Elements of String Theory

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Why String Theory?

The impressive edifice of modern physics firmly rests on two foundations: Quantum Theory and the General Theory of Relativity. But these two fundamental theories of modern physics are incompatible with each other. String Theory is the only convincing candidate for a theory that resolves this incompatibility.

Quantum Theory

The effects of quantum theory become noticeable at very small distances. For example, the physics of molecules, atoms, nuclei, and elementary particles can be correctly described only within the framework of quantum theory. Even though the formalism is rather abstract and far-removed from everyday experience, it has by now come to play an essential role in many practical applications. It is at the heart of much of the modern technology that has entered our living rooms, including the semiconductor chips in computers or the lasers in CD players.

General Theory of Relativity

General relativity describes gravity at large distances. For example, the physics of the solar system, neutron stars, black holes, and the universe itself can be adequately described only within the framework of general relativity. Unlike quantum mechanics, general relativity has few immediate practical applications. But the beauty of its theoretical structure is so compelling that it is widely recognized as one the greatest achievements of the human mind.

The observational consequences of the theory have been verified in a wide range of subtle physical effects. It is at work in many exotic phenomena in astrophysics and cosmology such as the gravitational collapse of a star into a black hole, or the expansion of the universe, or the slowing down of pulsars.

String Theory

Quantum theory and general relativity each has been experimentally tested in its own domain of applicability to an astonishing degree of accuracy. A correct fundamental theory must incorporate both, but these two theories of modern physics are inconsistent with each other.

General relativity is a satisfactory theory of gravity in situations where quantum effects can be ignored. But a complete theory must be a quantum theory of gravity. Earlier attempts to formulate such a theory led to a mathematical contradiction and unacceptable infinite answers for the values of physical quantities. Despite heroic efforts by some of the best minds in the field, this glaring contradiction remained one of the most important unresolved problems in theoretical physics for over half a century.

String theory is finally revealing to us the glimpses of a more majestic framework that can successfully resolve this contradiction and which can combine both quantum mechanics and general relativity in a consistent picture of the world. Explorations of this rich and marvelous structure have engaged the attention of some of the brightest physicists.

What is String Theory?

String theory is currently the most promising candidate for a unified theory of all forces including gravity. To appreciate this better it is necessary to put it in a historical perspective.

Elementary Particles and Fundamental Forces

The modern view of the world is fundamentally atomistic.

From the reduction of all matter to ``earth, air, fire, water'', we have progressed considerably. Chemistry reduced all of matter to a hundred or so types of atoms, called ``elements''. But the atoms themselves turned out to consist of smaller, more elementary particles interacting with each other. Elementary particles are thus the indivisible elements that the world is made up of. They interact with each other via four basic forces-- gravity, electromagnetism, the weak nuclear force and the strong nuclear force. The weak nuclear force is responsible for radioactive decay of an atomic nucleus while the strong force is the glue that binds protons and neutrons together to make up the nucleus.

Elementary particles can roughly be divided into two categories: `particles of matter' that constitute the matter around us, and `particles of force' that transmit various forces. For example, the electron is a familiar `particle of matter' that is running around in electric wires. Other more exotic particles of matter are muons, neutrinos and quarks. On the other hand, the photon is a `particle of force' that transmits the electromagnetic force between two charged objects. Similarly, graviton is the particle that transmits gravity, W and Z bosons transmit the weak force, and gluons transmit the strong force.

A comprehensive quantum theory of electromagnetic, weak and strong interactions is summarized in the Standard Model of Particle Physics. This model has now been confirmed in a large number of delicate experiments and is capable of describing the basic constituents of matter and their interactions to distances a thousand times smaller than the radius of the atomic nucleus. It is an extraordinary accomplishment of science that the bewildering variety of phenomena around us is seen to arise from a handful of simple building blocks.

However, gravity stubbornly refuses to be incorporated into the Standard Model. As we have said earlier, at large distances, where quantum effects are negligible, general relativity is a very successful and adequate description of gravity. But at very small distances, this description must be supplanted by a full-fledged quantum theory of gravity.

This is where string theory comes in.

Elementary Particles in String theory

String theory posits that the fundamental constituents of matter are elementary strings. As with a musical string, this basic string can vibrate. Each vibrational mode of the string can be viewed as a point-like elementary particle, much as each vibration of a musical string is perceived as a distinct note! Thus, according to string theory, an electron is a tiny loop of string vibrating in a particular way as it moves around. The loop looks like a point because it is extremely tiny.

This deceptively simple idea was found to have many far-reaching and surprising consequences:

- Not only the electron, but ALL elementary particles can arise as different vibrations of this single elementary string.
- One of the biggest early surprises in string theory was that one of the modes of vibration of the string is the graviton, the particle which transmits the force of gravity. Thus, for the first time, the force of gravity is on the same footing as the other three forces and is naturally incorporated within a quantum framework.

Fundamental Forces in String Theory

When one electron exerts electromagnetic force on another, it does so by emitting a photon which is later absorbed by the other electron. In the standard model, the electromagnetic interaction of an electron is completely specified by specifying the precise rule for the emission of a photon from the electron and its absorption.

In string theory, the description of this interaction is somewhat different. Since both the photon and the electron are simply the same string vibrating in different modes, the emission of a photon from an electron appears as splitting of a string into two strings. Conversely, the absorption of a photon by an electron appears as joining of two strings into one. The same is in fact true for all other interactions because all force carriers are different excitations of the same string.

Therefore, ALL interactions in string theory take place by splitting and joining of strings. This simplicity of interactions in string theory should be contrasted with the Standard Model where one needs to specify different rules for the emission and absorption of different particles of force.

Unification

String theory is the most promising candidate for a unified theory of all forces. In string theory, as we have seen, all particles arise as different vibrations of the same elementary string. Thus, there is no fundamental distinction between `particles of matter' and `particles of force'. Moreover, all interactions are completely specified by specifying the rule for the splitting and joining of the elementary string.

It follows that `matter' and `force' are simply different aspects of the same fundamental entity and are thus unified. For the same reason, all fundamental forces including gravity are also unified.

Unification of all forces has been the holy grail of theoretical physics since Einstein. The fact that unification is so naturally built into the structure of string theory is therefore very exciting.

Implications of String Theory

String theory dramatically alters even the most basic notions of space and geometry. As we will see, some of these ideas can appear completely contrary to everyday experience but can yet be very important as we probe nature at very short distances.

Compactification

The world around us appears to have only three dimensions. Each object has length, breadth and height. String theory, on the other hand, predicts that the world should have nine dimensions and not just three. To understand how such a theory can describe the real world, consider the following analogy.

If we take a long, thin wire, then for all practical purposes, the wire appears to have only one dimension -- its length. For a large insect living on the wire, the thickness of the wire is not noticeable. Of course, we can find out that the wire is really three dimensional by viewing it under a magnifying glass. It will then be clear to us that it is in fact a solid cylinder that has all the three dimensions.

Similarly, in string theory, it is possible that the six extra dimensions curl into a tiny ball. This process is called compactification. If these extra dimensions are sufficiently small, then they would not be noticeable to us and the world would appear effectively three-dimensional. For string theory to describe the real world, the size of the curled up six dimensions would have to be at least ten thousand times smaller than the atomic nucleus.

If we could magnify the extra six dimensions sufficiently then they would become visible to us. The `magnifying glass' used in particle physics is a high energy accelerator. Greater magnification requires higher energies. The energies required to `see' these extra dimensions are well beyond present experimental capabilities.

Stringy Geometry and Duality

Yet another surprise of stringy geometry is that in string theory, very large distances can be exactly equivalent to very small distances. This extraordinary equivalence is known as duality.

This apparently bizarre feature of stringy geometry is possible because unlike point particles, strings are extended objects and therefore cannot be completely squeezed into a point. There is a minimum length in string theory called the string length which is at least ten thousand times smaller than the atomic nucleus. If we probe the theory at distances much smaller than the string length, it looks exactly identical to the theory at distances much larger than the string length. As a result, in string theory there is no physical meaning to arbitrarily short distances.

Black Holes in String Theory

String theory is beginning to address some of the long-standing puzzles in quantum gravity. One particularly striking application of these ideas is to the quantum physics of black hole.

A Black Hole is an exotic astrophysical objects, whose gravitational pull is so strong that whatever falls inside can never come out. It appears black because even light cannot escape its enormous gravity.

In a seminal paper, Hawking showed that when quantum effects are taken into account, a black hole is not really black because it emits a steady stream of particles. A black hole in fact appears exactly like a glowing piece of charcoal emitting heat and light.

This remarkable discovery, however, raised a number of very serious puzzles. A hot body is characterized by its temperature and a more subtle attribute called the `Entropy'. Ordinarily, the entropy is a measure of the number of internal states of the body. For example, a piece of charcoal is composed of a large number of atoms. Its entropy is a measure of all possible ways these atoms can jiggle around. It was far from clear what the internal states of a black hole are and how, if at all, the entropy of the black hole can be understood in terms of these internal states.

In an exciting recent development in string theory, it was shown that a black hole is indeed very much like an ordinary hot object. At least for a class of black holes, the entropy and other properties of a black hole can indeed be understood in terms of its internal states. This is considered one of the convincing successes of string theory.

Future Of String Theory

String theory has revealed to us many wonderful structures but we are still far from understanding the full import of the theory. At present, we do not even know the full equations of the theory and how the Standard Model in all its details would follow from it. Ultimately, the fate of the theory will be determined by its experimentally testable predictions. Exploration at this very frontier of research is an exciting intellectual endeavor. If these ideas turn out to be true and string theory is eventually verified in experiments, it will completely revolutionize our conception of space time and matter.

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