects. But whichever kind of reductionist you may be, you are never in doubt about which things are composites, and which are constituents. One might say, of course it's that way: How else could it be? Reductionism as a philosophy goes back at least to the Greeks, and it's probably hard wired into our cognitive apparatus.

Nevertheless, if one listens carefully, string theory is telling us that in a deep way reductionism is wrong, at least beyond some point. I'll begin with the example of electrons and magnetic monopoles. Magnetic monopoles are usually imagined to be complicated extended field configurations full of virtual Higgs bosons, gauge bosons, and photons that make them very massive. Electrons, on the other hand are claimed to be point-like. That, of course, is not quite true: electrons have a weak coulomb field of virtual photons. The coulomb field polarizes the vacuum and creates pairs but this is a very small effect. The weak field doesn't make the electron particularly massive. It is pretty clear that electrons, photons, and Higgs bosons are elementary, and monopoles are heavy complicated composites.

But as field theorists know very well, in some gauge theories the role of elementary and composite can be interchanged, monopoles becoming the elementary objects and electric charges being the composites. It really is a matter of convenience which is which. The more useful building block is determined by the value of the fine structure constant. If one could start increasing α the coulomb field would get stronger, the vacuum would get more polarized, and the electron would get heavier and start to resemble a composite object. It would start to resemble a composite object. At the same time the monopole would get lighter, smaller, and start to look more like a point. This is called electric-magnetic duality.

In string theory this kind of ambiguity is the rule. I'll just mention a few examples. The analog of the electron in weakly coupled string theory is the fundamental string—everything else is made of them. Contrast the fundamental strings with D-branes. D-branes are in a sense made of string. If you collide two of them at high velocity you will fine that they are full of strings that are attached by their ends to the branes. They are also very heavy. A particular example is the D1-brane of type IIB string theory. The D1-brane is itself a kind of heavy string.

Now start increasing the string coupling constant. Just like electrons, the fundamental strings start getting more complex and heavier, and at the same time the D string gets simpler and lighter. At some point they become interchanged: the D-strings become the elementary objects, and the fundamental strings replace them as the complex heavy objects.

There is of course the matter of convenience: when the coupling g is very small, it is useful to write the theory in terms of the fundamental strings. Likewise when g is very big it becomes useful to use the D-strings as the elementary objects. But there is one more point about string theory that makes this pragmatic choice of starting point even more ambiguous that it is in field theory. In string theory the coupling constant is not a constant; it is a field that can vary in space-time. The field is called the dilaton field. Thus, in a strong dilaton wave, there will be places where the fundamental strings are the simplest objects, and other places where the D-strings are simplest. In fact there will be places where the coupling is of order one where neither is more elementary than the other.

Type IIA string theory is even more bizarre. Again when the coupling is small the fundamental strings behave simply and are the convenient starting point for expanding the theory. In this case there are no D-strings but there are D0-branes. The D0-branes are very heavy particles with lots of string attached to them. Now start increasing the coupling. A very strange thing happens: the D0-branes get lighter, the fundamental strings get heavier, but weirdest of all, a new (compact) dimension of space emerges. As the coupling grows the length of the new dimension grows and the theory becomes 11-dimensional. Oddly the heavy complex D0-branes morph into 11-dimensional gravitons. And the fundamental strings? They become membranes wrapped around the new direction.

But again, the generic situation is one in which the coupling constant varies in space and time. In some places the theory has only 10 dimensions, strings are simple, and D0-branes are massive composites: in other places the theory has opened up an 11th dimension, the strings are heavy membranes, and the D0-branes are gravitons.

I could go on and on, taking you on a tour of the space of string theories, and show you how everything is mutable, nothing being more elementary than anything else. Personally, I would bet that this kind of anti-reductionist behavior is true in any consistent synthesis of quantum mechanics and gravity.

3.2 How Big Are the Building Blocks?

In fact the situation is even more subtle than I have described. I have spoken of big things and small things. But even this distinction is not always to be trusted. A famous example is T-duality in which, as you shrink a compact dimension of space, momentum and winding number get interchanged. The upshot is that the theory with a very small extra dimension cannot be distinguished from the theory with a very large extra dimension. This duality between small and big is pervasive in string theory. Similar things recur in many contexts.

3.3 Where Are the Building Blocks?

It is very possible that by studying the quantum mechanics of black holes we have learned more about the future foundations of physics than from any other theoretical enterprise. In particular it has given rise to an entirely new level of quantum ambiguity that goes well beyond what we've seen previously. Two observers can disagree about the location of a bit of information, not by a small microscopic amount, but by huge distances. What one observer sees as being inside a large black hole, another will see as part of the Hawking radiation, far outside the black hole. But all of that is predicated on the idea that information is not irrevocably lost when black holes evaporate.

The debate about black holes and information was a long one that was only settled by string theory. To be brief I'll just list the questions and the answers that string theory provided.

- Does Bekenstein-Hawking entropy really represent microscopic information in the same sense as in more ordinary systems. In other words is the entropy counting the number of orthogonal quantum states of a black hole? Most relativists thought not, since the entropy is proportional to the surface area of the black hole and seems to ignore the object that fell into the black hole.

  String theory provided a clear affirmative answer: The entropy of a black hole is exactly the logarithm of the number of quantum states of the black hole. The first arguments were crude, and based on the idea that as the coupling is varied, black holes will mutate to long tangled strings, and back again to black holes. This type of argument was effective in showing that the entropy of a black hole is proportional to its area, but it was not precise enough to calculate the coefficient. But again, supersymmetry provided the missing precision, and it was possible to correctly fix the relation between area and entropy.

  The implications are enormous: there is no longer any question that a consistent theory of gravity must have a hidden microscopic structure whose degrees of freedom describes the quantum states and entropy of black holes. String theory provides a working example, whether or not it is the true theory of nature.
- Is information lost in black hole evaporation?

  Again string theory is clear: information is not lost. The fundamental rules of quantum mechanics are not inconsistent with general relativity. This can be seen in several ways including Matrix theory, ADS/CFT and the famous D1,D5 black holes. In each case black holes are described by systems which are definite quantum-mechanical systems, and Hawking radiation satisfies the rules of linearity and unitarity.
- Finally a question with a very surprising answer: where is information? The answer to the question—where are the basic building blocks, is the most surprising and radical thing we have learned since the Heisenberg uncertainty principle. The answer is they are at the boundaries of the universe, stored on a kind of two-dimensional hologram. The holographic principle was not discovered first in string theory. It was a response to Hawking's claim that information, once it crosses the horizon of a black hole, is lost. The answer to Hawking is that the information was not where you thought it was. The holographic principle tells us that the degrees of freedom of a system can be thought of as residing on the outer boundary of space. This is a very radical departure from conventional physics in which the storage of information occurs in the three-dimensional bulk of space. Instead, the combination of quantum mechanics and general relativity give an altogether different answer to the question "where are the building blocks."

  The holographic principle is very surprising, and it probably would not have been embraced by the community had it not been for the extraordinary confirmation from string theory. The ADS/CFT duality is a very precise example of the holographic principle in which the detailed equivalence between a bulk gravitating system, and a holographic boundary dual system can be tested.

4 Particle Physics and Cosmology

One unstated principle of reductionism is that things get simpler as you dig deeper. For those who believe in a deepest level, the building blocks should be very simple—elementary is the word we use. But things are not moving in that direction, at least at the present time. The standard model has several gauge groups, a Higgs sector, unexplained flavor replication, about 20 free parameters, and a bad fine-tuning problem. When supersymmetry (or Technicolor) is added in order to get rid of the fine-tuning, things get even worse. The minimal supersymmetric standard model (mssm) has over a hundred parameters. In addition it requires a whole new gauge sector to break supersymmetry. Add a sector for inflation and another one for the axion (needed to solve the U(1) problem), a right handed neutrino, X and Y bosons for unification, and a heavy Higgs sector. It is obvious that we are not heading toward simplicity.

What does string theory say? Different people have different views. Some say that string theory has been a failure: it has not explained any of this. Others say give us more time, we are getting closer every day. But there is a third view that is gaining ground.

The third view begins with the observation that string theory itself is very complicated. It has a lot of moving parts: a compactification geometry with many topological features, branes, fluxes, orbifolds, and orientifolds. These parts can be assembled in a stupendous variety of ways which are collectively called the String Theory Landscape. Particle physics at a generic point on this landscape is no less complicated than what we are trying to explain.

The parts of the landscape that we understand well are supersymmetric. As I said earlier, they include vacua with zero and negative cosmological constant, but to describe nature we have to move past what I earlier defined to be string theory. The fact that we live in a universe (or possibly a pocket of the multiverse) with a positive cosmological constant, means that we have to leave the comfort of the known world and head for terra incognita. I will not go into the various constructions that have been proposed for "string inspired" theories with positive cosmological constant.

Some people are horrified by this complexity, and even more so by the idea of a multiverse populated by bubble-universes that fill the landscape. Others find the idea exciting because if fits nicely with cosmologists' speculations about eternal inflation, and environmental selection. At the moment it is too soon to say who will be right. But what we can say is that if the multiverse concept proves correct, it will be an enormous success for string theory. If it proves wrong then it's back to the drawing board.

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