

THE THEORY OF EVERYTHING

Stephen Hawking

The following is a summary of Stephen Hawking's talk as printed by The Bulletin of the University of Toronto.



On April 29, 1980, I gave my inaugural lecture as the Lucasian Professor of mathematics at Cambridge. My title was, *Is the End in Sight for Theoretical Physics?* I described the progress we had already made in the last hundred years in understanding the universe and asked what the chances were that we would find a complete unified theory of everything by the end of the century. Well, the end of the century is almost here. Although we have come a long way, particularly in the last three years, it doesn't look as if we are going to quite make it.

In my 1980 lecture I described how we had broken down the problem of finding a theory of everything into a number of more manageable parts. First of all we had divided the description of the universe around us into two parts. One part is a set of local laws that tell us how each region of the universe evolves in time, if we know its initial state, and how it is affected by other regions. The other part is a set of what are called boundary conditions. These specify what happens at the edge of space and time. They determine how the universe begins and, maybe, how it ends. Many people, including probably a majority of physicists, feel that the task of theoretical physics should be confined to the first part, that of formulating local laws that describe how the universe evolves in time. They would regard the question of how the initial state is determined as being beyond the scope of physics and belonging to the realms of metaphysics or religion. But I'm an unashamed rationalist. In my opinion the boundary conditions of the universe that determine its initial state are as legitimate a matter for scientific inquiry as are the laws that govern how it evolves.

In the early 1960s the forces that were known to physics were classified into four categories that seemed to be separate and independent of each other. The first of the four categories was the gravitational force, which is carried by a particle called the graviton. Gravity is by far the weakest of the four forces. However, it makes up for its low strength by having two important properties. The first is that it is universal. That is, it affects every particle in the universe in the same way. All bodies are attracted to each other. None are unaffected or repelled by gravity. The second important property of the gravitational force is that it can operate over long distances. Together, these two properties mean that the gravitational forces between the particles in a large body all add up and can dominate over all other forces.

The second of the four categories into which the forces were divided is the electromagnetic force, which is carried by a particle called the photon. Electromagnetism is a million billion billion billion billion times more powerful than the gravitational force, and like gravity, it can act over great distances. However, unlike gravity, it does not act on all particles in the same way. Some particles are attracted, some are unaffected and some are repelled.





The attractions and repulsions between the particles in two large bodies will cancel each out almost exactly, unlike the gravitational forces between the particles, which will all be attractive. That is why one falls towards the Earth, and not towards a television set. On the other hand, on the scale of molecules and atoms, with only a relatively small number of particles, electromagnetic forces dominate gravitational forces utterly. On the even smaller scale of the nucleus of an atom, a trillionth of a centimetre, the third and fourth categories, the weak and strong nuclear forces, dominate other forces.

Gravity and electromagnetism are described by what are called field theories, in which there are a set of numbers at each point of space and time that determine the gravitational or electromagnetic forces. When I began research in 1962, it was generally believed that the weak and strong nuclear forces could not be described by a field theory. But reports of the death of field theory proved to be an exaggeration. A new type of field theory was put forward by Chen Ning Yang and Robert Mills. In 1967 Abdus Salam and Steven Weinberg showed that a theory of this type could not only describe the weak nuclear forces but could also unify them with the electromagnetic force. I remember this field theory being treated with great scorn by most particle physicists. However, it agreed so well with experiments that the 1979 Nobel Prize was awarded to Salam, Weinberg and Glashow, who had proposed similar unified theories. The Nobel committee took quite a gamble because the final confirmation of the theory didn't come until 1983, with the discovery of the W and Z particles. (That is to say, the W and Zed particles, for those of us who are British and don't use an American speech synthesizer.)

The success sparked a search for a single "grand unified" Yang-Mills theory that would describe all three kinds of force. Grand unified theories are not very satisfactory. Indeed, their name is rather an exaggeration. They are not that grand as theories because they contain about 40 numbers that cannot be predicted in advance but have to be adjusted to agree with experiments. One would hope the ultimate theory of the universe is unique and does not contain any adjustable quantities. How would those values have been chosen? But the most powerful objection to the grand unified theories was that they weren't fully unified. They didn't include gravity and there wasn't any obvious way of extending them so that they did. It may be that there is no single fundamental theory. Instead there may be a collection of apparently different theories, each of which works well in certain situations. Different theories agree with each other where their regions of validity overlap. Thus they can all be regarded as different aspects of the same theory. But there may be no single formulation of the theory that can be applied in all situations.

Theoretical physics may be like mapping the Earth. One can accurately represent a small region of the Earth's surface, as a map on a sheet of paper. But if one tries to map a larger region, one gets distortions because of the curvature of the Earth. It is not possible to represent every point on the Earth's surface on a single map. Instead one uses a collection of maps, which agree in the regions where they overlap.



As I said, even if we find a complete unified theory, either in a single formulation, or as a series of overlapping theories, we will have solved only half the problem. The unified theory will tell us how the universe evolves in time, given the initial state. But the theory does not in itself specify the boundary conditions at the edge of space and time that determine the initial state. This question is fundamental to cosmology. We can observe the present state of the universe and we can use the laws of physics to calculate what it must have been at earlier times. But all that tells us is that the universe is as it is now because it was as it was then. We cannot understand why the universe is the way it is unless cosmology becomes a science, in the sense it can make predictions. And that requires a theory of the boundary conditions of the universe.



There have been various suggestions for the initial conditions of the universe, such as the tunnelling hypothesis and the so-called pre-big bang scenario. But in my opinion by far the most elegant is what Jim Hartle and I called the no-boundary proposal. This can be paraphrased as, the boundary condition of the universe is that it has no boundary. In other words space and imaginary time together are curved back on themselves to form a closed surface like the surface of the Earth but with more dimensions. The surface of the Earth has no boundary, either. There are no reliable reports of someone falling over the edge of the world.

The no-boundary condition and the other theories are just proposals for the boundary conditions of the universe. To test them we have to calculate what predictions they make and compare them with the new observations that are coming in. At the moment, the observations are not good enough to distinguish between these different kinds of maps. But new observations in the next few years may settle the question. This is an exciting time in cosmology. My money is on the no-boundary condition. It is such an elegant explanation, I'm sure God would have chosen it.



The progress that has been made in unifying gravity with the other forces has been entirely theoretical. This has led to charges from people like John Horgan that physics is dead because it has become just a mathematical game, not related to experiment. But I don't agree. Although we can't produce particles of the Planck energy -- the energy at which gravity would be unified with other forces -- there are predictions that can be tested at lower energies. The Superconducting Super Collider that was being built in Texas would have reached these energies but it was cancelled when the U.S. went through a fit of feeling poor. So we shall have to wait for the Large Hadron Collider that is being built in Geneva.

Assuming that the Geneva experiments confirm current theory, what are the prospects for a complete unified theory? In 1980 I said I thought there was a 50-50 chance of us finding a complete unified theory in the next 20 years. That is still my estimate, but the 20 years begins now. I will be back in another 20 years to tell you if we made it.

Professor Stephen Hawking of the University of Cambridge spoke to a sellout crowd at Convocation Hall April 27, 1998. The event was sponsored by the Global Knowledge Foundation.