Black Holes, Strings and Quantum Gravity

Juan Maldacena

Institute for Advanced Study
School of Natural Sciences
Einstein Drive
Princeton, NJ, 08540, USA

On leave from
Jefferson Laboratory of Physics
Harvard University
Cambridge, MA 02138, USA

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1 Introduction

In this article we are going to describe some ideas about the most microscopic or most fundamental laws of physics. Before that we will review, in very general and oversimplified terms, the laws of physics as we understand them today. We will remark that there is an important logical inconsistency in these laws. There is a conflict between quantum mechanics and gravity. String theory was invented to solve this contradiction. We will explain what string theory is and how it describes some quantum aspects of black holes. This will be possible through a relationship between string theory and more conventional theories of particle physics.

2 Presently known physics

2.1 What are things made of?

When we ask ourselves what things are made of, we think of molecules, atoms, or elementary particles. Ordinary matter is made of molecules, which in turn contain atoms which in turn contain more elementary particles. An elementary particle is, by definition, a particle which is not made of some other particles. The particles which today we consider elementary might some day turn out to be made of some other more elementary particles. All we can say is that current experiments have not seen that they have any smaller constituents. Consider for example a piece of iron. It is made of atoms, these atoms consistn of a nucleus and some number of electrons, 26 for the case of iron. The electrons are elementary, as far as we know now. The nucleus contains protons and neutrons, which in turn contain particles called "quarks" which are elementary. All these particles interact by emitting and absorbing other particles. The electro-magnetic force, responsible for keeping atoms together, is due to the interchange of photons. The strong force, or nuclear force, is responsible for keeping the quarks together and keeping the nucleus together. This force is due to the exchange of other particles called gluons. All of the ordinary matter we see is made of these particles. In summary, we have a certain number of elementary particles, the ones mentioned explicitly above plus some other ones. They make all the matter we see, including the matter in distant galaxies, the matter making living organisms, etc. In this picture of matter it is extremely important that the laws governing their motion are not the laws of classical physics, but the laws of quantum mechanics. From our classical intuition we would say an electron moving around the nucleus would be like a planet moving around the sun. In both cases there is an attractive force, the gravitational force in one case the electric force in the other. But a moving electron would emit electro-magnetic waves, it would lose energy and after a fraction of second it would fall into the nucleus. What prevents the electron from falling in? Quantum mechanics is responsible for this. In quantum mechanics the energies of the system are quantized, this means that the electron can only have very definite energies. There is a minimum energy state and the electron cannot decay any further by emitting electro-magnetic waves. In conclusion, quantum mechanics is crucial for the stability of matter. It is the reason we do not fall through the floor. In quantum mechanics particles do not have well defined positions and velocities. In fact, when the electron is in its low energy state we cannot say precisely where it is. It is more probable to find it near the nucleus than far away. So in quantum mechanics some things are a bit fuzzy, like the position of the electron. Quantum mechanics gives us a very precise way of characterizing and describing this fuzziness.

2.2 Relativity

Another important ingredient in the description of nature is the intimate relationship between space and time that results from the principle of "relativity." Relativity says that two observers which move at constant velocity relative to each other should see the laws of physics in the same way. They should also see light propagating at the same speed. This is possible only if time flows differently for each of the observers. If someone flew by us we would see his or her watch ticking more slowly. This is a small effect if we move at ordinary velocities, but it is a large effect if we move at velocities close to the speed of light. For example, there are particles that are unstable and decay after some time. In particle accelerators physicists can make these particles travel very fast, at speeds close to the speed of light, then they observe that these particles take much longer to decay. The clock is ticking more slowly for them. Relativity implies that space and time are related. So it is convenient to think of them as a single entity, space-time. Our space-time has four dimensions. It has three spatial dimensions and one time dimension. Relativity also implies that information cannot travel faster than the speed of light.

2.3 Gravity

The final ingredient in our understanding of nature is gravity. We have all heard about Newton's theory of gravity, which says massive bodies attract each other through gravitational forces. For this reason objects fall, the earth goes around the sun, etc. In Newton's theory gravitational forces are instantaneous, so that if we were to move the sun now, we would feel the change in the gravitational force instantaneously here on the earth. Relativity, on the other hand, says that no information can travel faster than light. So that if we move the sun, we could only feel any effect on the earth after eight minutes, the time it takes the light to go from the sun to the earth. Einstein realized that there was a contradiction between relativity and Newton's theory and he devised a way to solve it. His resolution to the problem involved a great conceptual jump. He proposed that space-time can be curved, it has some shape. This shape is determined by the matter distribution. Particles move along the trajectory that most closely resembles a straight line in this curved space-time. So the sun curves space-time and the earth is moving along a trajectory that most closely resembles a straight line. An analogy is the following. The classical picture of space-time and particles moving in it is like a billiard table where billiard balls move, hit each other, etc. The balls move but the billiard table is totally rigid and does not move. Einstein's theory is analogous to replacing the billiard table by an elastic rubber sheet. The billiard balls deform the shape of the rubber sheet. If we have a very heavy billiard ball it will deform more the rubber sheet and if we throw another ball its trajectory will be determined by the shape of the rubber sheet. Interestingly, even if we do not have any balls the rubber sheet can oscillate and waves can propagate. Similarly in space-time there can be gravitational waves. These have been measured indirectly and some experiments are currently under way to see them directly. In summary, space-time is dynamical, it can oscillate, it can move. Matter curves space-time and the motion of matter depends on the shape of space-time.

3 The Problem

These are the laws of physics as we know them today, they explain most of what we see, including how we see. Biology and chemistry boil down to the interactions of these particles. Most of physics today is devoted to trying to approximate these laws, developing methods to do calculations with them, experimentally observing how different configurations of particles behave, observing how matter is distributed in the universe, etc.

Both the theory of interacting quantum particles that we described above and the theory of gravity have been tested to a high degree of precision. You might be surprised then to learn that these laws are inconsistent! Yes, they are mathematically, logically inconsistent. In practice this means that there are processes, or physical situations, that we cannot possibly explain using these laws. The problem comes from the fact that the theory of gravity is not consistent with quantum mechanics, which is a crucial component of our understanding of matter. Why does this contradiction never show up in the experiments we do? The reason is that quantum mechanics is important for small things and it is negligible for large things. On the other hand gravity is important for heavy things. Most objects that we deal with are either small and light, like atoms, elementary particles, etc, so that we can neglect gravity, or big and heavy, like us, planets, etc, so that we can neglect quantum mechanics.

So all experiments done to date only involve situations where one can neglect gravity or one can neglect quantum mechanics. If we had a small and heavy object we would need a new theory to describe it, a theory that manages to put together quantum mechanics and gravity. Such a theory is called a theory of "quantum gravity." The most important problem where something small and heavy arises is in the beginning of the universe. There is a big amount of evidence that the universe is expanding. So if we go back in time the universe would appear smaller and smaller until it is all concentrated in a very small region. The universe as a whole is certainly heavy, so we have a small and heavy object and therefore the effects of quantum gravity would be important. The question is how to describe this process, to explain what comes out of it, why the universe is as it is, etc. It is crucial to understand quantum gravity to understand this process. Quantum gravity is not yet understood well enough to tackle this problem.

There is another problem where quantum gravity is relevant and where a lot of progress has recently been made. The problem is to understand the quantum aspects of black holes. If we tried to make a small and heavy object by putting lots of matter is a small region, we would find that it collapses to a black hole. There is evidence that this actually does happen for very massive stars, which collapse under their own weight. When a black hole forms a small region of very high curvature develops where current theories would fail. This region, however, is surrounded by a horizon, which is a surface separating the interior from the exterior in such a way that something in the interior can never escape to the exterior. This horizon surface has some size. This size is about one mile for a black hole of the mass of a typical collapsing star. The horizon's presence implies that one would never see the region of strong curvature from the outside, and that whatever happens there will not leak out to the outside, according to Einstein's theory. Quantum mechanics on the other hand implies that some of the energy that fell into the black hole does actually leak out. The black hole emits radiation with a characteristic temperature. For astrophysical black holes this radiation is too weak to be detected, the temperature is too low. A black hole in empty space would gradually loose its mass due to this radiation. To first approximation this radiation seems to be unrelated to what fell into the black hole. But according to quantum mechanics the radiation should know about the objects that fell into the black hole. In the full quantum theory one should *in principle* be able to calculate what comes out from the black hole. Let us make an analogy. Suppose we had a star. If we knew all the quantum state of the star we would know all the properties of the radiation that comes out. In practice it is very difficult to know the quantum state of a system of many particles, let alone a star. In the case of the black hole, all the information about its quantum state seems to have fallen behind the horizon, so it seem that we cannot know it even in principle. The fact that quantum mechanics says that we need the information and that gravity says that we cannot have it, because it is behind the horizon, is called the "information paradox." We will see how quantum gravity resolves this paradox.

In summary, our current theories of physics are not consistent. Despite this we can use them for explaining almost everything except processes like the creation of the universe or some aspects of the evolution of black holes. For this need a better theory.

4 String theory

4.1 The Problem with Quantum Gravity

Before the 20th century we had just classical physics. In the beginning of the 20th century relativity and quantum mechanics were discovered. During the 20th century it was understood how to put together relativity and quantum mechanics into the modern theory of particle physics. In 1915 Einstein understood how to put together relativity and gravitation into the theory called "general relativity." We can think of classical physics as describing particles moving in a fixed space-time. Quantum physics describes fuzzy particles, particles that do not have well defined positions in a fixed space-time. General relativity describes particles moving in a moving space-time. The full theory of nature should incorporate both departures from classical physics, quantum mechanics and general relativity, this full theory is a theory of quantum gravity.

The earliest attempts in trying to put together Einstein's gravity together with quantum mechanics failed. The simplest calculational procedures that work in the case of particle physics give infinite answers that do not make sense. In the 1970's string theory was born. Though it started its life as an attempt to understand the strong force, it became clear that the theory was really describing gravity and that it could be used to solve the contradiction between quantum mechanics and gravity. It is really a theory under construction and we have not figured out all the rules that govern the theory, but we have figured out a great deal of them. It gives a unified description of all interactions. It can explain quantum aspects of black holes, and that is what we will focus on.

4.2 Basic Idea

The way normal theories are quantized is to start with a simple configuration, in this case it could be a flat space-time, and then consider small deviations or small excitations around it. The small excitations of a flat, empty, space-time are gravitational waves. According to the rules of quantum mechanics the energy that these waves can carry are quantized. The wave carrying the minimum amount of energy, the quantum of energy, can be viewed as a particle. In the case of gravitational waves this particle is called a graviton. In normal quantum theories this particle would be point-like.

In string theory we replace particles by strings. Strings are one dimensional objects. They are tiny loops. We can view them as microscopic rubber bands. These strings can oscillate. These strings can oscillate with no friction, as opposed to rubber bands. The string oscillation energies are quantized, as in any other quantum mechanical system. The string with the least possible oscillation energy is the graviton and it is massless since the minimum oscillation energy is zero. Massless particles always travel at the speed of light. This agrees with the fact that gravitational waves also move at the speed of light. Strings that have more oscillation energy are interpreted as massive particles. Different particles would be strings that oscillate in different ways. These strings can interact by splitting and joining interactions. So two strings can join to form a single string. These interactions lead to a consistent theory. There are precise mathematical formulas behind these words. The results of calculations using these formulas are sensible, i.e. we do not get infinite answers. At long distances we would see the strings as point-like objects. Since we have not yet seen experimentally any string inside known particles we conclude that the size of these vibrating strings should be smaller than the smallest distance we can probe with our current experiments, which is about 10^{-18} meters. There has been a lot of work understanding more precisely how strings can have properties similar to the properties today's elementary particles.

4.3 Black holes

We said that black holes arise when we bring many particles together in a small region of space. Since particles are strings, we would say that black holes are a collection of strings all put together. The problem with this picture is that it is very hard to say how a large and strongly interacting collection of strings behaves. So despite that it has been known for a long time that strings describe quantum gravity, it was only recently that concrete calculations describing quantum aspects of black hole were done.

The progress in recent years was possible thanks to development of new ways of viewing string theory. We are going to describe now one such new description of string theory.

Imagine that you have some object, it could be a black hole, a normal star, a gravitational wave, or any other object, including just the vacuum. Then we surround it with an imaginary surface that is very far away from the object. Then we have two ways of describing what is happening inside. One is the traditional way that we were describing above, through strings, quantum gravity, etc. The second is to think that we have a theory of particles that move on the sphere that is far away. We will call this particle theory the "boundary theory." Then we can describe any object in the interior, including black holes, as excitations in the boundary theory. So we translated the problem of understanding black holes to the problem of understanding certain special configurations in the boundary theory. What is the advantage? First, we know that normal particle theories preserve information, then black holes should preserve information too. Second, in some cases it is possible to do concrete computations in the boundary theory which explain some of the quantum aspects of black holes.

This boundary theory is really an appropriate description for special space-times that have a natural boundaries. The simplest example is a negatively curved space-time with constant curvature. The simplest possible positively curved space that we can imagine is a sphere. If we add time we get the simplest positively curved space-time, it is called "de Sitter" after its discoverer. The simplest negatively curved one is called anti-de-Sitter. This space-time is static, it does not expand or contract (as opposed to the expanding space-time that describes our universe). That is has a boundary just means that there is a region far away where light can go and come back in finite time, so that it looks as if it has a boundary from which it is reflecting. The particle theory that lives at the boundary is a rather conventional particle theory, of the type we believe we understand, at least conceptually, fairly well. So one is replacing the complicated problem of quantizing gravity, by the problem of understanding a particular particle theory that lives at the boundary of space-time.

This description of the bulk physics in terms of theory at the boundary is analogous to the way a hologram works. A hologram is one of those pictures that looks three dimensional. A hologram is stored on a two dimensional photographic plate. Nevertheless, it manages to encode the full three dimensional information of the three dimensional object. Our boundary theory, which lives in the three dimensional boundary of space-time, encodes the full four dimensional information about an object in a four dimensional space-time.

5 Where are we? Where are we going?

Let us now summarize a bit the status of string theory. In the 1970's string theory was discovered as a possible theory for the strong force. It was later realized that it can be used to describe quantum gravity. But for some time very few people worked on it. In the mid 1980's some calculations showed that the theory passed very stringent mathematical consistency checks and that it was a viable theory for describing all interactions in a unified way. This sparked a great deal of interest and there was more activity in the field. Some physicists however thought that the ideas were too speculative and were not very enthusiastic about it. Princeton was then the most active center in this field. In the mid 1990's many interesting results were found, it was understood that string theory was part of a bigger theory called M-theory which admitted many equivalent descriptions. All of known consistent quantum gravity theories were special limits of the same theory. This theory contains also other objects such as membranes. The understanding of these objects led to the theories we saw today about black holes.

At this point one of the major unresolved problems is to understand string theory, or M-theory, in space-times that describe cosmological situations, space-times that expand. Understanding these space-times would lead to a resolution of the big bang singularity and would explain how the universe started.

One of the lessons of the black hole problem is that it is useful to go to another description where spacetime arises dynamically, as an approximation. The black hole singularity is similar in some respects to the big bang singularity. So understanding black holes better would probably lead to a better understanding of cosmology.

Let us end by drawing a comparison. Einstein saw that Newton's theory and relativity were inconsistent. It took him around 10 years to come up with a consistent solution. It can be argued that his theory of general relativity was born out of trying to solve this contradiction and it did not have much experimental input. Later experiments were done that tested his theory in an impressive way. String theorists are playing a similar game. We are trying to solve a similar contradiction. We do not have experiments to guide us, unfortunately. However we hope that once we find a solution, that will be the right theory describing nature. The problem is more complex, it has taken more people, working for around 20 years to get us where we are now. A lot of progress has been made, but there is still a lot of work to do.

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